Organic Rotational No-Till System Adapted for Manitoba, Canada

BY

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ABSTRACT

Halde, Caroline. Ph.D., The University of Manitoba, August, 2014. Organic Rotational No-Till System Adapted for Manitoba, Canada. Major Professor; Martin H. Entz.

In the northern Great Plains of Canada, there has been limited research conducted on reduced-tillage grain production systems managed organically. The overall goal of the thesis was to adapt an organic rotational no-till system to the growing conditions of Manitoba, and to test its agronomic performance. A set of four experiments were conducted between 2010 and 2012, in Carman, MB, Canada. The first study selected cover crop mulches suitable for organic rotational no-till systems in Manitoba. Mulches with hairy vetch (*Vicia villosa* Roth) showed the most promising results, producing the highest mulch biomass and organic no-till spring wheat (*Triticum aestivum* L.) yield. The second study compared the agronomic performance of an organic rotational no-till system with two organic tilled systems. Organic flax (*Linum usitatissimum* L.) yield was significantly higher in no-till than in the two tillage treatments. The third experiment determined the agronomic performance of a continuous organic no-till system, and compared it with those of tilled and conventionally managed systems. Reduced content of soil nitrate-N and perennial weeds limited crop productivity after 4 yr under organic continuous no-till. The fourth experiment used the litter bag technique to determine the effect of plant species and mulch application rate on surface-applied cover crop decomposition and mulch quality parameters over time. Oilseed radish (*Raphanus sativus* L.) decomposed the fastest and barley (*Hordeum vulgare* L.) decomposed the slowest,

and the effect of mulch application rate on mulch biomass was not consistent among sites. In conclusion, the successful adaptation of the organic rotational no-till system to the growing conditions of Manitoba reduced the need for tillage for a period of 1.5 to 2 yr.

FOREWORD

The format of the Agronomy Journal has been used for preparation of the manuscripts within the thesis. The thesis follows the style outlined by the Department of Plant Science of the University of Manitoba, Winnipeg, MB, Canada. The thesis includes four manuscripts, preceded by an introduction and a literature review. A general discussion and conclusions section, a list of references cited, and appendices follow the four manuscripts.

1.0 INTRODUCTION

Grain growers in Canada face many challenges linked to agricultural production. Among them, increased occurrence of herbicide-resistant weeds has been observed in all regions of the country (Beckie et al., 2006) and have become an economical problem for Canadian farmers. A traditional alternative to herbicide use for weed control is the use of tillage. Tillage also plays a crucial role in seed bed preparation and nutrient cycling (e.g. organic matter mineralization) by incorporating crop residue, amendments and fertilizers into the soil. However, frequent tillage may lead to soil degradation and environmental pollution by soil erosion (Tiessen et al., 2010), and it requires a large quantity of fossil fuel energy (Woods et al., 2010). Tillage has also caused organic matter losses in the Canadian Prairies (Janzen, 2001). Extreme weather events and fluctuations of the cost of fossil fuel and agricultural inputs are other important challenges faced by farmers.

To address these complex issues, efforts have been invested in designing innovative sustainable farming systems that would reduce both tillage and herbicide use intensity (Brainard et al., 2013). These agricultural systems aim at reducing tillage without increasing dependence on herbicides or enhancing the selection pressure for herbicide resistant weeds, while still maintaining adequate weed control with satisfactory grain crop productivity. Reduced-tillage systems include non-inversion tillage practices such as full-width tillage, ridge-till, strip-till, as well as no-till practices (Brainard et al., 2013), with various levels of herbicide use.

Reduced-tillage systems without herbicides have received great attention in Europe (Melander et al., 2013). Research teams in 11 European countries initiated a joint research project in 2011, called TILMAN-ORG. This project is currently investigating the impact of reduced tillage and green manures on organic farms. Preliminary results showed increased organic carbon (C) content, microbial biomass C, and microbial activity in soil top layers, and water conservation in reduced tillage organic cropping systems (Cooper et al., 2013).

Contrary to Europe, where efforts have focused on decreasing the frequency of inversion tillage used by organic farmers, the focus of North American researchers has been on eliminating tillage in organic cropping systems for consecutive months (Carr et al., 2012). Consequently, a no-till system with mulches inspired from South American no-till farmers has been adapted to the North American organic grain production conditions to become an “organic rotational no-till system”. This system reduces tillage by rotating between a cover crop established with tillage and a cash crop no-till planted into the cover crop mulch. These organic rotational no-till systems have been studied intensively in the past decade in the United States of America, and there are a number of successful examples of its adaptation in various regions of the country (Davis, 2010; Delate et al., 2011; Mirsky et al., 2012; Mischler et al., 2010a; Mischler et al., 2010b; Ryan et al., 2011). These systems have shown important environmental gains, with less energy use than organic till systems while maintaining similar yields (Ryan, 2010). Hence, there is an interest to study this organic rotational no-till system in Canada, and in Manitoba, particularly.

The overall objective of the following Ph.D. thesis is to adapt the cover crop-based organic rotational no-till system to the growing conditions of Manitoba, Canada. The thesis presents results of research conducted on the agronomy of the organic rotational no-till system for Manitoba, Canada. Four field experiments were conducted during 2010-2012 at Carman, Manitoba. The main research objectives of these studies were:

1. To identify cover crops suited for an organic rotational no-system in Manitoba (manuscript #1);
2. To compare the agronomic performance of the organic rotational no-till system with systems where cover crops are terminated by tillage (manuscript #2);
3. To determine the agronomic performance of a continuous organic no-till system, and to compare it with those of tilled and conventionally managed systems, to identify the factors limiting the productivity of the organic no-till system (manuscript #3);
4. To study the decomposition and nutrient release from cover crop mulches in a production condition in Manitoba (manuscript #4).

2.0 LITERATURE REVIEW

2.1 Reduced-Tillage Systems in Organic Agriculture in the Northern Great Plains of Canada

No-till grain production is very common in conventional agriculture in the northern Great Plains of Canada. About 65%, 70%, and 24% of the land is farmed under no-tillage practices in Alberta, Saskatchewan, and Manitoba, respectively (Statistics Canada, 2011). However, in the northern Great Plains of Canada, there has been limited research conducted on reduced-tillage grain production systems managed organically or without herbicides.

Several implements for minimum tillage have been tested to terminate cover crops in organic reduced-tillage grain systems, including the minimum till rotary hoe, wide blade cultivator, flail mower, and roller-crimper. Shirtliffe and Johnson (2012) tested the efficacy of rotary hoeing for weed control in field pea (*Pisum sativum* L.) in Saskatchewan. Another experiment by Shirtliffe and Johnson (2012) also compared the effect of flail-mowing, roller-crimping, and tillage for terminating a faba bean (*Vicia faba* L.) and a field pea green manure crop. The authors concluded that the use of the roller-crimper was a viable option to terminate a field pea green manure crop. However, tillage was still required in the fall and the following spring.

The wide blade cultivator, also known as the Nobel blade, was found to be a viable alternative to terminate a spring-seeded field pea/barley (*Hordeum vulgare* L.) green manure (Podolsky, 2013). In this study conducted between 2010 and 2012 at Carman, Manitoba, the use of the wide blade cultivator resulted in spring wheat (*Triticum aestivum* L.) yields which were not significantly different than a standard tilled treatment, at three site-years out of four. In an earlier study conducted by Blackshaw et al. (2001) in Alberta, a yellow sweet clover [*Melilotus officinalis* (L.) Pall.] green manure fallow replacement crop was successfully terminated with a wide blade cultivator. Weed suppression by yellow sweet clover in June after the fallow year did not differ when the green manure was disced in, incorporated using the wide blade cultivator, hayed, or mowed and left on the soil surface. Therefore, replacing tillage by the use of the wide-blade cultivator or mowing was effective at terminating a yellow sweet clover green manure and provided sufficient weed control (Blackshaw et al., 2001).

Grazing has also been investigated as a method for green manure management and weed control in organic reduced-tillage systems in Canada. A three-year experiment conducted in Manitoba concluded that grazing green manures by sheep does not affect subsequent spring wheat and cereal rye (*Secale cereale* L.) crop yields, when compared with a treatment with green manures incorporated using a tandem disk treatment (Cicek et al., 2014). In that study, grazing by sheep even increased N availability of green manures for the subsequent crop. A review by Thiessen Martens and Entz (2011) also showed that even at high nutrient retention rates, 70-75% of nutrients ingested by grazing animals are excreted and subsequently recycled within the system, making grazing of green manures a viable option to manage green manures and reduce tillage.

Replacing fallow by continuously cropping the land also allows for a reduction in tillage. When reviewing findings from long-term studies across the Canadian Prairies, Janzen et al. (1998) found that reduction in tillage intensity in Canadian Prairie soils increased soil organic carbon, with greater gains in soil organic carbon under continuous cropping than in a system with fallow. Integrating a perennial or biennial forage in the crop rotation is another efficient way to reduce the need for tillage. A study by Blackshaw et al. (2001), yellow sweet clover, a biennial forage, was successfully used as a replacement for fallow. It was undersown in to various cash crops such as field pea, flax (*Linum usitatissimum* L.), and Indian mustard [*Brassica juncea* (L.) Czern.], and then terminated in June of the following fallow year.

One technique of reduced-tillage, roller-crimpers, has received considerable attention in the U.S.A., but only little attention by farmers and researchers in Canada. Only a handful of experiments have been conducted across Canada to examine the feasibility of implementing no-till practices using the roller-crimper in herbicide-free grain production systems. The next section of the literature review will focus on this technique.

2.2 Organic Rotational No-Till System

2.2.1 Origin of the System

One way to reduce tillage on organic farms without using herbicides is to integrate the use of mulches in the cropping system. The mulch farming system has been widely used by Brazilian no-till farmers for over three decades (Bernoux et al., 2006). The use of cover crop mulches has been widely integrated in Brazilian no-till cropping systems since the 1980s and has been qualified “the single most fundamental key to the success of [zero-till] systems in Brazil” (Bolliger et al., 2006). Many benefits have been associated with the use of cover crop mulches in the zero-till system in Brazil, including water retention, permanent soil surface cover, weed control, increase in soil organic matter, and pest management (Bernoux et al., 2006; Bolliger et al., 2006). However, most of the findings on the zero-till system in Brazil and other South American countries are published in conference proceedings and local literature in the Portuguese or Spanish language, creating a barrier for the dissemination of knowledge in this area of research.

2.2.2 Adaptation of the South American Mulch Production Systems in North America

In an effort to limit tillage and herbicide use on grain farms, an organic rotational system inspired by no-till Brazilian agriculture has been developed in North American growing conditions. This system combines the use of cover crops with that of a roller-crimper to terminate them, creating a mulch that provides weed control to the subsequent cash crop. In the organic rotational no-till system, mulch from cover crops are used to suppress weeds instead of mechanical cultivation. It is an innovative and ecologically-based weed management strategy for sustainable farming systems. Farmers using this alternative to herbicides can get an interesting premium by marketing their grains on the ‘organic’, ‘herbicide-free’ or 'pesticide-free’ market.

Great progress in adapting organic rotational no-till crop production to North American growing conditions has been made in the past decade. Research has been conducted on organic no-till production systems in U.S.A. since the early 2000s (Carr et al., 2013), and in Canada since 2006 (Estevez, 2008). The organic rotational no-till system has been adapted differently in eastern U.S.A. and Canada and in the northern Great Plains. Local adaptation of the organic rotational no-till system is influenced by the geographical and environmental conditions such as precipitation, growing season length, and soil type.

2.2.2.1 For a Long Growing Season in Eastern U.S.A. and Canada

The work on organic rotational no-till systems in North America was pioneered in the early 2000s at the Rodale Institute, in Pennsylvania, U.S.A. (Moyer, 2011) and by engineers and agricultural scientists at USDA-ARS National Soil Dynamics Laboratory in Alabama, U.S.A. (Ashford and Reeves, 2003; Kornecki et al., 2006; Raper et al., 2004). The organic rotational no-till systems adapted for the eastern regions of U.S.A. and Canada consist of fall-seeded cover crops to produce biomass that is rolled in early-spring to produce mulch for the subsequent spring-seeded crop.

There have been many successful examples of adaptation of the mulch production system in various regions of the U.S.A., located in USDA zones 7A to 5A. In Pennsylvania, organic no-till corn (*Zea mays* L.) was grown in a hairy vetch (*Vicia villosa* Roth) mulch and organic no-till soybean [*Glycine max* (L.) Merr.] into a cereal rye mulch, with overall comparable or greater yields than county averages (Mirsky et al., 2012; Mischler et al., 2010a; Mischler et al., 2010b). In Iowa, a cereal rye/vetch and a winter wheat/winter pea mulch has been tested for weed control in organic no-till soybean, corn and irrigated tomato (*Solanum lycopersicum* L.), with the cereal rye/vetch mulch providing the best weed suppression (Delate et al., 2011). Trials have also been conducted in Illinois with organic soybeans grown into pure cereal rye or pure vetch mulch in Illinois (Davis, 2010). Farmers have shown interest in cover crop-based organic rotational no-till systems, because it can save time and energy, and it also moderates soil temperature, reduces soil erosion, and conserves soil moisture. Mirsky et al. (2012) reported that organic rotational no-till required 27% less diesel fuel and 31% less labor and resulted in 22% lower greenhouse gas emissions than organic tilled systems.

Promising studies on rolled fall-seeded cover crops inspired by work done in U.S.A are also being conducted across Canada. The first field trials assessing the use of the roller-crimper to terminate cover crops in an organic rotational no-till system in eastern Canada were conducted in Québec in 2006-2007 by Estevez (2008). Organic no-till soybeans were grown into a mulch of pure cereal rye, pure winter wheat, and a mixture of cereal rye and winter wheat. The author observed reduced soybean yields in the organic rotational system compared with those in a system with tillage. The difference in yield was attributed to low mulch biomass and to difficulties in terminating the cover crop with the roller-crimper. Other research trials have shown promising results for sweet corn and soybean seeded into hairy vetch and/or cereal rye mulches in Québec (Lefebvre et al., 2011; Leroux et al., 2011).

2.2.2.2 For a Short Growing Season in the Northern Great Plains of Canada

The organic rotational no-till system adapted for the northern continental climate of Manitoba (Agriculture Canada plant hardiness zone 3A) differs in many aspects from the system studied in the mid-Atlantic region of the U.S.A. (USDA zones 5A-7A). First, environmental conditions due to Manitoba's geographical location pose important limitations to the successful adaptation of the organic rotational no-till system in Manitoba, Canada. The climate of the northern Great Plains of Canada is characterized by a short growing season and low annual precipitation (~300-550 mm), that greatly reduces the possibilities of growing cover crops of adequate biomass after a cash crop harvest in the fall. In southern Manitoba, the short growing season makes it difficult to produce biomass of fall-seeded cover crops greater than 2.4 Mg ha^{-1} (H. Cicek, personal communication, 2013; Thiessen Martens et al., 2001). Cover crops can be difficult to establish later in the growing season (July or August), because water becomes limiting in mid-summer in this environment receiving on average less than 400 mm of precipitation during the growing season (1 May – 31 Oct.) (Environment Canada, 2013). Therefore, opportunities for cover cropping are limited in Manitoba.

Secondly, the singularity of the farming system in Manitoba also influences how the system can be adapted in the region. Access to animal manure is limited (Légère et al., 2013). Organic farmers in the eastern region of the northern Great Plains depend mostly on N-fixing green manures and their mineralization by incorporation into the soil for N fertility (Entz et al., 2001). Full-year cover cropping is a common practice by organic farmers in the northern Great Plains of Canada (Entz et al., 2001). This practice of growing a green manure over a full-year has been found profitable for growers in the northern Great Plains of Canada, compared with a year of fallow (Smith et al., 2004) or continuous cropping under conventional management (Fryza, 2013).

Vaisman et al. (2011) were the first to report results on organic rotational no-till grain production using the roller-crimper in the northern Great Plains of Canada. In Manitoba, Canada, the organic rotational system consists of a spring-seeded cover crop grown to produce a mulch, followed by a spring-seeded cash crop no-till planted into the cover crop mulch. The cover crops are seeded with tillage in the spring (mid-May to early-June). A roller-crimper is used to terminate the cover crops at the flowering stage in mid-summer (late-July to early-August), instead of letting the cover crops winter-kill, in order to insure that they will not set seed. The cover crop mulch is then left to decompose on the soil surface over the fall and the winter (August to May), until a cash crop is no-till planted into the mulch in the following spring. These rolled mulches provide weed control and N inputs for the subsequent crop (Vaisman et al., 2011).

Vaisman et al. (2011) observed no yield penalty when completely eliminating tillage in organic no-till spring wheat grown on rolled pea/oat (*Avena sativa* L.) and pure pea cover crop mulches compared with five other green manure management treatments with different intensities of tillage, at two site-years out of three. However, other trials conducted in the northern Great Plains of Canada did not result in the same success. Podolsky (2013) reported reduced yields of organic no-till spring wheat grown on a pea/barley cover crop mulch in Carman, MB, and in Lethbridge, AB. They attributed the yield penalty in organic rotational no-till systems to low mulch biomass, low soil nitrate in the spring, weed competition, and the inadequate termination timing and efficacy of the roller-crimper to control barley regrowth. Other field studies testing the efficacy of the roller-crimper have also been conducted in Lethbridge, AB (Blackshaw et al., 2014).

Spring-seeded hairy vetch survived the winters in southern Alberta, and became a volunteer weed the following year. Therefore, mulches with hairy vetch did not provide sufficient weed control to the cash crops.

2.3 Technicalities of the Organic Rotational No-Till Systems

2.3.1 Mulch Production

2.3.1.1 Selecting Cover Crop Species

Cover crops are the key component to the organic rotational no-till system, and selecting cover crop species to create mulch is the first step in making the system work. Cover crop species will affect biomass production and decomposition, the ability to control weeds and supply N to the subsequent cash crop.

Legume-containing cover crops are beneficial to crop productivity in an organic rotational no-till system, by providing N to soils through biological N fixation. However, while legume species have the ability to fix N, they also have high seed cost compared with grasses (Brandi-Dohrn et al., 1997). Grasses are also fast-growing and have the ability to capture excess soil nitrates. Among legume species, hairy vetch is a key legume species used to create mulches in organic rotational no-till systems across the world. Hairy vetch has been used in pure stand or in mixture with a grass (e.g. cereal rye). Hairy vetch’s high N concentration (Maul et al., 2011) makes it an ideal cover crop species to create N-rich mulches and to supply N to the subsequent crop. Recent research has focused on the development and evaluation of new hairy vetch cultivars (Maul et al., 2011; Teasdale et al., 2004). Desirable traits of fall-seeded hairy vetch specific for organic rotational no-till systems in northeastern U.S.A. are winter hardiness and early flowering for early termination and planting of the cash crop.

The selection of cover crop species will also affect the ability of the mulch to manage weeds due to their physical properties and allelopathic activity (discussed in section 2.3.3.1). For example, Davis (2010) observed differences in weed suppression from a rolled cereal rye compared with that of a rolled hairy vetch, suggesting that the benefits of terminating a cover crop with a roller-crimper depends on the species of the cover crop. Another criterion in cover crop species selection regards the response of cover crop species to the roller-crimper (discussed in section 2.3.1.3).

Benefits linked to cover crop use can be optimized by using a mixture of different cover crop species. Diverse cover crop mixtures (≥ four species) can increase productivity and resilience of the cover crop community (Wortman et al., 2012). Allelopathic activity can also be enhanced in cover crop mixtures (Wortman et al., 2013). Including both legume and nonlegume species in mixture can also increase the availability of N to the nonlegume species (Mulder et al., 2002). Using a mixture of cover crop species can also affect soil biota during the decomposition process of the mulch. Szanser et al. (2011) compared the decomposition rate in single-species litter and in diverse litter mixtures with three and twelve species. They observed a greatest abundance of mesofauna and large predatory arthropods and a higher soil organic matter accumulation under the diverse plant litter than under the single-species litter.

2.3.1.2 Cover Crop Biomass Accumulation

Biomass production of the cover crop influences the efficacy of weed control and the amount of N release by mulches. This biomass accumulation is affected by a few factors, such as cover crop species, planting date, and termination date by the roller-crimper (Mirsky et al., 2011). Insufficient production of cover crop biomass has been a challenge that has prevailed farmers from adopting this organic rotational no-till system. Therefore, increasing cover crop biomass for optimizing weed control has been a focus of cover crop research in the U.S.A. in the past decades (Mirsky et al., 2013). The benchmark of minimum mulch biomass for effective weed control will be discussed in a later section.

2.3.1.3 Termination of Cover Crops to Create Mulch

The successful termination of cover crops depends on many factors, such as the timing of termination, the equipment used, and the cover crop species chosen.

Unsuccessful attempts at adapting the organic rotational no-till system have been linked to inadequate timing of termination of the cover crop (Ashford and Reeves, 2003; Mirsky et al., 2009). Parr et al. (2011) observed that some species, including some hairy vetch cultivars, appear to effectively regrow after rolling. A field study conducted in 2008 and 2009 in Manitoba also found that roller-crimping in mid-summer did not kill a spring-seeded hairy vetch cover crop (I. Vaisman, unpublished data). Vetch was completely resistant to crushing, and kept growing between the time of rolling in mid-summer until late-fall. Failure to terminate the cover crop with the roller-crimper can be problematic when the cover crop becomes a volunteer weed and competes with the main cash crop, as observed with barley in a field pea/barley cover crop at Lethbridge, AB (Podolsky, 2013). The roller-crimper is only effective at terminating a cover crop if the plants have reached the right phenological stage, e.g. at 50% anthesis for cereal rye (Mirsky et al., 2009) or the flat pod growth stage for field pea (Izard, 2007). Therefore, termination of cover crops with the roller-crimper in organic systems demands observational skills and is less flexible than its termination with herbicides or tillage. Improper design of the roller-crimper was also a factor in the failure of the organic rotational no-till system (Estevez, 2008). Research has been conducted to identify roller-crimper designs that would consistently terminate the cover crops, while minimizing vibrations on the tractor and roller-crimper frames when operated in the field (Kornecki et al., 2009). The use of the roller-crimper has also been combined with the use of acetic acid (10%) in organic no-till field trials in Montana, and successfully terminated a pea cover crop (Izard, 2007).

2.3.2 Mulch Decomposition

2.3.2.1 Factors Affecting Mulch Decomposition

Decomposition of rolled cover crops differs greatly from that of tilled cover crops, and this topic has received little attention in the literature. Most studies measuring decomposition of surface-applied litter are conducted in forests, or with post-harvest crop residues in agricultural fields. However, the chemical properties of early-terminated cover crop mulches are distinct from those of post-harvest crop residues or forest litter widely studied in litter bag decomposition studies. Rolled cover crop mulches have relatively high N concentration, low C:N ratio, and low lignin concentration. They are less mature than post-harvest crop residues, and they include the entire above-ground plant biomass (stem and grains).

Mechanisms involved in surface-applied residue decomposition include microbial decomposition, leaching of nitrogen-rich compounds, and photodegradation (Berg and McClaugherty, 2008; Henry et al., 2008). Many factors affect the decomposition of surface-applied cover crop mulches, such as litter chemical properties, litter physical properties, environmental conditions, and the nature and abundance of surrounding plant and soil microbial communities.

2.3.2.1.1 Litter chemical properties

The decomposition process of litter has predominantly been explained with litter quality parameters. Initial N content plays a predominant role in litter decomposition (Parton et al., 2007). Taylor et al. (1989) also found C:N ratio to be the best predictor of mass loss rates, along with N concentration. In an important 10-yr decomposition study conducted at 21 sites in seven biomes, Parton et al. (2007) established that net N release started when litter C:N ratio was less than 40 (with a range of 31 to 48). Mulder et al. (1969) established the C:N ratio limit for net N accumulation or release to be 25. Other nutrients, such as Ca, Mg, K, P and S, have also been found to influence the decomposition process (Neely et al., 1991).

Lignin content and lignin:N ratio also appear to determine the decomposition rate of different plant species (Cookson et al., 1998), although lignin:N was a poor predictor of mass loss rate (Taylor et al., 1989). Early in the decomposition process, microorganisms metabolize fractions other than lignin first, therefore preferentially selecting for cellulose over lignin (Taylor et al., 1989). The proportion of lignin increases in the plant material as cellulose is metabolized by detritivores. Consequently, Taylor et al. (1989) found that lignin concentration was a stronger predictor of mass loss during the 2-4 mo period than the 0-2 mo period.

Lignin plays a dual role in plant decomposition. Lignin is a recalcitrant material resistant to microbial decomposition, but it is also susceptible to photodegradation. Lignin is the key light absorber in decomposing plant material and has a high capacity of autoxydation (Austin and Ballaré. 2010). When exposing samples to solar radiation, Austin and Ballaré (2010) found a significant positive linear relationship between mass loss and lignin concentration, suggesting that lignin increases photodegradation. However, microbial degradation is often the driver of litter decomposition that is more important than photodegradation (Austin and Ballaré, 2010; Henry et al., 2008).

2.3.2.1.2 Litter Physical Properties

Litter quality is not the only predictor of decomposition rates. Litter physical properties are also an important determinant of decomposition rate, however few studies have explored the effect of mulch application rate on litter quality in ecosystems, and particularly in agricultural systems. Particle size of plant residues affects their decomposition by soil biota by influencing the physical protection of the material and the accessibility of its N (Angers and Recous, 1997). A mulch area index has been developed to quantify physical properties of mulches used in organic rotational no-till systems (Teasdale and Mohler, 2000). Mulch area index is the area-to-mass ratio of mulch multiplied by the dry mass of mulch. Berg and Laskowski (2006) also observed that plant species and their physical properties affected the intensity of N leaching from litter. Researchers have also recommended a move away from litter chemistry as the main determinant of decomposition rate (Ruderfer, 2003). Ruderfer advocated that litter structure (e.g. physical size) and environment play a greater role than litter chemistry, since microbial growth is dictated by habitat rather than nutrient supply in plant material decomposing on the soil surface.

2.3.2.1.3 Environmental Conditions

The process of decomposition is affected by many abiotic factors including temperature, moisture, and light intensity (Berg and McClaugherty, 2008; Manning et al., 2008). Litter moisture enhances its decomposition (Manning et al., 2008). Dry plant material decomposes slower than moist material, at similar nutrient concentrations (Enriquez et al., 1993). Microbial activity and litter decomposition is positively correlated with soil temperature (Crohn and Valenzuela-Solano, 2003). Light intensity also influences the abiotic process of photodegradation in the decomposition of surface-applied mulches. Photodegradation may be the dominating process of decomposition in arid grasslands where moisture availability is limited and decomposition by microorganisms is not favored (Parton et al., 2007).

2.3.2.1.4 Surrounding plant and soil microbial communities

Living plants and the decomposer community surrounding the litter can affect litter decomposition. For example, the nature and abundance of the neighboring living plants will affect litter decomposition. This phenomenon called “home-field advantage” has been observed during the process of biological decomposition of leaf litter in forests (Ayres et al., 2009; Wallenstein et al., 2010). Decomposition of leaf litter occurs faster when litter is placed beneath the plant species from which it had been derived instead of beneath a different plant species. Wallenstein et al. (2010) attributed the differences in decomposition rates of leaf litter in sites with differing vegetation to difference in decomposer community among stands of each tree species. Moreover, decomposition of litter above the soil surface by the decomposer community may be limited more by habitat availability than nutrient availability (Ruderfer, 2003). Surface-applied litter like cover crop mulches is not in direct contact with the soil solution. Cover crop mulches are rather hostile environments for the growth of certain microorganisms due to important variations in moisture and temperature (Ruderfer, 2003).

2.3.2.2 Nutrient Supply from Mulches in Organic Rotational No-Till Systems

Cover crop mulches in organic rotational no-till systems are ideally expected to decompose slowly (for extended soil cover and weed control) and to release their N when the subsequent cash crop requires it. Many questions remain unanswered about the synchrony of N release from mulches with the subsequent crop N requirements and possible N losses or immobilization in reduced-tillage systems.

Cover crop mulches can accumulate high content of N in their biomass, especially for legume-containing mulches (Parr et al., 2011). In North Carolina, U.S.A., a biomass of fall-seeded hairy vetch cover crop ranged between 6.5 to 8.8 Mg ha^{-1} (Brown, 2013). This mulch biomass contained high contents of N, ranging between 175 to 288 kg N ha^{-1}. More research is needed to manage these high contents of N, and to improve the synchrony between N release from N-rich mulches with hairy vetch and the N requirements of the subsequent crop seeded into mulches with hairy vetch.

A quick release of N commonly occurs in the initial phase of decomposition of cover crop mulches. This rapid loss of N from the cover crop mulch biomass is attributed to the leaching of water-soluble compounds from the litter, described by Berg and Laskowski (2006) as the first phase of N dynamics in decomposing litter. This rapid nutrient release is not caused by microbial decomposition, but rather by water movement (e.g. rainfall) and freezing-thawing cycles. In a field experiment conducted in Beltsville, MD, U.S.A., Teasdale and Mohler (2000) reported a loss of a third of the mulch mass for legume mulches of hairy vetch and crimson clover (*Trifolium incarnatum* L.), within the initial 30 days of their study. Drinkwater et al. (2000) also observed an increase in C:N ratio of vetch residues over the 5 mo of their litter bag decomposition study. Other fates of the N in the mulch biomass include mineralization, volatilization, weed uptake, or incorporation into the microbial biomass causing N immobilization.

Nitrogen from external sources can also be accumulated in the mulch biomass. Possible mechanisms for net N accumulation in litter are translocation of soil N by fungal hyphae

(Frey et al., 2000), N_2 fixation by microorganisms present in the litter (Berg and Laskowski, 2006), addition of external litter or insect/decomposer biota, capillary flow from the soil solution, or soil attached on the litter. Frey et al. (2000) were the first to report on fungal N translocation in agricultural systems, a mechanism commonly reported in forestry literature. They observed the transfer of N from mineral soil to winter wheat straw residues on the soil surface occurred via fungal N translocation, and it was the cause of the net N immobilization by surface residues decomposing in the field. Nitrogen deposition from the atmosphere can also occur and affect litter decomposition. Manning et al. (2008) found that litter decomposition was 2% greater when large N deposition occurred.

One challenge for farmers wanting to adopt the organic rotational no-till system is the possibility for reduced nitrogen mineralization of cover crops, which may lead to reduced yields. Numerous studies reported reduced soil N content in systems with roller-killed cover crops (organic rotational no-till system) compared with cover crops incorporated with tillage (Podolsky, 2013; Sullivan, 2012; Vaisman et al., 2011). In the northern Great Plains of Canada, Vaisman et al. (2011) found that terminating a field pea/oat green manure with the roller-crimper, hence completely eliminating tillage for 1.5 yr, caused a lack of synchrony of N availability from the cover crop to a spring wheat crop, causing a reduced crop N uptake and spring wheat grain yield.

Researchers are now investigating the N contribution of rolled mulches with more specialized tools, such as plant root simulator probes. Brown (2013), Wells et al. (2013), and Parr et al. (2011) have all used plant root simulator probes to determine the soil nutrient supply rate in cover crop-based organic rotational no-till systems. Wells et al. (2013) compared the soil N supply rates of a rolled cereal rye with that of a tilled cereal rye. They observed a faster N release from the incorporated cover crops than from the mulched cover crops. This may be attributed to a better soil-residue contact due to the incorporation of cover crop the previous fall allowing faster microbial mineralization of the cover crop in tilled systems.

Reduced mineralization of the cover crop due to rolling instead of soil incorporation can lead to a lack of synchrony between N availability from the cover crop and the cash crop N need, causing reduced cash crop N uptake and yield (Parr et al., 2011). Changes in N availability in organic rotational no-till systems have an impact on the competitive ability of weeds and crops (Wells et al., 2013), due to differences in N responsiveness between plant species, and weed-crop competition has been found to reduce crop yield in organic rotational no-till soybean production. Drinkwater et al. (2000) and Vaisman et al. (2011) also observed that reduced content of N were taken up by the cash crop (corn and spring wheat, respectively) and weeds in the no-till treatment due to reduced mineralization of the cover crop.

2.3.3 Weed Control by Mulches

2.3.3.1 Mechanisms of Weed Control by Mulches

Weed control is a central function of mulches in organic rotational no-till systems. Mulches suppress weeds through many different mechanisms including allelopathy, physical impedance, providing a habitat to seed predators, and the alteration of soil properties.

2.3.3.1.1 Allelopathy

Cover crop residues can inhibit the germination of weed seeds through allelopathy. During the decomposition of cover crop residues, organic substances may be released or/and produced. Many of these substances are phytotoxic. Hence, allelopathic compounds from cover crop residues affect weed emergence and growth (Caamal-Maldonado et al., 2001). For example, hairy vetch showed allelopathic inhibition of germination of selected weed species, with shoot extracts more-inhibitory than root extracts (Geddes et al., 2012). Sunflower (*Helianthus annuus* L.) residues also have an allelopathic effect on weeds (Leather, 1983). Heliannuols, terpenoids, and flavonoids are the most important allelopathic compounds isolated from sunflowers (Vyvyan, 2002). Grass cover crop species, such as cereal rye, barley, triticale (x *Triticosecale* Wittm.) and winter wheat, have also demonstrated allelopathic activity (Dhima et al., 2006; Geddes et al., 2012).

Moreover, weed suppression by allelopathy is species-specific (Creamer et al., 1996). Having a mixture of various cover crop species can then enhance allelopathic activity and suppress a greater weed species spectrum more effectively than a stand of a single cover crop species (Wortman et al., 2013).

2.3.3.1.2 Physical Impedance

Mulches cause physical impedance and create a physical barrier blocking weeds from emerging through the mulches. A field study by Creamer et al. (1996) evaluated the weed suppression mechanisms of cover crops leached of their allelochemicals. They observed that the emergence of small light-sensitive weed seedlings such as eastern black nightshade (*Solanum ptycanthum* Dun.) was physically suppressed, independently of mechanisms of allelopathy. By providing a physical barrier, mulches also cause light deprivation, blocking light from reaching the soil surface. Mulches reduce the quantity of light reaching the soil surface and also change the quality of light reaching the soil surface. Reduced transmittance of photosynthetically active radiation (PAR) reaching the soil surface has been observed through cereal rye and vetch mulches (Teasdale and Mohler, 2000). This has a direct effect on the germination of light-sensitive weed species, and may also give a competitive advantage to weeds that do not require light to germinate (Teasdale, 1993).

2.3.3.1.3 Seed Predation

Seed predation has also been reported as a mechanism of weed suppression in no-till systems (Cromar et al., 1999). Since weed seeds are not incorporated into the soil with tillage, invertebrate granivores feed on the weed seed at the soil surface in no-till systems (Pullaro et al., 2006). There is increased seed predation of seeds close on to the soil surface, as opposed to seeds found in deeper soil layers. In a study conducted in organic cereal fields in The Netherlands, vertebrates like mice accounted for the larger part of weed seed consumption, compared to inverbrates (Westerman et al., 2003).

2.3.3.1.4 Alteration of Soil Properties

Mulches in conjunction with little soil disturbance in reduced-tillage systems also alter soil properties and soil environmental conditions, affecting weeds. Leaving crop residues at the soil surface will modify the soil water regime and temperatures. Conservation of soil moisture has been observed by mulches (Kornecki et al., 2009; Tu et al., 2006). They reduce soil water evaporation and increases rainfall retention. Mulches also act as a buffer and decrease the maximum soil temperature (Lal, 1974). Mulches on no-till soils limit soil warming, causing a delay in weed seed germination. Moreover, mulches with high C:N ratio may temporarily immobilize N during their decomposition, leaving less N available for subsequent weed growth (Wells et al., 2013).

2.3.3.2 Weed Control in Organic Rotational No-Till Systems

As explored in the previous section, mulches affect weeds through various mechanisms, and mulch biomass is an important parameter that determines the impact of these mechanisms on weeds. The biomass of cover crop produced is critical to the success of the organic rotational no-till system, since the cover crop mulch is its key tool for weed control. Not enough mulch biomass present on the soil surface can reduce efficacy of weed control and crop yield (Podolsky, 2013; Teasdale et al., 2012). The minimum biomass of cover crop mulch necessary for suppressing summer annual weeds in organic rotational no-till system was found to be 8 Mg ha^{-1} in the mid-Atlantic region of the U.S.A. (Mirsky et al., 2012). However, lower minimum biomass (> 4 Mg ha^{-1}) of oat straw residues was found to be sufficient for weed suppression in occasional direct-seeding of organic faba beans in Germany (Massucati and Köpke, 2011), although the quality and maturity of the residues differed greatly from those of cover crop mulches used in northeastern U.S.A.

The efficacy of weed control provided by cover crop mulches also depends on cover crop species used. For example, mulches of hairy vetch in pure stands or mixed with cereal rye have provided effective weed control in field (Mischler et al., 2010b; Parr et al., 2011) and vegetable crops (Leavitt et al., 2011; Price and Norsworthy, 2013) at various locations across North America. However, discrepancies were observed in weed control provided by mulches with vetch. Winter survival of rolled spring-seeded hairy vetch considerably reduced spring wheat yields in Lethbridge, AB, Canada (Blackshaw et al., 2014). Drinkwater et al. (2000) observed that the success of a hairy vetch cover crop mulch in a no-till system was highly variable, concluding that weed control by mulches with vetch was not reliable.

Not all weed species are equally suppressed by cover crop mulches. Small-seeded summer annuals are better suppressed by cover crop mulches than perennial weeds (Mirsky et al., 2012). A shift in weed population, from summer annual to perennial weeds, has also been observed after the adoption of the organic rotational no-till system (Mirsky et al., 2012; Ryan et al., 2009). Perennial weeds have caused a reduction in corn and soybean yields in organic rotational no-till systems in the mid-Atlantic region of U.S.A. (Mirsky et al., 2012). The elimination of tillage for a period greater than a year in organic production brings additional challenges to the already complex organic farming systems. Therefore, there is a need for low perennial weed populations before implementing the organic rotational no-till system (Mirsky et al., 2012).

2.3.4 Cash Crop Performance in Organic Rotational No-Till Systems

2.3.4.1 Selection of Cash Crop Species

A variety of cash crop species have been no-till planted in cover crop mulches in organic rotational no-till systems. Corn, soybean and tomato in northeast U.S.A. have received the greatest attention in the published literature. Selection of cash crop species has also been adapted to regional climatic conditions. For example, spring wheat has been tested in colder climatic conditions, such as the northern Great Plains of Canada (Podolsky, 2013; Vaisman et al., 2011) and eastern Canada (Leroux et al., 2011). Cotton (*Gossypium hirsutum* L.) (Kornecki et al., 2005; Reeves et al., 2005) and peanut (*Arachis hypogaea* L.) (Price et al., 2007) were tested in the warmer climatic conditions of southeast U.S.A.

Vegetable and fruit production have also been tested in reduced-tillage systems with cover crop and living mulches, with tomato production receiving most of the attention. Literature reviews have covered the topic of vegetable and fruit production under cover crop mulches (Masiunas, 1998; Morse, 1999; Price and Norsworthy, 2013).

2.3.4.2 Cash Crop Establishment and Yield

Cash crops no-till planted into cover crop mulches can suffer delayed crop emergence and reduced plant population density, compared with tilled treatments (Davis, 2010; Mischler et al., 2010b). This may be attributed to lower surface soil temperature under mulches (Podolsky, 2013) or difficulties cutting through a heavy biomass of mulch to achieve adequate seed placement (Mirsky et al., 2012).

Yields of organic crops no-till planted in cover crop mulches have been variable. Research conducted in the northeast U.S.A. between 2007 and 2010 has demonstrated that corn and soybean grown in organic rotational no-till systems produce similar or greater yields than county averages (Mirsky et al., 2012). Soybeans seeded into cereal rye mulch had more consistent yield than corn. In northeast U.S.A., yield reduction for corn grown into a hairy vetch mulch was attributed to delayed seeding date of corn due to the late flowering and termination of hairy vetch (Mirsky et al., 2012). Delayed termination of the fall-seeded cover crop in the spring also prevented subsequent no-till cash crops from producing grain in North Dakota because of the short growing season remaining for the cash crop growth. Other studies have observed lower yields for no-till crops compared with crops established with tillage in organic production (Podolsky, 2013; Estevez, 2008).

In summary, there are a wide array of complex interactions between cover crops, weeds, cash crops, and the soil environment in the organic rotational no-till system. The overall objective of the following Ph.D. thesis is to adapt the cover crop-based organic rotational no-till system to the growing conditions of Manitoba, Canada. Therefore, this thesis will address the following key agronomical questions linked to the adaptation of the organic rotational no-till system for Manitoba, Canada:

- How much cover crop biomass is produced at the time of rolling the cover crops in mid-summer?

- How much mulch biomass is produced by late-fall of the cover crop year?
- How much cover crop mulch biomass is present in the spring of the cash crop year?
- How much mulch is lost overwinter?
- Was N released to the soil overwinter?
- Which cover crop species are the most competitive with weeds, between the time of their establishment to their termination by rolling?
- Which cover crop mulches provide the best weed control to the cash crop?
- Which weed species are difficult to control with cover crop mulches?
- How do crop yields in the organic rotational no-till system compare to those of other management/tillage systems?
- What are the reasons for a failure of the organic rotational no-till system in Manitoba?

MANUSCRIPT #1

3.0 SELECTING COVER CROP MULCHES FOR ORGANIC ROTATIONAL NO-TILL SYSTEMS IN MANITOBA, CANADA

This manuscript was published in Agronomy Journal on 6 June 2014, doi:10.2134/agronj13.0402. Authors: Caroline Halde, Robert H. Gulden, and Martin H. Entz. Used with permission.

3.1 Abstract

In the northern Great Plains of Canada, limited research has been conducted on reduced-tillage grain production systems managed organically. The objective was to select cover crop mulches for an organic rotational no-till system in Manitoba. A two-year field study (2010-2011, and repeated 2011-2012) was conducted in Carman, MB, Canada. In the cover crop year, 10 different combinations of cover crop species were seeded in the spring, in pure stand or in mixtures, and rolled using a roller-crimper in mid-summer, at the flowering stage. These rolled mulches were then left on the soil surface over the fall and winter. The following spring, spring wheat (*Triticum aestivum* L.) was seeded directly into these mulches (no-till). Mulches with hairy vetch (*Vicia villosa* Roth) showed the most promising results. Cover crop treatments with vetch had the highest mulch biomass in September of the cover crop year (9.1-10.7 Mg ha^{-1}), and in the following spring (6.0-7.6 Mg ha^{-1}) and provided the best weed control. In late-fall of the cover crop year, nitrogen content of mulches with vetch was high (308 kg N ha^{-1} on

average), and high amounts of nitrogen (93-164 kg N ha^{-1}) were released from these mulches over winter. Consequently, there was an increase in soil NO_3-N (0-90 cm) overwinter in treatments with vetch. Organic spring wheat no-till planted into these mulches with vetch produced yields comparable to regional conventional average yields. In conclusion, mulches with vetch used in an organic rotational no-till system reduced the need for tillage for a period of 1.5 to 2 yr without affecting yields in organic spring wheat production.

3.2 Introduction

In recent years, there has been a growing interest in trying to reduce tillage on organic farms by adapting the mulch production systems widely used by Brazilian no-till farmers since the late 1980s (Bolliger et al., 2006). The Brazilian no-till systems with mulches have been adapted to the North American organic grain production conditions to become an "organic rotational no-till system" that reduces tillage by rotating between a cover crop established with tillage and a cash crop no-till planted into the cover crop mulch. There are a number of successful examples of adaptation of the organic rotational no-till system in various regions of the United States (Davis, 2010; Delate et al., 2011; Mischler et al., 2010a; Mischler et al., 2010b; Mirsky et al., 2012; Ryan et al., 2011).

Research on these organic rotational no-till systems is limited in the northern Great Plains of Canada, partially because the environmental conditions pose important limitations to the successful adaptation of the mulch production system. The climate of the northern Great Plains of Canada is characterized by a short growing season and low annual precipitation (~350-550 mm), that greatly reduces the possibilities of growing cover crops of adequate biomass after a cash crop harvest in the fall. Moreover, organic farmers in the region also have limited access to animal manure (Légère et al., 2013), and depend mostly on nitrogen-fixing cover crops and their mineralization by incorporation into the soil for N fertility. Therefore, full-year cover crops are most appropriate for the northern Great Plains of Canada and a common practice by organic farmers in that region (Entz et al., 2001).

Reduced tillage efforts in full-year cover cropping have been started in the northern Great Plains of Canada. Vaisman et al. (2011) were the first to report results on organic rotational no-till grain production using the roller-crimper in the northern Great Plains of Canada. They observed no yield penalty when completely eliminating tillage in organic no-till spring wheat (*Triticum aestivum* L.) grown on rolled pea (*Pisum sativum* L.)/oat (*Avena sativa* L.) and pure pea cover crop mulches compared with five other cover crop management treatments with different intensities of tillage, at two site-years out of three.

The selection of cover crop species to create mulch is a key step in making the organic rotational no-till system work. Characteristics of a desirable mulch include high biomass and slow decomposition for prolonged weed control, as well as its N release synchronized with subsequent crop nutrient requirements. Cover crop species choice is important to produce mulch that accomplishes these goals. Legume species have the ability to fix N, but have high seed cost, while grasses are fast-growing and have the ability to capture excess soil nitrates (Brandi-Dohrn et al., 1997). The selection of cover crop species will also affect the ability of the mulch to manage weeds. For example, Davis (2010) observed differences in weed suppression from a rolled cereal rye (*Secale cereale* L.) compared with that of a rolled hairy vetch (*Vicia villosa* Roth), suggesting that the benefits of terminating a cover crop with a roller-crimper depends on the species of the cover crop. Furthermore, some cover crop species have demonstrated allelopathic activity, such as hairy vetch, cereal rye, barley (*Hordeum vulgare* L.), and sunflower (*Helianthus annuus* L.) (Dhima et al., 2006; Geddes et al., 2012; Leather, 1983). Another criterion in cover crop species selection is the response of cover crop species to the roller-crimper. Parr et al. (2011) observed that some species, including some hairy vetch cultivars, appear to effectively regrow after rolling. The roller-crimper is only effective at terminating a cover crop if the plants have reached the right phenological stage, e.g. at 50% anthesis for cereal rye (Mirsky et al., 2009). Therefore, termination of cover crops with the roller-crimper in organic systems demands observational skills and is less flexible than its termination with herbicides or tillage.

Using a mixture of different species may maximize the benefits of cover crops. Wortman et al. (2012) tested mixtures of 2, 4, 6, and 8 cover crop species, and found that diverse cover crop mixtures increased productivity and resilience of the cover crop community. Legume species can also increase N availability to nonlegume species in mixture (Mulder et al., 2002). Allelopathic activity can also be enhanced in cover crop mixtures. Since an allelopathic compound may act strictly on one specific weed species, a mixture of many cover crop species may be more effective than a pure stand for suppressing a diverse weed population (Wortman et al., 2013).

The overall goal of this present study was to test different cover crop species for mulch production in an organic rotational no-till system in southern Manitoba where the roller-crimper was used for cover crop management. The four objectives of the study were a) to determine the ability of various plant species to produce high-biomass mulch over time, b) to determine their ability for weed control over time, c) to determine the agronomic performance of the subsequent crop (spring wheat) planted without tillage into these mulches, and d) to investigate N dynamics over time in the organic rotational no-till system adapted for southern Manitoba. Study objectives were framed by the following hypotheses: 1) Species combinations of high plant diversity (3-4 species) will have the highest mulch biomass production; 2) The best weed control is provided by mulches with the greatest biomass; 3) Mulches that provide the best weed control produce the highest spring wheat yield; and 4) Sufficient N is available to fulfill the N requirement of the subsequent crop.

3.3 Materials and Methods

3.3.1 Study Site

A two-year field study was conducted twice between 2010 and 2012 at the University of Manitoba Ian N. Morrison Research Farm in Carman, MB, Canada (49°29'53.200" N lat, 98°01'47.100" W long). The study site was located in the Winkler Ecodistrict, in the Lake Manitoba Plain Ecoregion of the Prairies Ecozone (Smith et al., 1998) at 268.2 m above sea level. This ecodistrict has a mean annual temperature of 3.1°C and a mean number of growing degree-days (T_{base} = 5°C) of about 1800 (Smith et al., 1998). The ecodistrict receives about 515 mm of annual precipitation. Soils at the study site are Orthic Black

Chernozems (Mollisols) of the Hochfeld series with < 1% slope that are moderately well drained to imperfectly drained (Mills and Haluschak, 1993). These soils have developed on shallow sandy, loamy and clayey glaciolacustrine sediments. Soils at the study site are underlain by a clay substrate at depths ranging from the surface to two meters. The site has been under organic management (without pesticide or synthetic fertilizer application) since 2003. Weather data were collected directly on site, at the Research Farm in Carman, MB.

3.3.2 Experimental Design

The experimental design was a randomized complete block design, with four blocks. Each experimental unit was 2 m x 11 m. The factor of interest was cover crop species, and the 10 levels of the factor of interest included pure stand and multi-species combinations (with 2, 3 or 4 species) of cover crops (Table 3-1). The cover crop species tested included barley, hairy vetch, field pea, oilseed radish (*Raphanus sativus* L.), and sunflower.

An 11th control treatment consisting of a fallow in the cover crop year (roto-tilled, without cover crop) was added at the North site only, but was not included in the statistical analysis of the data. The experiment was repeated twice, in two different fields at Carman. At the South site, cover crops were grown in 2010 and spring wheat was grown in 2011, whereas at the North site, cover crops were grown in 2011 and spring wheat was grown in 2012.

Table 3-1. Seeding rates of individual cover crop species, in the ten cover crop treatments (pure stand or mixtures) tested.

Ten cover crop treatments	**Seeding rate**				
	Barley	**Field pea**	**Hairy vetch**	**Oilseed radish**	**Sunflower**
	--------------------------kg ha^{-1}--------------------------				
Pure stand					
Barley	152.3	-	-	-	-
Pea	-	216.4	-	-	-
Vetch	-	-	51.8	-	-
2-species mixture					
Barley/pea	76.1	108.2	-	-	-
Barley/vetch	76.1	-	25.9	-	-
Barley/radish	76.1	-	-	8.1	-
Barley/sunflower	76.1	-	-	-	5.1† and 8.5‡
3-species mixture					
Barley/pea/radish	50.8	72.1	-	5.4	-
Barley/pea/sunflower	50.8	72.1	-	-	3.4† and 5.7‡
4-species mixture					
Barley/pea/radish/sunflower	38.1	54.1	-	4.1	2.5† and 4.3‡

† Seeding rate used in 2010.
‡ Seeding rate used in 2011.

3.3.3 Field Management

The organic rotational no-till system tested consisted of establishing a cover crop with tillage in the first year (cover crop year), followed by growing a no-till seeded cash crop into the cover crop mulches in the 2nd yr (wheat year). Tillage was necessary only in spring of the cover crop year and in fall of the wheat year (or the following spring), eliminating tillage for a period of 1.5 to 2 yr. In the cover crop year, ten combinations of cover crop species were seeded in the spring, and then rolled twice on the same day (once in each direction) with a roller-crimper (Figure 3-1) in mid-summer.

None of the cover crop seeds used in the present study were scarified before use. All ten cover crop species treatments were rolled on the same day, once barley had reached the

Figure 3-1. Roller-crimper used to terminate cover crops and to create mulches (© Caroline Halde 2009).

flowering stage. Seeding rates for pure stand and mixtures of cover crops are presented in Table 3-1, and dates of field operations and sampling dates are presented in Table 3-2. These rolled mulches remained anchored to the soil and were left on the soil surface without further disturbance until the next crop cycle of the following year.

In mid-May of the wheat year, spring wheat (cv. Waskada) was seeded directly into these mulches (using a disk-opener no-till seeder (2-m wide, 15-cm row spacing). Seeding rates for spring wheat were 147 and 148 kg ha^{-1} in 2011 and 2012, respectively. Spring wheat was harvested in mid-August.

3.3.4 Data Collection

3.3.4.1 Plant Sampling in the Cover Crop Year

In the cover crop year, plant population densities of each cover crop species (barley, hairy vetch, pea, oilseed radish and sunflower) were assessed by counting the number of individual plants of each crop species along two 1-m row in each experimental unit in

Table 3-2. Field operations and soil/plant sampling performed at both sites over the two-year field study.

Year	Operation	Date at the South site	Date at the North site
Cover crop	Spring tillage	20 May 2010	10 June 2011
	Seed cover crops	20 May 2010	10 June 2011
	Above-ground plant biomass and N concentration at rolling, sorted into individual cover crop species and weeds	19-20 July 2010	2 Aug. 2011
	Roll cover crops twice	22 July 2010	2-3 Aug. 2011
	Mulch biomass and N concentration	28 and 30 Sept. 2010	11 Oct. 2011
	Soil chemical properties	n/a †	17-18 Oct. 2011
	Roll cover crops twice	30 Sept. 2010	18 Oct. 2011
Spring wheat	Soil chemical properties	16 May 2011	8 May 2012
	Seed spring wheat into the cover crop mulches	19 May 2011	9 May 2012
	Spring wheat plant population density and developmental stage	16 June 2011	29 May 2012
	Mulch biomass and N concentration	14 and 16 June 2011	6 June 2012
	Above-ground weed biomass	29 June 2011	19 June 2012
	Above-ground spring wheat and weed biomass, and spring wheat grain yield	22 Aug. 2011	11 Aug. 2012
	Harvest spring wheat	22 Aug. 2011	11 Aug. 2012
	Soil chemical properties	6 Oct. 2011	13 and 15 Oct. 2012

† Soils at the South site were not sampled and analyzed for soil chemical properties in fall of the cover crop year.

spring. Two quadrats (0.5 m x 0.45 m) per experimental unit were harvested to assess above-ground plant biomass at rolling and mulch biomass in fall (Table 3-2). Above-ground plant biomass at rolling was hand-sorted into individual crop species (barley, vetch, pea, radish and sunflower) and weeds. For all plant biomass determination, all quadrats were clipped at 2 to 5 cm above the soil surface and the fresh plant material was collected in paper bags. Fresh sorted plant samples were oven-dried at 60°C for 48 h and weighed to determine dry biomass.

3.3.4.2 Plant Sampling in the Wheat Year

In the wheat year, spring wheat plant population density was determined along three 1-m rows in each experimental unit in spring. Spring wheat developmental stages were determined using the Haun scale (Haun, 1973) on eight randomly chosen plants per experimental unit, on the same day that spring wheat densities were recorded. Two quadrats (0.5 m x 0.45 m) per experimental unit were harvested to assess mulch biomass in spring (3-4 wk after seeding spring wheat) and above-ground plant biomass at spring wheat harvest (Table 3-2). Above-ground plant biomass at spring wheat harvest was hand-sorted into spring wheat and weeds. Spring wheat heads were removed from these above-ground plant biomass samples collected at spring wheat harvest. They were threshed using a belt thresher and a grain winnower (Bill’s welding, Pullman, WA, U.S.A.) to obtain spring wheat grain yield. In mid-summer, above-ground weed biomass was assessed in two quadrats (0.25 m x 0.25 m) per experimental unit.

3.3.4.3 Plant Tissue Nitrogen Concentration

Mulch biomass and spring wheat and weed dry biomasses at harvest were ground to 2 mm with a grinder (Arthur H. Thomas Co., Philadelphia, PA, U.S.A.). Plant tissue (mulch, spring wheat, and weed) and spring wheat grain were analyzed for N concentration using a nitrogen analyzer (FP-528, LECO Co., St Joseph, MI, U.S.A.). Grain protein content was calculated from grain N concentration (5.7 x [N]), then corrected for moisture and reported on a 13.5% moisture content basis.

3.3.4.4 Soil Chemical Properties

Soil chemical properties were assessed at three time periods: in fall of the cover crop year, in spring of the wheat year, and in fall of the wheat year (Table 3-2). Soil sampling was performed using a hand auger and a hydraulic soil auger (Giddings Machine Co., Windsor, CO, U.S.A.). Two cores were removed from each experimental unit, and both cores were bulked by depth increment in the field. Sampling in fall 2010 at the South site was not performed. Soil samples were taken at four depths: 0-15, 15-30, 30-60, and 60-90 cm. A complete analysis of soil chemical properties was performed at the top 15 cm soil layer (NO_3-N, pH, organic matter, Olsen-P, K, Zn), whereas only soil nitrates were assessed at deeper depths in the soil profile. Soil analysis was conducted by Agvise Laboratories (Northwood, ND, U.S.A.).

3.3.5 Statistical Analysis

Statistical analyses were conducted using Statistical Analysis System 9.2 (SAS Institute Inc., 2008) software. To compare the effects of cover crop species and site on plant and soil responses, analysis of variance ($\alpha = 0.05$) was conducted using the MIXED procedure of SAS. Repeated measures were used to compare the effects of cover crop species and site on soil chemical properties, mulch biomass and weeds biomass over time. Fixed effects were cover crop species, site, and time, whereas block(site) was considered a random effect. Outliers were identified using Lund’s test (Lund, 1975) and were removed. For each analysis, residuals were verified to conform to normality and homogeneity of variance. Logarithm and square root transformations were used to achieve normality and homogeneity of variance, as required by analysis of residuals. The

Satterthwaite approximation (ddfm = satterthwaite) was used for estimating denominator degrees of freedom and to produce a more accurate F-test approximation than the original containment method (Satterthwaite, 1946). Means were separated using the Least Square Difference test. The SLICE statement was used to test the effect of cover crop species on cover crop biomass at rolling at each individual site. An analysis of covariance was performed in proc MIXED to examine the effect of spring wheat plant population density on spring wheat yields. Correlation analyses were performed among weed and spring wheat responses, and within spring wheat responses, using the CORR procedure of SAS ($\alpha = 0.05$).

3.4 Results

3.4.1 Environmental Conditions

Total precipitation for the growing season (1 May until 31 Oct.) at the study site was 573, 253, and 309 mm for 2010 to 2012, respectively (Environment Canada, 2013), and the 30-yr (1971-2000) precipitation average for the growing season was 386 mm. Annual precipitation was 635, 325, and 397 mm for 2010 to 2012, respectively (Environment Canada, 2013). The mean daily air temperature for the growing season was 14.4, 14.8, and 14.6°C for 2010 to 2012, respectively, whereas the 30-yr mean air temperature during the growing season was 14.9°C.

Growing conditions in spring 2011 were not optimal for crop emergence and growth because of: 1) above average precipitation in fall 2010 (635.1 mm, compared with 325 and 397 mm for 2011 and 2012, respectively; Environment Canada, 2013); 2) abnormally cold temperatures over the 2010-2011 winter (particularly in March 2011), causing a deep soil-frost that prevented spring meltwater to soak in. This resulted in a historic flood in spring 2011 in southern Manitoba, which affected overall crop yields in the region that year (Environment Canada, 2011).

3.4.2 Mulch Biomass

Mulch biomass was affected by both cover crop species and site. There was a significant cover crop x site x time interaction effect on mulch biomass ($P < 0.001$, $n = 238$). Maximum cover crop biomass at time of termination by rolling was 8.7 Mg ha^{-1} in 2010 and 4.6 Mg ha^{-1} in 2011 (Table 3-3). Plant species composition of mulches at the time of rolling varied between sites. For example, hairy vetch represented < 10% of cover crop biomass in barley/vetch mixtures at rolling in 2010, but up to 35% in 2011. Also, pea biomass at rolling in pure pea was greater in 2010 than in 2011 (7.8 and 4.6 Mg ha^{-1}, respectively). Higher sunflower biomass in 2011 than in 2010 was due to an increased sunflower seeding rate at the North site in 2011.

Hairy vetch established slowly in the spring (with < 3 Mg ha^{-1} of biomass by mid-July) compared with other cover crop treatments, therefore poorly competing with weeds early in the cover crop year. At the time of termination, weeds represented a higher proportion of the plant biomass in pure hairy vetch than in any other mulch (20% in 2010, and 56% in 2011), and weed biomass was numerically the highest in pure vetch.

Table 3-3. Cover crop x site interaction effect on mean above-ground biomass of individual cover crop species and all cover crop species cumulated, at rolling , and summary of analysis of variance.†

	Above-ground biomass					
	Barley	**Pea**	**Vetch**	**Radish**	**Sunflower**	**All cover crops**
	----------Mg ha^{-1}----------					
South site (in 2010)						
Pure stand						
Barley	7.1 a	-	-	-	-	7.1 ab
Pea	-	7.8 a	-	-	-	7.8 a
Vetch	-	-	2.8 a	-	-	2.8 hijk
2-species mixture						
Barley/pea	3.8 c	1.9 cd	-	-	-	5.7 cd
Barley/vetch	6.0 b	-	0.6 c	-	-	6.6 abc
Barley/radish	6.1 b	-	-	0.4	-	6.5 bc
Barley/sunflower	5.4 b	-	-	-	0.2	5.6 cd
3-species mixture						
Barley/pea/radish	3.9 c	2.3 c	-	0.4	-	6.6 abc
Barley/pea/sunflower	3.2 cd	2.3 c	-	-	0.1	5.6 cde
4-species mixture						
Barley/pea/radish/sunflower	3.1 cde	2.2 c	-	0.2	0.3	5.8 cd
North site (in 2011)						
Pure stand						
Barley	3.1 cde	-	-	-	-	3.1 hijk
Pea	-	4.6 b	-	-	-	4.6 def
Vetch	-	-	1.9 b	-	-	1.9 k
2-species mixture						
Barley/pea	1.6 fgh	2.5 c	-	-	-	4.1 fgh
Barley/vetch	1.7 fgh	-	0.9 c	-	-	2.6 jk
Barley/radish	2.1 efg	-	-	1.1	-	3.2 ghij
Barley/sunflower	2.4 def	-	-	-	1.8	4.2 efgh
3-species mixture						
Barley/pea/radish	1.0 hi	1.3 d	-	0.5	-	2.8 ijk
Barley/pea/sunflower	1.0 h	1.1 d	-	-	1.8	3.9 fghi
4-species mixture						
Barley/pea/radish/sunflower	1.2 gh	1.6 cd	-	0.4	1.3	4.5 defg
Source of variation	----------*P* value----------					
Cover crop (C)	***	***	***	ns‡	ns	***
Site (S)	***	**	ns	ns	***	***
C x S	***	*	**	ns	ns	***
n	64	40	16	23	23	80

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Within columns, means followed by the same letter are not significantly different from each other according to LSD test at α = 0.05. Log-transformed data were used to perform ANOVA and means separation on pea, vetch, radish and sunflower biomass, but back-transformed means are presented above.

‡ ns, not significant at the 0.05 probability level.

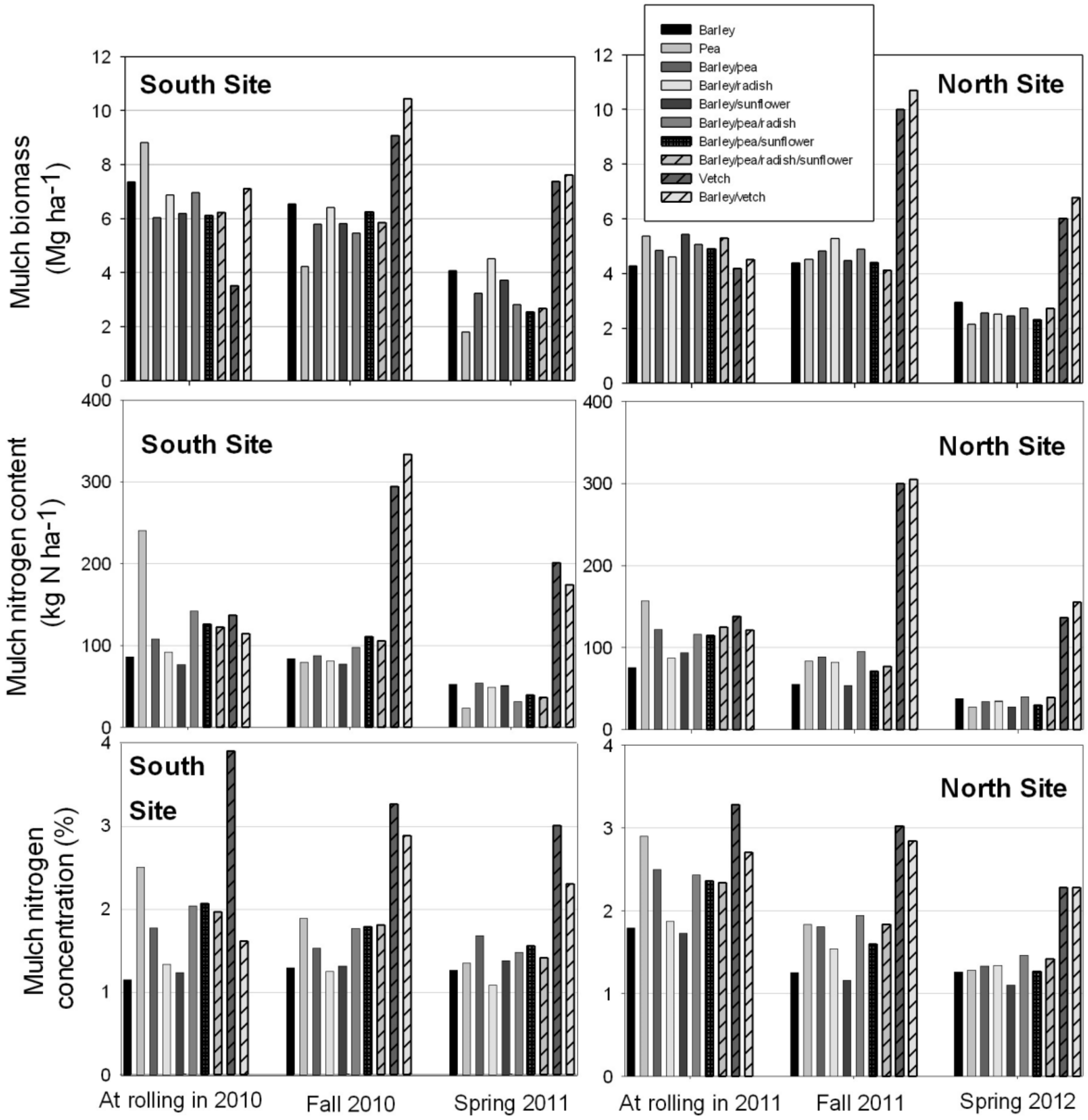

Figure 3-2. Cover crop x site x time interaction effect on mulch biomass (s.e. = 0.1433 Mg ha^{-1}, *n* = 238), mulch nitrogen content (s.e. = 4.75 kg N ha^{-1}, *n* = 237), and mulch nitrogen concentration (s.e. = 0.044 %, *n* = 238), at both sites. Log-transformed data were used to perform ANOVA and means separation on mulch nitrogen concentration and mulch nitrogen content.

After being rolled by the roller-crimper, mulches started to decompose. Between rolling and late-fall of the cover crop year, mulch biomass either declined or remained unchanged for most mulches, except those containing vetch (Figure 3-2). Biomass of mulches with vetch increased by up to 158% between rolling and late-fall, reaching between 9.1 and 10.7 Mg ha^{-1} of biomass by late-fall, because hairy vetch was not killed by rolling and continued growing until late-fall.

Because of decomposition during the winter season, a decrease in mulch biomass, ranging between 19 and 59%, was observed between fall and spring for all mulches, leaving as little as 1.8 Mg ha^{-1} on the soil surface in spring 2011 in pure pea (Figure 3-2). Mulches with vetch had higher biomass (6.0-7.6 Mg ha^{-1}) than other mulches (1.8-4.5 Mg ha^{-1}) in spring of the wheat year at both site-years. Mulches of pure pea had particularly fast decomposition after rolling and overwintering, losing 80 and 60% of their biomass between rolling and the following spring, at the South and North sites, respectively (Figure 3-2).

3.4.3 Mulch Nitrogen

The effect of cover crop species varied between sites and over time, as indicated by the significant cover crop x site x time interaction effect on mulch N concentration (P = 0.013, n = 233) and mulch N content (P < 0.001, n = 237). Mulch N concentration at time of rolling ranged between 1.15 and 3.90 g g^{-1}, with the highest N concentration for pure vetch in 2010 (Figure 3-2). Mulch N content decreased or remained unchanged for all treatments between termination and late-fall, except for mulches containing vetch. By late-fall, N content averaged 308 kg N ha^{-1} for mulches with hairy vetch, compared with 54 to 111 kg N ha^{-1} for mulches without hairy vetch. By late-fall, mulch N concentration was the highest in mulches with vetch (3 g g^{-1} on average across both sites, compared with < 2 g g^{-1} for other mulches). Mulch N content between late-fall and the following spring decreased in all treatments, with a loss ranging between 32% and 71% of initial N content (Figure 3-2). This indicates a significant amount of N is released overwinter from mulches with vetch (93-164 kg N ha^{-1}) and without vetch (18-71 kg N ha^{-1}).

3.4.4 Weed Control by Mulches

Weed species observed were similar at both sites, and included redroot pigweed (*Amaranthus retroflexus* L.), shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik.], lamb's quarters (*Chenopodium album* L.), Canada fleabane [*Conyza canadensis* (L.) Cronquist], barnyard grass [*Echinochloa crus-galli* (L.) Beauv.], woodsorrel (*Oxalis* spp.), wild buckwheat (*Polygonum convolvulus* L.), lady's thumb (*P. persicaria* L.), yellow foxtail [*Setaria glauca* (L.) Beauv.], green foxtail [*Setaria viridis* (L.) Beauv.], London rocket (*Sisymbrium irio* L.), field penny-cress (*Thlaspi arvense* L.), and volunteer oilseed radish and barley. Perennial weed species observed in this study included Canada thistle [*Cirsium arvense* (L.) Scop.], quackgrass [*Elymus repens* (L.) Gould], and dandelion (*Taraxacum officinale* Weber).

The effect of cover crop treatment on weed biomass varied over time ($P < 0.0001$, Figure 3-3). At the time of wheat harvest, both mulches with vetch (pure vetch and barley/vetch) had fewer weeds (< 1 Mg ha^{-1}) than all other mulches (> 2 Mg ha^{-1}). There were also fewer weeds in mid-summer in the wheat year in barley/vetch mulches than in any other mulch.

The pure stand of pea established well and was competitive with weeds early in the cover crop year, resulting in weeds occupying less than 7% of total plant biomass at time of rolling at both sites. Weed biomass in the pure pea stand at time of rolling was lower than all other mulches except the barley/pea mixture (Figure 3-3). However, low weed biomass at rolling in the pure pea mulch did not result in better weed control the following year, as indicated by high weed biomass in the spring wheat crop.

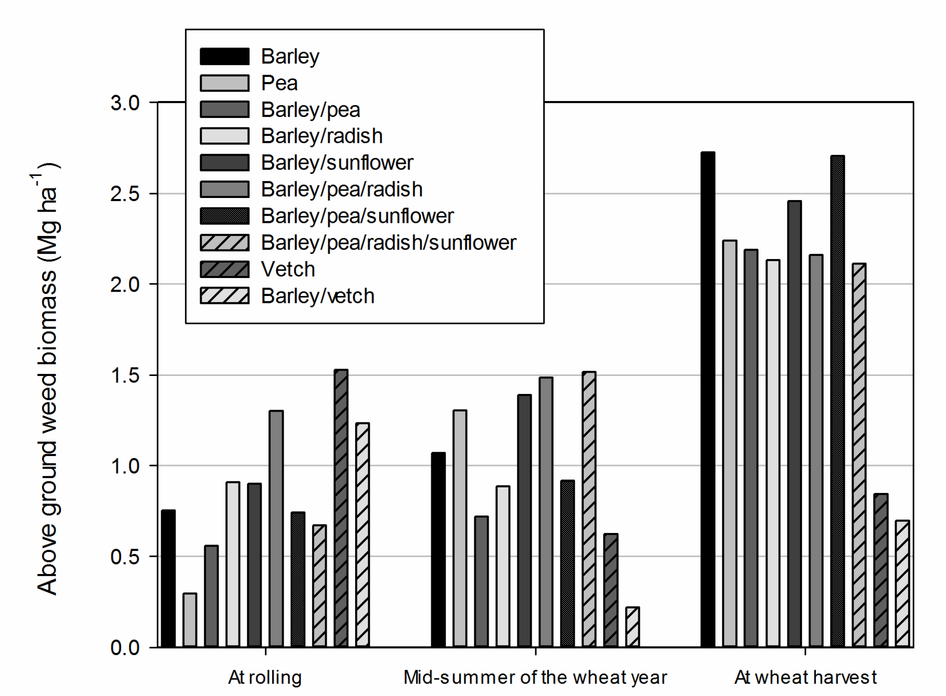

Figure 3-3. Cover crop x time interaction effect on above-ground weed biomass, at both sites (s.e. = 74.9 kg ha^{-1}, n = 238). Square-root transformed data were used to perform ANOVA and means separation, but back-transformed means are presented above.

Weed biomass varied among sites and over time, as indicated by a significant site x time interaction effect ($P < 0.0001$). At time of rolling, there were more weeds in 2011 than in 2010, across all cover crop treatments (1.3 and 0.4 Mg ha^{-1}, respectively). However, the opposite occurred in the wheat year, with a higher weed biomass at spring wheat harvest in 2011 than in 2012 (2.8 and 1.2 Mg ha^{-1}, respectively).

3.4.5 Organic Spring Wheat Agronomic Performance

Cover crops had no effect on wheat plant population density. However, spring wheat under mulches containing hairy vetch showed slower emergence than in other mulches (Table 3-4). Spring wheat seeded into hairy vetch-containing mulches had the highest biomass at harvest and the greatest grain yield, across both sites, compared with mulches without hairy vetch (Table 3-4). Spring wheat grain yield was negatively correlated to weed biomass at spring wheat harvest (r = -0.84, P < 0.0001, n = 80). Spring wheat yields were more than double in 2012 compared to 2011, across all cover crop treatments (Table 3-4), and wheat grain yield was correlated to spring wheat plant population density (r = 0.73, P < 0.0001, n = 80).

3.4.6 Nitrogen Uptake in the Wheat Year

There was a significant main effect of cover crop species on total above-ground plant N uptake (Table 3-5). Total above-ground plant N uptake (in wheat and weeds combined) was the greatest in pure vetch, barley/vetch and pure pea mulches, and ranged between 95 and 100 kg N ha^{-1}. Nitrogen content of wheat grain at harvest was negatively correlated with weed biomass at wheat harvest (r = -0.81, P < 0.0001, n = 80) and positively correlated with wheat grain yield (r = 0.98, P < 0.0001, n = 80), suggesting that N content of wheat was affected by weed competition. Less than 10 kg N ha^{-1} was lost to weeds in the wheat crop grown in mulches containing vetch. In other mulches, weeds

Table 3-4. Main effects of cover crop and site on spring wheat agronomic performance, and summary of analysis of variance.†

Main effects	**Spring wheat plant population density**	**Spring wheat developmental stage (measured with Haun scale)**	**Aboveground spring wheat biomass at harvest**	**Spring wheat grain yield**	
				Without any covariate	**Adjusted with spring wheat plant population density as a covariate**
	plant m^{-2}		---------------Mg ha^{-1}---------------		
Cover crop (C)					
Pure stand					
Barley	226 a	2.62 ab	2.0 de	0.8 d	0.9 d
Pea	260 a	2.72 a	5.1 b	2.2 b	2.1 b
Vetch	262 a	2.49 bc	8.0 a	3.3 a	3.2 a
2-species mixture					
Barley/pea	212 a	2.71 a	4.2 bc	1.7 bc	1.9 bc
Barley/vetch	254 a	2.36 c	7.7 a	3.2 a	3.1 a
Barley/radish	253 a	2.68 a	3.5 c	1.4 cd	1.3 cd
Barley/sunflower	208 a	2.58 ab	2.0 e	0.8 d	0.9 d
3-species mixture					
Barley/pea/radish	229 a	2.72 a	3.5 cd	1.5 c	1.5 bc
Barley/pea/sunflower	223 a	2.68 a	3.6 bc	1.5 c	1.6 bc
4-species mixture					
Barley/pea/radish/sunflower	230 a	2.74 a	3.7 bc	1.5 c	1.6 bc
Site (S)					
South site (2011)	125 b	3.08 a	2.3 b	1.0 b	1.5 a
North site (2012)	346 a	2.18 b	6.4 a	2.6 a	2.1 a
Source of variation	---------------------------*P* value---------------------------				
C	ns‡	***	***	***	***
S	***	***	***	***	ns
C x S	ns	ns	ns	ns	ns
Covariate	n/a	n/a	n/a	n/a	***

*** Significant at the 0.001 probability level.

† Within columns, means of a same main effect followed by the same letter are not significantly different from each other according to LSD test at α = 0.05 (*n* = 80, for each response).

‡ ns, not significant at the 0.05 probability level.

Table 3-5. Main effects of cover crop and site on nitrogen uptake by spring wheat and weeds at harvest, and summary of analysis of variance.†

Main effects	**Spring wheat straw N concen-tration**	**Weed N concen-tration**	**Spring wheat straw N content**	**Spring wheat grain N content**	**Total spring wheat (straw and grain) N content**	**Weeds N content**	**Total (spring wheat straw + grain + weeds) N content**
	------------g g^{-1}------------		----------------------------------kg N ha^{-1}----------------------------------				
Cover crop (C)							
Pure stand							
Barley	0.30 a	1.03 cd	3.92 de	19.98 d	27. 17 cd	26.53 a	52.20 cd
Pea	0.27 a	1.28 bc	8.81 bc	61.74 b	75.62 a	22.30 ab	94.95 a
Vetch	0.23 a	1.57ab	11.31 ab	77.76 ab	89.07 a	9.10 c	98.17 a
2-species mixture							
Barley/pea	0.21 a	1.23 cd	5.68 cd	43.63 c	52.90 b	21.69 ab	76.25 b
Barley/vetch	0.26 a	1.65 a	12.14 a	79.65 a	91.79 a	8.43 c	100.22 a
Barley/radish	0.21 a	1.19cd	3.76 de	31.85 cd	37.15 bcd	22.32 ab	56.89 cd
Barley/sunflower	0.24 a	1.07 cd	2.70 e	18.62 d	21.55 d	24.21 ab	46.05 d
3-species mixture							
Barley/pea/radish	0.19 a	1.16 cd	3.46 de	34.98 cd	42.70 bcd	19.54 ab	61.68 bcd
Barley/pea/sunflower	0.22 a	1.10 cd	4.74 de	37.47 c	44.25 bc	26.00 a	68.38 bc
4-species mixture							
Barley/pea/radish/sunflower	0.20 a	0.93 d	3.99 de	38.08 c	42.83 bc	17.73 b	60.03 bcd
Site (S)							
South site (2011)	0.23 a	0.83 b	3.40 b	20.02 b	27.57 b	22.77 a	48.74 b
North site (2012)	0.23 a	1.61 a	8.70 a	68.73 a	77.43 a	16.79 a	94.23 a
Source of variation	--*P* value--						
C	ns‡	***	***	***	***	***	***
S	ns	***	**	***	***	ns	***
C x S	ns	ns	ns	ns	ns	ns	ns
n	70	79	70	80	70	80	70

** Significant at the 0.01 probability level, *** Significant at the 0.001 probability level, ‡ NS, not significant at the 0.05 probability level.

† Within columns, means of a same main effect followed by the same letter are not significantly different from each other according to LSD test at $\alpha = 0.05$. All N concentration and N content are reported on a dry matter basis. Square-root transformed data were used to perform ANOVA and means separation on weed N concentration and spring wheat straw N content, but back-transformed means are presented above.

took up between 18 and 27 kg N ha^{-1}. Also, N concentration in weed tissue was numerically the highest in pure vetch and barley/vetch mulches. There was a significant cover crop x site effect on wheat grain protein concentration ($P = 0.0012$). Wheat grain protein concentration ranged between 8.6 and 14.1 g g^{-1}, with no trend towards a high or low grain protein concentration for spring wheat grown on mulches with vetch (data not shown).

3.4.7 Soil Chemical Properties

Enrichment of N into the soil (ranging between 13 to 28 kg NO_3-N ha^{-1}) occurred overwinter since soil NO_3-N (0-90 cm) increased between fall of the cover crop year (2011) and the following spring (2012) in all treatments (soil was not sampled in fall of the cover crop year in 2010) ($P < 0.001$, Figure 3-4 and Table 3-6). There was also a decrease in soil NO_3-N (0-90 cm) between spring and fall of the wheat year (Figure 3-4), attributed to N uptake by the growing wheat and weeds. This trend was observed for all cover crop treatments, at both sites. Subsoil soil NO_3-N content (60-90 cm) was low, averaging 5, 12, and 3 kg NO_3-N ha^{-1} in the fall of the cover crop year, and in the subsequent spring and fall, respectively, across all cover crop treatments and sites. Cover crop treatments had no significant effect on soil pH, soil organic matter, and soil phosphorous content over the entire duration of this present study (data not shown).

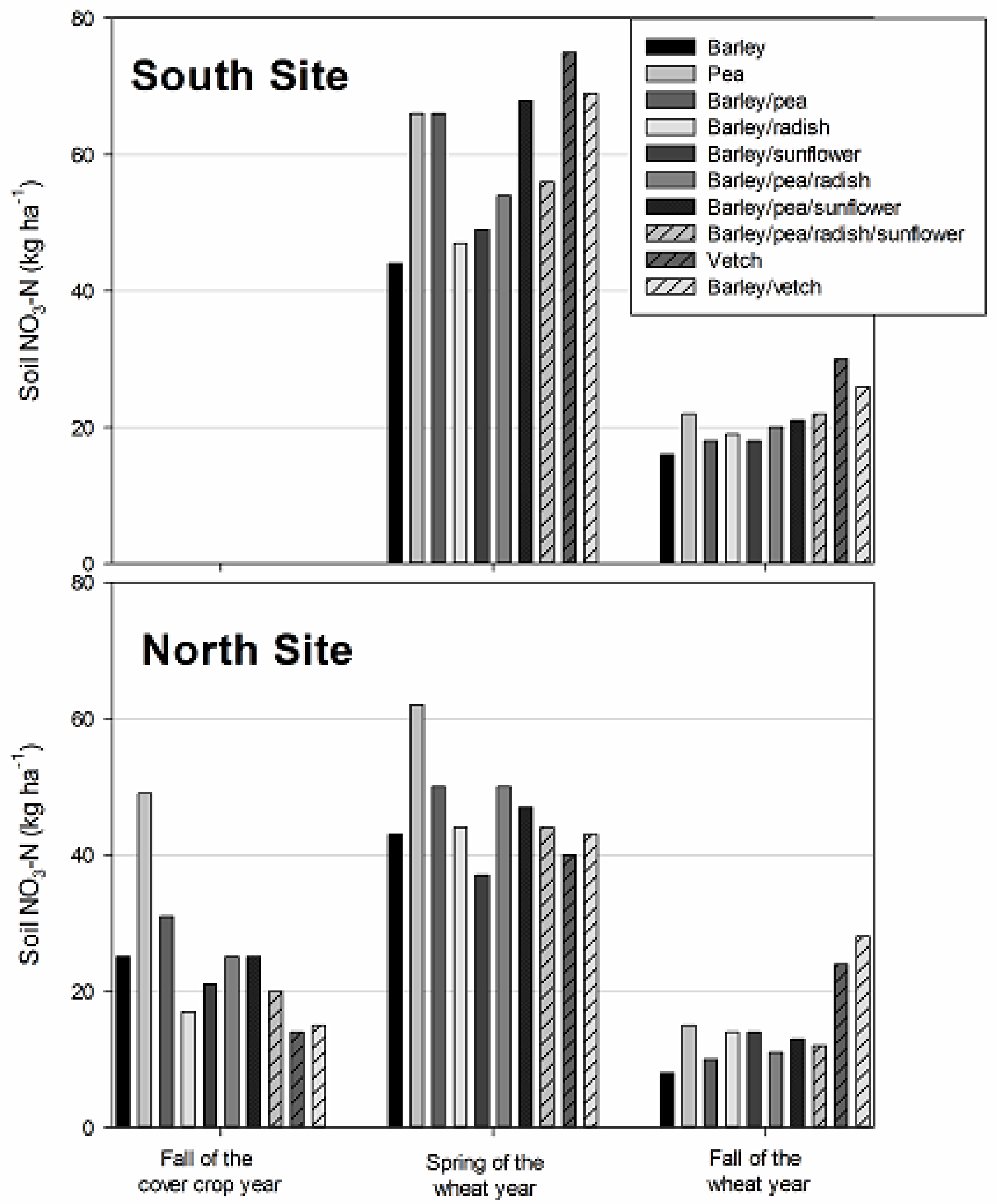

Figure 3-4. Cover crop x site x time interaction effect on cumulative soil nitrate N (0-90 cm) (s.e. = 1.40 kg NO_3-N ha^{-1}, *n* = 197). Square-root transformed data were used to perform ANOVA and means separation, but back-transformed means are presented above. Soil was not sampled in fall of the cover crop year at the South site.

Table 3-6. Summary of analysis of variance of cover crop, site and time for soil nitrate-N.†

Source of variation	**NO_3-N**				
	0-15 cm	**15-30 cm**	**30-60 cm**	**60-90 cm**	**Cumulative 0-90 cm**
	----------------------------*P* value----------------------------				
Cover crop (C)	***	**	***	***	***
Site (S)	***	ns‡	**	***	**
Time (T)	***	***	***	***	***
C x S	*	ns	ns	ns	ns
C x T	***	***	***	**	***
S x T	**	ns	**	*	ns
C x S x T	ns	***	***	NS	***
n	199	198	196	197	197

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Square-root transformed data were used to perform ANOVA and means separation for NO_3-N at 15-30, 30-60, 60-90, and 0-90 cm.

‡ ns, not significant at the 0.05 probability level.

3.5 Discussion

3.5.1 Adaptation of the Organic Rotational No-till System for a Short Season Region

The organic rotational no-till system adapted for the northern climate of Manitoba differs in many aspects from the system studied in the mid-Atlantic region of the U.S.A. In eastern U.S.A., fall-seeded cover crops such as cereal rye and hairy vetch are used to produce a biomass that will be rolled in early-spring to produce mulch for the subsequent spring-seeded crop. In southern Manitoba, the short growing season (Agriculture Canada plant hardiness zone 3a) makes it difficult to grow a biomass production of fall-seeded cover crops greater than 2.4 Mg ha^{-1} (H. Cicek, personal communication, 2013; Thiessen Martens et al., 2001). Cover crops are also not established later in the growing season (July or August), because water becomes quickly limiting in mid-summer in this environment receiving on average less than 400 mm of precipitation during the growing season (1 May – 31 Oct.) (Environment Canada, 2013). Hence, a full-year growth of cover crop is needed to produce mulch of sufficient biomass. Moreover, investing an entire growing season to grow cover crops is a profitable practice for growers in the northern Great Plains, compared with a year of continuous cropping (Fryza, 2013) or fallow (Smith et al., 2004).

Therefore, in the organic rotational no-till system for southern Manitoba, cover crops are seeded with tillage in the spring (mid-May to early-June), and then rolled with a roller-crimper in mid-summer (late-July to early-August). The roller crimper is used to terminate the cover crops at the flowering stage instead of letting the cover crops winter-kill, in order to insure that they will not set seeds. The rolled cover crops are left decomposing on the soil surface for about 9 mo (August to May) before a cash crop is no-till seeded into these mulches.

3.5.2 Hairy Vetch's Extended Growth

Hairy vetch was the only cover crop species tested that was not killed by the crimping action of the roller-crimper, confirming an earlier observation of this phenomenon by I. Vaisman (personal communication, 2010) with spring-seeded hairy vetch in southern Manitoba. Hairy vetch was completely resistant to crushing, and kept growing between the time of rolling until late-fall, giving it the characteristic of 'living mulch' for that period. Hairy vetch was also resistant to the second rolling event in late-fall. As a winter-annual, hairy vetch never reached full-blossom when seeded in the spring, and it only produced a few flowers in the cover crop year. Spring-seeded hairy vetch winter-killed and no hairy vetch plant survived the winters at Carman, MB. A few hairy vetch plants were observed at the same location in consecutive years, primarily due to delayed germination of hairy vetch non-scarified seeds due to its hard seedcoat.

3.5.3 Selecting Cover Crop Mulches for Weed Control and Crop Yield

Mulch biomass production varied among cover crop treatments, resulting in a wide range of mulch biomass accumulated by late-fall (4.1-10.7 Mg ha^{-1}) and present the following spring (1.8-7.6 Mg ha^{-1}). The biomass of cover crop produced during a full-year in this study was similar to that reported by Vaisman et al. (2011) for a full-year growth of pea/oat cover crop at the same research station. Mulches with hairy vetch consistently had the highest mulch biomass. Species combinations of high plant diversity (3 or 4 species mixture) did not have the highest mulch biomass production, because of hairy vetch's resistance to the action of the roller-crimper, negating our first hypothesis.

The most successful mulches for weed control were those containing hairy vetch. Extended growth of hairy vetch in fall yielded high mulch biomass (6.0-7.6 Mg ha^{-1} in spring of the wheat year). Vetch mulches also resulted in better weed control in the wheat year, despite slow growth of hairy vetch in the spring of the cover crop year. Mulches of 6.0-7.6 Mg ha^{-1} at time of spring wheat seeding were sufficient to provide good weed control in organic rotational no-till spring wheat in southern Manitoba, corroborating the second hypothesis that the best weed control was provided by mulches with the greatest biomass. This range is lower than minimum biomass levels of 8 Mg ha^{-1} necessary for suppressing summer annual weeds in organic rotational no-till grain production with cover crop mulches in the mid-Atlantic region of the U.S.A. (Mirsky et al., 2012), but higher than the minimum biomass levels of 4 Mg ha^{-1} of oat straw residues for sufficient weed suppression in occasional direct-seeding of organic faba beans (*Vicia faba* L.) in Germany (Massucati and Köepke, 2011). Mulch biomass has an important effect on weed suppression; therefore enhancing cover crop biomass for optimizing weed control has been a focus of cover crop research in the U.S.A. in the past decades (Mirsky et al., 2013).

Weed competition affected spring wheat yields, as indicated by the negative correlation between weed biomass and spring wheat yield in the present study. Our third hypothesis stating that mulches providing the best weed control produce the highest spring wheat yield was corroborated. The highest wheat yields were found in the mulches containing hairy vetch, at both sites. However, mulches with vetch also supplied the highest amounts of N, confounding the effect of weed control on crop yield. These yields under vetch mulches were comparable to conventional hard red spring wheat yields in the rural municipality of Dufferin where the study sites were located (2.78 Mg ha^{-1} in 2011, 4.05 Mg ha^{-1} in 2012, and an average of 3.41 Mg ha^{-1} across both years) (MMPP, 2013). Slower emergence of spring wheat in mulches containing hairy vetch was likely due to lower soil temperatures in the spring and did not result in a yield penalty. Lower surface soil temperatures under high biomass mulches have been observed in previous studies (e.g. Podolsky, 2013), which contributed to delayed crop emergence. Yields in other mulches represented only 23 to 64% of regional yields. Overall, spring wheat seeded into mulches containing no legume species (pure barley, barley/radish, and barley/sunflower) yielded the lowest.

3.5.4 Nitrogen Dynamics

Our fourth hypothesis stating that sufficient N is available to fulfill the N requirement of the subsequent crop was corroborated by our results. Hairy vetch-containing mulches were found to be the best at supplying high amounts of N to the subsequent plants (crop and weeds). In late-fall of the cover crop year, mulch N content averaged 308 kg N ha^{-1} for mulches containing hairy vetch, compared with 83 kg N ha^{-1} in other treatments. Brown (2013) reported similar high levels (175-288 kg N ha^{-1}) of N accumulation with a winter annual vetch cover crop of biomass ranging between 6.5 to 8.8 Mg ha^{-1} in North Carolina, U.S.A. It is important to note that mulch N measurements in the present study represented only the N content of the mulch biomass, and that root N contribution is not included in these values.

An average of 48% of N remained in the mulch biomass over winter and was still present in the various mulches in the spring of the wheat year. Therefore, large amounts of N (18-164 kg N ha^{-1}) were released from the mulch biomass overwinter. This N may have been mineralized, volatilized, taken up by weeds in early-spring, incorporated into the soil microbial biomass, or directly transferred to the soil through leaching of soluble components. Results from the present study showed that some of the N lost from the mulch overwinter was transferred to the soil since soil nitrate-N (0-90 cm) increased by 13 to 28 kg NO_3-N ha^{-1} between late-fall and spring planting.

Soil nitrate-N content at deeper depths (60-90 cm) was generally low (< 12 NO_3-N ha^{-1}), indicating low risk for soil nitrate leaching for all cover crop treatments. Soil nitrate-N (0-90 cm) present in spring for the spring wheat crop growing in the mulches averaged 53 kg NO_3-N ha^{-1}. Nitrogen uptake by wheat and weeds during the growing season averaged 71.5 kg N ha^{-1} across all cover crop mulches.

Further work is needed on nutrient synchrony between mulch N release and crop N uptake in organic rotational no-till systems in southern Manitoba. In our system, cover crop mulches without vetch start releasing N in mid-summer, after being terminated by the roller-crimper. Nine months pass until the following cash crop is no-till seeded into these mulches. There is no living plant scavenging the N provided by the mulch decomposition, leaving room for N losses. In contrast, in mulches with vetch, hairy vetch’s extended growth provides a sink for N until freeze-up in October. There are still about 6 mo without any plant growth before a crop is seeded into the mulches, but soil temperatures are below 0°C for much of this time period. Our system differs in many ways to the organic rotational no-till system in the eastern U.S.A., where cash crops are planted into the mulches in the spring, simultaneously or within 1-2 wk after rolling (Mirsky et al., 2012).

3.5.5 Wheat Performance

Spring wheat yields in 2012 were more than double than those in 2011. This is mainly due to a spring wheat plant population density in 2012 more than double that of 2011, despite similar seeding rates at both locations. Spring wheat grain yield was positively correlated to spring wheat plant population density in this study. When corrected with spring wheat plant population density as a covariate, the main effect of site became non-significant, indicating that most of the differences in spring wheat yields among the two sites were due to the large difference in wheat density between sites. Moreover, poor establishment and yield of spring wheat in 2011 was likely due to excessive water content of soil and cold temperatures in the spring, which reduced crop yield throughout the region (Environment Canada, 2011). Precipitation during spring wheat growth (May until August) was also higher in 2012 than in 2011, with 222 and 181 mm, respectively (Environment Canada, 2013).

Despite the differences in environmental conditions between sites, the effect of cover crop mulches on weed biomass did not vary over sites, across all sampling dates. Mulches with hairy vetch provided better weed control in spring wheat than the other mulches did, at both sites, independently of having different environmental conditions in both experiment repetitions. This confirms the validity of our mulch selection (i.e. mulches with hairy vetch) for organic rotational no-till spring wheat production in southern Manitoba.

3.5.6 Implications for Management

Results presented in this paper showed that mulches with hairy vetch were able to suppress weeds and produce wheat yields comparable to rural municipality averages in an organic rotational no-till system in Carman, MB, Canada. The successful adaptation of the organic rotational no-till system to the growing conditions of southern Manitoba reduced the need for tillage for a period of 1.5 to 2 yr in organic spring wheat production. This practice would be also useful to conventional farmers interested in reducing their use of synthetic N fertilizer by integrating cover crops into their farming systems. It may also help farmers reduce their herbicide use and decrease the selection pressure for herbicide-resistant weed biotypes.

The roller-crimper has been a key component of the adaptation of the organic rotational no-till system in eastern U.S.A. (Mirsky et al., 2013). It has also been a useful cover crop management tool in southern Manitoba for mechanically terminating cover crop mixtures containing summer-annual species before they could set seeds, such as barley. However, in pure hairy vetch mulch in southern Manitoba, the roller-crimper did not kill or reduce growth of hairy vetch. In the present study, hairy vetch died overwinter. This observation begs the question if the roller-crimper is even necessary in pure hairy vetch stands, or could the roller-crimper pass be eliminated in order to reduce machinery traffic and fossil fuel use. Our experience with the roller-crimper used in pure hairy vetch stand showed that the action of the roller-crimper in mid-summer and later in late-fall did have a place in the management of the weeds growing along with the vetch. Hairy vetch’s slow establishment in the spring (< 3 Mg ha^{-1} by mid-July), resulted in weeds establishing, with weeds representing up to 56% of biomass at first rolling in 2011. The roller-crimper was also useful to kill some weeds in mid-summer and in late-fall, before they could set seeds.

3.6 Conclusions

Results from field experiments in 2010-2012 indicated that high-biomass mulches (6.0-7.6 Mg ha^{-1}) of pure hairy vetch or of a barley/hairy vetch mixture have the ability to suppress weeds and to produce spring wheat yields comparable to rural municipality averages in an organic rotational no-till system in Carman, MB, Canada. Cover crop species mixtures of high plant diversity (3-4 species) were not able to achieve the same high mulch biomass production as hairy vetch. This was mainly due to hairy vetch's ability to continue growing after the rolling operation. High amounts of N (93-164 kg N ha^{-1}) were released over winter from mulches with vetch. Overall, the successful adaptation of the organic rotational no-till system to the growing conditions of southern Manitoba reduced the need for tillage for a period of 1.5 to 2 years in organic spring wheat production.

Future research could include breeding cover crops for high biomass production and developing a better understanding of the economic implications of the organic rotational no-till system for various cash crops in southern Manitoba. Moreover, since annual precipitation is low and soil water often limits crop production in western Canada, it would be important to assess water use by the cover crop grown to produce the mulch, in years of drought particularly.

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MANUSCRIPT #2

4.0 FLAX (*LINUM USITATISSIMUM* L.) PRODUCTION SYSTEM PERFORMANCE UNDER ORGANIC ROTATIONAL NO-TILL AND TWO ORGANIC TILLED SYSTEMS IN A COOL SUBHUMID CONTINENTAL CLIMATE

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4.1 Abstract

Studies comparing crop agronomic response in organic production systems under contrasting tillage practices are lacking. The objective of the study was to compare the effect of organic rotational no-till and two organic tilled systems on the basis of mulch biomass, soil chemical properties, weed control, and subsequent crop productivity. A field study consisting of two-year sequences was conducted at three sites in close proximity located in Carman, MB, Canada (2009-2010 at site A, 2010-2011 at site B, and 2011-2012 at site C), on Chernozem soils. Three management systems of cover crops were tested, in a randomized complete block design. A barley (*Hordeum vulgare* L.)/hairy vetch (*Vicia villosa* Roth) cover crop was grown in the first year of the study and terminated by rolling (No-Till), rolling and tillage (Roll+Till), or haying and tillage (Hay+Till). Flax (*Linum usitatissimum* L.) was seeded the following year. Four hypotheses were tested. Our first hypothesis that a full-year growth of barley/hairy vetch

cover crop allows the production of between 6 and 8 Mg ha^{-1} of mulch biomass for the subsequent crop was confirmed in two of three years. Flax was no-till seeded into 6.7, 7.7, and 4.2 Mg ha^{-1} of mulch at sites A, B, and C, respectively. At two of three sites, flax seed yields were significantly higher in No-Till than in the two tillage treatments. Across all three sites, there was no penalty on flax seed yield for haying the cover crop in mid-summer instead of incorporating it into the soil by tillage. There was an overall trend towards lower content of soil nitrate-N in No-Till, although it did not greatly influence total plant nitrogen uptake at two of three sites. This corroborates the second hypothesis that while flax N uptake would be reduced by the reduced soil N status in No-till, there will be sufficient N for optimum flax yield. The third hypothesis that barley/hairy vetch cover crop mulches have the ability to provide adequate weed control was generally supported, though there were important exceptions when insufficient mulch biomass was produced. Success of flax crop grown in an organic rotational no-till system in southern Manitoba depended on weather, mulch biomass production (> 6.7 Mg ha^{-1}), and weed species present. The fourth hypothesis that there is no yield penalty for eliminating tillage for 1.5 yr in an organic flax crop in southern Manitoba held true only if the minimum mulch biomass benchmark of 6.7 Mg ha^{-1} was reached.

4.2 Introduction

Many studies comparing different tillage intensities (e.g. inversion vs conservation tillage) on crop performance have been conducted in the past decades. However, studies comparing no-tillage to tilled systems in organic systems are lacking (Carr et al., 2013). Experiments comparing the crop performance of organic rotational no-till systems to those of organic tilled systems are rare in the northern Great Plains of Canada (Podolsky, 2013; Sullivan, 2012; Vaisman et al., 2011), and elsewhere. There is a need to assess the effectiveness of organic rotational no-till systems in terms of weed control, nitrogen dynamics and crop performance to those of organic tilled systems, for a broader adoption of the organic rotational no-till practices by farmers.

In organic rotational no-till systems, a cover crop is established with tillage and terminated using a roller-crimper to create mulch, in which a cash crop is no-till planted. Most organic rotational no-till systems adapted or studied in Canada (Estevez, 2008; Lefebvre et al., 2011; Leroux et al., 2011) or in the U.S.A. (Carr et al., 2013; Mirsky et al., 2012) use fall-seeded cover crops such as cereal rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth) to produce a biomass that will be rolled in early-spring to produce mulch for the subsequent spring-seeded crop. In southern Manitoba, biomass production of late-summer or fall-seeded cover crops tends to be low (< 2.4 Mg ha^{-1}) due to the short growing season and low annual precipitation (H. Cicek, unpublished data; Thiessen Martens et al., 2001). Hence, a full-year growth of cover crop is needed to produce mulch of sufficient biomass (MANUSCRIPT #1). Moreover, organic growers in the eastern region of the northern Great Plains of Canada also depend on cover crops for N, since the availability of animal manure is low (Entz et al., 2001). The organic rotational no-till system tested in this study (with a full-year growth of cover crop) is similar to traditional use of cover crops by organic growers of the region, i.e. 1 yr out of 3. The investment of growing a cover crop instead of a year of fallow (Smith et al., 2004) or continuous cropping (Fryza, 2013) has been found to be profitable for growers in the northern Great Plains of Canada.

In the organic rotational no-till system, the elimination of tillage for a period greater than a year in organic production brings additional challenges to the already complex organic farming systems. Poor weed control and reduced N mineralization are the most important challenges when grain crops are direct-seeded into a cover crop mulch in organic no-till systems (Carr et al., 2013; Mirsky et al., 2012). The biomass of cover crop produced is very critical to the success of the organic no-till system, since it is key for weed control.

For successful establishment and growth of a no-till seeded crop into cover crop mulches in organic cropping systems, the minimum biomass of mulch required for sufficient weed control has been found to be between 6 and 8 Mg ha^{-1} (MANUSCRIPT #1; Mirsky et al., 2012). Hence, with less mulch, weed control, and hence crop yield, will suffer (Podolsky, 2013; Teasdale et al., 2012). Moreover, reduced mineralization of the cover crop due to rolling instead of soil incorporation often leads to a lack of synchrony N availability from the cover crop and the cash crop N need (Parr et al., 2011; Vaisman et al., 2011). Changes in N availability in organic rotational no-till systems have an impact on the competitive ability of weeds and crops (Wells et al., 2013), due to differences in N responsiveness between plant species. Weed-crop competition has been found to reduce crop yield in organic rotational no-till soybean [*Glycine max* (L.) Merr.] production. Unsuccessful attempts at adopting the organic rotational no-till system have also been linked to inappropriate termination time of the cover crop (Ashford and Reeves, 2003; Mirsky et al., 2009) and improper design of the roller-crimper (Estevez, 2008).

Hairy vetch has been widely used in organic rotational no-till systems across North America and Europe. In pure stands or mixed with cereal rye, mulches that include vetch have provided effective weed control in field (Mischler et al., 2010; Parr et al., 2011) and vegetable crops (Leavitt et al., 2011; Price and Norsworthy, 2013) at various locations across North America. Efforts have also been invested in developing new hairy vetch cultivars for early flowering, high biomass production, and winter hardiness (Maul et al., 2011; Teasdale et al., 2004). In southern Manitoba, Canada, mulches with hairy vetch (in pure stand or in a mixture with barley (*Hordeum vulgare* L.)) have been identified as the best mulches for organic rotational no-till systems (MANUSCRIPT #1). They can produce high biomass (9.1-11.5 Mg ha^{-1}) in one full-year and provide efficient weed control and sufficient N input to the subsequent wheat crop.

The main objective of this study was to compare the effect of the organic rotational no-till system to that of two organic management systems of cover crops with tillage on mulch biomass, soil chemical properties, weed control, and subsequent crop productivity of flax. The study also aimed to determine a minimum mulch biomass benchmark at which the organic rotational no-till system produces similar or greater flax (*Linum usitatissimum* L.) yields than the organic tilled systems. The hypotheses of the study were the following: 1) A full-year growth of barley/hairy vetch cover crop allows the production of between 6 and 8 Mg ha^{-1} of dry mulch biomass in southern Manitoba; 2)

Soil nitrate-N content is reduced in organic rotational no-till system (No-Till), affecting N uptake in the subsequent crop but still sufficient for optimum flax yield; 3) Mulches of barley/hairy vetch cover crop provide adequate weed control for the subsequent crop; 4) There is no yield penalty for eliminating tillage for 1.5 yr in an organic flax crop in southern Manitoba.

4.3 Materials and Methods

4.3.1 Study Sites

The field studies were conducted at the University of Manitoba Ian N. Morrison Research Farm in Carman, MB, Canada (49°29'53.200" N lat, 98°01'47.100" W long). Soils at the study sites were Orthic Black Chernozems of the Hochfeld series, with a fine sandy loam texture (76.0% sand, 10.3% silt, and 13.7% clay) (Mills and Haluschak, 1993). The 0-15 cm topsoil had a $pH_{(H2O)}$ of 5.6 and an organic C content of 22 g kg^{-1}. These soils were moderately well drained, with < 1% slope (Mills and Haluschak, 1993), and they have developed on shallow sandy, loamy and clayey glaciolacustrine sediments. Soils at the study sites were underlain by a clay substrate at depths ranging from the soil surface to 2 m. The sites had been under organic management since 2003, although not certified organic. Weather data were collected directly on site, at the Research Farm in Carman, MB. The study sites were located within the Winkler Ecodistrict, within the Lake Manitoba Plain Ecoregion of the Prairies Ecozone (Smith et al., 1998) at 268.2 m above sea level. The ecodistrict had a mean number of growing degree-days of about 1800 (T_{base} = 5°C).

4.3.2 Experimental Design

A field study consisting of two-year sequences was conducted three times, each time on a different site within the same research farm: site A (2009-2010), site B (2010-2011), and site C (2011-2012). All sites were located within a 500 m-radius from each other. In the cover crop year, a mixture of barley and hairy vetch was seeded in the spring after tillage, and then rolled or hayed in mid-summer. In the fall, the cover crop was incorporated into the soil or remained untouched, depending on the management system of cover crops. In the following year, flax was seeded directly into the mulch or the tilled seedbed in spring.

The experimental design was a randomized complete block design, with four blocks. Each experimental unit was 8 m x 8 m. Alleyways of 8 m wide separated the four blocks. Management system of cover crops was the factor of interest, with three levels: No-Till, Roll+Till, and Hay+Till. In No-Till, the cover crop was rolled in mid-summer and left on the soil surface without further disturbance into the next crop cycle of the following year (no-till for 2 yr). In Roll+Till, the cover crop was rolled in mid-summer of the cover crop year, then tilled in the fall, and tilled the following spring in the flax year. In Hay+Till, the cover crop was cut and removed from the plots in mid-summer, allowed to regrow, then tilled in the fall, and tilled again the following spring in the flax year.

4.3.3 Field Operations

In the cover crop year, all treatments were tilled in early-spring, before the establishment of a cover crop of barley and hairy vetch (seeded at about 75 and 35 kg ha^{-1}, respectively). The cover crop in the No-Till and Roll+Till was rolled twice (once in each direction) with a roller-crimper in mid-summer (late-July) once barley had reached the flowering stage. The cover crop in the Hay+Till treatment was mowed using a 4.3-m swather (Versatile #104, Winnipeg, MB, Canada) on the same day as the rolling happened in the other two treatments, and then removed from the plots a few days later. In late-September or early-October, the cover crop regrowth and/or rolled mulch was tilled in Roll+Till and Hay+Till using a tandem-disk, or rolled again twice (once in each direction) in No-Till. The second rolling in late-fall in No-Till was performed to kill weeds, before they could set seeds.

In spring of the flax year, tillage was performed in the Roll+Till and Hay+Till treatments. Flax (cv. CDC Bethune) was then seeded in mid-May using a disk-opener no-till seeder (2-m wide, 15-cm row spacing) at 51, 55, and 59 kg ha^{-1}, at sites A, B, and C, respectively. Depth-band disks were used on the seeder at site C exclusively. After collecting quadrats to estimate above-ground biomass of flax and weeds at harvest, the remaining plant biomass was swathed with a swather, harvested for flax grain with a combine (New Holland #1400, New Holland, PA, U.S.A.). Then the left over straw biomass was removed from all plots.

None of the three treatments received any pesticide, synthetic fertilizer, or animal manure during the duration of the study. All tillage operations were non-inversion tillage and they were performed using a tandem-disk at the top 10 cm soil layer.

4.3.4 Data Collection

4.3.4.1 Mulch Sampling

Two quadrats (0.45 m x 0.50 m) per experimental unit were harvested to assess above-ground biomass of plants at rolling and biomass of mulch every 30 days between rolling and October (Table 4-1). All quadrats were clipped at 2 to 5 cm above-ground and the fresh plant material was collected in paper bags. Above-ground plant biomass at rolling was hand-sorted into individual crop species (barley, hairy vetch) and weeds. Above-ground biomass at termination was not measured at site A. Freshly sorted plant and mulch samples were oven-dried at 60°C for 48 h and weighed to determine dry biomass. Mulch samples were collected in the cover crop year at sites B and C only, in 2010 and 2011, respectively.

Mulch remaining was sampled in the flax year at all three sites, between 2010 and 2012. Two quadrats (0.45 m x 0.50 m) per experimental unit were harvested to assess mulch biomass monthly between April and September. Mulch could not always be sampled monthly as initially planned, because of weather conditions or because the sampling would have been too destructive to the flax immediately before harvest.

4.3.4.2 Soil Sampling

Soil was sampled at four depths (0-15, 15-30, 30-60, and 60-120 cm) in fall of the cover crop year, and in spring and fall of the flax year (Table 4-1). Soil samples were collected using a hand auger or a hydraulic soil auger (Giddings Machine Co., Windsor, CO, U.S.A.) mounted on a tractor, depending on equipment availability. No soil sampling was

Table 4-1. Calendar of soil and plant sampling performed at the three sites over the two-year field sequence.

Crop	**Response observed / measured**	**Sampling period**	**Sampling date at site A**	**Sampling date at site B**	**Sampling date at site C**
Cover crop of barley and hairy vetch	Above-ground plant biomass, sorted into barley, hairy vetch, and weeds	At rolling	- †	19 July 2010	28 July 2011
	Cover crop mulch biomass	Every 30 days, from rolling until October	- †	17 Aug. 2010 17 Sept. 2010 20 Oct. 2010	30 Aug. 2011 23 Sept. 2011 26 Oct. 2011
	Soil sampling	Fall	- †	30 Sept. 2010	5 Oct. 2011
Flax	Soil sampling	Spring	- †	5 May 2011	7 May 2012
	Cover crop mulch biomass remaining	Every 30 days	23 Apr. 2010 23 May 2010 30 June 2010 26 July 2010 20 Sept. 2010	21 June 2011 22 July 2011 19 Aug. 2011	10 May 2012 12 June 2012 7 Sept. 2012
	Flax plant population density	Spring	- †	16 June 2011	1 June 2012
	Above-ground plant biomass, sorted into flax and weeds	At harvest	25 Aug. 2010	23 Aug. 2011	21 Aug. 2012
	Flax seed yield	At harvest	25 Aug. 2010	23 Aug. 2011	21-22 Aug. 2012 (hand-harvested), and 28 and 30 Aug. 2012 (combined)
	Soil sampling	Fall	7 Oct. 2010	7 Oct. 2011	7 Oct. 2012

† Not performed.

done in fall of the cover crop year and the following spring at site A.Two soil samples were taken from each experimental unit and these were combined by depth increment in the field to create one composite sample per experimental unit per depth. These soil samples were analyzed by Agvise Laboratories (Northwood, ND, U.S.A.) for chemical properties. Samples collected from 0-15 cm were analyzed for pH, organic matter content, nitrate-N, phosphorus (Olsen), potassium, and zinc. The other three depths (15-30, 30-60, and 60-120 cm) were analyzed for nitrate-N only.

4.3.4.3 Flax and Weed Sampling

Plants were sampled in the flax year at all three sites, between 2010 and 2012 (Table 4-1) to assess flax and weed performance. Flax plant population density was assessed in spring using a meter stick and by counting the number of individual plants of each crop species along a 1-m row, five times in each experimental unit. Two quadrats (0.45 m x 0.50 m) per experimental unit were harvested to assess above-ground biomass of plants at flax harvest. Above-ground biomass at flax harvest was hand-sorted into flax and weeds. At site C, above-ground biomass of weeds at harvest was also sorted into wild oats (*Avena fatua* L.) and other weeds to estimate the proportion of wild oats in the weed population, because of wild oat populations were exceptionally high. Biomass samples were oven-dried at 60°C for 48 h and weighed to determine dry biomass. Dry biomass of flax and weeds at harvest was ground at 2-mm with a grinder (Arthur H. Thomas Co., Philadelphia, PA, U.S.A.) to determine N concentration by combustion analysis using a nitrogen analyzer (FP-528, LECO Co., St Joseph, MI, U.S.A.).

Three quadrats (1.05 m x 1.00 m) per experimental unit were harvested to assess flax seed yield. These samples were threshed through a combine, cleaned by hand using a sieve, and weighed. At site C, flax left in the experimental units after collecting the three quadrats of biomass was also swathed then combined two days later to compare these seed yield results to those of samples harvested by hand and then threshed using the combine and hand-sieved for further cleaning.

4.3.5 Statistical Analysis

Statistical analyses were conducted using Statistical Analysis System 9.2 (SAS Institute Inc., 2008) software. To compare the effects of management systems of cover crops on plant and soil responses, analysis of variance ($\alpha = 0.05$) was conducted using the MIXED procedure of SAS. Repeated measures were used to compare the effects of management systems of cover crops on soil chemical properties and mulch biomass over time. Fixed effects were management system of cover crops (and time, when applicable), whereas block was considered a random effect. Lund’s test (Lund, 1975) was used to identify outliers. All data were verified for normality and constant variance of residuals. Independence of residuals was assumed through randomization. Means were separated using the Least Square Difference test. The Satterthwaite approximation (ddfm = satterthwaite) was used for estimating denominator degrees of freedom and to produce a more accurate F-test approximation than the original containment method (Satterthwaite, 1946). All responses from the three different sites were analyzed separately, because of missing data due to differences in sampling schedule between the sites. Hence, the effect of site was not tested using statistical analysis. Correlation analyses were performed among mulch-weed-flax responses, using the CORR procedure of SAS ($\alpha = 0.05$).

4.4 Results and Discussion

4.4.1 Weather

Average annual temperature over the duration of the study (2009-2012) varied between 2.3°C and 4.8°C (Environment Canada, 2013). Annual precipitation in 2010 was 635 mm, greater than that of 2009, 2011, and 2012 (458, 325, and 397 mm, respectively, Figure 4-1). High precipitation in fall 2010, combined with a slow snow-melt in 2011, led to wet soils in spring 2011 (Environment Canada, 2011). Crops suffered from excess water for several weeks in spring 2011, affecting crop agronomic performance that year. Monthly temperatures between December and March were on average 6.5°C higher in 2011-2012 than during the 2009-2010 and 2010-2011 winters (Environment Canada, 2013). Weather was similar at each site within a given year, since sites were located close to each other.

4.4.2 Mulch Production and Decomposition

Total biomass of plants produced at time of termination (mid-summer of the cover crop year) was similar across the three management treatments (measured at sites B and C only, Table 4-2), since these treatments were only applied while terminating the cover crops. At site B, average biomass of cover crops at time of termination was 6.1 Mg ha^{-1}. A lower total plant biomass (3.9 Mg ha^{-1}) was produced at time of cover crop termination

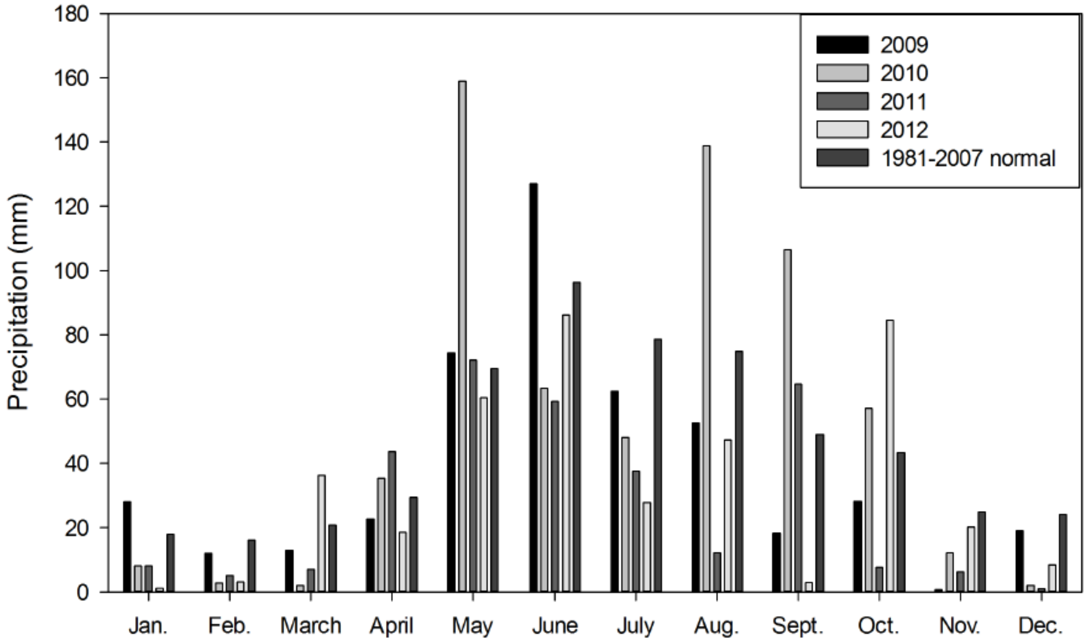

Figure 4-1. Monthly precipitation in Carman, Manitoba, for 2009 to 2012 [adapted from Environment Canada (2013)].

Table 4-2. Mean above-ground biomass of individual cover crop species and weeds at time of termination at sites B and C in mid-summer of the cover crop year, and summary of analysis of variance of management system of cover crops.†

	Above-ground biomass of cover crops and weeds							
	Barley		**Hairy vetch**		**Weeds**		**Total (barley, hairy vetch, and weeds)**	
Site	**B**	**C**	**B**	**C**	**B**	**C**	**B**	**C**
	-----------------------------------Mg ha^{-1}-----------------------------------							
Cover crop management								
No-till	3.45 a	0.70 a	0.80 a	0.80 a	1.97 a	2.22 a	6.22 a	3.72 a
Roll+Till	2.42 b	1.44 a	0.71 a	0.82 a	2.67 a	1.68 a	5.80 a	3.95 a
Hay+Till	3.79 a	0.87 a	0.57 a	0.95 a	2.03 a	2.09 a	6.40 a	3.91 a
Mean of the site	3.22	1.00	0.69	0.86	2.22	2.00	6.14	3.86
Source of variation	---------------------------------*P* value---------------------------------							
Cover crop management	*	ns‡	ns	ns	ns	ns	ns	ns

* Significant at the 0.05 probability level.

† Column means followed by the same letter are not significantly different from each other according to Least Square Difference test at α = 0.05 (*n* = 12, for each response).

‡ ns, not significant at the 0.05 probability level.

at site C during the 2011 growing season. Poor growing conditions due to excess water for cover crop seedling emergence and growth in spring 2011 led to a reduction in barley biomass in the cover crop year at site C. Weed biomass in the cover crop at time of termination by roller-crimping was similar at site B and C, with 2.2 and 2.0 Mg ha^{-1}, respectively, although weeds represented approximately 36 and 52% of total biomass of plants at termination, respectively.

Hairy vetch represented only 11 and 22% of total biomass at time of rolling the cover crop at sites B and C, respectively, due to the slow growth of hairy vetch in the spring compared with barley (Table 4-2). However, the rolling and crimping action of the roller-crimper in mid-summer did not kill hairy vetch. Earlier studies have shown that roller-crimping in mid-summer does not kill a spring-seeded hairy vetch cover crop in Manitoba (MANUSCRIPT #1; I. Vaisman, unpublished data). In the present study, hairy vetch continued to grow until freeze-up in the fall in the No-Till and Roll+Till treatments (Figure 4-2). The pattern of hairy vetch growth was such that it occupied the space on top of the previously killed barley. The continued growth of hairy vetch after barley termination explains the biomass accumulation observed between mid-summer and late-fall in the No-Till and Roll+Till treatments (Figure 4-2). By the end of the fall, cover crop biomass was between 7.9 and 10.8 Mg ha^{-1}. In the Hay+Till treatment, hairy vetch and barley were cut and removed from the plots at time of termination (mid-summer). In this case, the hairy vetch also continued to grow until the end of the fall, along with weeds, but resulted in much less total biomass accumulation (Figure 4-2). Hairy vetch was killed

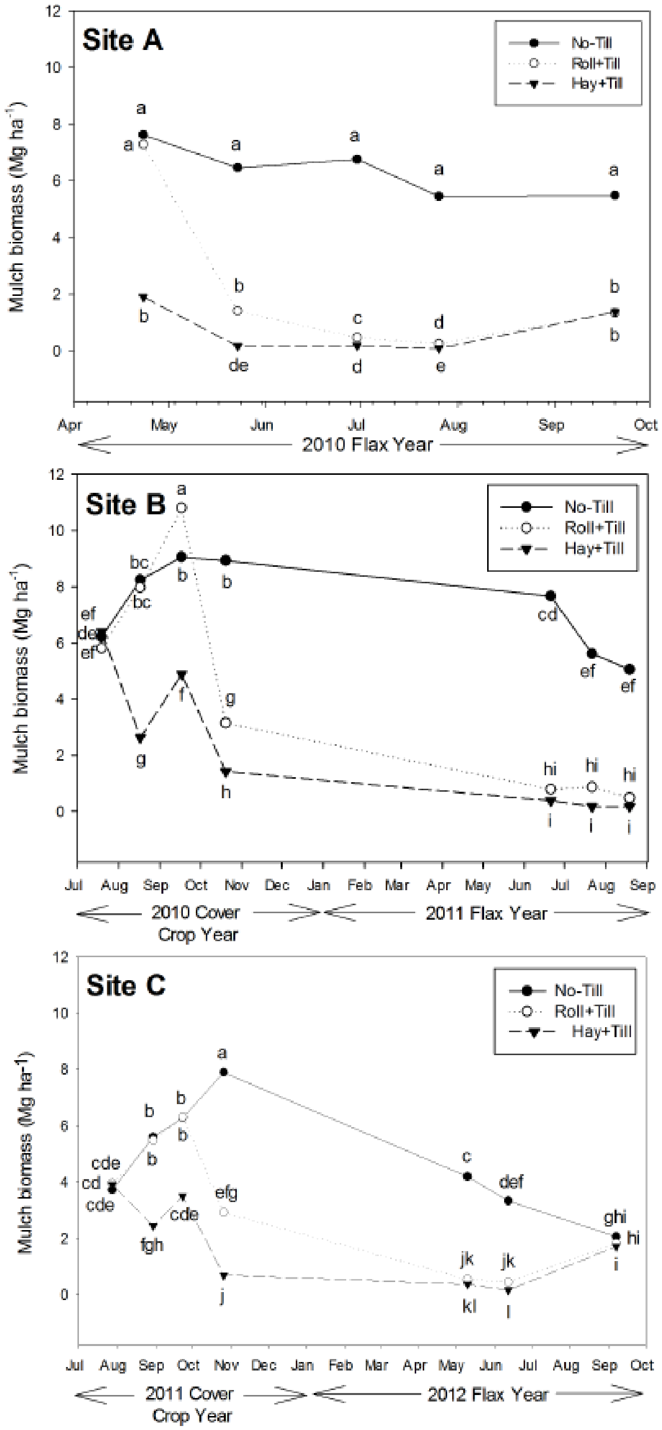

Figure 4-2. Management system of cover crops x time interaction effect on mulch biomass at sites A, B, and C (*n* = 58, 84, and 82, respectively). Within sites, data points with different letters indicate significant difference in mulch biomass among cover crop management system (Least Square Difference, *P* ≤0.05). Natural log- and square-root transformed data were used to perform analysis of variance and means separation on mulch biomass at sites A and C, respectively, but back-transformed means are presented above.

over the winter in all three treatments. There was no growth of hairy vetch or barley over the winter or in spring of the flax year.

The biomass of mulch produced and its decomposition varied among sites and over years. There was a significant interaction between management treatment and time for mulch biomass, at all three sites ($P < 0.001$). In spring of the flax year, no-till flax was seeded into very different biomass of mulch at the three sites. Flax was seeded into 6.7, 7.7, and 4.2 Mg ha^{-1} of mulch in the No-Till treatment at sites A, B, and C, respectively (Figure 4-2). For successful establishment and growth of a no-till seeded crop into cover crop mulches in organic cropping systems, the minimum biomass of mulch required for sufficient weed control has been found to be between 6 and 8 Mg ha^{-1} (MANUSCRIPT #1; Mirsky et al., 2012). Hence, not enough mulch was present in spring 2012 at site C (4.2 Mg ha^{-1}), affecting the ability of the cover crop mulch to control weeds and improve crop yield (discussed in sections 4.4.4 and 4.4.5). Hence, a full-year growth of barley/hairy vetch cover crop did not always produce a mulch biomass between 6 and 8 Mg ha^{-1} for the subsequent crop, rejecting our first hypothesis.

There were different patterns of overwinter cover crop decomposition at sites B and C (Figure 4-2). Barley/hairy vetch mulches in the No-Till treatment had lost 14 and 47% of their biomass overwinter at sites B and C, representing 1.3 and 3.7 Mg ha^{-1}, respectively (Figure 4-2). Soil temperature under the mulches was not recorded at the study site. However, air temperature recorded in Carman, MB, showed warmer winter temperatures in 2011-2012 (site C) than at sites A and B in 2009-2010 and 2010-2011, respectively.

These abnormally high winter temperatures (in March 2012, especially) may have enhanced microbial activity and mineralization of the mulches, accelerating their decomposition rate.

4.4.3 Soil Chemical Properties

The effect of management system on soil nitrate-N varied among sites and soil depths, and was consistent across sampling dates. There was an overall trend towards lower contents of soil nitrate-N in the No-Till treatment (Figure 4-3). At site A, the No-Till treatment had lower total soil nitrate-N content (0-120 cm) than Hay+Till, but not significantly different from Roll+Till. At site B, total soil nitrate-N (0-120 cm) was lower in the No-Till treatment than in the other two management treatments with tillage, across all sampling dates. The No-Till treatment also had the lowest soil nitrate-N at the 0-15, 15-30, and 30-60 cm individual depths. At site C, there was no significant difference in content of soil nitrate-N among management systems.

Lower soil mineral N contents in no-till compared with tilled treatments have been previously reported (Drinkwater et al., 2000; Wells et al., 2013). In the present study, the reduction in available N in No-Till was attributed to the absence of tillage that increases soil organic matter mineralization. The absence of tillage and the presence of the mulch in no-till systems also reduce soil maximum temperature (Teasdale and Mohler, 1993). Lower soil nitrate-N in the No-Till partially corroborates our second hypothesis.

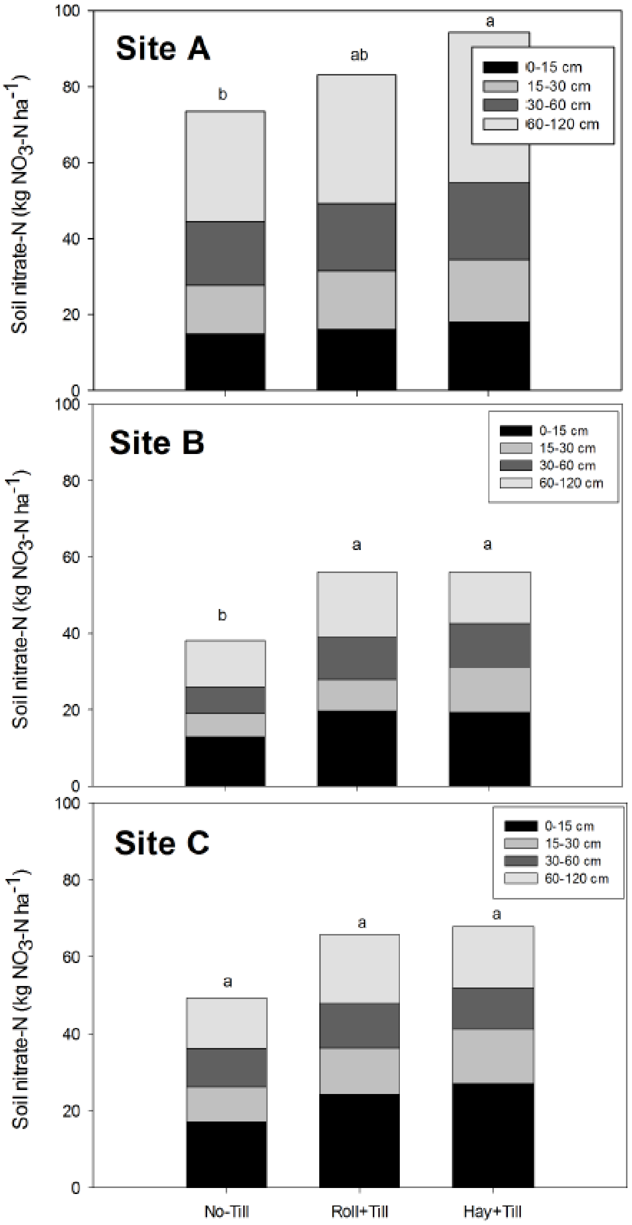

Figure 4-3. Main effect of management system of cover crops on soil nitrate-N in the soil profile (0-120 cm) across all sampling dates, at sites A, B, and C (*n* = 12, 36, and 36, respectively). Square root-transformed data were used to perform analysis of variance and means separation on soil nitrate-N at site C, but back-transformed means are presented above. Within sites, bars with different letters indicate significant difference in soil nitrate-N among management systems (Least Square Difference, $P \leq 0.05$).

However, no conclusion can be drawn on the N-mineralization potential of both systems since it was not measured in the present study. Drinkwater et al. (2000) showed that the organic no-till treatment with vetch residues on the soil surface had a greater N-mineralization potential in the top soil layer (0-5 cm) than organic tilled treatments.

Plant nutrient uptake during the flax year also influenced soil nitrate-N contents. There was an overall reduction in soil nitrate-N due to flax crop and weed N uptake over the growing season (data not shown). This reduction between spring and fall of the flax year was significant at all depths at site C, and at 15-30, 30-60, and 60-120 cm depths at site B (although limited to the Roll+Till and Hay+Till treatments at 15-30 cm). Soil nitrate-N was not sampled in fall of the cover crop year and in spring of the flax year at site A.

Management systems had no significant effect on pH, organic matter, phosphorus, potassium, and zinc at sites A, B, and C (data not shown). Phosphorus, K, and Zn contents, as well as pH at 0-15 cm significantly varied over time (data not shown), but with no consistent trend across all sites.

4.4.4 Weed Control by Mulches

The most common weeds observed at the study sites were redroot pigweed (*Amaranthus retroflexus* L.), wild oat, lamb’s quarters (*Chenopodium album* L.), Canada thistle [*Cirsium arvense* (L.) Scop.], barnyard grass [*Echinochloa crus-galli* (L.) Beauv.], wild buckwheat (*Polygonum convolvulus* L.), lady’s thumb (*P. persicaria* L.), green foxtail [*Setaria viridis* (L.) Beauv.], dandelion (*Taraxacum officinale* Weber), volunteer barley, and volunteer hairy vetch.

Our third hypothesis that barley/hairy vetch cover crop mulches have the ability to provide adequate weed control was generally supported in this research, though there were important exceptions. At sites A and B, management systems did not significantly affect weed biomass at the time of flax harvest (Figure 4-4). However, there was a trend

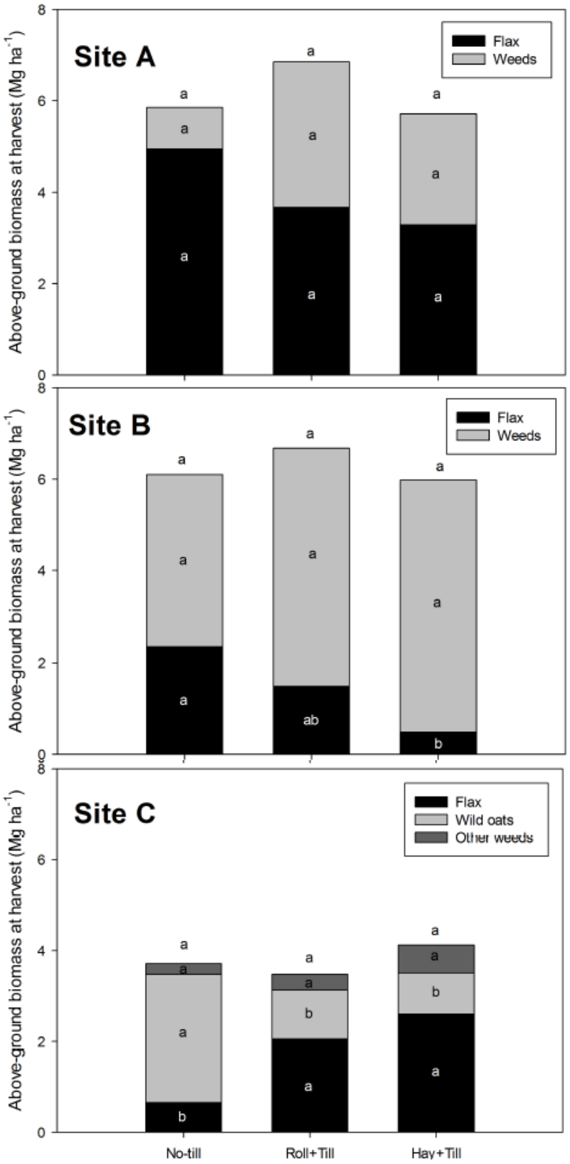

Figure 4-4. Main effect of management system of cover crops on above-ground biomass of flax and weeds at flax harvest, at sites A, B, and C (*n* = 12, for each site). Letters above the bars represents the above-ground biomass of flax and weeds at harvest. Within sites, bars with different letters indicate significant difference among management systems (Least Square Difference, $P \leq 0.05$).

with lower weeds in No-Till, since the No-Till treatment had on average 68% and 30% less weeds than the two treatments with tillage, at sites A and B, respectively. At those two sites, between 6.7 and 7.7 Mg ha^{-1} of barley/hairy vetch mulch provided weed control in the No-Till management treatment at time of flax seeding, within the 6-8 Mg ha^{-1} range of necessary mulch biomass for effective weed control in organic no-till rotational systems (MANUSCRIPT #1; Mirsky et al., 2012). In a companion study by Halde et al. (MANUSCRIPT #1), similar mulch biomass of barley/hairy vetch and pure vetch (6.0 to 7.6 Mg ha^{-1}) was found to provide effective weed control in an organic rotational no-till spring wheat (*Triticum aestivum* L.) crop. Even if the mulch provided better weed control than tillage at sites A and B, weeds still represented more than half of total (flax and weeds) biomass at harvest for all treatments at site B (Figure 4-4). This may be attributed to excess water content of soil and the presence of standing water at site B in the days following flax seeding, negatively affecting plant population density of flax and its early growth.

At site C, weed control by barley/hairy vetch mulches was poor. The No-Till flax crop started out with low biomass of mulch (4.2 Mg ha^{-1}) at time of seeding. By flax harvest, there were significantly more weeds in No-Till than in the other two management systems with tillage (Figure 4-4). Moreover, the difference in weed biomass between treatments was explained by the significantly higher biomass of a single weed species, wild oat, in the No-Till treatment. The high presence of wild oats at the present study site was caused by a deliberate wild oat seeding about 15 yr prior to conducting the present study (Shirtliffe and Entz, 2005). More than 15 yr later, wild oats could still be found at the study site, because of wild oat’s ability to produce a large number of seeds with staggered germination (Sharma and Vanden Born, 1978).

Tillage and haying helped control wild oat populations in the present study (Figure 4-4). In both Roll+Till and Hay+Till treatments, fields were tilled in spring and fall of the cover crop year, and the following spring before seeding flax. These tillage passes performed in Roll+Till and Hay+Till killed some of the wild oat plants. Additionally, cover crops in fields under the Hay+Till treatments were hayed in mid-summer, before wild oat could set seeds. Haying the cover crop before wild oats reached maturity was effective at reducing wild oat population in the flax (subsequent year) at site C (Figure 4-4). Schoofs and Entz (2000) also observed that cutting forage in a single year forage crop before wild oat seeds could disperse reduced the wild oat population in a subsequent field pea (*Pisum sativum* L.) crop by up to 80%. Biomass of weeds other than wild oat did not significantly vary across management systems at site C (Figure 4-4). Therefore the failure of the No-Till system at site C was unique to this particular weed species.

4.4.5. Flax Crop Agronomic Performance

Flax seed yields in No-Till were significantly higher than in the other two tilled treatments, at two of three sites. At site A, flax seed yields were significantly higher in No-Till than in the Roll+Till and Hay+Till treatments (Table 4-3). Flax in the organic No-Till treatment (1.80 Mg ha^{-1}) produced greater seed yields than the 2010 regional and provincial average yields of 0.76 and 1.13 Mg ha^{-1}, respectively (MMPP, 2013). At site B, flax seed yields in No-Till was also significantly higher than in the other two treatments (Table 4-3). Flax seed yields for all treatments were below the 2011 provincial average yields of 0.93 Mg ha^{-1} (MMPP, 2013). Average regional yields were not available for the Dufferin municipal district where the study site is located due to the flood that left a large proportion of fields unseeded in 2011 and that has encouraged the Government of Manitoba to put in place a special program to assist farmers affected by extended periods of high water content of soil in 2011 (MASC, 2013).

Table 4-3. Mean agronomic performance of flax at sites A, B, and C, and summary of analysis of variance of management system of cover crops.†

Main effect	**Flax plant population density**		**Flax seed yield**			
Site	**B**	**C**	**A**	**B**	**C**	**C‡**
	-----plant m^{-2}-----		------------------Mg ha^{-1}------------------			
Cover crop management						
No-till	389 a	586 a	1.80 a	0.62 a	0.09 b	0.03 b
Roll+Till	221 b	650 a	1.13 b	0.27 b	0.19 ab	0.12 ab
Hay+Till	160 b	652 a	1.10 b	0.12 b	0.40 a	0.22 a
Mean of the site	257	629	1.34	0.34	0.23	0.12
Source of variation	-----------------------------*P* value-----------------------------					
Cover crop management	**	ns§	**	*	*	*

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† Column means followed by the same letter are not significantly different from each other according to Least Square Difference test at $\alpha = 0.05$ ($n = 12$, for each response). Flax plant population density was not measured at site A.

‡ Harvested with a combine. All other flax seed yields reported above were hand-harvested.

§ ns, not significant at the 0.05 probability level.

Higher No-Till flax seed yields at sites A and B may be partly attributed to weed competition, since No-Till had numerically the lowest weed biomass at flax harvest. Weed biomass at harvest was also negatively correlated to flax seed yield at site B ($r = -0.65$, $P = 0.0209$, $n = 12$). Higher No-Till seed yields may also be due to additional benefits of mulches other than weed control. There was a significant positive correlation between mulch biomass in spring of the flax year and flax seed yield at site A ($r = 0.75$, $P = 0.0054$, $n = 12$), even though there was no significant correlation between weed biomass at flax harvest and flax seed yield at that same site ($r = -0.47$, $P = 0.1215$, $n = 12$). Benefits of cover crop mulches reported in the literature for organic rotational no-till systems include conservation of water content of soil (Kornecki et al., 2009) and N input from legume-containing mulches (Parr et al., 2011).

At site B, the higher seed yield in No-Till was also due to a poor establishment of flax stand in both tilled treatments due to excessive water content of soil in spring 2011. At site B, flax population density was greater in No-Till than in the other two treatments (Table 4-3), and flax population density was positively correlated to flax seed yield ($r = 0.65$, $P = 0.0231$, $n = 12$). Researchers have most often reported reduced crop plant population density in no-till than in tilled treatments (Davis, 2010; Mischler et al., 2010). However, in the present study, the no-till planted flax crop seemed to have benefited from the presence of the mulch in conditions of excess moisture for prolonged periods of time. This may be due to increased water infiltration and water storage capacity under rotational tillage compared with conventional tillage, as observed by Hou et al. (2013), leading to a better plant survival rate in case of excessive water stress.

At site C, overall flax seed yields were exceptionally low (≤ 0.4 Mg ha^{-1}), and also considerably lower than the 2012 regional average yields of 0.70 Mg ha^{-1} (MMPP, 2013). No-Till had a lower flax seed yield than Hay+Till, but not significantly different for

Roll+Till. Low seed yields in No-Till might be attributed to poor growing conditions in the year of the cover crop in 2011 (flood and wild oats) that led to poor cover crop establishment and growth. Hence, mulch production in 2011 was not optimal and flax was seeded into only 4.2 Mg ha^{-1} of mulch in spring 2012. The competition of flax by wild oats was also greater in No-Till than in the other two treatments with tillage and/or haying. Wild oat is the most economically important weed in the northern Great Plains of Canada (Beckie and Shirriff, 2012), and wild oat biomass negatively affected flax seed yield at site C (r = -0.65, P = 0.0231, n = 12).

Harvesting cover crop biomass in mid-summer by haying did not cause a yield penalty for the subsequent flax crop, when compared with incorporating it into the soil by tillage. There was no significant difference in seed yield between flax grown in the Roll+Till and Hay+Till treatments, across all three sites (Table 4-3). This provides an opportunity for growers to harvest one cut of cover crop for forage, and still get the benefits associated with the growth of the cover crop. It also allows farmers to generate some income during the year invested in full-year growth of a cover crop.

The present study demonstrated that mulch biomass required for successful organic rotational flax production direct-seeded into a barley/hairy vetch cover crop mulch needs to be equal to or greater than 6.7 Mg ha^{-1}, at time of seeding the flax in the spring. The fourth hypothesis that there is no yield penalty for eliminating tillage for 1.5 yr in an organic flax crop in southern Manitoba held true only if that minimum mulch biomass benchmark of 6.7 Mg ha^{-1} was reached. Drinkwater et al. (2000) also observed that the success of a hairy vetch cover crop mulch in a no-till system was highly variable, concluding that weed control by mulches was not reliable. The authors of the present study came to a more nuanced conclusion, and they identified certain conditions in which a barley/hairy vetch mulch perform as well as a tilled system. These keys to success in an organic rotational no-till flax production were found to be: 1) A good establishment of the cover crop; 2) No excess moisture for prolonged periods of time, as experienced in southern Manitoba in spring 2011; 3) A low wild oat population before the establishment of a no-till system.

Flax was chosen as the test crop in the present study, because flax has poor competitive ability against weeds. Weeds in a flax crop may not only reduce its yield: they can also cause losses from dockage in shipments (Flax Council of Canada, 2013). The average flax seed yields under organic management in Manitoba for the duration of the present study (2010-2012) were 48% lower than under conventional management (MMPP, 2013). However, growers in the northern Great Plains of Canada can receive a price premium 115-190% of conventionally produced flax for certified organic flax (MOA, 2013). Hence, there is a need for better weed management in organic flax production, as well as a great opportunity for increasing yields in organic fields.

4.4.6 Nitrogen Dynamics

Crop N uptake response to management systems varied greatly among sites. At site A, the effect of management system on crop N uptake was not significant (Table 4-4). At site B, No-Till had the highest N uptake by flax. Inversely, flax N uptake was the lowest in No-Till at site C (Table 4-4). Thus, crop N uptake was affected by management treatment, but N limitation did not appear to cause any flax seed yield loss in No-Till (Table 4-3). This corroborates our second hypothesis that while flax N uptake would be reduced by the reduced soil N status in No-till, there will be sufficient N for comparable flax yield to traditional organic production methods. However, management system effect on overall plant N uptake (i.e. by flax and weeds) was more subtle than that of crop N uptake alone, suggesting that the content of N available to plant growth (crop and weeds) was similar across management systems. Total plant N uptake (i.e. by flax and weeds) was not affected by management systems at sites A and B. Overall plant N uptake was lower in No-Till than in Roll+Till at site C.

Therefore, it appears that overall reduced soil nitrate-N in No-Till (Figure 4-3) did not influence greatly total plant N uptake. Different conclusions were made by Drinkwater et al. (2000) and Vaisman et al. (2011), who observed that reduced contents of N were taken up by the cash crop [corn (*Zea mays* L.) and spring wheat, respectively] and weeds in the no-till treatment due to reduced mineralization of the cover crop. One reason for this discrepancy could be the lower N requirement of flax compared with corn or spring wheat.

Nitrogen concentration of flax and weeds was not affected by management system at sites A and B (data not shown). However, N concentration of weeds at site C varied between management systems ($P = 0.027$), with No-Till having the lowest N concentration in weeds (0.58 g g^{-1}). This reflects the variation in weed population

Table 4-4. Mean above-ground nitrogen content of flax and weeds at the three sites, and summary of analysis of variance of management system of cover crops.†

Main effect	**Nitrogen content of above-ground biomass**								
	Flax			**Weed**			**Total plant (flax and weeds)**		
Site	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
	---kg N ha^{-1}---								
Cover crop management									
No-till	38.0 a	26.4 a	4.8 b	14.5 a	30.4 a	17.0 a	52.5 a	56.8 a	21.8 b
Roll+Till	28.2 a	16.8 ab	18.1 a	38.3 a	50.2 a	16.4 a	66.5 a	66.9 a	34.5 a
Hay+Till	33.3 a	4.6 b	22.1 a	32.1 a	40.2 a	21.1 a	65.5 a	44.8 a	43.2 ab
Mean of the site	33.2	15.9	15.0	28.3	40.3	18.2	61.5	56.2	33.2
Source of variation	---P value---								
Cover crop management	ns‡	**	**	ns	ns	ns	ns	ns	*

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† Column means followed by the same letter are not significantly different from each other according to Least Square Difference test at $\alpha = 0.05$ ($n = 12$, for each response).

‡ ns, not significant at the 0.05 probability level.

between management systems, with No-Till treatment having significantly more wild oats, which has a lower N concentration than most broadleaf weeds observed at the site like wild buckwheat and dandelion (Blackshaw et al., 2003).

4.5 Conclusions

No-Till did not reduce flax plant establishment even though mulch biomass was greater in No-Till than in tilled systems. Under excess moisture conditions, flax establishment was increased in the No-Till system. There was an overall trend towards lower contents of soil nitrate-N in No-Till, although it did not greatly influence total plant N uptake. Flax seed yields were greater in No-Till than in tilled systems when weeds were controlled. Moreover, there was no penalty on flax seed yield for harvesting one cut of the cover crop in mid-summer.

Success of flax crop grown in an organic rotational no-till system in a cool subhumid continental climate like in southern Manitoba depended on weather, mulch biomass production (> 6.7 Mg ha^{-1}), and weed species present. The use of a barley/hairy vetch cover crop mulch in an organic rotational no-till system eliminated the need for tillage for a period of 1.5 to 2 years without affecting yields in organic flax production, if there was enough mulch produced and low wild oat pressure.

In addition to the agronomic responses of flax to our main experimental treatments, this study also described the seasonal growth dynamics of a cover crop intercrop of barley and hairy vetch in relation to the action of the roller-crimper. Spring-seeded hairy vetch was completely resistant to rolling, whereas barley was killed by the action of the roller-crimper. Hairy vetch's extended growth in the fall yielded high mulch biomass. Few studies have considered the interaction between the roller-crimper and the growth and development of different spring-seeded cover crop species. There appears to be potential to explore such interactions further.

4.6 Literature Cited

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MANUSCRIPT #3

5.0 CROP AGRONOMIC PERFORMANCE UNDER A FIVE-YEAR CONTINUOUS ORGANIC NO-TILL SYSTEM AND OTHER TILLED AND CONVENTIONALLY-MANAGED SYSTEMS

5.1 Abstract

Reducing tillage in herbicide-free cropping systems is a challenge for farmers and studies examining the limitations of organic continuous no-till systems are limited. The objective of the study was to determine the effect of tillage [no-till (NT) and conservation tillage (CT)] and management [organic (ORG) and conventional (CONV)] systems on mulch biomass, soil nutrient supply rate, weeds, and crop productivity, over time. A five-year field study was conducted in Carman, MB, Canada, between 2008 and 2012. The crop rotation was barley (*Hordeum vulgare* L.)/hairy vetch (*Vicia villosa* Roth) cover crop in 2008, flax (*Linum usitatissimum* L.) in 2009, oats (*Avena sativa* L.) followed by a 4-species fall-seeded cover crop mixture in 2010, barley/hairy vetch cover crop in 2011, and spring wheat (*Triticum aestivum* L.) followed by cereal rye (*Secale cereale* L.) in 2012. From 2008 until mid-2010, the experiment design consisted of two tillage systems (NT and CT), both under ORG management. In mid-2010, the experiment was modified into a split-plot design to allow for the comparison between the ORG and CONV management systems. In ORG NT, cash crops of flax and spring wheat were seeded into 4.5 and 4.7 Mg ha^{-1} of rolled cover crop mulch, respectively. Differences in soil nitrate-N content were evident in 2011, and soil nitrate-N content (0-120 cm) was the lowest in

ORG NT in both spring and fall 2012. The soil supply rate of total inorganic N (NO_3-N and NH_4-N) measured with PRS^{TM} probes was also lower in ORG NT than in ORG CT, in spring 2012. Differences in weed communities between treatments were statistically noticeable in 2012 only, with higher weed biomass and weed species richness in the ORG management system. Crop yields were reduced in ORG NT in 2009 (flax) and 2012 (spring wheat).

5.2 Introduction

Organic farming systems have been openly criticized for the frequency and intensity of tillage (Badgley and Perfecto, 2007; Trewavas, 2004; Trewavas, 2001). Organic farmers rely heavily on tillage for mechanical weed control and to terminate perennial forage crops, since the use of synthetic herbicides is prohibited in organic production. Tillage is also used in organic systems to incorporate animal manure and cover crops, therefore facilitating their mineralization and nutrient cycling. The sustainability of organic production systems compared with that of conventional no-till systems has been debated extensively (Trewavas, 2004). In a long-term study, Teasdale et al. (2007) found that organic systems with tillage improved soil quality compared with conventional no-till systems, highlighting the benefits of organic farming on the ecosystem, but these differences between organic and conventional systems are often caused by differences in the use of soil amendments (N synthetic fertilizer vs. animal manure and cover crops) rather than tillage.

Efforts have been made in recent years to reduce tillage on organic farms and thereby increase the organic systems' sustainability. In North America, an "organic no-till revolution" (Moyer, 2011) promoting the reduction of tillage on organic farms has been led by the Rodale Institute. The cover crop-based organic rotational no-till system rotates between a cover crop established with tillage and terminated with a roller-crimper, and a cash crop no-till seeded into the cover crop mulch. In this system, cover crop mulch provides weed control without a need for herbicides or tillage. The opportunity to reduce tillage in organic production has been studied in many research institutes in the United States of America (Carr et al., 2012; Mirsky et al., 2012), Canada (Podolsky, 2013; Sullivan, 2012), and Europe (Cooper et al., 2013; Melander et al., 2013).

The idea of direct-seeding a crop into stubble on land managed without herbicides is not novel. Early settlers of the Canadian Prairies practiced direct-seeding without the use of herbicides more than a century ago, before the commercialization of herbicides (Janzen, 2001). Thousands of acres were cropped this way, going up to 4 yr without ploughing (MacKay, 1893, in Janzen, 2001). However, because of "the more rapid spread of weeds" (Bracken, 1920) and the interest in soil cultivation to create a dustmulch for retaining moisture, the practice of direct-seeding was discouraged (Janzen, 2001).

More recently, scientists have come to the same conclusions. "Currently, across all regions and cropping systems, consistent weed control in continuous no-tillage crop production, without chemical weed control, is not considered possible" (Brainard et al., 2013). Similarly, Mirsky et al. (2012) qualified continuous organic no-till as “unachievable”, and Légère et al. (2013) also judged these systems as “extreme”. Among the difficulties of organic rotational no-till systems, reduced nitrogen mineralization and problematic perennial weeds seem to be the most important factors affecting crop yield. Numerous studies reported reduced soil N content in systems with roller-killed cover crops (organic rotational no-till system) compared with cover crops incorporated with tillage (Parr et al., 2011; Podolsky, 2013; Sullivan, 2012). In the northern Great Plains of Canada, Vaisman et al. (2011) found that terminating a pea (*Pisum sativum* L.)/oat (*Avena sativa* L.) green manure with the roller-crimper, hence completely eliminating tillage for 1.5 yr, caused a lack of synchrony of N availability from the green manure crop to a spring wheat (*Triticum aestivum* L.) crop. This reduced mineralization of the green manure resulted in reduced crop N uptake and spring wheat grain yield.

Although sufficient weed control and crop yield has been obtained in some organic rotational no-till systems across North America (Carr et al., 2013; Mirsky et al., 2012), the control of weeds, especially perennials, can become problematic in systems without herbicides. Crop yield reduction due to problematic weeds was also experienced in reduced-tillage organic farming systems (Melander et al., 2013; Podolsky, 2012). A shift in weed populations, from summer annuals to perennials, has been observed where tillage is removed from the cropping system (Melander et al., 2013; Mirsky et al., 2012). Moreover, weed abundance is closely correlated with the change in N availability in soils. In an organic rotational no-till system with cereal rye (*Secale cereale* L.) mulch, N availability in soils was reduced due to N immobilization by the mulch, and this restricted the growth of N-responsive weed species such as redroot pigweed (*Amaranthus* *retroflexus* L.) (Wells et al., 2013). Thus, changes in N availability in organic rotational no-till systems have an impact on the competitive ability of weeds and crops.

Unsuccessful attempts at adapting the organic rotational no-till system have also been linked to low mulch biomass production (Carr et al., 2013) and inadequacies in the design of the roller-crimper (Estevez, 2008). Inadequate termination of the cover crop due to untimely termination has also been a challenge (Ashford and Reeves, 2003; Mirsky et al., 2009).

Very few studies (Wagoner et al., 1993; Drinkwater et al., 2000) have attempted to examine the limits of continuous organic no-till systems over a time period longer than 2 yr. Moreover, no long-term study has considered the combined effect of continuous no-tillage/tillage in both organic and conventional systems in Canada. The overall goal of this study was to observe the crop productivity of an organic no-till system in Manitoba, Canada and to identify its limitations. The agronomic performance of a medium-term organic no-till (ORG NT) system was monitored during the 5 yr study and compared with those of an organic tilled and conventionally-managed no-till and tilled systems. The objective of the study was to determine the effect of tillage and management systems on mulch biomass, soil nutrient supply rate, weeds, and crop productivity, over time.

5.3 Materials and Methods

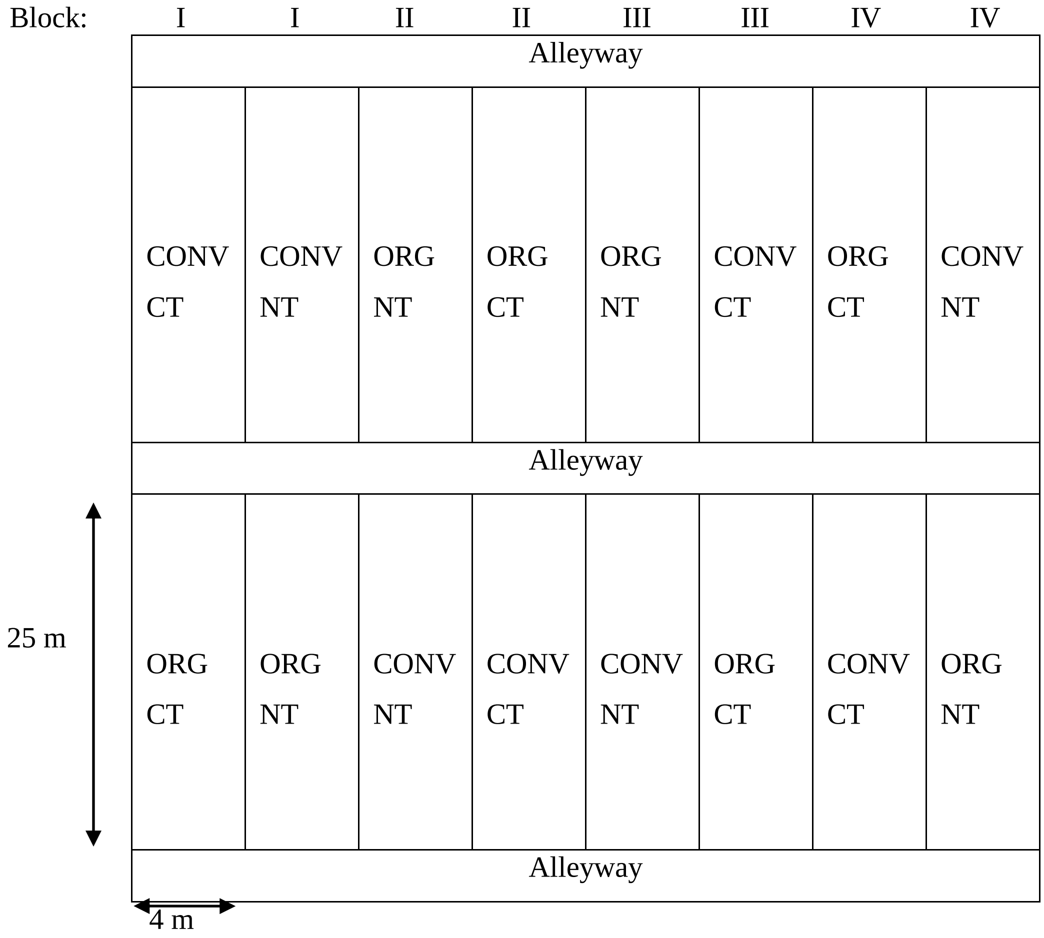
5.3.1 Study Site

The five-year field study was conducted at the University of Manitoba Ian N. Morrison Research Farm in Carman, MB, Canada, in a cool subhumid continental climate. Weather data were collected directly on site, at the Research Farm in Carman, MB. Properties of soils at the study site are described in sections 3.3.1 and 4.3.1 of this thesis. The site has been under organic management (without pesticide or synthetic fertilizer application) since 2003, although not certified organic. Soybeans [*Glycine max* (L.) Merr.] were grown at the study site in 2007, prior to the establishment of the present study.

5.3.2 Experimental Design

The experiment was established in spring 2008. The crop rotation between 2008 and 2012 was a spring-seeded cover crop of barley (*Hordeum vulgare* L.) and hairy vetch (*Vicia villosa* Roth) (Year 1), flax (*Linum usitatissimum* L.) (Year 2), oats followed by a fall-seeded cover crop mix (Year 3), a spring-seeded cover crop of barley and hairy vetch (Year 4), and spring wheat followed by fall-seeded cereal rye (Year 5). The experiment was initially a randomized complete block design, with one factor of interest (tillage systems) with two levels [conservation tillage (CT) and no-tillage (NT)]. The CT treatment consisted of non-inversion tillage to a maximum depth of 15 cm. The entire trial was under organic management between spring 2008 and early June 2010.

On 2 June 2010, the trial was split into a split-plot design to test for management system effect [organic (ORG) and conventional (CONV) management]. Most of the responses measured during the completion of this Ph.D. research project were thus observed while the experimental design was a split-plot design, with four blocks (Figure 5-1). The whole-plot factor was tillage system, with two levels (NT and CT). The sub-plot factor was management system, with two levels (ORG and CONV). The CONV treatment differed from the ORG treatment only from a pest management point of view. The CONV treatment received pesticide applications (herbicides and fungicides). Neither the ORG nor the CONV treatments received any fertilizer application (synthetic fertilizer or animal manure) for the entire duration of the study. Each experimental unit of the split-plot design was 25 m x 4 m, and the entire experiment was 60 m x 32 m.



Block:	I	I	II	II	III	III	IV	IV
	Alleyway							
	CONV CT	CONV NT	ORG NT	ORG CT	ORG NT	CONV CT	ORG CT	CONV NT
	Alleyway							
	ORG CT	ORG NT	CONV NT	CONV CT	CONV NT	ORG CT	CONV CT	ORG NT
	Alleyway							

Figure 5-1. Map of the split-plot experimental design, after its modification in spring 2010.

5.3.3 Field Operations

In 2008 (Year 1), a cover crop of barley and hairy vetch established in the spring was terminated in mid-summer using a roller-crimper in all treatments. In CT, the cover crop was incorporated into the soil by tillage in the fall, whereas the cover crop was left intact on the soil surface in NT.

In 2009 (Year 2), flax was seeded into the cover crop mulches (NT) and the incorporated cover crop residues (CT). The CT treatment was tilled after flax harvest.

In 2010 (Year 3), spring tillage was performed in the CT treatment on 8 Apr., to prepare the seedbed for seeding. Later that day, oats were seeded in all experimental units in two diagonal passes of 69 kg ha^{-1} each, with the second seeding at an angle of 45°. Hence, total seeding rate was 138 kg ha^{-1} (390 seeds m^{-2}). A post-emergence herbicide and fungicide were applied in CONV (Table 5-1). Active ingredients of the pesticides used are listed in Table 5-1. Oats were swathed on 3 Aug. and then harvested with a combine on 6 Aug. Oat residues were harrowed on 9 Aug. to spread them evenly across the field. Tillage was also performed in CT to incorporate the oat residues. A post-harvest herbicide was applied in the CONV NT plots. Finally, a 4- species cover crop was seeded on 9 Aug. It was a mixture of buckwheat (*Fagopyrum esculentum* Moench) (27.5 kg ha^{-1}), forage radish (*Raphanus sativus* L.) (3.9 kg ha^{-1}), turnip (*Brassica rapa* L. var. *rapa*) (0.9 kg ha^{-1}), and sunflower (*Helianthus annuus* L. cv. Sunola) (3.9 kg ha^{-1}). The cover crop was terminated with tillage (all CT treatments), with an herbicide (CONV NT), or with winter-kill (ORG NT).

Table 5-1. Pesticide applications performed at the study site in 2010, 2011 and 2012.

Year and crop	Date of pesticide application	Pesticide application rate	Experimental units sprayed
Year 3 Oats and fall-seeded cover crops	2 June 2010	Post-emergence herbicide: tank mixture of thifensulfuron methyl/tribenuron methyl at 0.03 kg ai ha^{-1} and MCPA at 0.60 kg a.e. ha^{-1}	All CONV
	22 June 2010	Post-emergence fungicide: propiconazole at 0.12 ai kg ha^{-1}	All CONV
	12 Aug. 2010	Post-harvest herbicide: glyphosate at 1.79 kg ha^{-1}	CONV NT only
	8 Oct. 2010	Herbicide: glyphosate at 1.62 g ha^{-1}	CONV NT only
Year 4 Cover crop of barley and hairy vetch	27 May 2011	Pre-emergence herbicide: glyphosate at 0.14 kg ha^{-1} (only 10% of the recommended rate was applied)	CONV NT only
	26 Sept. 2011	Herbicide: glyphosate at 1.74 kg ha^{-1}	All CONV
Year 5 Spring wheat and cereal rye	31 May 2012	Post-emergence herbicide: tank mixture of bromoxynil at 2.83 kg ha^{-1}, MCPA at 2.83 a.e. kg ha^{-1}, and clodinafop-propargyl at 0.06 kg ha^{-1}	All CONV
	Sept. 2012	Post-harvest herbicide: glyphosate at 1.49 kg ha^{-1}	CONV NT only

In 2011 (Year 4), spring tillage was performed on 20 May in the CT treatment. Barley (cv. Cowboy) and hairy vetch were seeded on 20 May at 81 kg ha^{-1} and 43 kg ha^{-1}, respectively. Pre-emergence herbicide was applied in the CONV NT plots (Table 5-1). Due to poor establishment, barley and hairy vetch were reseeded on 10 June, after a second tillage pass in the CT treatment. On 11 Aug., the cover crop mixture was rolled twice (once in each direction) using a roller-crimper. A herbicide was used to terminate the cover crops in CONV. On 7 Oct., cover crops were managed with flail-mowing and tillage (in CT) or by a second pass of roller-crimper (in NT).

In 2012 (Year 5), spring wheat (cv. Waskada) was seeded on 23 Apr. at 125 kg ha^{-1}. Post-emergence herbicide was applied in the CONV treatment (Table 5-1). Spring wheat was harvested with a combine on 9 Aug. After harvest, tillage was performed in the CT treatment and a post-harvest herbicide was applied in the CONV NT treatment.

Pesticides (herbicides and fungicides) were applied in the conventionally managed treatments (CONV) in 2010, 2011, and 2012 (Table 5-1). A compressed-air bicycle sprayer was used for all herbicide and fungicide applications. The bicycle sprayer (two wheels) had eight nozzles covering 0.5 m each, for a total spraying width of 4 m. The sprayer was calibrated before each pesticide application. Only 10% of the recommended herbicide rate was applied on 27 May 2011 due to miscalculations, hence this herbicide application had little to no effect on weeds. Since barley and hairy vetch were seeded on 20 May 2011, barley had already emerged before we realized our mistake; hence we could not reapply the herbicide at the correct dose.

5.3.4 Data Collection

5.3.4.1 Soil Sampling for Soil Chemical Properties

Soil chemical properties were assessed at six time periods: in spring and fall of 2010, 2011, and 2012 (Table 5-2). Soil sampling was performed using a hand auger and a hydraulic soil auger (Giddings Machine Co., Windsor, CO, U.S.A.), depending on sampling equipment availability. Two soil cores were collected per experimental unit, at depth increments of 0-15, 15-30, 30-60, and 60-120 cm, and cores were bulked by depth increment in the field. A complete analysis of soil chemical properties was performed on

Table 5-2. Soil and plant sampling performed over the five-year study.

Year and crop	Response measured	Sampling date
Year 1 Cover crop of barley and hairy vetch	Above-ground plant biomass, sorted into barley and hairy vetch	At first rolling
	Mulch biomass	17 Sept. 2008
Year 2 Flax	Mulch biomass	May 2009
	Flax seed yield	Fall 2009
	Weed count and identification	13 Oct. 2009
Year 3 Oat and fall-seeded cover crop	Mulch biomass	21 Apr. 2010 21 May 2010 28 June 2010 20 July 2010 17 Aug. 2010 21 Sept. 2010
	Oat plant population density and developmental stage	6 May 2010
	Soil chemical properties	18 May 2010
	Oat height	15 July 2010
	Above-ground plant biomass, sorted into oat and weed	28 July 2010
	Oat grain yield	6 Aug. 2010
	Soil chemical properties	8 Oct. 2010
Year 4 Cover crop of barley and hairy vetch	Soil chemical properties	19 May 2011
	Barley and hairy vetch plant population density	24 June 2011
	Weed count and identification	6 July 2011
	Above-ground plant biomass, sorted into barley, hairy vetch, and weeds	8 Aug. 2011
	Visual abundance of barley	8 Aug. 2011
	Mulch biomass	7 Sept. 2011 8 Oct. 2011
	Soil chemical properties	7 Oct. 2011
Year 5 Spring wheat and cereal rye	Soil chemical properties	4 May 2012
	Mulch biomass	17 May 2012 19 June 2012 16 July 2012 28 Aug. 2012 14 Sept. 2012
	Spring wheat plant population density and developmental stage	17 May 2012
	PRS^{TM} probes	Biweekly, between 16 May and 25 July 2012
	Soil gravimetric moisture	Weekly, between 16 May and 25 July 2012
	Weed count and identification	25 June 2012
	Above-ground plant biomass, sorted into spring wheat and weeds	6 Aug. 2012
	Spring wheat grain yield	9 Aug. 2012
	Soil chemical properties	7 Oct. 2012

the 0-15 cm soil layer [nitrate-N (NO_3-N), pH, organic matter, Olsen-P, K, Zn], whereas only soil nitrates were assessed at deeper depths in the soil profile. Soil analysis was conducted by Agvise Laboratories (Northwood, ND, U.S.A.).

Soil was not sampled in Year 1 (2008) and Year 2 (2009). In spring 2010, four soil cores were collected per experimental unit instead of two, and were analyzed individually. Fall 2011 soil samples were only analyzed for NO_3-N and Olsen-P contents. Since the conventional management treatment was first applied to subplots only on 2 June 2010, soil was sampled in 2010 strictly on the experimental units under organic management, whereas soil was sampled in 2011 and 2012 on all experimental units. Therefore, soil chemical properties from spring and fall 2010 were analyzed separately than those from spring and fall of 2011 and 2012, because it is not possible to test for any management system effect for sampling performed in 2010.

5.3.4.2 Plant Root Simulator Probes and Gravimetric Soil Moisture

In 2012 (Year 5), plant root simulator probes (PRS^{TM} probes; Western Ag Innovations Inc., Saskatoon, SK, Canada) were used to assess nutrient supply rate of anions (NO_3-N, phosphorus, zinc, sulfur, aluminum, iron, manganese, copper, boron, lead, and cadmium) and cations [ammonium-N (NH_4-N), potassium, calcium, magnesium]. PRS^{TM} probes were only installed in the ORG CT and ORG NT experimental units. Four probe pairs (each pair consisting of one anion probe and one cation probe) were buried for five consecutive sampling events, each lasting 2 wk (Table 5-2). This allowed a total of 10 wk of continuous nutrient supply to be recorded, between 16 May and 25 July 2012. The data from four probe pairs installed in each experimental unit were combined into one unique composite sample per experimental unit. After the 2-wk burial period, probes were retrieved from the field and washed thoroughly with deionized water using a toothbrush. Probes were then sent to Western Ag Innovations for laboratory analysis by ground shipping, in a styrofoam-lined box with an ice pack to keep the probes cool.

PRS^{TM} probes were buried within plastic sleeves (PVC pipes) of 16.0 cm external diameter, 15.4 cm internal diameter, and 20.0 cm length. These root-exclusion cylinders (REC) were used to prevent plant nutrient uptake during the 2-wk burial period into these RECs. Two probe pairs were buried in each REC. Every 2 wk, new RECs were installed in the field one day before the probes were installed, using a sledgehammer and a piece of wood. The RECs were inserted > 15 cm deep into the soil, leaving < 5 cm of the plastic sleeve out of the soil surface. Plants (spring wheat and weeds) within the RECs were clipped at about 1 cm above-ground. Root-exclusion cylinders were weeded at least once a week to remove any plants growing in them.

Soil samples at 0-10 cm depth also were collected every seven days, for 11 consecutive wk, from 16 May 2012 until 25 July 2012 to estimate gravimetric soil moisture. Soil was collected using a soil probe, weighed, and then dried at 105°C for 48 h and reweighed.

5.3.4.3 Cover Crop Mulch and Crop Residue Sampling

Mulch biomass was measured in the NT treatment only at first and second rolling in 2008, and in May 2009, at three random sampling spots in 0.25 m2 quadrats. Mulch biomass sampled at first rolling in 2008 was hand-sorted into barley and hairy vetch. In 2010, mulch biomass was collected approximately every 30 days in four quadrats (0.25 m x 0.25 m) in the ORG treatment only (Table 5-2). In 2011, plant population densities of barley and hairy vetch were assessed at five locations per experimental unit using a meter stick and by counting the number of individual plants of each crop species along a 1-m row. In 2011, two quadrats (0.5 m x 0.5 m) per experimental unit were clipped at 2 to 5 cm above-ground to assess above-ground plant biomass at time of termination by rolling. This fresh plant material was hand-sorted into individual cover crop species (barley, hairy vetch) and weeds. Two quadrats (0.5 m x 0.5 m) per experimental unit were harvested to assess mulch biomass at about 30 days and 60 days after rolling. In 2012, two quadrats (0.5 m x 0.45 m) per experimental unit were harvested every 30 days, approximately, to assess mulch biomass (Table 5-2). All mulch biomass samples collected between 2008 and 2012 were oven-dried at 60°C for 48 h and weighed to determine dry biomass.

5.3.4.4 Cash Crop Performance

Little sampling was performed in 2008 and 2009. Flax seed yields were recorded in fall 2009.

In 2010, oat plant population density was measured in the spring using a 0.45 m x 0.5 m quadrat, at four locations in each experimental unit (Table 5-2). Oat developmental stage was measured using the Haun scale (Haun, 1973) on twenty-five randomly chosen plants per experimental unit. Oat plant population density and oat developmental stage were determined in the ORG experimental units only, since the plots had not been split yet into

ORG and CONV management systems. All other plant responses sampled later in the season were assessed for all experimental units. Above-ground oat height was assessed using a meter stick, on ten plants per experimental unit. Three quadrats (0.5 m x 0.45 m) were harvested in the north half of each experimental unit at 2 to 5 cm above-ground then sorted into oats and weeds to assess above-ground oat biomass at harvest. All collected biomass was oven-dried at 60°C for 48 h and weighed to determine dry biomass. One undisturbed 2 m wide and 25 m long field area was harvested in the south half of each experimental unit with a combine to determine oat grain yield.

In 2012, spring wheat plant population densities were assessed in the spring and by counting the number of individual spring wheat plants along a 1-m row at five locations in each experimental unit (Table 5-2). Spring wheat developmental stage was determined using the Haun scale (Haun, 1973) on twenty-five randomly chosen plants per experimental unit, on the same day that spring wheat densities were recorded. Three quadrats (0.5 m x 0.45 m) per experimental unit were harvested at 2 to 5 cm above-ground to assess above-ground plant biomass at spring wheat harvest (Table 5-2). Above-ground plant biomass at spring wheat harvest was hand-sorted into spring wheat and weeds, and the number of spikes per sample was counted from the spring wheat subsamples. Plant biomass at harvest was oven-dried at 60°C for 48 h and weighed to determine dry biomass. Twenty heads of spring wheat were randomly selected per experimental unit to determine the number of spikelets per spike. The number of spikelets per m^2 was calculated by multiplying the number of spikelets per spike by the number of spikes per m^2. An area of approximately 35-40 m^2 (1.5 m x ~25 m) was harvested with a combine harvester to estimate spring wheat grain yield. Spring wheat grains were cleaned using a Clipper grain cleaner (Model M2BC, Blount/Ferrell-Ross, Bluffton, IN, U.S.A.). Ten 1000-kernel subsamples of the harvested spring wheat per experimental unit were counted using a seed counter (Model 850-2, Old Mill Company, Savage, MD, U.S.A.). Spring wheat grain mass was calculated on these ten 1000-kernel subsamples. Dry matter harvest index was calculated as the ratio of harvested spring wheat grain yield to total above-ground spring wheat biomass at harvest (Unkovich et al., 2010).

5.3.4.5 Weeds

On 13 Oct. 2009, weed counts were performed in 1-m^2 quadrats, at five randomly chosen sampling sites per experimental unit. In 2010, above-ground plant biomass samples harvested at oat harvest were hand-sorted into oats and weeds to assess above-ground weed biomass at oat harvest. In mid-summer 2011 and 2012, weeds were identified and counted at the species level in two quadrats (0.25 m x 0.25 m) per experimental unit. In 2012, above-ground plant biomass samples harvested at spring wheat harvest were hand-sorted into spring wheat and weeds to assess above-ground weed biomass at harvest. All weed biomass collected was oven-dried at 60°C for 48 h and weighed to determine dry biomass.

5.3.4.6 Plant Nitrogen Uptake

In 2010 and 2012, above-ground dry biomass of cash crop (oats in 2010 and spring wheat in 2012) and weeds at harvest was ground to 2-mm with a grinder (Arthur H. Thomas Co., Philadelphia, PA, U.S.A.) to determine nitrogen concentration by combustion analysis using a nitrogen analyzer (FP-528, LECO Co., St Joseph, MI, U.S.A.). Nitrogen content was calculated by multiplying N concentration by the above-ground biomass at harvest.

In 2012, a composite sample of eight subsamples of the harvested and cleaned spring wheat grain per experimental unit was ground using a cyclone lab sample mill (UDY Corporation, Fort Collins, CO, U.S.A.) for nitrogen analysis. Spring wheat grain protein content was calculated from grain nitrogen concentration (5.7 x [N]), then corrected for moisture and reported on a 13.5% moisture content basis.

5.3.5 Statistical Analysis

Statistical analyses were conducted using Statistical Analysis System 9.2 (SAS Institute Inc., 2008) software. Analysis of variance ($\alpha = 0.05$) was conducted using the MIXED procedure of SAS to compare the effects of tillage systems and management systems on soil and plant responses. Repeated measures were used to assess the effect of tillage systems and management systems on soil chemical properties and mulch biomass over time. Fixed effects were tillage systems, management systems, and time, whereas block and block*tillage system were considered random effects. Outliers were identified using Lund's test (Lund, 1975) and were removed. To account for soil moisture effect on soil nutrient supply rates (measured with PRS^{TM} probes), soil moisture (0-10 cm) was used as a covariate in the model. All data were verified for normality and constant variance of residuals. Independence of residuals was assumed through randomization. Means were separated using the Least Square Difference test, and the Satterthwaite approximation (ddfm = satterthwaite) was used (Satterthwaite, 1946). Correlation analyses were performed among soil chemical properties and cash crop responses, using the CORR procedure of SAS ($\alpha = 0.05$).

5.4 Results and Discussion

5.4.1 Environmental Conditions

Between 2008 and 2012, total annual precipitation was below the 30-yr normal of 533.4 mm in 4 out of 5 yr. The year 2010 received high precipitation over the entire year (635.1 mm) and over the growing season (1 May until 31 Oct.; 572.7 mm). In spring 2011, a flood affected crop growth in the region of the study site (Environment Canada, 2011). Average annual temperature over the 5 yr study ranged between 1.9 and 4.8°C, for 2008 and 2012, respectively. During the PRS^{TM} probes burial period in 2012 (16 May to 25 July), mean temperature ranged between 11.6 and 22.0°C, and cumulative precipitation ranged between 11.7 and 48.7 mm (Table 5-3).

Table 5-3. Mean air temperature and cumulative precipitation during the burial periods of the PRS^{TM} probes.†

Burial period	Probes placement date	Probes retrieval date	Mean air temperature during the burial period	Cumulative precipitation during the burial period
			°C	mm
1	16 May 2012	30 May 2012	11.6 (4.06)	35.6 (5.43)
2	30 May 2012	13 June 2012	16.9 (4.64)	37.2 (3.82)
3	13 June 2012	27 June 2012	17.4 (2.53)	48.7 (7.88)
4	27 June 2012	11 July 2012	22.0 (1.86)	11.7 (2.21)
5	11 July 2012	25 July 2012	21.9 (2.35)	16.4 (2.98)

† Source: Environment Canada, 2013. Standard deviations are presented in parentheses.

5.4.2 Cover Crop Mulch: Production and Decomposition

Cover crops of barley/hairy vetch were grown and rolled to create mulch for weed suppression and N supply in every third year of the crop rotation (i.e. in 2008 and again in 2011). At time of rolling in mid-summer 2008, biomass of the barley/hairy vetch cover crop was 4.7 Mg ha^{-1}, with barley and hairy vetch representing 89% and 11% of that biomass, respectively. Cover crop biomass increased between the first rolling and late-fall (second rolling with the roller-crimper in NT or incorporation into the soil in CT) in all treatments, because hairy vetch was not affected by the action of the roller-crimper in mid-summer. Hairy vetch kept growing on top of the rolled barley until late-fall (Figure 5-2). This resistance of spring-seeded hairy vetch to the roller-crimper and its extended growth into the fall had been observed previously in Manitoba (MANUSCRIPT #1; MANUSCRIPT #2; I. Vaisman, personal communication, 2010). Barley was killed in mid-summer, at the first rolling. Biomass of mulched cover crop averaged 7.6 Mg ha^{-1} on 17 Sept. 2008, at time of cover crop incorporation (CT) or second rolling (NT).

In spring of 2009, mulch biomass collected in May at time of flax seeding averaged 4.5 Mg ha^{-1} in NT. The biomass of mulch necessary for sufficient weed control in organic rotational no-till systems in southern Manitoba has been identified to be between 6 and 7.6 Mg ha^{-1} for spring wheat (MANUSCRIPT #1) and between 6.7 and 7.7 Mg ha^{-1} for flax (MANUSCRIPT #2), at the time of seeding the cash crop into the mulch. A minimum of 8 Mg ha^{-1} was found to be necessary to suppress summer annual weeds in cover-crop based organic rotational no-till systems in the mid-Atlantic region of the U.S.A. (Mirsky et al., 2012). The mulch biomass present in spring 2009 at the time of flax seeding was below all these benchmarks for mulch, affecting weed control and flax crop seed yields (discussed below).

Between 2010 and 2012, mulch biomass varied among tillage system, management system, and time, as indicated by the significant tillage system x management system x time interaction effect ($P < 0.0001$, Figure 5-2). In 2010, there was more mulch in ORG NT than in ORG CT for all six monthly sampling events that year, due to yearly spring and fall tillage in ORG CT. Mulch in 2010 consisted mostly of rolled-killed cover crop biomass from 2008, with the addition of flax (fall 2009) and oat (fall 2010) harvest residues. Mulch biomass in 2010 never exceeded 1.2 and 5.4 Mg ha^{-1} in ORG CT and ORG NT, respectively (Figure 5-2). In spring 2010, mulch biomass in ORG NT declined rapidly, losing 2.6 Mg ha^{-1} between 21 Apr. and 21 May.

A cover crop of barley and hairy vetch was grown again in 2011 to produce mulch for the two subsequent crops. In 2011, barley plant population density was the lowest in ORG NT (135 plants m^{-2}), and was similar among the other three treatments, averaging 178 plants m^{-2}. Hairy vetch plant population density did not differ among tillage or management treatments. Hairy vetch represented a large proportion (83%) of the total cover crop biomass at first rolling. In 2011, the growth of the barley/hairy vetch cover crop was not reduced in ORG NT, despite the low barley plant population density in ORG NT. The biomass of cover crop mulch produced was similar in all treatments at first rolling and in September, and averaged 4.5 and 5.3 Mg ha^{-1}, respectively (Figure 5-2). Similarly to 2008 and to the phenomenon observed by I. Vaisman (personal communication, 2010) and Halde et al. (MANUSCRIPT #1; MANUSCRIPT #2), cover crop biomass increased between the first rolling and late-fall (i.e. second rolling in NT or incorporation in CT), because hairy vetch was resistant to crushing by the roller-crimper, and kept growing until late-fall. Consequently, biomass of cover crop increased to about 8.0 Mg ha^{-1} of cover crop biomass in NT on 8 Oct. 2011, with no difference in mulch biomass between ORG NT and CONV NT systems (Figure 5-2). The biomass of mulch

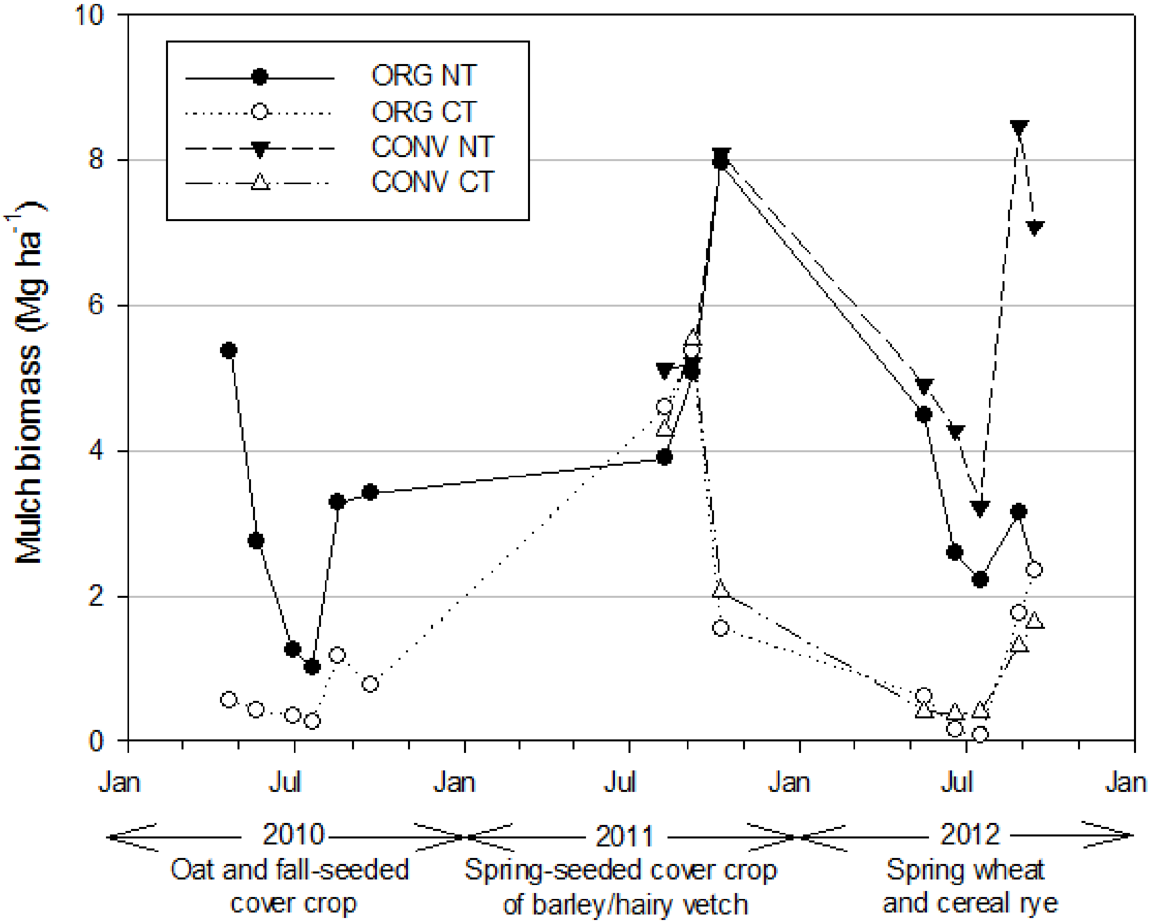


Figure 5-2. Tillage system x management system x time interaction effect on mulch biomass in 2010-2012 (s.e. = 0.18 Mg ha^{-1}, n = 174). Square-root transformed data were used to perform ANOVA and means separation, but back-transformed means are presented above. ORG = Organic management system; CONV = Conventional management system; NT = No-tillage system; CT = Conservation tillage system.

on 8 Oct. was lower in CT than NT due to the cover crop biomass being flail-mowed and then incorporated into the soil the day before sampling the mulch in CT.

In 2012, mulch biomass consisted of barley/hairy vetch cover crop, mixed with little remaining biomass of flax (2009) and oat (2010) harvest residues. In 2012, NT had on average 4.7 Mg ha^{-1} of mulch in the spring, shortly after seeding spring wheat, with no significant difference between management systems (Figure 5-2). Similarly to spring 2009, the biomass of cover crop mulch in spring 2012 was lower than the mulch biomass necessary for efficient weed control to the cash crop (spring wheat) in organic rotational no-till systems (MANUSCRIPT #1; MANUSCRIPT #2; Mirsky et al., 2012). Mulch biomass in CT was < 1 Mg ha^{-1} until harvest of spring wheat. It reached 1.3-2.3 Mg ha^{-1} after spring wheat harvest, in the fall. The biomass of residues on the soil surface after wheat harvest was higher in CONV NT compared with that of the other treatments, due to high spring wheat straw production, in CONV NT.

5.4.3 Soil Inorganic Nitrogen and Gravimetric Moisture

The barley/hairy vetch cover crop had a dual role in the crop rotation. It provided a mulch for weed control, but the legume species (hairy vetch) in the cover crop mixture also supplied N to the system through biological N fixation. The cover crop was managed differently in both tillage systems, affecting the content of inorganic N in soils, but this effect of tillage systems varied over years.

Tillage system had no significant effect on soil nitrate-N in spring or fall 2010, at any depth of the top 120 cm soil profile (Appendix 1). Soil nitrate-N decreased between spring and fall 2010, regardless of tillage systems, due to oats and cover crops N uptake over the growing season. Only 32 kg NO_3-N ha^{-1} was left in the 0-120 cm soil profile in fall 2010, on average across all treatments.

Differences in content of soil inorganic N between ORG NT and the other systems started to occur only in 2011, four years after the beginning of the experiment (ORG NT vs. ORG CT) and one year after the conversion of half of the sub-plots to a conventional management with herbicides (CONV NT and CONV CT). An interaction effect between tillage system, management system, and season was significant for soil nitrate-N at 0-120 cm depth, in spring and fall 2011 and 2012 (Table 5-4). In spring 2011, soil nitrate-N content (0-120 cm) was lower in ORG NT than in ORG CT and CONV NT (Figure 5-3), however these differences disappeared in the fall, after a season-long growth of barley/hairy vetch cover crop. In fall 2011, content of soil nitrate-N at 0-120 cm depth in ORG NT was similar to that of other treatments. There was a significant increase in soil nitrate-N over the 2011-2012 winter for all treatments (Figure 5-3), due to N release from the barley/hairy vetch cover crop.

In 2012, the difference in soil inorganic N contents between ORG NT and the other treatments was more accentuated. Soil nitrate-N content in the entire soil profile (0-120 cm) was the lowest in ORG NT in both spring and fall 2012 (Figure 5-3). The reduced content of available soil nitrate-N for the spring wheat crop in ORG NT was also confirmed with data from PRS^{TM} probes, although the effect of tillage system on total soil inorganic N and nitrate-N measured with PRS^{TM} probes varied over time (Table 5-5). The soil supply rate of total inorganic N (NO_3-N and NH_4-N) was lower in ORG NT than in ORG CT, for the first two burial periods of the PRS^{TM} probes (between 16 May and 13 June 2012) (Figure 5-4). ORG NT had reduced soil inorganic N content, and this reduction occurred early in the season. In the following 6 wk (between 13 June and 25 July 2012), there was no significant difference in soil nutrient supply rate of total inorganic N between ORG NT and ORG CT.

Table 5-4. Summary of analysis of variance of tillage system, management system, and season for soil nitrate-N at four depths in spring and fall of 2011 and 2012.†

Source of variation	**NO_3-N**				
	0-15 cm	**15-30 cm**	**30-60 cm**	**60-120 cm**	**Cumulative 0-120 cm**
	------------------------------*P* value------------------------------				
Tillage system (T)	***	***	ns‡	ns	***
Management system (M)	***	***	*	ns	***
Season (S)	***	***	***	***	***
T x M	***	**	***	**	***
T x S	***	***	ns	***	***
M x S	ns	ns	ns	ns	ns
T x M x S	ns	ns	ns	*	***
n	63	63	64	62	64

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Square-root transformed data were used to perform ANOVA and means separation for soil NO_3-N for each depth.
‡ ns, not significant at the 0.05 probability level.

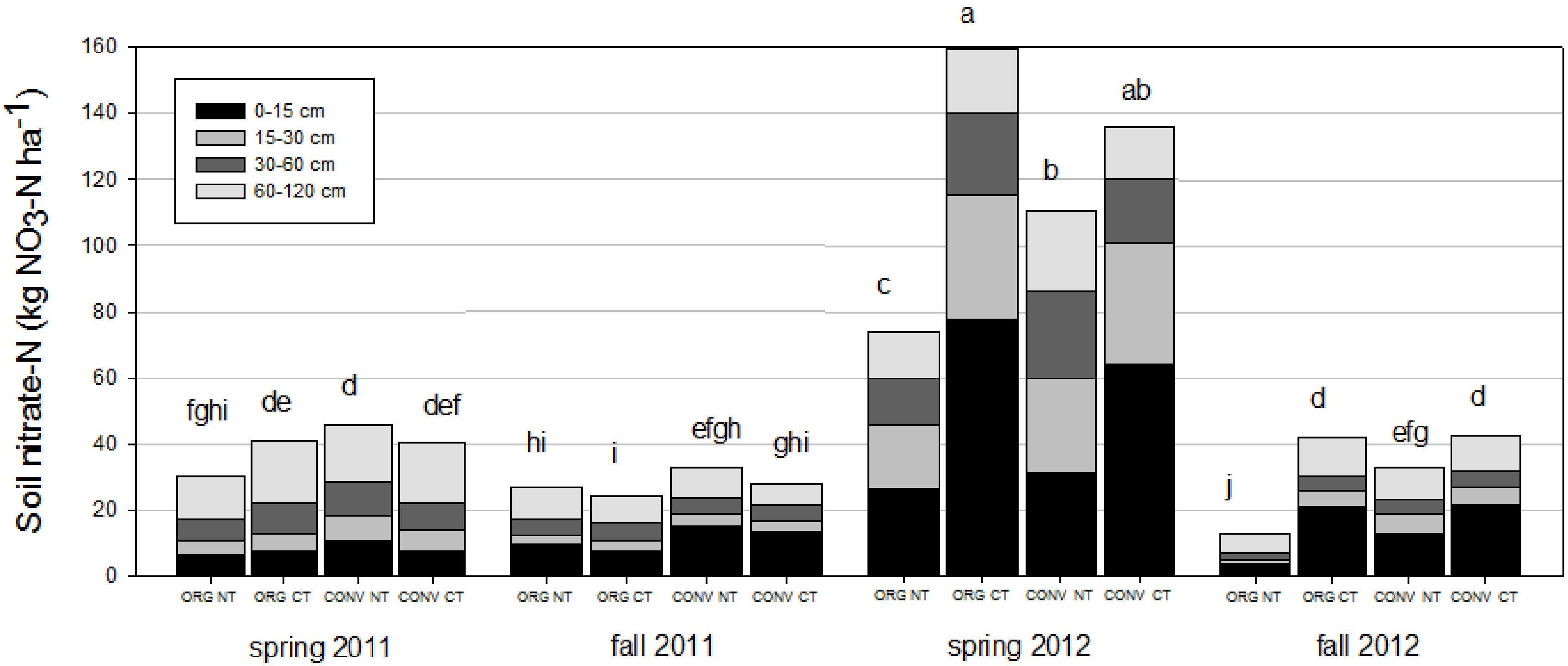


Figure 5-3. Tillage system x management system x season interaction effect on soil nitrate-N in spring and fall of 2011 and 2012, at depths increments of 0-15, 15-30, 30-60, and 60-120 cm. Means followed by the same letter are not significantly different from each other according to LSD test at α = 0.05 (*n* = 64). Square-root transformed data were used to perform ANOVA and means separation for each depth, but back-transformed means are presented above. ORG = Organic management system; CONV = Conventional management system; NT = No-tillage system; CT = Conservation tillage system.

Table 5-5. Summary of analysis of variance of tillage system and burial time period of the PRS^{TM} probes on soil nutrient supply rate in 2012.

Source of variation	**Total inorganic N**	**NO_3-N**	**NH_4-N**	**Ca**	**Mg**	**K**	**P**	**S**	**Fe**	**Mn**	**Cu**	**Zn**	**B**	**Pb**	**Al**	**Cd**
	-----*P* value-----															
Tillage system (T)	***	***	ns†	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Burial time (B)	***	***	ns	**	ns	***	***	**	***	***	*	***	**	***	***	**
T x B	***	***	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	*	ns	ns

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† ns, not significant at the 0.05 probability level.

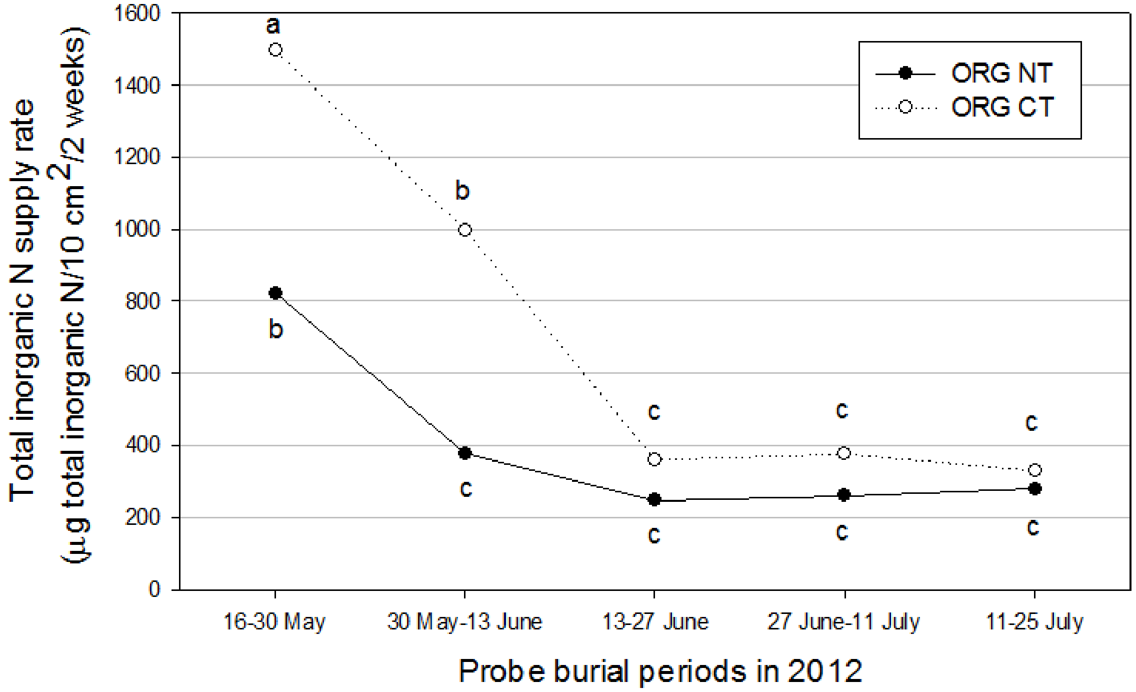


Figure 5-4. Soil supply rate of total inorganic nitrogen in the organic management system plots in 2012, as affected by tillage systems. Data points followed by the same letter are not significantly different from each other according to LSD test at $\alpha = 0.05$ (*n* = 40). Means were not corrected for soil moisture, since soil moisture as a covariate had no significant effect on total inorganic N supply rate. ORG = Organic management system; NT = No-tillage system; CT = Conservation tillage system.

Results from soil nitrate-N (0-120 cm) and PRS^{TM} probes (0-10 cm) both indicated that ORG CT offered a better synchrony of N release from the cover crop with the spring wheat crop N uptake than ORG NT, early in the season. Greater soil inorganic N content in ORG CT than in ORG NT in spring 2012 indicated that N release from the cover crop incorporated (CT) was faster than from the mulched treatment (NT). A better soil-residue contact due to the incorporation of cover crop the previous fall allowed faster microbial mineralization of the cover crop in CT. This is similar to findings by Brown (2013), Parr et al. (2011), and Wells et al. (2013), who all used plant root simulator probes to determine the soil nutrient supply rate in cover crop-based organic rotational no-till systems. Wells et al. (2013) compared the soil N supply rates of a rolled cereal rye with that of a tilled cereal rye, and found that the rolled cereal rye created "an extremely low N environment" compared with the incorporated cereal rye cover crop.

The difference in soil inorganic N supply rate between tillage systems in ORG was significant for the first 4 wk of PRS^{TM} probe burial only and not significant for the following 6 wk of burial. This may be due to low overall soil moisture in soils during the months of July and August at the study site (Figure 5-5), reducing movement of nitrate-N within the soil solution and its uptake by the ion membrane PRS^{TM} probes. Maybe the inorganic N was still present in the soil, as observed by Parr et al. (2011). Parr et al. observed the presence of soil mineral N with standard soil extract N while the ion resin probe did not show the presence of soil mineral N in dry conditions. However, in the present study, soil moisture did not seem to influence soil inorganic N supply rate, because soil moisture as a covariate had no significant effect on total soil inorganic N supply rate (P = 0.7431). Hence, in the present study, the overall low supply rate of total inorganic N may simply be due to spring wheat N uptake, since the spring wheat was seeded on 23 April 2012.

In the present study, most of the inorganic soil N absorbed onto the PRS^{TM} probes was in the form of nitrates. Ammonium-N represented only 0.5-2.1% of total inorganic N in soils at the study site. Moreover, soil ammonium-N was not affected by either tillage system or burial time (Table 5-5).

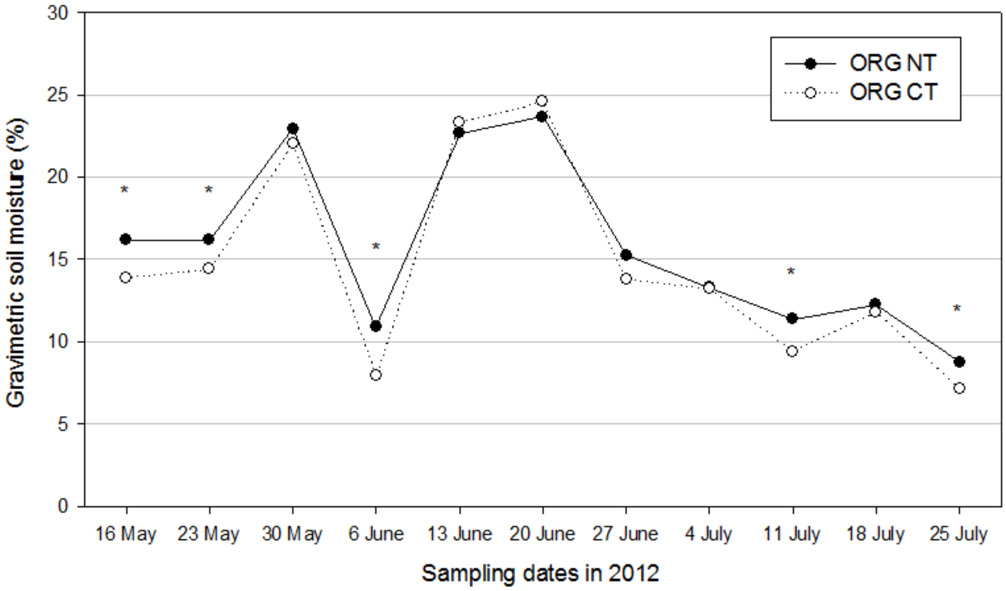


Figure 5-5. Tillage system x time interaction effect on gravimetric soil moisture (0-10 cm). Asterisks indicates that means are significantly different from each other according to Least Square Difference test at α = 0.05 (*n* = 88). ORG = Organic management system; NT = No-till tillage system; CT = Conservation tillage system.

No-till system conserved moisture better than the tilled system (Figure 5-5). There was a significant interaction effect between tillage system and time on gravimetric soil moisture content measured between mid-May and late-July 2012, at 0-10 cm depth (*P* = 0.0079). Gravimetric soil moisture content (0-10 cm) was higher in ORG NT than in ORG CT at five out of eleven sampling dates in spring-summer 2012 (Figure 5-5). Water did not seem to be the limiting factor of N availability in ORG NT in early-spring and mid-summer.

5.4.4 Other Soil Properties

Tillage and management system did not affect organic matter, P, K, and Zn contents in spring and fall of 2010, 2011, and 2012, at 0-15 cm (Appendix 1). In early-spring and summer 2012, tillage system had no significant effect on the supply rates of other soil nutrients: NH_4-N, Ca, Mg, K, S, Fe, Mn, Cu, Zn, B, Al, and Cd, as measured with the PRS^{TM} probes (Table 5-5). There was a significant tillage x time interaction effect on the content of P and Pb in soils.

5.4.5 Weeds

Seventeen weed species were observed at the study site in June 2011 and 2012. Most weed species observed were annual weeds, and included redroot pigweed (*Amaranthus retroflexus* L.), shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik.], lamb's quarters (*Chenopodium album* L.), Canada fleabane [*Conyza canadensis* (L.) Cronquist], barnyard grass [*Echinochloa crus-galli* (L.) Beauv.], woodsorrel (*Oxalis* spp.), wild buckwheat (*Polygonum convolvulus* L.), lady's thumb (*P. persicaria* L.), yellow foxtail [*Setaria glauca* (L.) Beauv.], green foxtail [*Setaria viridis* (L.) Beauv.], London rocket (*Sisymbrium irio* L.), and volunteer hairy vetch. Perennial weed species observed at the study site included dandelion (*Taraxacum officinale* Weber), Canada thistle [*Cirsium arvense* (L.) Scop.], wormwood (*Artemisia absinthium* L.), timothy (*Phleum pratense* L.), and broadleaf plantain (*Plantago major* L.). American dragonhead (*Dracocephalum parviflorum* Nutt.) was also identified at the study site on 13 Oct. 2009.

In fall 2009, there was no significant difference in the frequency of six weed species between tillage systems (n = 8, data not shown). There was also no significant difference in weed biomass between tillage system and management system in 2010 and 2011 (Table 5-6). Moreover, weed species richness in June 2011 was not significantly affected by tillage or management systems (Table 5-6), although perennials (mostly dandelion and

Canada thistle) became visually well-established under ORG NT. Similar weed biomass among tillage systems in 2010 may be explained by the early seeding of the oat crop, its high competiveness against weeds, and similar content of soil nitrate-N. Early oat seeding on 8 April 2010 allowed the crop to gain an advantage on the weeds by emerging early and occupying the canopy early. Therefore, oats competed effectively against weeds in all treatments, regardless of the low biomass of mulch in ORG NT (< 5.4 Mg ha^{-1}). However, the low biomass of mulch and the absence of tillage over the growing season may be responsible for the establishment of perennial weeds in ORG NT, and for their proliferation in subsequent years.

Table 5-6. Weed biomass and weed species richness in 2010-2012, and summary of analysis of variance.†

Main effects	**Above-ground weed biomass**			**Weed species richness**	
	at oat harvest in 2010	**at rolling in 2011**	**at wheat harvest in 2012**	**June 2011**	**June 2012**
	---------------kg ha^{-1}---------------			---# species 0.0625 m^{-2}---	
Tillage system (T)					
No-tillage	432 a	882 a	178 a	3.9 a	3.9 b
Conservation tillage	308 a	584 a	211 a	4.8 a	6.9 a
Management system (M)					
Organic	479 a	794 a	385 a	4.6 a	6.3 a
Conventional	261 a	671 a	5 b	4.1 a	4.6 b
Source of variation	--------------------------------*P* value--------------------------------				
T	ns‡	ns	ns	ns	***
M	ns	ns	***	ns	**
T x M	ns	ns	ns	ns	ns

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Within column of a same response, means followed by the same letter are not significantly different from each other according to LSD test at α = 0.05 (*n* = 16, for each response). Log-transformed data were used to perform ANOVA and means separation on above-ground weed biomass at spring wheat harvest in 2012, but back-transformed means are presented above.

‡ ns, not significant at the 0.05 probability level.

Differences in weed communities (biomass and species richness) between treatments were statistically significant in the 5th yr of the experiment only. In fall 2012, weed biomass at harvest was higher in ORG than in CONV treatments where herbicides had been used since spring 2010, regardless of tillage systems (Table 5-6). Weed species richness was also different between tillage and management treatments in June 2012. The CONV system had lower weed species richness than ORG. A lower number of weed species was also observed in NT than in CT (Table 5-6). The reduction in the richness of weed species in NT may be attributed to the establishment of dandelion as the dominant species in NT. Tillage allowed fair competition for sunlight and resources without having a dominant, well-established species taking up the resources early in the season (Smith, 2006). In NT, perennial weed species like dandelion was more frequently observed than in CT. A shift from summer annual to winter annual and perennial weeds has also been reported in reduced-tillage systems without herbicide (Melander et al., 2013), such as organic rotational no-till systems in eastern U.S.A. (Mirsky et al., 2012). Légère et al. (2013) qualified the inability to control perennial weeds “the greatest weakness” of organic no-till systems.

Surprisingly, weed biomass in ORG NT in fall 2012 was not greater than the other treatments, although the ORG NT treatment was visibly infested by a high plant population density of dandelion. The main reason for comparable weed biomass between ORG NT and the other treatments was because at time of sampling for weed biomass, most of dandelion above-ground biomass had dessicated and started to decompose. An additional sampling event in the spring or mid-summer may have better captured the enhanced abundance of dandelion in ORG NT that was visually noticeable in May and June 2012 (Figure 5-6).

Figure 5- 6. Dandelion population in the spring wheat crop of the organic no-till (left) and conventional no-till (right) systems on 22 June 2012 (© Caroline Halde 2012).

5.4.6 Agronomic Performance of Cash Crops

Over the 5 yr study, crop yields, and crop yield components were affected by tillage systems and/or management systems, depending on year. Crop yields in the ORG NT system were reduced in 2 (2009 and 2012) out of 3 yr. The main factors limiting crop agronomic performance in ORG NT in those years were weeds, soil inorganic nitrogen, and, indirectly, low mulch biomass, depending on crop year.

In 2009 (Year 2), there was a significant effect of tillage system on flax seed yield (P = 0.0403, n = 8). ORG NT flax seed yields (1984 kg ha^{-1}) were lower than those of ORG CT flax (2265 kg ha^{-1}). The difference in yield between ORG CT and ORG NT may be attributed to low mulch production the previous year. Not enough cover crop biomass was produced in the previous year (2008) to provide effective weed control by mulches in ORG NT the subsequent year, reducing flax seed yield in ORG NT by 12% compared with ORG CT. In 2009, mulch biomass collected in May at the time of flax seeding averaged 4.5 Mg ha^{-1} in ORG NT, considerably below the required mulch biomass requirement. Reduced cash crop yields due to low mulch biomass in the first year of establishing an ORG NT system have also been observed by Podolsky (2013) and Teasdale et al. (2012). In the present study, organic flax produced in both CT and NT treatments yielded more than the regional and provincial conventional average flax seed yields (1.56 and 1.69 Mg ha^{-1}, respectively; MMPP, 2013). This present study was also among the first trials of the organic rotational no-till system in Manitoba, along with those by Vaisman et al. (2011), hence the system was still in its adaptation phase. Acceptable crop yields in the 2nd yr of organic no-till have been successfully achieved in subsequent field trials in Manitoba (MANUSCRIPT #1; MANUSCRIPT #2; Podolsky, 2013; Vaisman et al., 2011).

In 2010 (Year 3), tillage system and management system had no effect on most crop performance indicators observed for oats (i.e. oat plant population density, oat yield, above-ground oat biomass at harvest, and harvest index for oats) (Table 5-7). Oats established well and yielded similarly in all treatments. The only differences observed between tillage systems on oat agronomic performance were on oat developmental stage and oat height in mid-summer. No-till oats developed slower than CT oats in early-spring, resulting in shorter oat plants at the time of plant height determination on 15 July 2010. Other studies reported slow crop emergence in no-tillage, and attributed the difference to colder temperature in no-till compared with tilled systems (Podolsky, 2013). Management systems had no significant effect on any of the oat crop agronomic performance in 2010 (Table 5-7).

Table 5-7. Agronomic performance of the oat crop in 2010, and summary of analysis of variance.†

Main effects	**Oat plant population density**	**Oat developmental stage (measured with Haun scale)**	**Oat height in mid-summer**	**Above-ground oat biomass at harvest**	**Oat grain yield**	**Harvest index for oats**
	plant m^{-2}		cm	-----Mg ha^{-1}-----		%
Tillage system (T)						
No-tillage	300 a	1.84 b	84.5 b	6.8 a	2.6 a	38.2 a
Conservation tillage	324 a	2.32 a	94.4 a	8.3 a	2.9 a	35.7 a
Management system (M)						
Organic	-	-	91.1 a	7.9 a	2.8 a	35.9 a
Conventional	-	-	87.9 a	7.2 a	2.7 a	38.0 a
Source of variation	-------------------------------*P* value-------------------------------					
T	ns‡	***	***	ns	ns	ns
M	-	-	ns	ns	ns	ns
T x M	-	-	ns	ns	ns	ns

*** Significant at the 0.001 probability level.

† Within column of a same response, means followed by the same letter are not significantly different from each other according to LSD test at α = 0.05 (*n* = 16, for each response).

‡ ns, not significant at the 0.05 probability level.

In 2012 (Year 5), the agronomic performance of the spring wheat crop was generally the lowest in the ORG NT. Earlier emergence and higher plant population density of spring wheat was observed in CT compared with NT, regardless of management system (Table 5-8). ORG NT produced the lowest spring wheat biomass at harvest and spring wheat grain yield (Tables 5-8 and 5-9). Spring wheat grain yields in ORG NT represented only 32% of the average yield of the other treatments. Reduced crop yields in ORG NT were also reported in a number of studies, as discussed previously.

Table 5-8. Spring wheat agronomic performance in 2012, and summary of analysis of variance.†

Main effects	**Spring wheat plant population**	**Number of tillered spring wheat plants on 17 May**	**Dry matter harvest index**	**Grain mass**	**Grain protein concentration**
	plant m^{-2}	------------%------------		g seed^{-1}	g g^{-1}
Tillage system (T)					
No-tillage	274 b	3 b	36.6 a	0.0276 a	12.17 b
Conservation tillage	361 a	50 a	33.5 a	0.0279 a	13.64 a
Management system (M)					
Organic	317 a	28 a	38.1 a	0.0290 a	12.19 b
Conventional	319 a	25 a	31.9 a	0.0265 b	13.63 a
Source of variation	--------------------------------*P* value--------------------------------				
T	***	***	ns‡	ns	*
M	ns	ns	ns	**	**
T x M	ns	ns	ns	ns	ns
n	16	15	16	16	16

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Within column of a same response, means followed by the same letter are not significantly different from each other according to LSD test at α = 0.05.

‡ ns, not significant at the 0.05 probability level.

Yield penalty in organic no-till systems is usually attributed to weed competition and low soil N due to reduced mineralization (Mirsky et al., 2012; Carr et al., 2013). In the present study, reduced soil inorganic nitrogen played a role in producing poor yields in ORG NT. Spring wheat grain yields were positively correlated with both soil nitrate-N at 0-120 cm in spring 2012 (r = 0.62, P = 0.0103, n = 16) and with total soil inorganic N between 16 May and 25 July 2012 (r = 0.92, P = 0.0013, n = 8). Hence, in conditions of limited N availability, the spring wheat grain yields were reduced.

The second major factor limiting yield in ORG NT was the presence of weeds, partially due to low mulch biomass (only 4.7 Mg ha^{-1} of mulch in NT, on average). Moreover, lower yields in ORG NT were not linked to lower spring wheat plant population density in NT, since no significant correlation was observed between spring wheat plant population density and spring wheat grain yield (r = 0.48, P = 0.0601, n = 16).

The reduced productivity in ORG NT was also observed in grain yield components (number of spikelets per spike, number of spikes per m^2, and number of spikelets per m^2), with the lowest values in ORG NT (Table 5-9). Reduced number of spikes per m^2 and number of spikelets per spike in ORG NT indicated that resources were limited early in the season (Fischer, 2008). Grain mass, determined during the grain filling stage, was greater in ORG than in CONV systems, whereas tillage systems had no significant effect on grain mass (Table 5-8). Dry matter harvest index was not affected by tillage nor management system.

Table 5-9. Tillage system x management system interaction effect on spring wheat agronomic performance in 2012, and summary of analysis of variance.†

	Above-ground biomass at harvest		**Nitrogen content of the above-ground biomass at harvest**		**Spring wheat grain yield**	**Number of seeds per head**	**Number of heads per area**	**Number of grains per area**
	Spring wheat	**Total plant (spring wheat and weeds)**	**Spring wheat**	**Total plant (spring wheat and weeds)**				
	--------Mg ha^{-1}--------		-------kg N ha^{-1}-------		Mg ha^{-1}	grain head^{-1}	head m^{-2}	grains m^{-2}
Tillage (T) x Management (M)								
CONV CT	10.3 a	10.3 a	118 a	118 a	3.4 a	13 a	831 a	10860 a
CONV NT	11.2 a	11.2 a	102 a	102 a	3.4 a	13 a	801 a	10738 a
ORG CT	9.6 a	10.1 a	97 a	106 a	3.2 a	13 a	689 b	9070 b
ORG NT	2.6 b	3.0 b	26 b	32 b	1.1 b	9 b	270 c	2484 c
Source of variation	--*P* value--							
T	***	***	***	***	**	***	***	***
M	***	***	***	***	***	***	***	***
T x M	***	***	***	***	**	***	***	***

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Within column of a same response, means followed by the same letter are not significantly different from each other according to LSD test at α = 0.05 (*n* = 16, for each response). Square-root transformed data were used to perform ANOVA and means separation on above-ground spring wheat biomass at harvest, but back-transformed means are presented above. ORG = Organic management system; CONV = Conventional management system; NT = No-tillage system; CT = Conservation tillage system.

5.4.7 Plant Nitrogen Uptake

In 2010 (Year 3), tillage system and management system had no significant impact on N concentration and content of oats and weeds at the time of harvest in late-summer (data not shown). This indicates that competition for soil N between the oat crop and weeds was not reduced in the ORG NT treatment, since N uptake by oat plants and weeds did not differ among tillage or management systems.

Differences in N uptake by crop and weeds occurred in Year 5 (2012). In 2012, total plant N uptake (by both spring wheat and weeds) was the lowest in ORG NT (Table 5-9). There was also a strong positive correlation between N uptake by spring wheat and both soil nitrate-N at 0-120 cm in spring 2012 (r = 0.66, P = 0.0053, n = 16) and with total soil inorganic N between 16 May and 25 July 2012 (r = 0.93, P = 0.0007, n = 8), suggesting that low N uptake in ORG NT was linked to low inorganic N content in soils in ORG NT. Spring wheat grain protein concentration was affected by both tillage and management systems (Table 5-8). Spring wheat grains grown in CT systems had a higher protein concentration than in NT systems, and spring wheat grain protein concentration was higher in CONV than in ORG.

5.4.8 Comparing Organic vs. Conventional Management of Tilled Systems

In the present study, there were no crop yield difference between ORG CT and CONV CT for the five-year duration of the study. Little difference in soil chemical properties, weeds, and crop responses between ORG and CONV tilled systems may be attributed to the nature of the CONV management. Conventionally-managed plots received herbicides and fungicides, but did not receive synthetic fertilizers. The conventional and organic managements did not differ in fertilization, both having biological N fixation from cover crops as the main N input in the system. Moreover, CONV CT received less pesticide application than CONV NT. Pesticides were not applied to CONV CT when a tillage pass was scheduled on the same day of the herbicide application to avoid overuse of herbicides and to mimic farmers' practices. Weeds were efficiently controlled by tillage in ORG CT, causing no yield penalty compared with CONV CT. Spring wheat in ORG CT, CONV CT, and CONV NT produced yields similar to average provincial yields (3.2 Mg ha^{-1}) (MMPP, 2013). Therefore, this rotation with a green manure crop every 3rd yr allowed the ORG CT system to produce similar yields as the two CONV systems, without the use of pesticides.

5.4.9 Field Management for Successful Continuous Organic No-Till

The productivity of continuous organic no-till system declined after eliminating tillage for an extended period of time. However, results of the present study indicated that it is possible to maintain an organic no-till system somewhat productive for a period of 4 yr, in Manitoba. Tillage is required every 4 yr, minimum, to avoid a reduction in crop productivity in organic no-till systems in Manitoba.

In the present study, many techniques were used to extend the longevity and productivity of the organic no-till system. Competitive cash crop species with fast emergence were selected and they were seeded early in the spring (oats were seeding on 8 Apr. 2010 and spring wheat was seeded on 23 Apr. 2012), to give a competitive advantage to the crop over the weeds. In 2010, the oat crop was seeded in two passes, with the second seeding pass at an angle of 45°, to increase oat ground coverage. A cover crop was grown every 3 yr to create mulch. Cover crops were used in 2010 after the early cash crop harvest to scavenge the excess N and occupy the canopy. Other techniques were also used to prolong the productivity of the organic no-till system beyond the scope of the study reported here, i.e. after late-summer 2012. In fall 2012, sheep were integrated to the ORG NT system to graze weeds before a competitive fall cereal was established. Defoliation caused by sheep grazing reduced perennials' ability for photosynthesis (Popay and Field, 1996). Perennials used their below-ground resources (carbohydrates) to make new shoot biomass, depleting its abilities for winter survival (Cyr et al., 1990). However, despite sheep grazing for weed control in fall 2012, organic no-till management failed to produce acceptable cereal rye yield. The study was terminated in spring 2013.

Additionally, the geographical location of the study site may have played a role in the success of the continuous ORG NT for a five-year period. In southern Manitoba, the short growing season (~1800 GDD) limits the period for weed seedling recruitment. In other environmental conditions with a longer growing season, there may be more opportunity for weeds to emerge due to a large window for weed seedling recruitment, which would make it harder to maintain a continuous organic no-till system.

5.5 Conclusions

Results from our 5-yr field study showed that reduced nitrate-N levels in soils and weeds were the main limitations for organic continuous no-till cropping system in a cool subhumid continental climate. Crop yields were lower in ORG NT than in other management and/or tillage treatments in 2009 (flax) and 2012 (spring wheat).

To our knowledge, this field study is the first one to compare the effect of continuous organic no-till with those of organic tilled and conventionally-managed systems over a 5-yr period. Although very few farmers would attempt to sustain an organic no-till cropping system for more than 2-3 years, this 5-yr study was useful to identify the limitations of a continuous organic no-till system in the northern Great Plains of Canada. In a changing climate, there is a need for medium- to long-term cropping field studies that aim to find bold, innovative solutions to complex agronomical problems.

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MANUSCRIPT #4

6.0 PLANT SPECIES AND MULCH APPLICATION RATE AFFECTED DECOMPOSITION OF COVER CROP MULCHES USED IN AN ORGANIC ROTATIONAL NO-TILL SYSTEM

6.1 Abstract

Cover crops in organic rotational no-till system are managed using a roller-crimper for their termination, without the need for tillage. Decomposition of cover crop mulches have received little attention in the scientific literature, particularly in the context of the organic rotational system adapted for the northern climatic conditions of the northern Great Plains of Canada. The objective of the study was to determine the effect of plant species and mulch application rate on surface-applied cover crop decomposition and mulch quality parameters over time. Using the litter bag technique, six plant species and two mulch application rates were tested twice in field studies at Carman, Manitoba, Canada. Among the plant species tested, oilseed radish (*Raphanus sativus* L.) decomposed the fastest and barley (*Hordeum vulgare* L.) decomposed the slowest, with decomposition rate assessment based on mass loss. Hairy vetch (*Vicia villosa* Roth) had the highest nitrogen (N) concentration and lowest C:N ratio. The effect of mulch application rate on mulch biomass was not consistent among sites. Remaining biomass of each individual species and mulch application rate level was fitted to an exponential decay curve, and oilseed radish had the highest decomposition constant at both sites. Nitrogen content of cover crop mulches varied greatly over time. Mulches released a

large amount (46.4%) of their initial N content by 30 Sept. (after only 30 days of field placement), for all plant species and mulch application rates combined. Forty-four percent of initial N content still remained in the mulches by early-May (Day 250), and may be available for the subsequent crops seeded in the spring or later in the crop rotation. Net N immobilization was not observed in any of the mulches during the course of the field study. Our results support the use of N concentration, lignin concentration, and C:N ratio as indexes of substrate quality for cover crop mulches.

6.2 Introduction

Cover crops are important contributors to soil fertility in organic farming. Legume-containing cover crops are particularly beneficial to crop productivity in this system by providing nitrogen (N) to soils through biological N fixation. Cover crops are traditionally incorporated into the soil with tillage, to facilitate and accelerate their decomposition and nutrient release. A number of studies have looked at the contribution of incorporated cover crop biomass as a source of N for the subsequent crop in farming systems (Cherr et al., 2006; Janzen and Radder, 1989).

A new way of managing cover crops is to use roller-crimpers for their termination, without the need for tillage. This technique is a key component of organic rotational no-till systems (Carr et al., 2013; Mirsky et al., 2012). In Manitoba, Canada, the organic rotational system consists of a spring-seeded cover crop grown until it reaches the flowering stage, then terminated by rolling in mid-summer using a roller-crimper. The cover crop mulch is then left on the soil surface over the fall and the winter, until a cash crop is no-till planted into the mulch the following spring. These rolled mulches provide weed control and N inputs for the subsequent crop (Vaisman et al., 2011).

No prior study has focused on the decomposition of cover crop mulches using the litter bag technique, in the context of an organic rotational no-till system. A better understanding of decomposition of surface-applied mulches will help to identify cover crop mulches suited for an organic rotational no-till in Manitoba. Suitable mulches are expected to decompose slowly (for extended soil cover and weed control) and to release N when the subsequent cash crop requires it. Many questions remain unanswered about the synchrony of N release from mulches with the subsequent crop N requirements and possible N losses or immobilization in these reduced-tillage systems. Although researchers have started to investigate the N contribution of rolled mulches in North America (Brown, 2013; Wells et al., 2013), none have done so by conducting a litter bag decomposition study.

Decomposition of rolled cover crops differs greatly from that of tilled cover crops, and this topic has received little attention in the literature. Mechanisms involved in surface-applied residue decomposition include microbial decomposition, leaching of nitrogen-rich compounds, and photodegradation (Berg and McClaugherty, 2008; Henry et al., 2008). Many factors affect the decomposition of surface-applied cover crop mulches, such as mulch chemical properties, mulch physical properties, environmental properties, and the nature and abundance of the decomposing organisms.

The decomposition process has predominantly been explained with mulch quality parameters. Initial N content plays a predominant role in mulch decomposition (Parton et al., 2007). Lignin content and lignin:N ratio also seems to determine the decomposition rate of different plant species (Cookson et al., 1998). Other nutrients, such as Ca, Mg, K, P and S, have also been found to influence the decomposition process (Neely et al., 1991). However, chemical properties of cover crop mulches are distinct from those of post-harvest crop residues or forest litter widely studied in litter bag decomposition study. The rolled cover crop mulches have relatively high N concentration (2-5 %), low C:N ratios, and low lignin concentration (< 10%). They are less mature than post-harvest crop residues since the plant material has been rolled at the flowering stage. This plant material also includes the entire above-ground plant biomass, not exclusively the stems.

Mulch physical properties are also an important determinant of the decomposition constant associated with these materials. Particle size of plant residues affects their decomposition by soil biota by influencing the physical protection of the material and the accessibility of its N (Angers and Recous, 1997). Mulch area index have been developed to quantify physical properties of mulches used in organic rotational no-till systems (Teasdale and Mohler, 2000). Some researchers have also advocated against the use of mulch quality as the sole determinant of decomposition rate (Ruderfer, 2003) to give more importance to mulch physical properties. Environmental conditions such as temperature and soil moisture also affect the process of decomposition (Berg and McClaugherty, 2008, Manning et al., 2008). Dry plant material decomposes slower than moist material, at similar nutrient concentrations (Enriquez et al., 1993).

The objective of the study was to determine the effect of plant species and mulch application rate on surface-applied cover crop decomposition and mulch quality parameters over time. The hypotheses tested were that: 1) Decomposition of mulches can be explained by mulch chemical properties (C, N, lignin, C:N, lignin:N); 2) Thick mulches have a lower decomposition constant than thin mulches. Understanding the decomposition of cover crop mulches will provide valuable information on nutrient release, soil cover, and potential weed control from mulches.

6.3 Materials and Methods

6.3.1 Study Site

Two separate two-year litter bag decomposition studies (2010-2011 and 2011-2012) were conducted at two locations within a few metres of each other at the University of Manitoba Research Station at Carman, Manitoba, Canada (lat. 49°29'53.200" N, lon. 98°01'47.100" W). The study site was located within the Winkler Ecodistrict, within the Lake Manitoba Plain Ecoregion of the Prairies Ecozone (Smith et al. 1998), at 268 m above sea level (Environment Canada, 2013). The ecodistrict has a mean annual temperature of 3.1°C, a mean number of growing degree-days of about 1800 (T_{base} = 5°C), and receives about 515 mm of annual precipitation (Smith et al., 1998). Soils in Carman are Black Chernozems of the Hochfeld series that are moderately drained to imperfectly drained (Smith et al., 1998). The study site has been managed organically since 2003.

6.3.2 Experimental Design

The experimental design was a split-plot design with four blocks, with a 6x2 factorial within each main plot. The main plot factor was retrieval time of litter bags, whereas the subplot factors were plant species x mulch application rate. Four blocks (each 1.2 m x 2.4 m) were each divided into six main plots (each 1.2 m x 0.4 m), for each retrieval date at the particular site. Each main plot included 12 litter bags (subplots) randomized within the main plot, representing six levels of plant species and two levels of mulch application rate.

The six plant species tested were hairy vetch (*Vicia villosa* Roth), field pea (*Pisum sativum* L.), oilseed radish (*Raphanus sativus* L.), sunflower (*Helianthus annuus* L.), flax (*Linum usitatissimum* L.) and barley (*Hordeum vulgare* L.), representing a wide range of mulch quality. The two mulch application rates (mulch mass per unit of area in the litter bag) tested were 0.5 kg m^{-2} (5 Mg ha^{-1}) and 1.0 kg m^{-2} (10 Mg ha^{-1}). The six retrieval dates of litter bags were Day 15, 30, 45, 60, and 250 after initial field placement of the litter bags, and an initial characterization of the mulch the day of the field placement, at Day 0. Two separate litter bag decomposition studies were conducted at two different sites (sites A and B). At site A, the experiment was conducted in 2010 and 2011, whereas the experiment at site B took place the subsequent years (2011 to 2012). At site A, twelve retrieval dates were initially planned to run for 600 days (with retrieval at Day 280, 310, 340, 370, 400, and 600), instead of 250 days. However, weeds growing into the litter bags after Day 250 at site A confounded mulch biomass and mulch quality results, hence the experiment was terminated after the sixth retrieval date (Day 250).

6.3.3 Litter Bags Fabrication and Field Placement

All six cover crop species were seeded in a field adjacent to the study sites A and B on 3 June 2010 (site A) and on 10 June 2011 (site B). Cover crop plots were hand-weeded twice during the summer at site A to increase cover crop biomass yield. Above-ground biomass of pea, oilseed radish, sunflower, flax, and barley was harvested manually on 26 July 2010 (53 days after seeding (DAS), 707 GDD) (MAFRI, 2013a) at site A, and on 3 Aug. 2011 (55 DAS, 788 GDD) at site B. Flax, oilseed radishes and barley were at the flowering stage. Oilseed radishes and peas were flowering and had set a few seeds, but these were not mature yet. Sunflowers were at the early-flowering stage and had reached 1.0 to 1.3 m high. Hairy vetch was harvested 16 to 18 days later, on 13 Aug. 2010 at site A (71 DAS, 989 GDD) and on 19 Aug. 2011 (16 DAS, 1008 GDD), because hairy vetch had not reached full-blossom at the initial harvesting date. After harvesting, mulch was dried at 60°C for 48 h. Mulch was manually cut into 10 to 15 cm long pieces, to mimic field mulches. Litter bags (20 cm x 20 cm) were constructed with fiberglass mesh (RCR International inc., Boucherville, QC, Canada) with a 1-mm mesh size. Consequently, fauna larger than 1 mm were excluded from the bags. The litter bags were filled with 20.0 g oven-dry mulch for the 0.5 kg m^{-2} application rate level, and 40.0 g for the 1.0 kg m^{-2} application rate level, for each species, independent of mulch produced by each individual species in field conditions.

At both sites, litter bags were placed on 31 Aug. (Day 0; in 2010 at site A and in 2011 at site B) on fields where oats (*Avena sativa* L.) had been grown and harvested earlier that year, to avoid any home-field advantage for one specific plant species tested (Ayres et al., 2009). The fields were not tilled after oat harvest. The oat stubble was cut and removed using a gas-powered portable string trimmer and a manual brush, to ensure adequate bag-soil contact. Litter bags were positioned directly on the soil surface and maintained in that position with 15 cm long nails. Each block was also covered with 1.5 m x 5 m chicken wire at site A to prevent wind damage to the litter bags. Chicken wire was not used at site B, because of its questionable usefulness. The study site was hand-weeded once a month, in-between bags and in the 15 cm length surrounding the litter bags. A few oat volunteers grew in some bags between Day 0 and 60, but their biomass was easily discarded from the desired species biomass at each retrieval date.

6.3.4 Data Collection

Litter bags were collected at Day 15, 30, 45, 60, and 250 after field placement (Table 6-1). Litter bags were also collected the day of the field placement (Day 0) to estimate the loss of dry biomass due to field placement and bag removal from the field. All biomass values were corrected considering this initial loss, for all other dates. After field retrieval, litter bags at site B were washed in water to remove soil residues. Mulch was dried at 60°C for 48 h and weighed to determine dry remaining biomass. These samples were then ground to 2-mm particle size with a grinder (Arthur H. Thomas Co., Philadelphia, PA, U.S.A.).

Dry plant biomass collected in bags at Day 0, 30, 60 and 250 at site A were analyzed for carbon and lignin concentrations by Central Testing Laboratories Ltd. (Winnipeg, MB,

Table 6-1. Retrieval dates, air temperatures, precipitation, and growing degree-days at both sites.

		Retrieval date	**Julian day**	**Cumulative precipitation since the previous retrieval date †§**	**Cumulative precipitation since Day 0 †§**	**Mean daily air temperature since the previous retrieval date‡**	**Growing degree-days since the previous retrieval date †§**	**Cumulative GDD since Day 0 †§**
				-------------------mm-------------------		°C		
Site A (2010-2011)	Day 0 – bag placement	31 Aug. 2010	243	n/a	0	n/a	n/a	0
	Day 15	15 Sept. 2010	258	67 (27)	67 (27)	12.8	117 (137)	117 (137)
	Day 30	30 Sept. 2010	273	39 (24)	106 (52)	10.9	89 (84)	206 (222)
	Day 45	15 Oct. 2010	288	0 (22)	106 (75)	12.3	109 (42)	316 (264)
	Day 60	30 Oct. 2010	303	56 (14)	163 (89)	5.5	23 (5)	340 (269)
	Day 250	8 May 2011	128	81 (174)	244 (263)	-8.0	82 (44)	422 (313)
Site B (2011-2012)	Day 0 – bag placement	31 Aug. 2011	243	n/a	0	n/a	n/a	0
	Day 15	15 Sept. 2011	258	17 (27)	17 (27)	16.8	177 (137)	177 (137)
	Day 30	30 Sept. 2011	273	46 (24)	64 (52)	12.1	106 (84)	284 (222)
	Day 45	15 Oct. 2011	288	4 (22)	69 (75)	14.3	120 (42)	404 (264)
	Day 60	30 Oct. 2011	303	3 (14)	72 (89)	3.0	1 (5)	405 (269)
	Day 250	7 May 2012	128	90 (174)	161 (262)	-2.4	162 (40)	567 (309)

† Data from MAFRI (2013a).

‡ Data from MAFRI (2013b).

§ Normal values based on 30-yr average are presented in parenthesis.

Canada) and to determine nitrogen concentration by combustion analysis using a nitrogen analyzer (FP-528, LECO Co., St Joseph, MI, U.S.A.) at the Department of Plant Science of the University of Manitoba (Winnipeg, MB, Canada). Ratios (C:N, lignin:N) were calculated on a dry matter basis. Carbon, nitrogen, and lignin contents were calculated from their respective concentration and remaining biomass using Equation 6-1.

Eq. 6-1.

$$\text{Content (\% of initial content)} = \frac{\text{concentration (\%)} \times \text{remaining biomass (\%)}}{\text{initial concentration (\%)} \times \text{initial biomass (\%)}}$$

Nitrogen immobilization was considered to be an increase in the N content above its initial content. Only samples from site A were analyzed for N, C, and lignin concentrations, because samples from site B had been washed in water. Hence, mulch quality was not assessed at site B and conclusions on mulch chemistry will only be done with data collected at site A.

6.3.5 Statistical Analyses and Decomposition Model

Statistical Analysis System 9.2 (SAS Institute Inc., 2008) software was used to conduct statistical analyses. To compare the effects of plant species, thickness, time, and site on remaining biomass, analysis of variance ($\alpha = 0.05$) was conducted using the MIXED procedure of SAS. Fixed effects were plant species, mulch application rate, time, site, and their interaction effects, whereas block(site) and time*block(site) were considered random effects. To compare the effects of plant species, mulch application rate, and time on mulch quality parameters at site A exclusively, analysis of variance ($\alpha = 0.05$) was conducted using the MIXED procedure of SAS. Fixed effects were plant species, mulch application rate, time, and their interaction effects, whereas block and block*time were considered random effects. Outliers were identified using Lund's test (Lund, 1975) and were removed. For each analysis, residuals were verified to conform to normality and homogeneity of variance. Independence of residuals was assumed through randomization. Means were separated using the Least Square Difference test. The Satterthwaite approximation (ddfm = satterthwaite) was used for estimating denominator degrees of freedom and to produce a more accurate F-test approximation (Satterthwaite, 1946). Data from both sites were combined to assess the effect of site and its interactions with other factors on remaining biomass. However, since mulch quality was assessed only at site A, the effect of site on mulch quality was not tested using statistical analysis. Initial retrieval date (Day 0) data values were not included in the analysis of variance of the remaining biomass, but they were included in the analysis of variance of mulch quality. Correlation analyses were performed among remaining biomass of mulch and mulch quality parameters, using the CORR procedure of SAS ($\alpha = 0.05$).

Mulch decomposition constant (k) was estimated using the standard first-order decay function:

Eq. 6-2. $$M_t = M_o \times e^{(-k \times t)}$$

where M_o = initial dry mass of the decaying material, M_t = dry mass of the decaying material at time t, and k = decomposition constant (Swift et al., 1979; Vivanco and Austin, 2008). Curve fitting was performed using the NLIN procedure of SAS. The remaining biomass was fitted to an exponential decay curve for each individual species and mulch application rate level. The Gauss-Newton method was the non-linear least squares method used to estimate the regression parameters. Data from each site were fitted separately to the exponential decay model. Analysis of variance ($\alpha = 0.05$) was conducted using the MIXED procedure of SAS to compare the effect of plant species and mulch application rate on decomposition constant.

6.4 Results

6.4.1 Environmental Conditions

Cumulative precipitation for the duration of the 250-day study (31 August to 7/8 May) was greater at site A than at site B, but both were under the 30-yr normal average (Table 6-1). The study site had received 138 and 12 mm at site A and B, respectively, in the 30-day period prior to the placement of the litter bags in the field (August 1-30). Site B accumulated more growing degree-days than site A for the duration of the study (Table 6-1), because the two decomposition studies were conducted in different years. Mean daily air temperature was higher at site B than at site A, for most retrieval periods.

6.4.2 Initial Characteristics of the Mulch

Initial mulch quality varied greatly among plant species. Flax had the highest C concentration, lignin concentration, and lignin:N ratio (Table 6-2). Hairy vetch had the highest N concentration (4.8%). Other plant species in the present study had initial N concentrations ranging between 2.3 and 3.2%. Initial C:N ratios varied greatly between plant species (11.2-23.0), with hairy vetch having the lowest C:N ratio (Table 6-2). Barley had the lowest lignin concentration.

Table 6-2. Initial characteristics of the mulch at site A as affected by plant species, and summary of analysis of variance.†

Main effect	**C concentration**	**N concentration**	**Lignin concentration**	**C:N**	**Lignin:N**
	---------------	% of dry matter	---------------		
Plant species					
Hairy vetch	53.2 b	4.8 a	5.6 c	11.2 e	1.2 d
Pea	53.9 b	3.0 bcd	6.5 b	18.1 bcd	2.3 bc
Oilseed radish	51.3 c	3.2 b	5.0 c	16.3 d	1.6 c
Sunflower	50.4 c	2.7 c	5.7 bc	19.2 c	2.2 b
Flax	56.4 a	2.5 cd	9.6 a	22.6 ab	3.9 a
Barley	53.1 b	2.3 d	3.5 d	23.0 a	1.5 cd
Source of variation	-------------------	------------	*P* value	------------	-------------------
Plant species	***	***	***	***	***

*** Significant at the 0.001 probability level.

† Within column of a same response, means followed by the same letter are not significantly different from each other according to LSD test at α = 0.05 (*n* = 47 for N concentration, and *n* = 48 for all other responses).

6.4.3 Remaining Mulch Biomass as Affected by Plant Species, Mulch Application Rate, and Time

6.4.3.1 Plant Species Effect

The effect of plant species on mulch decomposition varied over time and site, as indicated by the significant plant species x time x site interaction effect on remaining biomass of mulch (Table 6-3). A trend towards overall lower remaining biomass for oilseed radish, and overall higher remaining biomass for barley was observed at both sites (Figure 6-1). Oilseed radish had the fastest overall decomposition of all mulches. At site A, remaining biomass of oilseed radish was the lowest of all other plant species, for all dates (Figure 6-1). At site B, oilseed radish had a significantly lower remaining biomass than all other plant species at Day 45 and 60. Overall, barley decomposed slower than other mulches. At site A, remaining biomass of barley was higher than that of all other plant species at Day 30, and not significantly different than that of flax at all other dates (Figure 6-1). This trend was less clear at site B.

Table 6-3. Summary of analysis of variance of plant species, mulch application rate, time, and site for remaining biomass of mulch.†

Source of variation	**Remaining biomass**
	P value
Plant Species (P)	***
Application Rate (R)	ns‡
Time (T)	***
Site (S)	***
P x R	**
P x T	ns
P x S	***
R x T	*
R x S	***
T x S	**
P x R x T	ns
P x R x S	ns
P x T x S	*
R x T x S	ns
P x R x T x S	ns

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† *n* = 474. Remaining biomass at Day 0 (100%) was not included in the analysis of variance.

‡ ns, not significant at the 0.05 probability level.

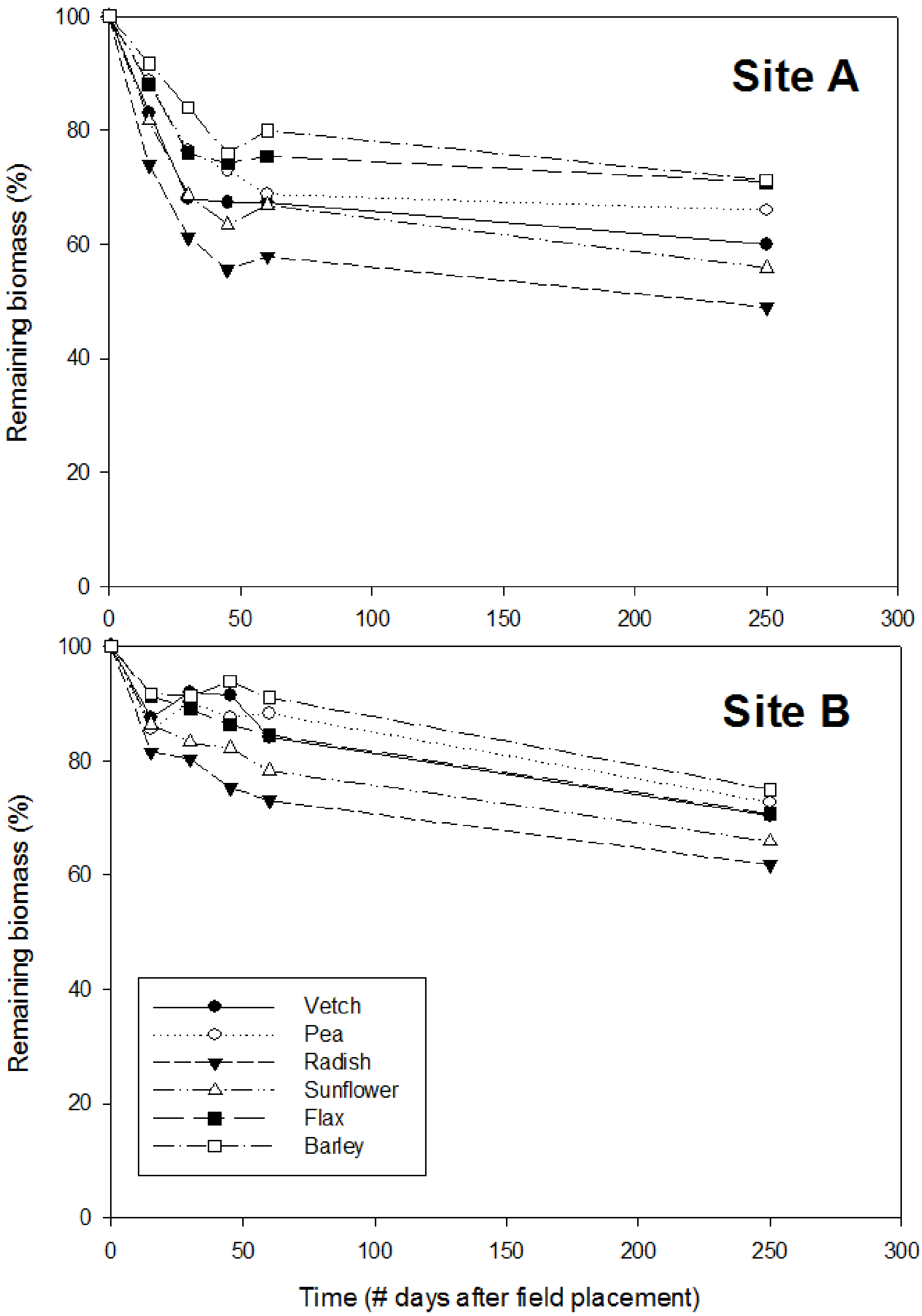

Figure 6-1. Plant species x time x site interaction effect on remaining biomass, at sites A and B (s.e. = 0.57%, *n* = 474). Remaining biomass at Day 0 (100%) was not included in the analysis of variance.

6.4.3.2 Mulch Application Rate Effect

The interaction effect between mulch application rate, time, and site on remaining biomass was marginally significant (*P* = 0.0869; Table 6-3). At site A, mulches of greater application rate (1.0 kg m^{-2}) decomposed slightly faster than mulches of lower application rate (0.5 kg m^{-2}), with significantly lower remaining biomass in 1.0 kg m^{-2} mulches than 0.5 kg m^{-2} mulches at Day 30, 60, and 250 (Figure 6-2). Inversely, at site B, mulches of lower application rate decomposed slightly faster than mulches of greater application rate, with significantly lower remaining biomass in 0.5 kg m^{-2} mulches than 1.0 kg m^{-2} mulches at Day 30, 45, and 60. There was no significant difference in remaining biomass between both application rates at Day 15, at both sites.

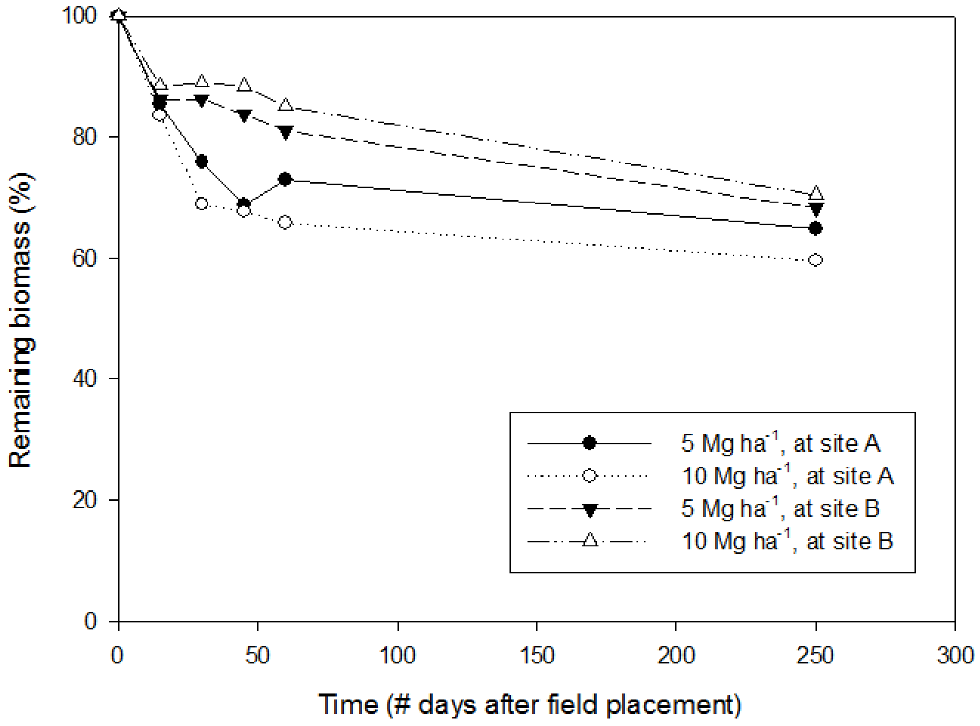

Figure 6-2. Mulch application rate x time x site interaction effect on remaining biomass (s.e. = 0.57%, *n* = 474). Remaining biomass at Day 0 (100%) was not included in the analysis of variance.

6.4.3.3 Time Effect

Fifteen days after field placement of litter bags, mulches in bags had already lost an average of 14% of their initial biomass. Mulches in litter bags lost on average 28% and 12% in the first 30 days of the study, at sites A and B, respectively. No significant loss of mulch biomass was observed between Day 15 and 60 for vetch, pea and barley, at site B. All other mulches significant decreased their biomass between Day 15 and 60, at both sites. There was a significant decrease in remaining biomass overwinter for most plant species. Mulch biomass decreased on average 11% and 17% overwinter, at sites A and B, respectively, varying among plant species and mulch application rate (Figures 6-1 and 6-2).

6.4.4 Decomposition Constant

Remaining biomass of each individual species and mulch application rate level was fitted to an exponential decay curve. Oilseed radish had the k of all plant species at both sites (Table 6-4). Barley had the lowest k at site B, but k of barley did not differ from those of pea and flax at site A. There was also a significant difference in k between mulch application rates. Decomposition constants were greater for mulches of 1.0 kg m^{-2} than 0.5 kg m^{-2} at site A, whereas the opposite was observed at site B (Table 6-4). Moreover, k at site A was 0.0039 day^{-1}, among all plant species and mulch application rate combined, significantly higher than that of site B (0.0019 day^{-1}).

Table 6-4. Model parameter for mulch decomposition of each plant species and mulch application rate, for each individual site.†

	Decomposition constant (k)	
	Site A	**Site B**
	---------------------day^{-1}---------------------	
Plant species		
Hairy vetch	0.0038 b	0.0016 c
Pea	0.0027 c	0.0015 c
Oilseed radish	0.0080 a	0.0029 a
Sunflower	0.0043 b	0.0022 b
Flax	0.0024 c	0.0017 c
Barley	0.0019 c	0.0013 d
P value	***	***
n	24	24
Application rate		
0.5 kg m^{-2}	0.0029 b	0.0020 a
1.0 kg m^{-2}	0.0039 a	0.0017 b
P value	*	*
n	8	8

* Significant at the 0.05 probability level.

*** Significant at the 0.001 probability level.

† Within column of same main effect, means followed by the same letter are not significantly different from each other according to LSD test at α = 0.05.

6.4.5 Mulch Quality as Affected by Plant Species, Mulch Application Rate, and Time, at Site A

6.4.5.1 Carbon Concentration and Content

The effect of plant species on C concentration and content varied over time (Table 6-5). Carbon concentration of mulch significantly decreased by 8-21% in the first 30 days of field placement, for all plant species (Table 6-6). There was no significant change in C concentration and content between Day 30 and Day 60 for all plant species other than pea and oilseed radish. The decrease in C concentration and carbon content overwinter (Day 250 – Day 60) was significant for all plant species (Table 6-6). Carbon content in the spring (Day 250) was the highest for flax, and the lowest for radish and hairy vetch.

Table 6-5. Summary of analysis of variance of plant species, mulch application rate, and time for mulch quality parameters, at site A.†

Source of variation	C concentration	C content	N concentration	N content	Lignin concentration	Lignin content	C:N	Lignin:N
	----------------------	----------------------	----------------------	----------*P* value----------	----------------------	----------------------	----------------------	----------------------
Plant Species (P)	***	***	***	***	***	***	***	***
Application Rate (R)	ns‡	***	*	ns	ns	***	ns	ns
Time (T)	***	***	***	***	***	ns	***	***
P x R	ns	**	ns	ns	ns	ns	ns	ns
P x T	***	**	***	ns	***	ns	***	**
R x T	ns	ns	**	ns	ns	ns	**	*
P x R x T	ns	ns	ns	ns	ns	ns	ns	ns
n	191	140	189	140	190	143	190	190

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Analysis of variance includes Day 0, 30, 60 and 250 for C concentration, N concentration, lignin concentration, C:N, and lignin:N. Analysis of variance includes Day 30, 60, and 250 for C and N contents. Transformed data (using exponent 4 and $\log_{10}$) were used to perform ANOVA on C concentration, N concentration, C:N ratio, and lignin:N ratio.

‡ ns, not significant at the 0.05 probability level.

Table 6-6. Plant species x time interaction effect on carbon concentration, carbon content, nitrogen concentration, lignin concentration, C:N, and lignin:N of mulch.†

	C concentration	**C content**	**N concentration**	**Lignin concentration**	**C:N**	**Lignin: N**
	% of dry matter	% of initial C content	---% of dry matter---			
Hairy vetch						
Day 0	53.2 bc	100.0	4.8 a	5.6 kl	11.2 i	1.2 m
Day 30	42.0 ijkl	56.5 ef	3.1 bc	10.6 hij	13.9 h	3.6 h
Day 60	42.4 jkl	50.6 fgh	2.9 bcd	11.3 ghi	15.1 gh	4.0 gh
Day 250	30.5 o	34.1 k	2.8 bcd	13.0 cdef	10.9 i	4.7 efg
Pea						
Day 0	53.9 b	100.0	2.9 bcd	6.5 k	19.4 ef	2.5 jk
Day 30	48.5 ef	68.3 abc	2.0 ghij	11.9 efghi	24.5 cd	6.0 cd
Day 60	42.9 ijk	56.0 def	2.1 ghi	11.4 fghi	21.5 de	5.8 cde
Day 250	32.9 no	42.1 ij	2.0 ij	12.3 defgh	17.1 fg	6.0 cd
Oilseed radish						
Day 0	51.3 d	100.0	3.2 b	5.0 kl	16.3 g	1.6 l
Day 30	44.3 hij	52.8 efg	2.0 hij	10.7 hij	22.5 cde	5.5 de
Day 60	40.3 klm	47.0 ghi	1.8 ijkl	10.2 ij	23.7 cd	5.7 cde
Day 250	33.7 no	32.0 k	2.3 fgh	13.0 cdef	15.0 gh	5.9 cd
Sunflower						
Day 0	50.4 de	100.0	2.7 cde	5.7 kl	19.2 ef	2.2 k
Day 30	46.3 fgh	62.9 cd	3.0 bc	12.8 cdefg	15.7 gh	4.3 fg
Day 60	43.9 hij	58.1 de	2.8 bcd	13.2 cde	17.4 fg	5.2 def
Day 250	35.7 mno	39.5 j	2.7 cde	17.0 a	14.0 h	7.0 c
Flax						
Day 0	56.4 a	100.0	2.5 def	9.6 j	22.6 cd	3.9 gh
Day 30	51.2 cd	68.9 ab	1.7 klm	13.4 cd	31.3 ab	8.2 b
Day 60	50.3 de	64.8 bc	1.6 lm	14.2 c	32.0 a	9.0 ab
Day 250	38.6 lmn	46.6 h	1.4 m	15.4 b	26.4 bc	10.6 a
Barley						
Day 0	53.1 bc	100.0	2.3 efg	3.5 m	23.0 cd	1.5 lm
Day 30	47.0 fg	73.7 a	1.8 ijk	5.1 l	25.7 c	2.8 ij
Day 60	45.7 ghi	68.7 abc	1.8 jkl	5.9 kl	26.1 c	3.4 hi
Day 250	31.1 o	41.6 ij	1.9 ijk	6.3 k	16.8 fg	3.4 hi

† Analysis of variance for C content does not include Day 0. Transformed data (using exponent 4 and $\log_{10}$) were used to perform ANOVA and means separation on C concentration, N concentration, C:N ratio, and lignin:N ratio, but back-transformed means are presented above. Within same column, means followed by the same letter are not significantly different from each other according to LSD test at $\alpha = 0.05$.

A plant species x mulch application rate interaction effect was significant for C content (Table 6-5). Carbon loss was 19, 13, and 20% greater in mulches of 1.0 kg m^{-2} than in mulches of 0.5 kg m^{-2} for pea, oilseed radish, and sunflower, respectively, but did not differ between mulch application rate for hairy vetch, flax, and barley (Table 6-7).

Table 6-7. Plant species x mulch application rate interaction effect on carbon content of mulch, at site A.†

	C content
	% of initial C content
Hairy vetch	
0.5 kg m^{-2}	47.7 c
10 kg m^{-2}	46.4 c
Pea	
0.5 kg m^{-2}	60.3 ab
10 kg m^{-2}	50.6 c
Oilseed radish	
0.5 kg m^{-2}	46.5 c
10 kg m^{-2}	41.3 d
Sunflower	
0.5 kg m^{-2}	58.4 b
10 kg m^{-2}	48.6 c
Flax	
0.5 kg m^{-2}	60.2 ab
10 kg m^{-2}	60.0 ab
Barley	
0.5 kg m^{-2}	63.0 a
10 kg m^{-2}	59.6 ab

† Carbon content at Day 0 (100%) was not included in the analysis of variance. Within same column, means followed by the same letter are not significantly different from each other according to LSD test at α = 0.05.

6.4.5.2 Nitrogen Concentration and Content

Nitrogen release varied according to plant species (Table 6-5). N was conserved the most in sunflower, whereas N lost was greatest in oilseed radish (Table 6-8). Mulch application rate had no effect on N content of the mulches (Table 6-8). Nitrogen concentrations were lower in mulches of 0.5 kg m^{-2} than in mulches of 1.0 kg m^{-2} at Day 30 and 60, but were similar at Day 0 and 250 (Table 6-9).

Table 6-8. Main effect of plant species, mulch application rate, and time on nitrogen and lignin content of mulch, at site A.†

Main effects	**N content**	**Lignin content**
	% of initial N content	% of initial lignin content
Plant species		
Hairy vetch	39.3 d	132.5 b
Pea	43.9 c	130.3 b
Oilseed radish	35.0 e	125.3 b
Sunflower	67.5 a	158.4 a
Flax	45.3 c	107.6 c
Barley	61.4 b	128.9 b
Application rate		
0.5 kg m^{-2}	49.6 a	138.7 a
10 kg m^{-2}	47.9 a	122.3 b
Time		
Day 0	100.0	100.0
Day 30	53.6 a	129.2 a
Day 60	48.4 b	129.3 a
Day 250	44.2 c	133.1 a

† Nitrogen and lignin contents at Day 0 (100%) were not included in the analysis of variance. Within column of same main treatment effect, means followed by the same letter are not significantly different from each other according to LSD test at α = 0.05.

Table 6-9. Mulch application rate x time interaction effect on nitrogen concentration, C:N and lignin:N of mulch, at site A.†

	N concentration	**C:N**	**Lignin:N**
	% of dry matter		
0.5 kg m^{-2}			
Day 0	3.2 a	18.0 de	2.1 e
Day 30	2.1 cd	23.4 ab	5.4 bc
Day 60	2.0 d	23.9 a	6.0 ab
Day 250	2.2 bcd	16.4 e	6.2 ab
1.0 kg m^{-2}			
Day 0	3.0 a	19.2 cd	2.2 e
Day 30	2.4 b	21.1 c	4.7 d
Day 60	2.2 bc	21.3 bc	5.0 cd
Day 250	2.2 bcd	17.0 e	6.3 a

† Log-transformed data were used to perform ANOVA and means separation on nitrogen concentration, C:N ratio, and lignin:N ratio, but back-transformed means are presented above. Within same column, means followed by the same letter are not significantly different from each other according to LSD test at α = 0.05.

Nitrogen content varied greatly over time (Table 6-5). Mulches released a large amount (46.4%) of their initial N content after only 30 days of field placement, for all plant species and mulch application rate combined (Table 6-8). Another 5.2% of initial N content was lost from mulches between Day 30 and Day 60 of the experiment. About half of initial N content was still present in the mulch on October 30th (Day 60). Significant N release also occurred over winter, but it represented only 4.2 % of initial N content of mulches. Forty-four percent of initial N content still remained in the mulches at Day 250 (Table 6-8), and may be available for the subsequent crops seeded in the spring or later in the crop rotation.

Changes in N concentration were less pronounced than those observed for N content. There was a significant decrease in N concentration from Day 0 to Day 30, representing a decrease of 21-37% of initial N concentration, for all plant species except for sunflower (Table 6-6). There were little to no change in N concentration between Day 30, 60, and 250 across plant species or mulch application rate levels (Tables 6-6 and 6-9). There was a significant change in N concentration of mulch over winter only for oilseed radish (Table 6-6). There was no significant change in N concentration over winter, for either level of mulch application rate (Table 6-9).

6.4.5.3 Lignin Concentration and Content

There was an overall increase in lignin concentration over time, although the effect varied over plant species (Table 6-5). Barley had the lowest lignin concentration at every litter bag retrieval date. Lignin concentration significantly increased between Day 0 and 30, for all plant species, representing a 40-125% increase from initial lignin concentration (Table 6-6). No change in lignin concentration occurred between Day 30 and 60, for all plant species. Lignin concentration increased overwinter for hairy vetch, oilseed radish, sunflower, flax, but did not vary for pea and barley (Table 6-6).

Lignin content was significantly affected by plant species and mulch application rate (Table 6-8). Lignin content of sunflower was the highest, whereas that of flax was the lowest. Mulches of 0.5 kg m^{-2} had higher lignin content than mulches of 1.0 kg m^{-2}. Lignin content did not vary over time between Day 30 and 250.

An increase in both lignin concentration and content was observed over time in the present study (Tables 6-6 and 6-8). Lignin content values between Day 30 and 250 were about 30% greater than initial lignin content value at Day 0.

6.4.5.4 Carbon:Nitrogen and Lignin:Nitrogen Ratios

A significant plant species x time interaction effect was found for C:N and lignin:N ratios (Table 6-5), indicating that the effect of plant species on C:N and lignin:N differed over time. The highest C:N ratio observed over the duration of the study was 32.0, for flax at Day 60, although not significantly different from C:N of flax at Day 30 (Table 6-6). The lowest C:N ratios were for hairy vetch at Day 0 and 250, with 11.2 and 10.9, respectively. Carbon to nitrogen ratios decreased overwinter for all plant species. Lignin:N rapidly increased during the first 30 days of the experiment for all plant species, and then stayed the same or increased over time after Day 30, depending on plant species (Table 6-6).

An interaction between mulch application rate and time was significant for C:N and lignin:N ratios (Table 6-5). Differences in ratios between mulch application rates occurred at Day 30 and 60 only. C:N and lignin:N ratios were greater in mulches of 0.5 kg m^{-2} than those of 1.0 kg m^{-2}, at Day 30 and 60 (Table 6-9). C:N ratios at the end of the study (Day 250) were similar to those at the initial field placement day (Day 0) for mulches of 0.5 kg m^{-2}, but significantly lower for mulches of 1.0 kg m^{-2} (Table 6-9). Moreover, lignin:N increased overwinter for mulches of 1.0 kg m^{-2}, but stayed constant for mulches of 0.5 kg m^{-2}.

6.5 Discussion

6.5.1 Effect of Plant Species on Remaining Biomass

Decomposition varied among the six plant species tested. Decomposition was fastest with oilseed radish and slowest with barley (Figure 6-1). Higher decomposition constants (k) for oilseed radish than barley also confirmed this observation (Table 6-4). Initial mulch quality did not explain the differences in decomposition between oilseed radish and barley. Both species had often similar chemical properties from at least one other plant species (Table 6-2). However, the mulch physical properties (e.g. three-dimensional architecture) visually greatly differed between the two plant species. The importance of mulch quality vs. plant architecture is discussed in a subsequent section.

In organic rotational no-till systems in Manitoba, slow decomposition is a desirable characteristic of cover crop mulches for extended weed control to the subsequent crop. At time of seeding a cash crop into the mulches the following spring (Day 250), 73% of barley biomass remained on the soil surface, compared with 55% for oilseed radish, averaged across both sites (Figure 6-1). Low biomass of oilseed radish mulch in the spring due to its fast decomposition would have the potential to reduce its ability for weed control. This observation was also made in another field experiment conducted in Carman, Manitoba, in which mulches with oilseed radish were found to provide reduced weed control due to its fast decomposition (MANUSCRIPT #1).

6.5.2 Effect of Mulch Application Rate on Remaining Biomass

The effect of mulch application rate on remaining biomass was not consistent and varied among sites. Mulches of greater application rate (1.0 kg m^{-2}) tended to decompose faster than mulches of smaller application rate (0.5 kg m^{-2}) at site A, whereas they tended to decompose slower at site B (Figure 6-2). There was also a significant difference in decomposition constant (k) between mulch application rates when a decay curve was fitted for each mulch application rate (Table 6-4), supporting the prior observation that the effect of mulch application rate on remaining biomass differed among sites.

It is still unclear why 1.0 kg m^{-2} mulches decomposed faster than 0.5 kg m^{-2} mulches at site A, but not at site B. One hypothesis is that the importance of the various processes involved in mulch decomposition on the soil surface varied among environmental conditions and therefore sites. No measure of photodegradation or soil microbial activity was taken over the course of the study, hence the reasons explaining the effect of mulch application rate on mulch decomposition presented below are only hypothetical.

The abiotic process of photodegradation may have played an important role in the decomposition of surface-applied mulches in this study, and at site B particularly. In arid grasslands with limited moisture availability and where decomposition by microorganisms is not favored, photodegradation may be the dominating process of decomposition (Parton et al., 2007). In the present study, fall (31 Aug. - 30 Oct.) was warmer in 2011 (site B) than in 2010 (site A), and more growing degree-days were accumulated in the fall at site B than at site A, presuming that sun radiation would have been greater in fall 2011 than 2010. Hence, photodegradation may have been more important in fall 2011 (at site B) than in fall 2010 (site A), favoring a faster decomposition for mulches of 0.5 kg m^{-2} than 1.0 kg m^{-2}. A greater proportion of total mulch was exposed to sun radiation in mulches of lower application rate compared with those of greater application rate. Therefore, UV-B radiation would be absorbed principally by the top layer of mulch, leaving the majority of mulch in high application rate mulches protected from UV-B degradation, reducing its degradation (Henry et al., 2008).

Another hypothesis explaining the fastest decomposition of mulches of greater application rate over those of smaller application rate as observed at site A is that mulches of great application rate dry up more slowly than mulches of lower application rate. Decomposition is strongly affected by soil moisture, and mulch moisture also enhances its decomposition (Manning et al., 2008). By conserving moisture better, mulches of great application rate would decompose faster than mulches of low application rate. Since mulch moisture was not measured in this experiment, it is difficult to extrapolate on the effect of soil moisture on the decomposition process. However, in the present study, fall precipitation was less than half at site B than at site A (72 and 163 mm, respectively). In conditions of low precipitation and limited moisture as observed at site B, it does not appear that mulches of higher application rate benefited from moisture conservation, since mulches of 1.0 kg m^{-2} did not decompose faster than mulches of 0.5 kg m^{-2} at site B.

Another hypothesis explaining the difference in mulch decomposition between mulch application rates is that microbial decomposition was favored in mulches of low application rate. The proportion of total mulch in direct contact with the soil surface and its microbial population is expected to be greater in mulches of lower application rate than of greater application rate, enhancing soil-driven decomposition processes in mulches of 0.5 kg m^{-2}. This is consistent with the findings at site B, where 0.5 kg m^{-2} mulches decomposed faster than 1.0 kg m^{-2} mulches, but not at site A. One reason for that could be the difference in environmental conditions at both sites. Air temperature and growing degree days in the fall were greater at site B than at site A. Therefore, mulch decomposition by microorganisms may have been greater at site B than site A, since microbial activity and mulch decomposition is positively correlated with soil temperature (e.g. Crohn and Valenzuela-Solano, 2003).

Finally, another factor affecting mulch decomposition is the movement of soil splashing on the mulch. In conditions of high precipitation, soil residues would splash on the mulch (C. Lowry, personal communication, 2013), and this may occur more prominently for mulches of low application rate. This would create an upward movement of N from the mineral soil onto the mulch, favoring decomposition in N-limited conditions. Again, this does not seem to have been the case here. There was more fall precipitation at site A than site B, which may have caused greater soil splash onto mulch of low application rate at site A. However, mulches of low application rate did not decompose faster than mulches of great application rate at site A; the opposite was observed. A reason why this possible N input of N from soil for thin mulches did not influence decomposition might have been because of mulch's high initial N concentration.

6.5.3 Effect of Mulch Application Rate on Mulch Quality

Very few studies have explored the effect of mulch application rate on mulch quality in ecosystems, and particularly in agricultural systems. The present study showed that mulch quality was affected by mulch application rate. Mulches of great application rate had greater N concentration, at Day 30 and 60, than mulches of low application rate (Table 6-9). One hypothesis explaining this observation may be the conservation of some N within the layers of mulches of great application rate. As N-rich water-soluble compounds leach from the top layer of the mulch (Berg and Laskowski, 2006), some of these leachates would be transferred to the lower layer of the mulch. In mulches of low application rate, this N would be transferred more quickly to the soil environment. This low N concentration in mulches of low application rate resulted in greater ratios of C:N and lignin:N in mulches of low application rate than in mulches of high application rate for those same dates (Day 30 and 60; Table 6-9).

6.5.4 Nitrogen Dynamics of Cover Crop Mulches

6.5.4.1 Nitrogen Release from Mulches

Mulch biomass losses in the first month after field placement (31 Aug.-30 Sept.) were high (12-28%, Figures 6-1 and 6-2). Teasdale and Mohler (2000) reported a similar loss for legume mulches of hairy vetch and crimson clover (*Trifolium incarnatum* L.), with a third of the mulch mass lost in the initial 30 days of their study. In the present study, this rapid mass loss translated into changes in mulch quality. Many changes in mulch quality occurred in the first 30 days after field placement of the litter bags, whereas changes in mulch chemistry between Day 30 and 60 were more subtle and varied widely among plant species.

There was a quick release of N in the first 30 days of the experiment. This N release was attributed to the leaching of water-soluble compounds from the mulch, described by Berg and Laskowski (2006) as the first phase of N dynamics in decomposing mulch. This rapid nutrient release is not caused by microbial decomposition, but rather by water movement (e.g. rainfall) and freezing-thawing cycles.

This fast decrease in N content and concentration in the first 30 days was paired with an increase in lignin concentration, for all plant species (Table 6-6). Early in the decomposition process, detritivores preferentially select for cellulose over lignin (Taylor et al., 1989). As cellulose undergoes decomposition, lignin occupies a greater portion of the plant material. Increase in lignin concentration and decrease in lignin content are commonly observed during decomposition of plant material (Berg and Laskowski, 2006).

However, an increase in both lignin concentration and content was observed over time in the present study (Tables 6-6 and 6-8). An increase in lignin content of plant material during decomposition in agricultural systems seems to have never been reported in the scientific literature. This increase in lignin content between Day 0 and 30 would imply that lignification occurred after their placement in the field, or that lignin was somehow gained or accumulated into the mulch. Therefore, it is plausible that lignin content data reported in this manuscript are erroneous. A few reasons attempting to explain why lignin content increased over time is presented in Appendix 2. Since it is not possible to identify the exact causes of the increase in lignin content over time, it would be wise to interpret lignin results and their respective discussion included in this manuscript with caution.

The lack of correlation between remaining biomass at Day 15 and the initial N concentration (Table 6-10) may indicate that N soluble compounds were leached in the same proportions for all species in the first 30 days, because of the overall high initial N concentration (2.3-4.8%) of most mulches. This is supported by the significant decrease of N content between in the first 30 days for all species (Table 6-8), and the lack of interaction between species and time for N content (Table 6-5), suggesting that all plant species leached N in same proportion.

This early N release was also reflected in the increase in C:N ratio between Day 0 and 30 for most mulches (Table 6-6), which indicated that more N than C was released from the mulch during that period. Drinkwater et al. (2000) also observed an increase in C:N ratio of vetch residues over the 5 mo of their litter bag decomposition study. In the present study, the effect of time on C:N ratio varied over species, with barley and sunflower being the only species that did not experience an increase in its C:N ratio between Day 0 and 30. This may be attributed to their low initial N concentration, compared with most other species tested (Table 6-2). Berg and Laskowski (2006) also observed that plant species and their physical properties affected the intensity of N leaching from the mulch.

Table 6-10. Pearson correlation coefficients (*r*) between remaining biomass and initial mulch characteristics.†

	Remaining biomass of mulch				
	Day 15	Day 30	Day 45	Day 60	Day 250
C concentration					
Day 0	**0.41** **	0.19 ns	**0.49** ***	0.19 ns	**0.42** **
Day 30	0.12 ns	-0.02 ns	0.28 ns	-0.01 ns	**0.33** *
Day 60	**0.29** *	0.10 ns	0.23 ns	-0.08 ns	**0.40** **
Day 250	0.09 ns	-0.28 ns	-0.10 ns	**-0.42** **	-0.20 ns
N concentration					
Day 0	-0.18 ns	-0.25 ns	-0.19 ns	-0.15 ns	**-0.29** *
Day 30	-0.25 ns	**-0.47** ***	**-0.30** *	-0.28 ns	**-0.38** **
Day 60	-0.14 ns	**-0.36** *	**-0.34** *	**-0.37** **	**-0.37** *
Day 250	-0.28 ns	**-0.36** *	**-0.51** ***	-0.28 ns	**-0.42** **
Lignin concentration					
Day 0	0.08 ns	-0.01 ns	0.17 ns	-0.01 ns	0.20 ns
Day 30	-0.20 ns	**-0.46** **	-0.20 ns	**-0.35** *	-0.21 ns
Day 60	-0.22 ns	**-0.38** **	-0.18 ns	**-0.31** *	-0.07 ns
Day 250	-0.22 ns	**-0.48** ***	**-0.34** *	**-0.45** **	**-0.42** **
C:N					
Day 0	**0.35** *	**0.37** **	**0.36** *	0.27ns	**0.45** **
Day 30	0.27 ns	**0.39** **	**0.43** **	0.26 ns	**0.47** ***
Day 60	0.23 ns	**0.34** *	**0.38** **	0.26 ns	**0.45** **
Day 250	**0.32** *	0.16 ns	**0.38** **	0.02 ns	0.26 ns
Lignin:N					
Day 0	0.20 ns	0.15 ns	0.27 ns	0.11 ns	**0.33** *
Day 30	0.03 ns	-0.01 ns	0.10 ns	-0.06 ns	0.11 ns
Day 60	-0.07 ns	-0.07 ns	0.09 ns	-0.02 ns	0.18 ns
Day 250	0.05 ns	-0.15 ns	0.10 ns	-0.17 ns	-0.02 ns

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† *n* = 48 for each date, except *n* = 47 for Day 250.

‡ ns, not significant at the 0.05 probability level.

This release of N from cover crop mulches between 31 Aug. and 30 Sept. occurred at a time that is not desirable in an organic rotational no-till system in Manitoba. Cash crops are grown in the mulches only the following spring, hence the nutrients released in the fall are subject to losses. Optimizing the timing of net mineralization of the mulches with crop nutrient uptake is an important step to make the organic rotational no-till system more sustainable. In a study conducted by Halde et al. (MANUSCRIPT #1) in Manitoba, most mulches tested started to decompose and release their nutrients in mid-summer, after rolling with a roller-crimper. However, mulches with hairy vetch were found to be resistant to the action of the roller-crimper in mid-summer, and continued to grow until freeze-up. Hence, mulches containing hairy vetch continued to take up nutrients until late-October, limiting the period for nutrient losses in the fall. Another option to limit N losses in mulches without hairy vetch would be to grow a winter annual cash crop or a catch crop in the fall to utilize the released N.

6.5.4.2 No Net Nitrogen Immobilization

Net N immobilization was not observed in any of the mulches. Nitrogen content of mulch did not increase above its initial N content over the duration of the study (Table 6-8), suggesting there has been no net N inflow in the mulch. Although we cannot discard the possibility that N immobilization may have occurred in between retrieval periods, it is most likely that decomposer organisms met their N requirement directly from the mulch without having to immobilize soil N. Mulches in the present study had high initial N concentrations (2.3-4.8%), as well as low initial C:N ratio (11.2-23.0). Parton et al. (2007) conducted a 10-yr decomposition study in 21 sites from seven biomes and concluded net N release started when mulch C:N ratio was less than 40 (with a range of 31 to 48). Mulder et al. (1969) established the C:N ratio limit for net N accumulation or release to be 25. In the present study, initial C:N ratios of mulches ranged between 11.2 and 23.0, thus N was not limiting for microbial growth and indirectly, mulch decomposition, for any of the plant species tested. This is supported by the absence of a N content increase in mulches during their decomposition (Table 6-8). N immobilization was not observed in the present study, for any of the six cover crop mulches tested. Moreover, C:N ratio of plant species tested varied over the course of the study, and C:N ratio of flax at Day 30 and Day 60 reached the highest level (> 30) of all species x time combinations during the study (Table 6-6). However, no net N accumulation was observed for flax or any other plant species at anytime of the study. This has important implications for soil fertility management and plant nutrition in cover crop-based organic rotational no-till systems.

Possible mechanisms for net N accumulation in mulch are translocation of soil N by fungal hyphae, atmospheric N deposition (Frey et al., 2000), N_2 fixation by microorganisms present in the mulch (Berg and Laskowski, 2006), addition of external plant material or insect/decomposer biota, capillary flow from the soil solution, or soil attached on the mulch. In a study by Frey et al. (2000), transfer of N from mineral soil to winter wheat (*Triticum aestivum* L.) straw residues on the soil surface occurred via fungal N translocation, and it was the cause of the net N immobilization by surface residues decomposing in the field. C:N ratio of winter wheat residues reported by Frey et al. (2000) ranged between 41 and 187, considerably higher than those of cover crop mulches tested in the present study. No microbial analysis to characterize fungal and bacterial populations of mulch or soil was conducted in the present study. Moreover, the present study did not assess the quantity of N deposited from the atmosphere and its role on decomposition. N deposition was estimated at 12.2 kg ha^{-1} yr^{-1} at Riding Mountain Park in Manitoba (Köchy and Wilson, 2001). Manning et al. (2008) found that mulch decomposition was 2% greater when large N deposition occurred, however there was no effect of plant species on its response to N deposition during decomposition using litter bags, suggesting that N deposition equally affects mulch decomposition of the various plant species tested.

6.5.5 Mulch Quality Parameters as Predictors of Decomposition

Remaining biomass was correlated with a few mulch quality characteristics, although most Pearson correlation coefficients (r) indicated only a weak to moderate relationship ($r < 0.5$) between both correlated variables (Table 6-10). Nitrogen concentration was a good indicator of mulch decomposition in the present study as N concentration was negatively correlated with remaining biomass. Carbon:N ratio was also a suitable index of substrate quality for cover crop mulch decomposition (Table 6-10). Taylor et al. (1989) also found N concentration to be the best predictor of mass loss rates, along with C:N ratio. In their study, N concentration of plant material ranged between 0.52 and 1.31%, and was considerably lower than the values in the present study (2.3-4.8%). In both studies, N concentration was a better predictor of decomposition than lignin:N ratio.

Initial lignin concentration (Day 0) was not correlated with remaining biomass. However, lignin concentration at Day 30, 60, and 250 were correlated with mulch biomass at their respective dates (Day 30, 60, and 250, respectively). This indicates that lignin concentration may not have played a predominant role in mulch decomposition in the first 15 days of the study, but became a relevant predictor of mulch decomposition later on. Taylor et al. (1989) also observed that as microbes metabolize chemical fractions other than lignin first, the proportion of lignin increases as decomposition occurs. They found that lignin concentration was a stronger predictor of mass loss during the 2-4 mo period than the 0-2 mo period. Results of the present study also followed this trend of a correlation between lignin concentration and biomass being significant only later in the decomposition period, along with an overall increase in lignin concentration over time (Table 6-6).

Lignin plays a dual role in plant decomposition. Lignin is a recalcitrant material resistant to microbial decomposition, but it is also susceptible to photodegradation. Lignin has been found to be an indicator of photodegradation, a process involved in the decomposition of surface-applied plant material (Austin and Ballaré, 2010). Lignin is the key light absorber in decomposing plant material and has a high capacity of autoxydation. When exposing samples to solar radiation, Austin and Ballaré (2010) found a significant positive linear relationship between mass loss and lignin concentration, suggesting that lignin increases photodegradation. In the present study, lignin concentration was negatively correlated with remaining biomass (Table 6-10), suggesting a positive influence of lignin concentration on mass loss. However, data also showed that lignin concentration increased over the duration of the experiment, suggesting that microbial degradation was a driver of mulch decomposition more important than photodegradation (Austin and Ballaré, 2010; Henry et al., 2008). Hence, it is unclear why lignin concentration was negatively correlated with remaining biomass of cover crop mulches in the present study. Most studies reporting on the effect of lignin concentration on mulch decomposition observed a positive correlation between these two variables (Cornwell et al., 2008; Taylor et al., 1989; Valenzuela-Solano and Crohn, 2006).

Both C concentration and lignin:N ratio were poorly correlated to remaining biomass, suggesting that these parameters had no impact on decomposition process of surface-applied cover crop mulches in the present study. Lignin:N ratio was also found to be a poor predictor of mass loss rate (Taylor et al., 1989).

Mulch quality may not be the only predictors of decomposition rates. The present data suggest that parameters other than mulch chemistry may influence decomposition of surface-applied cover crop mulches. Mulch architecture seems to play an important role in mulch decomposition. Physical description of mulch such as the mulch area index described by Teasdale and Mohler (2000) may be more useful than mulch quality to describe decomposition. In his thesis, Ruderfer (2003) even recommended a move away from mulch chemistry to explain mulch decomposition of surface-applied residues. He advocated that mulch structure plays a greater role than mulch chemistry, since microbial growth is dictated by habitat rather than nutrient supply in plant material decomposing on the soil surface. In the present study, the architecture of oilseed radish (Figure 6-3) may explain its high decomposition constant better than its chemical characteristics. Oilseed radish had an average N concentration, lignin concentration, and C:N ratio (Table 6-2). However, the hollow stem of oilseed radish offered a large surface area for microbial colonization, which explains its high decomposition rate.

Figure 6-3. Oilseed radish residue decomposing in a field in Carman, MB (© Caroline Halde 2012).

6.5.6 Hairy Vetch as a Key Cover Crop Species in Organic Rotational No-Till

In organic rotational no-till system in Manitoba, pure hairy vetch and hairy vetch/barley mixture have been identified as the most suitable cover crop mixture to create a mulch (MANUSCRIPT #1). This is partially due to their high N input to the system. In the present study, hairy vetch had the highest N concentration of all six cover crop species tested (Table 6-2). Hairy vetch's N concentration in the present study (4.8%) was similar to those reported for hairy vetch in the literature (Puget and Drinkwater, 2001; Drinkwater et al., 2000). Maul et al. (2011) also tested C and N concentration of 64 accessions of hairy vetch originating from more than 20 countries. They found a mean N concentration of 4.0% at spring green-up, with a difference of 2.5% between accessions with the lowest and highest accessions, and of 3.5% at 50% flowering. Moreover, other mulch characteristics of hairy vetch shoots in the present study (% lignin, C:N, lignin:N) are also similar to those reported by Puget and Drinkwater (2001). Hairy vetch's high N concentration combined to its resistance to the crimping action of the roller-crimper and its ability to accumulate biomass until late-fall when spring-seeded in Manitoba make hairy vetch a desirable species to be included in cover crop mulches. However, more research is needed to improve the synchrony between N release from N-rich mulches with hairy vetch and the N requirements of the subsequent crop seeded into mulches with hairy vetch.

6.6 Conclusions

This research shed some light on the effect of plant species and mulch application rate on the decomposition of cover crop mulches in a cool subhumid continental climate in Manitoba, Canada. Among the six plant species of cover crop mulches tested, barley decomposed the slowest and oilseed radish decomposed the fastest. The effect of mulch thickness on mulch biomass varied over time and among sites. Good predictors of cover crop mulch decomposition were N concentration and C:N ratio. The quick release of N from the cover crop mulches observed in the first 30 days of the experiment occurred at a time when no cash crop was growing into the mulches. Therefore, additional agronomic field research is needed to better synchronize the N release from cover crop mulches to the cash crop N requirement, and to reduce N loss to the environment.

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7.0 GENERAL DISCUSSION AND CONCLUSIONS

The four research projects in this thesis pioneered research on the organic rotational no-till system in Manitoba, Canada, and they met the overall objective of the Ph.D. thesis to adapt the organic rotational no-till system to the growing conditions of Manitoba, Canada. The research addressed the specific objectives of the thesis, which were:

1. To identify cover crops suited for an organic rotational no-system in Manitoba (manuscript #1);
2. To compare the agronomic performance of the organic rotational no-till system with systems where cover crops are terminated by tillage (manuscript #2);
3. To determine the agronomic performance of a continuous organic no-till system, and to compare it with those of tilled and conventionally managed systems, to identify the factors limiting the productivity of the organic no-till system (manuscript #3);
4. To study the decomposition and nutrient release from cover crop mulches in a production condition in Manitoba (manuscript #4).

This discussion section first synthesizes information acquired on this agroecosystem through the completion of the thesis, with the use of a schematic model. Future research needs are then addressed, followed by the implications of the research for farm managers and the importance of the Ph.D. work for the advancement of science.

7.1 The Schematic Model of the Organic Rotational No-Till System Adapted for Manitoban Growing Conditions

The schematic model presented below (Figure 7-1) represents the different phases of the organic rotational no-till system. The first year of the system is for the creation of the rolled cover crop mulches. Cover crops are established in the spring, following tillage. These cover crops are then terminated with a roller-crimper in mid-summer, for most cover crop species tested, or in the fall in the case of hairy vetch (*Vicia villosa* Roth). Rolled cover crop mulches undergo decomposition once the cover crops are terminated, and their decomposition is a continuous process that releases nutrients to the soil environment for many months. Cover crops affect weed dynamics throughout the 2 yr of the system. Cover crop mulches provide weed control in the fall, as well as the following year for the cash crop. In the spring of the 2nd yr, a cash crop [e.g.: spring wheat (*Triticum aestivum* L.), flax (*Linum usitatissimum* L.)] is no-till planted into the dead mulches. Soil nutrient content and plant nutrient uptake are affected by the decomposing mulch.

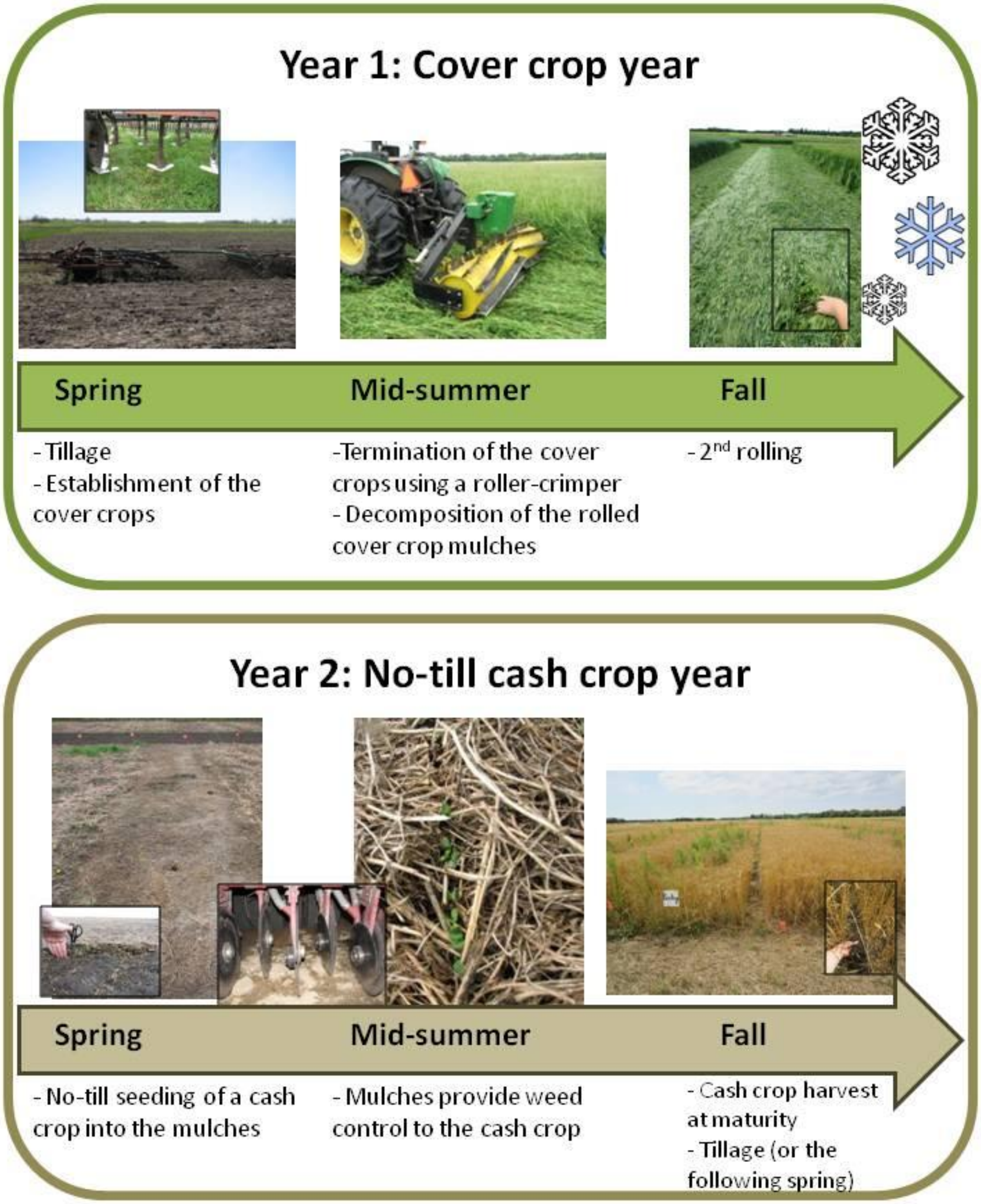

Figure 7-1. Model of the organic rotational no-till system adapted for the growing conditions of Manitoba, Canada.

7.2 Questions and Answers about the Organic Rotational No-Till System Adapted for Manitoba

Many research questions about the agronomics of the organic rotational no-till system in Manitoba were established while planning the experiments. These questions are grouped in four thematic sections: A) Mulch production; B) Mulch decomposition and nutrient supply; C) Weed control; D) Subsequent cash crop yield.

These themes of research questions are related to one or many phases illustrated on the schematic model, and findings related to those questions are summarized in the following section. Answers to questions are drawn from results of the four field experiments conducted for the completion of the Ph.D. program, with manuscript number indicated in parentheses in the text. The author of this thesis was actively involved in data collection in 2010, 2011, and 2012. However, results reported in this thesis summarize findings from field studies conducted between 2008 and 2012 in Carman, Manitoba, which represents data from a total of 19 site-years (with four, six, five, and four site-years in manuscripts #1, #2, #3, and #4, respectively).

The author is aware that mulches fulfill diverse additional functions in cropping systems other than those which have been explored though her research (e.g.: water conservation, pest control, etc.). A few research questions that have not been answered or only partially examined with this Ph.D. work are presented in the section on future research needs.

A) MULCH PRODUCTION:

Q: How much cover crop biomass is produced at the time of rolling the cover crops in mid-summer?

A: Cover crop biomass produced by the time of first rolling in mid-summer of the cover crop year varied among plant species and site-years, and ranged between 3.5 and 8.8 Mg ha^{-1}. In manuscript #1, cover crop biomass of various plant species at the time of first rolling ranged between 3.5 and 8.8 Mg ha^{-1} in 2010, and 4.2 and 5.4 Mg ha^{-1} in 2011. In manuscript #2, cover crop biomass of barley (*Hordeum vulgare* L.)-hairy vetch at the time of first rolling ranged between 3.9 and 6.1 Mg ha^{-1}. In manuscript #3, biomass of the barley/hairy vetch cover crop at the time of first rolling was 4.7 and 4.5 Mg ha^{-1} in 2008 and 2011, respectively.

Q: How much mulch biomass is produced by late-fall of the cover crop year?

A: Due to hairy vetch's extended growth period, mulches with vetch increased their biomass between mid-summer rolling and late-fall. In late-fall of the cover crop year, mulch biomass of cover crop treatments with vetch ranged between 5.3 and 10.8 Mg ha^{-1}. In manuscript #1, biomass of mulches with vetch increased by up to 158% between rolling and late-fall, reaching between 9.1 and 10.7 Mg ha^{-1} of biomass by late-fall. In manuscript #2, biomass of barley/hairy vetch mulch produced by late-fall of the cover crop year varied among sites and ranged between 7.9 and 10.8 Mg ha^{-1}, representing an increase in biomass of up to 112%. In manuscript #3, biomass of barley/hairy vetch averaged 7.6 and 5.3 Mg ha^{-1}, at the time of second rolling in 2008 and 2011. This extended growth of hairy vetch influenced weed dynamics and nutrient cycling by its extended nutrient uptake in the fall and its biological N fixation.

B) MULCH DECOMPOSITION AND NUTRIENT SUPPLY

Q: How much cover crop mulch biomass is present in the spring of the cash crop year?

A: At the time of seeding the cash crop into the mulch, the biomass of mulch present in the spring varied greatly with cover crop species and site-year. Mulch biomass present in spring at time of seeding the cash crop into the mulch ranged between 1.8 and 7.7 Mg ha^{-1}. The most mulch biomass in the spring was found in 2011 with a barley/vetch mixture (manuscript #2), whereas the least mulch biomass in the spring was found in 2011 with a pure pea (*Pisum sativum* L.) mulch (manuscript #1).

In manuscript #1, cover crop treatments with vetch (pure vetch and barley/vetch mixture) had the most mulch biomass in the springs of 2011 and 2012 (6.0-7.6 Mg ha^{-1}). Cover crop mulches without vetch had low mulch biomass in the spring (1.8-4.5 Mg ha^{-1}). In manuscript #2, there was 6.7, 7.7, and 4.2 Mg ha^{-1} of barley/vetch mulch at sites A (2010), B (2011), and C (2012), respectively. In manuscript #3, 4.5 Mg ha^{-1} of barley/vetch mulch was present in organic no-till in the spring of 2009, and 4.7 Mg ha^{-1} of barley/vetch mulch was present in the spring of 2012. Therefore, mulches with hairy vetch did not consistently have a large biomass (> 6 Mg ha^{-1}) in the spring.

Q: How much mulch is lost overwinter?

A: The biomass of mulch lost overwinter depended on cover crop species and site-specific weather conditions. There was a decrease in mulch biomass ranging between 19 and 59% between fall and spring for all mulches, in manuscript #1. In manuscript #2, barley/hairy vetch mulches lost 14 and 47% of their biomass overwinter at sites B and C, representing 1.3 and 3.7 Mg ha^{-1}, respectively (no data available for site A). In manuscript #3, barley/hairy vetch mulches lost 41% of their biomass over both the 2008-2009 and 2011-2012 winters, representing 3.1 and 3.3 Mg ha^{-1}, respectively. Mulches of pure pea had particularly fast decomposition after rolling and overwinter (manuscript #1).

Q: Was N released to the soil overwinter?

A: A fraction of the N contained in mulches was released from the mulches and transferred to the soil overwinter, providing N to the organic no-till cash crop. In manuscript #1, there was an increase in soil NO_3-N (0-90 cm) overwinter in treatments with vetch. In manuscript #3, there was a significant increase in soil nitrate-N over the 2011-2012 winter for all treatments, regardless of whether or not the barley/hairy vetch cover crop was mulched or tilled. However, soil NO_3-N in spring of the cash crop year was lower in organic no-till than in organic and conventional tilled systems (manuscript #3). This was also observed in manuscript #2, with an overall trend towards lower contents of soil nitrate-N in no-till than in two other organic tilled systems, although it did not influence total plant N uptake greatly (manuscript #2).

C) WEED CONTROL

Q: Which cover crop species are the most competitive with weeds, between the time of their establishment to their termination by rolling?

A: Hairy vetch was found to be poorly competitive with weeds at its early stage of establishment, compared with other cover crop species in pure stand (barley or pea) or 2-, 3-, or 4-species mixtures with barley, oilseed radish (*Raphanus sativus* L.), pea, and/or sunflower (*Helianthus annuus* L.). Hairy vetch established slowly in the spring (with < 3 Mg ha^{-1} of above-ground biomass by mid-July) compared with other cover crops, therefore poorly competing with weeds early in the cover crop year (manuscript #1). At the time of termination, weeds represented a higher proportion of the plant biomass in pure hairy vetch than in any other mulch (20% in 2010, and 56% in 2011) (manuscript #1). This slow establishment of hairy vetch in the spring was also observed in other field studies (manuscript #2 to 3).

Q: Which cover crop mulches provide the best weed control to the cash crop?

A: Cover crop mulches with vetch (pure vetch or barley/hairy vetch) provided the best weed control, compared with other cover crop species in pure stand or mixtures, such as oilseed radish, pea, sunflower, or barley (manuscript #1). This is likely due to a combination of factors. Firstly, hairy vetch's extended growth in the fall provided competition for weeds growing in the fall. With its vine-like growth habit, hairy vetch grew on top of other species to reach sunlight, monopolizing the canopy and shading other plant species. Moreover, cover crop treatments with vetch also produced a large mulch biomass in the cover crop year (through the fall), contributing to weed suppression in the cash crop year (manuscript #1-2-3). Hairy vetch mulch's intrinsic physical properties also played a role in its ability for weed control. Hairy vetch in mulches produced a dense mulch, with low light transmittance compared with other mulch species tested like oilseed radish (manuscript #4).

Q: Which weed species are difficult to control with cover crop mulches?

A: Overall, cover crop mulches with hairy vetch provided good control of summer annual weeds such as redroot pigweed (*Amaranthus retroflexus* L.), foxtail (*Setaria* spp.), and wild buckwheat (*Polygonum convolvulus* L.) (manuscript #1-2). However, cover crop mulches with vetch also showed poor suppression of other specific weed species. In a flax crop, a barley/hairy vetch mulch did not control a high density of wild oats (*Avena fatua* L.) (manuscript #2). Moreover, a shift from summer annual weeds to perennial weeds such as dandelion (*Taraxacum officinale* Weber) and Canada thistle [*Cirsium arvense* (L.) Scop.] was observed after many subsequent years of reduced soil disturbance (manuscript #3). Perennials were not effectively controlled by mulches, and reduced tillage regime of the system even favored their establishment and proliferation (manuscript #3).

4) SUBSEQUENT CASH CROP YIELD

Q: How do crop yields in the organic rotational no-till system compare to those of other management/tillage systems?

A: Organic spring wheat (manuscript #1, 3) and flax (manuscript #2, 3) have been spring-seeded into cover crop mulches as test crops to monitor the agronomic performance of organic no-till cash crops planted into mulches. Organic oat (*Avena sativa* L.) was seeded as a second no-till crop following a year of no-till flax production (manuscript #3).

Organic spring wheat no-till planted into mulches with vetch produced yields comparable to average yields produced in the region using conventional management in 2011 and 2012 (manuscript #1). However, organic spring wheat grown in mulches without vetch produced poor yields (< 2.2 Mg ha^{-1}; manuscript #1). Moreover, organic spring wheat grown in barley/hairy vetch mulch on the 5th yr of organic continuous no-till management produced yields lower than those in organic tilled, conventional tilled, or conventional no-till systems (manuscript #3).

The yield advantage of eliminating tillage for 1.5 to 2 yr on crop yield in organic flax production was not consistent among studies comparing yields from rotational no-till to tilled systems. In manuscript #2, flax seed yields were the greatest in organic rotational no-till, compared with two cropping systems with tillage, at two of three sites. However, at the third site (manuscript #2) and in another experiment (manuscript #3), organic rotational no-till flax seed yields were lower than those of organic tilled. The variation in success rate of organic rotational no-till flax production compared with that of spring wheat is attributed to flax's poor weed competitiveness.

Organic oats grown on the 3rd yr of organic rotational no-till management produced similar yields to oats grown in organic tilled, conventional tilled, and conventional no-till systems (manuscript #3).

Q: What are the reasons for a failure of the organic rotational no-till system in Manitoba?

A: Success of no-till crops grown in an organic rotational no-till system in Manitoba depended on cover crop species selection, mulch biomass production, weather, and weed species present.

Difficult environmental growing conditions in spring 2011 resulted in a poor establishment of the cover crop of barley and hairy vetch (manuscript #2 to 3). Consequently, low mulch biomass was produced that year, leading to inadequate weed control by the mulch the following year, and reduced no-till cash crop yields. Moreover, cover crop mulches without the presence of hairy vetch did not provide sufficient weed control to the no-till cash crops. As mentioned previously, some specific weed species were problematic to control using cover crop mulches. A high density of wild oats (manuscript #2) highly reduced the ability of cover crop mulches for weed control and negatively impacted organic no-till cash crop yields. The shift of the weed population to perennial weeds (manuscript #3) also caused failure of the organic rotational no-till system.

7.3 Future Research Needs

Resources and time are limited while conducting field experiments. Thus, many research questions remained unanswered after the completion of this Ph.D. research project. Future research needs that appeared relevant to the author of this thesis are identified below:

- To seed another summer annual cover crop into the mulch in mid-summer of the cover crop year. This may increase mulch biomass production while offering additional weed control in the fall.
- To investigate disease and insect management in organic rotational no-till systems under varying crop rotations in Manitoba. Do mulches help to propagate disease, or can they suppress disease?
- To develop a better understanding of the economic implications of the organic rotational no-till system for various cash crops in southern Manitoba, and to compare the economics of the organic rotational no-till system with those of organic tilled systems and conventional no-till/tilled systems.
- To breed summer annual cover crops for increased above-ground biomass production.
- To assess water use by the cover crop grown to produce the mulch, in years of drought particularly, since annual precipitation is low and soil water often limits crop production in the northern Great Plains of Canada.

7.4 Implications for Management

Practical advice for farmers wanting to adopt the organic rotational no-till system for field crop production in Manitoba is listed below:

- **Specific weed problems.** If weed pressure is significant in fields that will be converted to organic rotational no-till, it would be wiser to deal with the specific weed problem before attempting to switch to organic no-till field crop production, especially if the fields are infested with perennial weeds. Growing a perennial forage crop for a few years with frequent mowing or converting the field to a fallow year with frequent tillage are options to consider.

- **Selecting hairy vetch as your cover crop species.** Hairy vetch has a hard seed coat, which means that not all hairy vetch seeds seeded in the cover crop year will germinate that year. Some will germinate in the cash crop year and will become a weed. Hence, it is preferable to scarify the hairy vetch seeds before seeding. Moreover, hairy vetch varieties differ in their flowering habit. Field experiments have demonstrated that some spring-seeded hairy vetch varieties will flower in the cover crop year, some will not flower, and some are intermediate in their flowering response (K. Bamford, personal communication, 2013). Hence, attention should be drawn to variety selection of hairy vetch to avoid seed production of hairy vetch in the cover crop year.
- **The use of the roller-crimper.** Increasing the weight of the roller-crimper may enhance the crimping action of the blades and insure that the cover crops are effectively terminated. This can be done by adding weights on the roller-crimper or by filling the drum of the roller-crimper with sand/water/oil. However, adding too much weights on the roller-crimper may put too much pressure on the plant material, which may cut through the cover crop mulch and leave bare ground spots. Weeds may germinate and grow in these spots.
- **Evaluating the mulch biomass.** Measuring the mulch biomass in the fall of the cover crop year and/or the following spring is an efficient way to ensure that there is sufficient mulch biomass for effective weed control of the organic no-till crop.

- **Seeding equipment.** Seeding into high-biomass cover crop mulch cannot be done with just any type of seeder. In Carman, Manitoba, a few different cash crops (spring wheat, flax, sunflower) have been seeded into the mulches using a disk-drill seeder. Seeding occurs when the mulch is dry, to facilitate the cutting of the mulch by the disks, although there should be enough soil moisture for the seed to germinate. A video of the field technician seeding a field of organic flax into mulches using a disk-drill seeder can be found on the *Natural Systems Agriculture* website at: http://umanitoba.ca/outreach/naturalagriculture .
- **Going 100% organic no-till?** Adopting the organic rotational no-till system does not mean that no more tillage will ever be performed on that field. This system rotates between a cover crop establishment phase (established with tillage) and a period of cash crop production for 1 or 2 yr (no-till). It can eliminate the need for tillage for a period of 1.5 to 2 yr. However, tillage may still be needed if not enough mulch is produced, if perennial weeds or wild oats are present, if the weather is not favorable to organic rotational no-till, etc. Do not sell the tillage equipment just yet!

7.5 Importance of the Ph.D. Work for the Advancement of Science

Organic farming is not a panacea. Constant improvements of nutrient and pest management practices in organic agriculture will allow achieving improved sustainability, for our ecosystem and communities. Tillage reduction is an area in which improvements can and should be made. Indeed, tillage reduction has been identified as a research priority by the *Expert Committee on Organic Agriculture and Research and*

Innovation Working Group of the Organic Value Chain Round Table in 2011. My thesis aims to strengthen the basis for organic agriculture and more particularly for reduced-tillage systems in organic farming systems. Organic rotational no-till systems adapted for the northern Great Plains of Canada eliminate the need for tillage for a period of 1.5 to 2 yr in organic field crop production. As underlined in the thesis, periodic use of tillage is still needed in this system to avoid having a problematically high population of perennial weeds and to enhance cover crop mineralization. However, it is still a step towards improved sustainability of organic cropping systems.

The research work presented in this thesis tested a novel nonchemical weed management strategy that is also applicable to conventional farming systems. It provides a new weed control strategy for farmers that could be included in their integrated weed management toolbox. The roller-killed cover crop mulch also provides other externalities than weed control. On conventional and organic farms, a shift to a cover crop-based rotational no-till system could lead to greater use of cover crops in farming systems, providing many benefits for soil health. For example, the integration of cover crops to farming systems can contribute to soil health through biological nitrogen fixation from legumes in the mulches, and by conserving soil water under dry growing conditions. Cover crops are definitely a key component of organic rotational no-till systems.

In conclusion, the Ph.D. work presented in this thesis advanced science in the areas of organic agriculture, reduced-tillage systems, weed science, and cover crop agronomy. The research project aimed to reduce the impact of organic farming on the environment by reducing tillage and indirectly fossil fuel dependency. The organic rotational no-till system relies on ecological processes adapted to local conditions instead of the use of high-energy inputs. For example, nutrient cycling through the decomposition of rolled cover crops supplies nutrients to the crop for food and feed production. The absence of soil disturbance in the no-till phase of the system favors soil structure maintenance and provides a niche habitat for living organisms involved in food webs. Integrating cover crops in the crop rotation enhances the structural complexity of the system by adding new plant species in the rotation and by complexifying the biotic interactions between microorganisms, crops, and weeds. Mulches also affect many hydrological processes by intercepting precipitation, reducing soil water evaporation, limiting surface runoff, etc. In a changing climate, there is a need to design and implement these ecology-based innovative farming systems that combine scientific knowledge and technology with principles of ecology.

We need to embark on a transition process and develop sustainable, resilient agricultural systems that minimize the environmental footprint of agriculture on the environment. In a changing climate, maintaining the *status quo* is not an option. There is an urgent need to integrate the values of eco-responsibility and ecological accountability in farming practices, but also in research. It is time to embrace complexity, and focus on integrated, multidisciplinary research that puts sustainability at the core of its focus. Let’s facilitate on-farm innovation, interdepartmental and interinstitutional collaboration, and actively promote climate resilient sustainable agriculture. But most importantly, let’s develop agricultural systems in tune with local contexts and farmers’ needs.

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9.0 APPENDICES

9.1 Appendix 1

Table 9-1. Mean soil properties for each tillage system and season in spring and fall of 2010, and summary of analysis of variance.†

	NO_3-N					**pH**	**Organic matter**	**P**	**K**	**Zn**
	0-15 cm	**15-30 cm**	**30-60 cm**	**60-120 cm**	**Cumulative 0-120 cm**	**0-15 cm**	**0-15 cm**	**0-15 cm**	**0-15 cm**	**0-15 cm**
	------------------------------kg ha^{-1}------------------------------						%	----------------kg ha^{-1}----------------		
Tillage system (T)										
No-tillage	9 a	7 a	11 a	17 a	44 a	6.04 a	5.1 a	32 a	521 a	4.3 a
Conservation tillage	9 a	7 a	12 a	18 a	46 a	6.09 a	5.0 a	31 a	565 a	4.5 a
Season (S)										
Spring 2010	12 a	10 a	15 a	21 a	58 a	6.03 b	5.2 a	32 a	546 a	4.7 a
Fall 2010	6 b	4 b	7 b	14 b	32 b	6.10 a	4.9 b	30 b	540 a	4.1 b
Source of variation	--*P* value--									
T	ns‡	ns	ns	ns	ns	ns	ns	ns	ns	ns
S	***	**	**	*	**	*	*	*	ns	*
T x S	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Within column of a same response, means followed by the same letter are not significantly different from each other according to Least Square Difference test at $\alpha = 0.05$ ($n = 16$, for each response).

‡ NS, not significant at the 0.05 probability level.

9.2 Appendix 2

Reasons that could explain an increase in lignin content over time in decomposing plant material are listed below:

1) At site A, plant material from litter bags was not washed after their retrieval from the field, to remove soil from the litter before the analysis of litter chemical properties. It is possible that litter biomass was overestimated due to the presence of soil residues in the samples when litter was weighed, artificially increasing lignin content. However, these litter biomass values were also used to calculate N and C contents, and these latter values were within the range of values found in the scientific literature.

2) There may be an error in the analysis of lignin concentration. Litter samples were sent to Central Testing Labs for lignin concentration analysis. This lab had some trouble with the machine analyzing lignin in April 2011. Lignin concentration values for the plant material used in this experiment were of surprisingly high value, ranging between 4 and 61%. They have rerun the analysis on the samples, and fixed their machine. Moreover, initial lignin concentration data in the present study (3.5-9.6%) compares to those reported in the scientific literature. A study by Henry et al. (2008) reported lignin concentration of 2.9, 8.0, and 12.1% for forbs, grass leaves and grass stems, respectively. Moreover, lignin concentration increased over time, as expected.

3) There may have been a mathematical error in the calculation of lignin content using lignin concentration and litter dry biomass.

4) Compounds of microbial biomass that have a structure similar to that of lignin may have been included in the lignin fraction, leading to an overestimation of lignin content. For example, melanin is a compound produced by fungi living in harsh environments, such as those exposed to UV (Holmgren, 2008). Melanin has a structure that resembles that of lignin, since they are both the product of polymerization of phenolic compounds (Holmgren, 2008). Therefore, melanin may have been included in the lignin content values. However, it seems unlikely that the production of these compounds would increase lignin content by 30% in just 30 days.