REDUCED TILLAGE IMPLEMENTS FOR MANAGEMENT OF AN ORGANIC GREEN MANURE: EFFECTS ON NITROGEN, WEEDS AND WHEAT YIELD

BY

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ABSTRACT

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Reducing tillage in Canadian organic cropping systems is a priority to preserve soil quality and increase long term sustainability. Novel methods for management of cover crops offer farmers the opportunity to reduce both tillage and herbicide use during this phase of the crop rotation but require further investigation across a range of cropping systems. The objective of this study was to compare the blade roller, flail mower and wide blade cultivator (noble blade) with standard tillage for management of an annual pea-barley (*Pisum sativum L. – Hordeum vulgare L.)* green manure in the Canadian prairies. The experiment was conducted twice at Carman, Manitoba (long-term organic management) and Lethbridge, Alberta (previous herbicide and fertilizer use) from 2010-2012. The green manure was planted in spring of year 1 and grown until pea full bloom when five management treatments were applied; 1) standard tillage with a field disc 2) blade roller, 3) blade rolled once plus tillage in late fall and spring, 4) wide blade cultivator and 5) flail mower. Spring wheat (*Triticum aestivum* L.) was planted in spring of year 2. The effect of management treatment on surface residue, soil nitrogen, soil microclimate, weed population dynamics and subsequent spring wheat yield was evaluated. At Carman, managing green manure without tillage (blade roller or flail mower) significantly increased winter annual and perennial weed pressure and reduced soil nitrate availability; these factors contributed to wheat yield reductions in both years compared to standard tillage. Wide blade cultivation and blade rolling plus tillage maintained crop yield at one and both years, respectively, compared to tillage. Without sufficient mulch for weed suppression, soil disturbance was required to control weeds and ensure adequate nitrogen uptake in the crop. Replacing one tillage operation with blade rolling reduces energy costs and erosion risk without sacrificing yield. At Lethbridge, previous herbicide and fertilizer use masked the effect of green manure management. Markedly different results from Carman and Lethbridge emphasize that the adaptability of reduced tillage green manure management is site-specific due to differences in climate and cropping history. This research highlights

important differences in the efficacy, erosion risk, weed control, nitrogen availability, main crop yield and energy savings associated with each management method.

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1. INTRODUCTION

The contribution of organic agriculture to sustainable food production is increasingly being considered by the Canadian agri-food sector. According to the Canadian General Standards Board (2006), organic production is defined as "… a holistic system designed to optimize the productivity and fitness of diverse communities within the agro-ecosystem, including soil organisms, plants, livestock and people," with the overriding goal "to develop enterprises that are sustainable and harmonious with the environment". Empirical evidence from North American studies strongly suggest that environmental indicators such as soil biological properties, plant and wildlife biodiversity, energy use, nutrient loading and climate change, can benefit from the unique characteristics of organic production systems (Lynch 2009). Characteristics of organic crop production systems include green manuring, composting, crop-livestock integration and integrated pest management. Despite other environmental benefits, organic systems are criticized for their continued reliance on tillage for incorporation of green manures and weed control (Lynch 2009). The risk of soil erosion and degradation associated with increased tillage practices on Canadian organic farms compared to conventional farms (Nelson et al. 2010) is an important concern for the long-term sustainability of organic production systems.

The detrimental effects of tillage have been well documented: disruption of soil aggregates and structure, increased erosion and loss of nutrient rich topsoil, reduced biological communities and decreased fertility from loss of soil organic matter (Triplett and Dick 2008). In conventional systems, the wide adoption of conservation tillage has been widely dependent on modern herbicides, which are prohibited in organic farming. Therefore, without viable alternatives tillage remains an important management tool for organic farmers to control weeds and manage green manure crops.

The suitability of conservation tillage for organic agriculture is increasingly being explored by researchers in Europe and North America (Carr et al. 2011b). While benefits such as reduced erosion, increased microbial activity, greater macroporosity and less nutrient leaching may be achieved (Peigne et al. 2007), there exist important obstacles such as weed control and nutrient availability (Mirsky et al. 2012), which are evidently more difficult to overcome in organic systems. The opportunity to reduce tillage in organic cropping systems may be realized with innovative approaches to management of green manure cover crops (Peigne et al. 2007; Lynch 2009). New and existing technologies, including the blade roller, flail mower and wide blade cultivator, has been shown to effectively kill various cover crop species (Creamer and Dabney 2002) and can be used to terminate green manure cover crops as an alternative to tillage. Recent studies have compared the use of these implements individually to standard tillage practices for management of green manure crops in organic cropping systems (Drinkwater et al. 2000; Vaisman et al. 2011; Smith et al. 2011; Shirtliffe and Johnson 2012; Teasdale et al. 2012; Wortman et al. 2012). However, the majority of these studies are from the mid-Atlantic region of the United States and further investigation is warranted on the Canadian prairies. A direct comparison of these implements and quantification of their effect on soil and weed dynamics in an organic cropping system has also not been conducted.

The objective of this study was to compare the blade roller, flail mower and wide blade cultivator (noble blade) with standard tillage for management of an annual pea-barley green manure cover crop and determine the impact of each implement on:

1) Nitrogen dynamics
2) Weed density
3) Soil microclimate
4) Subsequent crop yield

The agronomic questions driving this research are as follows;

i. How will varying degrees of soil disturbance associated with different tools for green manure termination affect soil nitrogen availability and subsequent crop N uptake?
ii. Will green manure management method affect the species and density of weeds present in spring wheat?
iii. Will increased surface residue following zero till management result in moisture conservation benefits?
iv. Can we successfully reduce tillage associated with green manure management without comprising yield compared to the standard practice of tillage?

2. LITERATURE REVIEW

2.1 Organic Agriculture

Organic production is defined by the Canadian General Standards Board (CGSB) as "a holistic system designed to optimize the productivity and fitness of diverse communities within the agro-ecosystem, including soil organisms, plants, livestock and people" (CGSB 2006). The principles that organic production is based on include but are not limited to: minimize soil degradation and erosion, maintain long-term soil fertility, rely on renewable resources and maintain biological diversity (CGSB 2006). Organic agricultural practices are regulated by certifying bodies that ensure management practices carried out by organic producers comply with Canadian and international standards. As part of the organic standard, there is a list of prohibited substances, which includes synthetic pesticides and fertilizers.

The number of certified organic farms in Canada increased steadily from 1992-2004 and comprised 1.7% of all farms in Canada in 2006 (Macey 2010). While the number of organic farms has remained approximately steady since 2004, the number of acres farmed organically in Canada has increased from 2004 to 2009, stabilizing at approximately 695,000 ha (Macey 2010).

2.2 Tillage

Soil disturbance has been synonymous with food production around the world since the beginning of settled agriculture. Soil tillage is defined by Reicosky and Allmaras (2003) as the mechanical manipulation of soil and plant residue to prepare a seedbed where crop seeds are planted to produce grain for human and animal consumption. In Canada and the U.S., the moldboard plow was an essential tool for the early pioneers in settling the prairies. This intensive form of soil tillage improved soil fertility and agronomic productivity in the short term but led to a rapid decline in soil quality due to water, wind and tillage erosion (Lal et al. 2007), as remembered most clearly by the erosion events of the 1930s.

There has been a wide body of literature published outlining the negative effects of tillage on the physical, chemical and biological properties of soil. These include erosion and loss of topsoil, degraded soil structure, reduced microbial communities, compaction, loss of soil organic matter, and release of CO_2. The impact of soil degradation on primary production as a result of intensive tillage has been somewhat masked by the introduction of hybrid and genetically modified crops, increased use of fertilizers and development of synthetic pesticides during the Green Revolution, which have dramatically increased crop productivity (Triplett and Dick 2008). However in a recent publication describing the laws of sustainable soil management, Lal (2009) warns that as the world's population reaches an expected 10 billion by 2100, the problems of soil degradation are exacerbated by the increasing demand on finite soil resources for the food, feed, fiber and fuel needs of the world.

2.2.1 Conservation tillage

Conservation tillage encompasses a range of tillage practices, mostly non-inversion, which aim to preserve soil moisture and reduce soil erosion by leaving at least 30% of the soil surface covered by crop residues (Peigne et al. 2007). Benefits of conservation tillage include water conservation, erosion protection, increased biological activity, preserved soil organic matter, better aggregate stability and porosity, and reduced fuel, labour and energy costs. There can be several terms used that refer to methods of conservation tillage: no-till, reduced till, strip till and mulch till. Conservation tillage methods are distinctly different from rotational till and conventional tillage practices. Defined by Reicosky and Allmaras (2003), in no-till systems the soil is left undisturbed from harvest to planting, whereas reduced till systems are intermediate between conventional and no-till, leaving 15-30% residue cover. Rotational tillage refers to a system that would use tillage one year followed by a year of no till.

Although considered an ancient practice by indigenous cultures, the development and wide adoption of conservation tillage throughout the world has only occurred in the past 100 years (Triplett and Dick 2008). In North America, the earliest attempts were recorded in the 1940s but without the proper tools and techniques, conservation tillage was never widely adopted. In later years, the introduction of broad-spectrum herbicides and synthetic fertilizers greatly aided the transition. Today approximately 23% of total cropland in the US (Conservation Technology Information Center 2008) and over 45% in Canada (Statistics Canada 2006) are managed with no-till practices.

Three important factors in no tillage crop production systems are weed control, crop nutrition and equipment suitability (Triplett and Dick 2008). Herbicides are widely relied on for weed control, placement of synthetic fertilizer near the seedbed below the soil surface is critical for crop availability and uptake, and the use of specialized planting equipment to cut through surface residue for seed placement is utilized. Conservation tillage systems promote long-term sustainable agriculture but will continue to present new challenges to farmers and researchers as problems such as herbicide resistance arise in current systems and adjustments are made to fit new cropping systems.

2.2.2 Tillage and organic agriculture

Tillage and cropping system are interdependent; the type of tillage depends on the cropping system, which in turn depends on the climate and soil variables unique to a given geographic region (Reicosky and Allmaras 2003). Organic cropping systems restrict the use of pesticides and synthetic fertilizer – without these, tillage has been and continues to be an important tool for weed control and nutrient management on organic farms. Post-harvest, pre-plant and in-crop tillage passes are utilized to kill weeds and reduce crop-weed competition. Soil disturbance is also important for incorporating manure, compost, cover crops and other amendments to supply nutrients. Increasing environmental concerns and efforts to preserve soil quality are leading policy makers and researchers to examine the potential of conservation tillage in organic systems. In a comprehensive review, Peigne et al. (2007) concludes that weed control, topsoil compaction and limited nitrogen availability are major limitations for organic farms in western Europe to achieve conservation tillage. In this same review, Peigne et al. (2007)

mention that mechanical methods for control of cover crops used in North and South America appear promising.

Different strategies have been considered for adapting conservation tillage practices to organic farming systems in North America (Carr et al. 2011b). Of these strategies, mechanical termination of cover crops appears most promising. These techniques include mowing, undercutting, and rolling, and have been the focus of numerous studies aimed at no till cover crop termination in North America (Drinkwater et al. 2000; Creamer and Dabney 2002; Blackshaw et al. 2010; Wortman et al. 2012; Shirtliffe and Johnson 2012). The ability of these methods to successfully manage the cover crop, maintain a surface mulch to suppress weeds as well as provide nutrients to subsequent crops will determine its suitability to replace tillage in different cropping systems.

2.3 Green Manure Cover Crops

Cover crop is a general term used to encompass a wide range of plants that are grown for various ecological benefits other than as a cash crop (Teasdale et al. 2007). Cover crops have many contributions to the agro-ecosystem such as erosion control, reduced runoff, improved infiltration, soil moisture retention, improved soil tilth, nutrient enhancement, and weed control (Teasdale 1996). A green manure cover crop is used primarily as a soil amendment and a nutrient source for subsequent crops, but also provides other services (Cherr et al. 2006). Legume green manures gained wide spread attention during the 1990’s as a more sustainable option to fallow in wheat-fallow systems that predominated across the Northern Great Plains. Early literature assessed the suitability of various legume species in terms of nitrogen (N) contribution, water use and subsequent crop yield (Townley-Smith et al. 1993). In a recent survey of organic and conventional farm practices in Canada, green manure cover crops are utilized by 84% of organic farmers compared to 6% of conventional farmers (Nelson et al. 2010).

2.3.1 Types of green manure cover crops

In a critical review on the worldwide use of green manure crops, Cherr et al. (2006) point out that the options for using green manure can be complex, depending on factors such as life cycle (of both the green manure and subsequent economic crop), production environment (climate, weather, soil and pests), and management options (i.e. type, patterns, and timing of tillage). Organic farmers in particular rely on green manures to provide nutrients to subsequent crops (especially N).

Sweet clover (*Meliotus alba*), a biennial legume is the most popular green manure crop used on organic farms in Saskatchewan followed by alfalfa (*Medicago sativa*) and peas (Knight and Shirtliffe 2003). Despite high biomass production and nitrogen contribution, sweet clover has been shown to deplete soil water (Blackshaw et al. 2010**)**, thereby potentially decreasing subsequent crop yields in the semi-arid northern Great Plains. An important aspect of green manure use in these regions is to balance water use and N_2 fixation by the green manure with the water and N requirements of the subsequent crop (Pikul et al. 1997). Thus, annual legume crops are a viable alternative.

Field pea (*Pisum sativum*) is an annual cool-season legume crop that is well suited to the Central and Northern Great Plains. Benefits of field pea include water efficiency, high N fixation and high biomass production (Clark 2007). Field pea dry matter production in monoculture can be highly variable depending on precipitation, ranging from 3000-9000 kg/ha at Saskatoon (Townley-Smith et al. 1993) and when grown in an intercrop with another cereal such as oats (*Avena sativa*), has been shown to produce an average of 5400 kg/ha at Carman, MB **(**Natural Systems Agriculture 2011**).** Nitrogen yield of field peas in monoculture can range depending on total biomass yield and biomass quality but has been reported at 50, 68, 70 and 166 kg N ha^{-1} at Oxbow, SK (Vaisman et al. 2011), Big Sky, MT (Miller et al. 2011), Swift Current, SK (Biederbeck et al. 1995**),** and Saskatoon, SK, respectively (Townley-Smith et al. 1993). The average nitrogen yield of a field pea/oat intercrop green manure is 132 kg N ha^{-1} at Carman, MB **(**Natural Systems Agriculture 2011**).** Field peas are often grown with a small cereal grain for vertical support, to increase weed suppression, to increase forage quality and to slow down residue decomposition by increasing the C:N ratio of the intercrop residue as compared to field pea residue alone (Clark 2007). Common companion species include oat and barley (*Hordeum vulgare*). Both of these species are cool season annuals that suppress weeds, prevent erosion, scavenge excess nutrients and add biomass.

2.3.2 Management of Green Manure Cover Crops

The way in which green manure crops are managed affects important agronomic parameters including soil nitrogen dynamics, weed dynamics, soil water content and subsequent crop yield (Blackshaw et al. 2010; Miller et al. 2011; Vaisman et al. 2011; Wortman et al. 2012). Management techniques can differ in implement type, timing of termination, intensity and frequency.

On organic farms in western Canada, green manure crops have historically been managed with tillage. Tillage implements used to terminate these crops include disks, plows and cultivators. However, there is increasing interest for organic farmers to adopt conservation tillage practices (Peigne et al. 2007; Carr et al. 2011b) to improve soil quality and long term sustainability. Innovative approaches for the application of conservation tillage to organic farming include mechanical control of green manure crops. When switching to conservation tillage practices, the supply of nitrogen can be affected (Peigne et al. 2007). For example, decreasing tillage intensity (Blackshaw et al. 2010) and frequency (Vaisman et al. 2011) with green manure termination decreases soil inorganic nitrogen. Another important challenge associated with no-tillage termination of green manure cover crops is weed suppression (Carr et al. 2011b). Implements that offer alternatives to tillage for managing green manure cover crops include the blade roller, flail mower and wide blade cultivator.

2.3.2.1 Blade Roller

The method of blade rolling, also called roller crimping to terminate cover crops mechanically was developed by no-till farmers in Brazil (Derpsche et al. 1991 as cited in Kornecki et al. 2009). It has recently become popularized in the United States and now Canada due to further enhancement by the Rodale Institute (Sayre 2003) and most recently, the National Soil Dynamics Laboratory (Kornecki et al. 2009). The blade roller consists of a hollow steel drum (filled with water for additional weight) with blades attached lengthwise along the drum (Figure 1). The implement works by crushing the vascular tissue of the cover crop without completely killing the stems (Mischler et al. 2010) and ideally lays the killed cover crop down intact, flat on the soil surface (Creamer and Dabney 2002). This method creates a more persistent surface mulch with longer weed suppression potential and delayed decomposition, as compared to mowing. The blade roller has been used extensively in cover crop-based, organic rotational no-till grain systems of the mid-Atlantic region of the United States (Mirsky et al. 2012). In particular the blade roller is commonly used to terminate rye (*Secale cereale*) and hairy vetch (*Vicia villosa*) cover crops prior to soybean and corn production, respectively. In both cases, multiple studies have investigated weed management and soil fertility dynamics, two important aspects limiting adoption of organic no-till (Drinkwater et al. 2000; Smith et al. 2011; Teasdale et al. 2012).

In western Canada, the use of the blade roller has been studied recently by Vaisman et al. (2011) and Shirtliffe and Johnson (2012). At Carman, MB and Oxbow, SK, Vaisman et al. (2011) used the blade roller and tillage to terminate an annual pea green manure crop that was grown in the year prior to spring wheat production. At two of three site-years, total nitrogen supply (soil inorganic N + plant N) in the green manure-wheat system was reduced in the no-till (blade rolled) system compared to the tilled system by an average of 44%. Similarly, at two of the three site-years, spring wheat grain yield was reduced by an average of 30% in the no-till (blade rolled) system compared to the tillage only system. Total weed density was significantly greater in the tilled only system compared to the no-till system at only one of the three site-years, with small seeded spring annuals being the predominant weed species. At Saskatoon, SK, Shirtliffe and Johnson (2012) compared rolling, mowing and tillage for terminating two green manure crops (pea and faba bean) at various stages. All methods were effective in terminating the pea and faba bean crops with little re-growth. Additionally, spring wheat yield the following year was unaffected by termination method when pea was the previous green manure crop. However it should be noted that all treatments in this experiment were tilled prior to spring wheat planting thus tillage was not completely removed in this system.

2.3.2.2 Flail Mower

Mowing has been one of the most common methods used by growers for mechanical termination of green manure crops and has been the chief alternative to herbicides in no-till agriculture (Creamer et al. 1995; Creamer and Dabney 2002). This method chops the cover crop into many small pieces which decompose rapidly because they are in close contact with soil and soil microorganisms (Creamer et al. 1995). This may result in faster mineralization and release of plant available nitrogen. Also, mowing reduces the cover crop's bulk in comparison to leaving the material intact which may reduce weed suppression.

Various types of mowers have been assessed for their suitability in managing cover crops. In the current study, a flail mower was used; this implement is preferred over rotary-type mowers because it leaves the cover crop residues more uniformly distributed on the soil surface (Creamer and Dabney 2002). A sickle bar mower is also less suitable, especially in viney crops such as hairy vetch, due to tangling in the blades (Creamer et al. 1995).

Mowing has been used successfully to terminate sweet clover (Blackshaw et al. 2010), hairy vetch (Drinkwater et al. 2000) and pea-barley (Sullivan 2012) green manure crops. In Lethbridge, AB, mowing sweet clover led to fewer weeds and similar soil N at planting as compared to disked sweet clover, but decreased yield in one out of two site-years (Blackshaw et al. 2010). In Pennsylvania, decreasing tillage intensity from hairy vetch planting to corn harvest consistently decreased soil N availability, increased weed biomass and decreased corn yield (Drinkwater et al. 2000). Evidently, the success of reduced tillage management of green manure cover crops is cropping system specific.

2.3.3.3 Wide Blade Cultivation (Noble Blade)

Undercutting has been demonstrated to be a successful method of terminating green manure crops by severing the cover crop's roots and flattening the intact aboveground biomass on the soil surface (Creamer et al. 1995). The wide blade cultivator (also known as the Noble blade) was used in this experiment as a means of undercutting (Figure 1). History of the wide blade cultivator dates back to Germany 1918 where it was documented by Krafft (1918). It was later adapted by Alberta farmer Charles Noble in the 1930's in response to severe soil erosion associated with fallow and tillage practices that buried trash (Stewart et al. 2010). The 2 m wide V-blade used in this experiment penetrates below the soil surface, severing plant roots while leaving above ground residue intact (Figure 1). Although this method involves minimal soil disturbance, it is reported to leave 90% of crop residue intact after one pass (Manitoba Agriculture, Food and Rural Initiatives) and is still considered an acceptable technique for no-till agriculture, which is generally defined as planting crops in unprepared soil with at least 30% mulch cover (Triplett and Dick 2008).

Successful operation of this implement depends on proper soil conditions, especially soil moisture (Creamer and Dabney 2002). Soil penetration problems may be exacerbated by attempting to terminate a green manure crop, seeing as the implement was originally designed for fallow conditions, and green manure plant roots decrease soil moisture and increase resistance. Recent work at the University of Nebraska by Wortman et al. (2012) successfully used a sweep plow undercutter, designed by Creamer et al. (1995), to terminate various cover crop mixtures with biomass ranging from 3670-4090 kg ha^{-1}. Results from their study showed that cover crop termination with a sweep plow undercutter one week prior to main crop planting increased weed suppression, soil nitrogen availability and soil moisture and contributed to increased grain yield compared to termination with a field disk.

Figure 1. Implements used for management of the green manure crops at Carman (L-R): disc, wide blade cultivator (Noble blade), blade roller.

2.4 Reduced Tillage Management of Green Manures

Green manure management methods have direct and indirect effects on the physical, chemical and biological soil-plant environment. The overall objective of a green manure crop is to provide nutrients to subsequent crops. Aside from soil quality benefits, we hope that reduced tillage management of these green manures will provide mulch-based weed suppression while maintaining adequate nitrogen supply. The following section will discuss the relationship between green manure management methods and various soil and agronomic parameters and the potential to meet these goals.

2.4.1 Soil Microclimate

Crop residue and tillage practices have been shown to affect both soil temperature and soil moisture. Soil temperature is determined by the ratio of energy absorbed to that being lost (Brady and Weil 2008). Crop residue on the soil surface intercepts solar radiation therefore modifying soil temperature. Both straw residue (Gauer et al. 1982) and green manure residue (Teasdale and Mohler 1993) has been shown to reduce maximum soil temperature but had little impact on minimum soil temperature. Gauer et al. (1982) determined that the impact on soil temperature in zero till fields was due to the presence or absence of straw cover, and Teasdale and Mohler (1993) found that increased residue levels can enhance the effect. In the absence of crop residue, zero till soil had higher soil temperatures than conventional tillage, which may be attributed to greater bulk density and improved heat flow (Gauer et al. 1982). Lower soil temperatures in zero till fields with crop residue may effect crop establishment (Gauer et al. 1982; Borstlap and Entz 1994) or weed germination (Teasdale and Mohler 1993).

Soil temperature and soil moisture are closely related. The specific heat of water is greater than that of soil (Brady and Weil 2008), therefore wet soils take longer to warm up. Practices that promote surface residue retention also tend to promote moisture conservation. Residue cover in mulch systems reduces evaporative losses from the soil surface and facilitates greater snow-trap (Van Doren and Allmaras 1978). A study in Southern Manitoba found that herbicide terminated alfalfa consistently increased soil water content compared to tillage (Bullied and Entz 1999). Similarly in Lethbridge, AB, mowed sweet clover increased soil water content from 0-15 cm compared to plowed sweet clover by 15-31% during a dry period, but moisture conservation benefits were not consistently observed throughout the experiment (Blackshaw et al. 2010). In that same experiment, sweet clover green manure sometimes decreased soil water content compared to fallow but was always similar to, or higher than continuous cropping. The moisture conserving benefits of mulch are most evident during dry periods and under high mulch levels, as demonstrated by Teasdale and Mohler (1993) under hairy vetch and rye residue. Moisture benefits in zero tilled fields under continuous cropping in Manitoba are less consistent. For example, Gauer et al. (1982) consistently found more spring soil moisture under zero till but Borstlap and Entz (1994) did not. This could be due to less crop residue under continuous cropping as compared to green manure systems, although residue levels were not reported in the latter two studies.

2.4.2 Residue Decomposition and Nutrient Release

Broadly speaking, the decomposition of crop residue and associated carbon and nitrogen mineralization is dependent on three major interactive factors: (1) biochemical composition of the residue, (2) residue placement and (3) soil environmental factors. Decomposition refers to the chemical breakdown of a compound, often accomplished by microorganisms (Brady and Weil 2008). As a result of this process, mineralization and immobilization occur simultaneously, releasing and tying up nutrients, respectively. The balance of mineralization-immobilization turnover determines nitrogen supply from organic residues.

Coppens et al. (2007) describe the biochemical composition of residue as the availability of nitrogen and amount of soluble compounds and lignin. The availability of nitrogen is often described by the carbon:nitrogen (C:N) ratio and is commonly used as a main indicator of residue decomposition. However, it does not indicate the amount of nitrogen available to microorganisms and has not always correlated well with decomposition rates (Kumar and Goh 2003). Concentrations of lignin, polyphenols and their concentration relative to nitrogen are also important parameters for predicting decomposition (Kumar and Goh 2003; Coppens et al. 2007). In general, high total N, low C:N ratio and low lignin and polyphenol concentrations are favorable for rapid decomposition and mineralization. Green manure crops are typically terminated before maturity in an effort to maximize total N content in biomass and minimize the C:N ratio, which generally increases as plants mature. Legume green manure residues generally have a low C:N ratio and high N content and are expected to result in net mineralization although there may be an initial period of immobilization during early decomposition (Jensen 1997).

The placement of crop residue, as affected by management practices, has been shown to influence residue decomposition and associated N mineralization. For example, greater soil/straw contact has been shown to increase initial decomposition, due to greater positional availability of straw carbon to soil organisms in incorporated compared to surface-retained straw (Cogle et al. 1987), and is in agreement with most of the literature showing greater N availability following tilled vs. surface applied legume residue (Mohr et al. 1999; Drinkwater et al. 2000; Vaisman et al. 2011). Coppens et al. (2013) used the mechanistic model PASTIS to relate soil and residue water content to residue location and found a 35% lower decomposition rate for surface placed compared to incorporated rape (*Brassica napus*) and rye residue, emphasizing the importance of soil environmental factors. Water content of the surface mulch residue decreased more rapidly than incorporated residue following rain, resulting in a decrease in the activity of microbial decomposers.

Soil environmental factors that influence residue decomposition include soil moisture, soil temperature, pH, soil aeration and nutrient status (Parr and Papendick 1978). Since decomposition is carried out by microbial activity, it follows that conditions conducive for soil microorganisms would favor decomposition and mineralization. Microbial activity increases at warm temperatures with the optimum for microbial decomposition processes occurring between 20 and 40°C (Brady and Weil 2008). Microbial growth and diffusion of nutrients and oxygen is regulated by adequate soil moisture (Parr and Papendick 1978). For example, in extremely dry conditions some microorganisms may die rapidly from desiccation while in saturated conditions, others will be limited by oxygen supply. Agehara and Warncke (2005) found that net N release from alfalfa pellets and chicken manure increased with increasing temperature from 15 to 25°C and increasing moisture from 50 to 90% of water holding capacity.

Studies investigating reduced tillage management of green manure have consistently demonstrated that increasing tillage intensity, which warms the soil and buries crop residue, increases nitrogen availability (Drinkwater et al. 2000; Vaisman et al. 2011), sometimes in excess of crop demand. The key is whether or not alternative methods provide sufficient nitrogen supply to meet crop demand and if they can improve synchrony between release and crop uptake. Some researchers suggest that organic matter inputs can be manipulated to regulate mineralization (Peigne et al. 2007) and improve synchrony compared chemical fertilizer (Crews and Peoples 2004). Efforts to improve nitrogen supply and synchrony include mixing of species with varying C:N ratios, strategic timing of tillage and planting operations (Crews and Peoples 2004; Cherr et al. 2006) and advances in manure placement technology (Mirsky et al. 2012).

2.4.2.1 Mechanisms of Nitrogen Loss

Ammonium (NH_4^+) is produced from the mineralization of organic matter and is susceptible to many transformations. Ammonium can be: (a) taken up by plants, (b) adsorbed to the soil surface, (c) converted to nitrate (nitrification), or (d) converted to ammonia. The dynamic nature of nitrogen makes it difficult to match with crop uptake and also makes it more prone to environmental losses. There are three main mechanisms accounting for nitrogen losses associated with reduced tillage and surface applied residues: (1) volatilization, (2) leaching and (3) denitrification.

Ammonia volatilization refers to the loss of nitrogen to the atmosphere as ammonia gas (NH_3). Substantial losses of NH_3, sometimes as much as 50% of N applied have been documented from NH_4^+-forming fertilizers and animal manures applied to the soil surface (Terman 1979 as cited in Janzen and McGinn 1991). Surface applied fertilizers, manures or crop residues are particularly prone to ammonia formation and loss because ammonia is less likely to be adsorbed to soil particles. At the surface, soil conditions are often conducive to ammonia loss; high temperature and soil drying (Brady and Weil 2008). The potential volatile N losses from surface applied legume green manures is of considerable concern (Janzen and McGinn 1991) and may partially explain the differences in N availability following green manures managed with and without tillage. Investigations of ammonia losses following surface applied green manure legume residue in Canada have found a rapid initial flush followed by an indefinite period of slow volatilization with total losses ranging from 4.9-14% of biomass N (Janzen and McGuinn 1991; Vaisman et al. 2011). Incorporation of green manure residue almost eliminated volatilization losses in these studies.

In agricultural systems, populations of nitrifying bacteria rapidly convert ammonium to nitrate (Subbarao et al. 2006). Unfortunately, since nitrate is a negatively charged ion, it does not adsorb to soil surfaces and therefore moves downward freely with drainage water and can be readily leached from the soil (Brady and Weil 2008). Practices that increase the nitrogen status of soil, such as green manuring and summerfallow, can increase the risk of nitrate leaching, especially in presence of excess water and absence of plant uptake. For example, fall incorporation of a sweet clover green manure in the United Kingdom resulted in 102 kg nitrate-N ha^{-1} leached at 90 cm, representing 27% of accumulated N (Stopes et al. 1996). In this same study, nitrate leaching was reduced with spring incorporation; 26 kg nitrate-N ha^{-1} nitrate-N, representing 6% of accumulated N. According to Campbell et al. (2006), summerfallow practices increases nitrate leaching, but is still considered to be minimal on the semi-arid Canadian prairies (180 kg nitrate-N ha^{-1} in a wheat-fallow system over 37 years).

Denitrification is the opposite process of nitrification whereby nitrate is reduced to gaseous forms, and represents another mechanism that nitrogen can be lost to the atmosphere (Brady and Weil 2008). Denitrification is favored by low oxygen levels, thus denitrification rates can be higher in no-till soils due to potentially higher bulk density and water content. In poorly aerated no-till fields, N_2O emissions are increased (Rochette 2008), as a result of incomplete denitrification.

2.4.3 Weed Suppression

Cover crops can influence weeds either in the form of living plants or as plant residue remaining after the cover crop is killed (Teasdale et al. 2007). Successful organic no-till is based on the premise that adequate weed control will be achieved through a killed cover crop mulch that is left behind after termination of high biomass producing cover crops. Much of the previous research on mulch-based weed control has utilized herbicides (Mohr et al. 1999) or mowing (Drinkwater et al. 2000) to kill the cover crops but more recently, blade rolling (Vaisman et al. 2011) and undercutting (Wortman et al. 2012) have also become the focus of research projects, especially in organic no-till.

There are multiple ways that cover crop residue can affect weed seed germination and emergence; through effects on the radiation and chemical environment of the seed (Teasdale et al. 1997), by reducing light and daily temperature amplitude (Teasdale and Mohler 1993), inhibiting emergence by physically impeding the progress of seedlings from accessing light (Teasdale and Mohler 2000) as well as by releasing phytotoxins (Moyer et al. 2007; Geddes et al. 2012). Once seedlings become established, cover crop residue will usually have a negligible impact on weed growth and seed production and may even stimulate these processes (Teasdale et al. 2007). This may be due to moisture conservation or stimulation of mineralization due to the presence of crop residue on the soil surface, as discussed previously.

Teasdale and Mohler (2000) have done extensive work on mulch-based weed suppression and have shown that quantity of residue is more important than type of residue. In one of their studies, weed emergence of four summer annual weed species declined exponentially with increasing mulch rate from 2000-16000 kg ha^{-1}, with 75%

inhibition consistently achieved when mulch biomass exceeded 8000 kg ha^{-1}. Similarly, Smith et al. (2011) reported that rye biomass above 9000 kg ha^{-1} provided good weed control with no negative impact on soybean yield. Residue levels under 5000 kg ha^{-1} have shown variable effects on weed suppression, with other factors such as moisture conditions (Teasdale and Daughtry 1993) and subsequent weed control methods (Drinkwater et al. 2000) playing a role. For example, in the study by Teasdale and Daughtry (1993), the effect of desiccated hairy vetch (3200-4600 kg ha^{-1}) appeared to depend on moisture conditions. During two years of adequate soil moisture, hairy vetch residue reduced or had no influence on weed density and biomass relative to bare soil, but in one year with an extended hot dry period, weed biomass increased.

Cover crop residue is more effective at controlling annual weed species as compared to perennial weeds (Mirsky et al. 2012). Further, small seeded annuals, such as redroot pigweed *(Amaranthus retroflexus*), have been shown to be more sensitive to residue than those with larger seeds (Teasdale and Mohler 2000). Perennial weeds are more difficult to control with cover crops because of larger nutritional reserves and faster rates of establishment (Teasdale et al. 2007). In conventional cropping some perennial weeds such as dandelion *(Taraxacum officinale),* have been strongly associated with reduced tillage systems (Blackshaw et al. 1994; Thomas et al. 2004). A shift from annual to perennial weeds has been observed at Pennsylvania's Rodale institute after just one year of organic no-till (Ryan et al. 2009). Perennial weeds pose a challenge in organic no-till planted crops and illustrate the need for low perennial weed populations where the cover-crop based, organic no-till approach is implemented (Mirsky et al. 2012).

2.4.4 Wheat response

Wheat is one of the most important crops in Canada accounting for the largest seeded area of all crops with over 9.6 million hectares in 2012 (Statistics Canada 2012). Wheat is also the most commonly grown organic field crop accounting for over 100,000 ha in 2009 which represents 15% of certified organic land in Canada (Macey 2010). The strong preference to grow wheat by growers combined with the fact that it is a moderate nitrogen user makes it a logical choice to be grown after a green manure crop in rotation. Spring wheat has been used as a test crop in the majority of studies investigating reduced tillage management of green manures in Western Canada (Blackshaw et al. 2010; Vaisman et al. 2011; Shirtliffe and Johnson 2012). The effects of green manure management on the soil microclimate, residue decomposition and nutrient release, and weed dynamics have been discussed. The following section will discuss the relationship between these interactive factors and spring wheat development.

Temperature is one of the major environmental factors affecting wheat development. It most widely described by thermal time such as growing degree days, which are taken as the summation of differences between daily mean temperature and a base temperature (Miralles and Slafer 1999). Generally speaking, the higher the temperature the faster rate of development. Addae and Pearson (1992) found the rate of seedling elongation and emergence to increase linearly between 5 and 25°C. Therefore low temperatures early in the season can delay emergence and development, thereby limiting competitive ability and nutrient uptake.

Adequate soil water is the main physiological requirement for seed germination and seedling development (Dennett 1999) and is also required for adequate wheat development (Miralles and Slafer 1999) and nitrogen assimilation (Borghi 1999) throughout the growing season. Water shortages at particular stages may decrease tiller number, spikelet number or hasten the end of grain filling, all of which have detrimental effects on yield (Miralles and Slafer 1999).

As discussed previously, temperature and moisture conditions influence decomposition of green manure residue and thus will affect nitrogen availability. Nitrogen (N) plays a crucial role in plant metabolism and can be the main factor limiting yield potential in numerous wheat-growing areas of the world (Borghi 1999). The wheat plant preferentially takes up N as NO_3^- ions, which is also the most abundant form of N in agricultural systems (Subbarao et al. 2006). The amount of dry matter produced per unit of land and grain yield response to N is similar; a linear increase followed by a plateau; although the linear phase of grain yield is markedly lower (Borghi 1999). The nitrogen uptake of 2695 kg ha^{-1} of wheat ranges from 85-105 kg ha^{-1} (Manitoba Soil Fertility Guide). Malhi et al. (2006) found that maximum rate of nutrient uptake and maximum amount of nutrient uptake occurred at tillering to stem elongation and beginning of flowering to medium milk stages, respectively; emphasizing that the supply of nutrients must be sufficient at early growth stages for optimum crop yield. Limited nitrogen is taken up during grain filling; rather, nitrogen is remobilized from senescent vegetative tissues to reproductive organs, where most of the N absorbed by the plant is accumulated in the grain (Borghi 1999).

Weeds compete with crop plants for water and nutrient resources. Competition with weeds has similar detrimental effects on wheat as water or nitrogen shortage; early competition reduces tiller number and hence kernel number and possible grains per kernel; whereas late competition will affect grain filling and seed weight (Froud-Williams 1999). Strategies to improve crop competition include increased seed rate and early crop emergence while the effects of competition may be alleviated with nitrogen application. Green foxtail (*Setaria viridis*), wild mustard (*Sinapsis arvensis),* lamb`s quarters (*Chenopodium album*), wild oats (*Avena fatua*) and wild buckwheat (*Polygonum convolvulus*) were the top five most abundant weeds found on organic farms in Saskatchewan, respectively (Knight and Shirtliffe 2003). Canada thistle *(Cirsium arvense)* and dandelion, which have been found to be associated with conventional reduced tillage systems (Thomas et al. 2004), ranked #7 and #11, respectively based on relative abundance.

3. MATERIALS AND METHODS

3.1 Site Description

The field experiments were initiated in 2010 and 2011 at the Ian N. Morrison Research Farm in Carman, Manitoba and at the Agriculture and Agri-Food Canada (AAFC) Lethbridge Research Centre in Lethbridge, Alberta. These two locations represent two distinct agro-climatic regions of Canada; sub-humid (MB) and semi-arid (AB). The soil at Carman is an Orthic Black Chernozem with a fine sandy loam texture and pH of 6.5. The soil at Lethbridge is an Orthic Dark Brown Chernozem with a sandy clay loam texture and a pH of 7.8. Climatic conditions were variable among site years and are summarized in Table 1. Climatic data was obtained from weather monitoring stations in Carman (MAFRI) and Lethbridge (AAFC). Carman and Lethbridge both experienced a very wet spring in 2011, resulting in delayed seeding. In contrast, 2012 was generally warmer and drier than normal at both locations.

The Carman site has been managed organically since 2004 and was seeded on land previously sown to spring wheat in 2010 and 2011. The Lethbridge site had not been managed organically prior to the experiment and was seeded into oat cover crop stubble.

3.2 Experimental Design

In year 1 of the experiment, a green manure crop was grown and terminated with five different termination methods: 1) standard tillage; 2) blade roller; 3) blade roller followed by late fall tillage; 4) wide blade cultivation (undercut); or 5) flail mower. A fallow treatment with no cover crop was included in every site-year except Carman 2011, for a total of six treatments. For this treatment the green manure was still planted but tilled under within one month after planting and tilled occasionally for weed control thereafter. In year 2, a spring wheat test crop was seeded in all plots directly into the green manure residue or fallow. An additional fall rye test crop was planted after wheat harvest at Carman 2011 and Lethbridge 2011 and monitored into year 3. The experimental design was a randomized complete block design (RCBD) with 4 blocks.

Individual plot size was 2 x 8m in Carman 2010, 4 x 8m in Carman 2011 and 4 x 11m at Lethbridge in 2010 and 2011.

Table 1. Mean monthly temperature and precipitation during the growing season at Carman (MAFRI) and Lethbridge (AAFC) and long term averages at each experimental site.

Location	Sept-April†	Apr.	May	June	July	Aug.	Sept.	Growing Season‡
Temperature (°C)								
Carman 2011	-5.1	4.4	10.4	16.7	20.3	19.3	14.0	16.7
Carman 2012	0.0	6.5	12.2	17.7	21.9	19.0	12.5	17.7
LTA§	-5.2	4.4	12.4	17.2	19.7	18.1	12.2	16.9
Lethbridge 2011	-0.3	4.2	10.3	14.7	18.3	18.9	16.3	15.6
Lethbridge 2012	3.8	7.7	10.7	15.5	20.0	19.0	15.5	16.3
LTA¶	1.6	6.3	11.5	15.4	18.4	17.9	13.0	15.8
Precipitation (mm)								
Carman 2011	198	44	72	59	38	12	65	181
Carman 2012	119	19	63	86	28	47	3	224
LTA§	219	31	60	76	74	67	60	276
Lethbridge 2011	277	84	98	85	54	40	9	278
Lethbridge 2012	171	51	68	125	16	20	7	229
LTA¶	178	33	55	85	41	41	41	220

† September of the previous calendar year until April of the seeding year.
‡ Growing season is May to end of August.
§ Long term averages (1971-2001) for Graysville, MB (Environment Canada), 14 km west of Carman.
¶ Long term averages (1981-2011) for Lethbridge, AB (Agriculture and Agri-Food Canada).

Table 2. Description of experimental site-years from 2010-2012 with crop type in parentheses.

Location	2010	2011	2012
Ian N. Morrison Research Farm Carman, MB	Year 1 (pea-barley)	Year 2 (wheat/buckwheat)‡	Year 3 (fall rye)
		Year 1 (pea-oat-soybean)	Year 2 (spring wheat)
AAFC† Research Station Lethbridge, AB	Year 1 (pea-barley)	Year 2 (spring wheat)	Year 3 (fall rye)
		Year 1 (pea-barley)	Year 2 (spring wheat)

† Agriculture and Agri-Food Canada.
‡ In 2011, the spring wheat crop was terminated with tillage and re-planted to buckwheat due to excessive weed pressure.

At Carman 2010, the green manure was an intercrop of peas (cv. 4010) and barley (cv. CDC Cowboy) seeded on May 14, 2010 (seeding rate not available). In 2011, the green manure was a polycrop of peas (cv. 4010), soybeans (cv. OAC Prudence) and oats (cv. Leggett) seeded at 73 kg ha^{-1}, 69 kg ha^{-1} and 73 kg ha^{-1}, respectively on June 5, 2011. Both green manure crops at Carman were planted with an air seeder at 20 cm spacing. At Lethbridge, the green manure was an intercrop of peas (cv. 4010) and barley (cv. CDC Cowboy) in both 2010 and 2011. The seeding density was 80 seeds m^{-2} of pea and 42 seeds m^{-2} of barley, planted in alternate rows with 11.25 cm spacing on a double disc zero till drill. The green manure was planted July 1, 2010 and June 28, 2011, due to wet spring conditions in both years. Peas and soybeans at Carman were inoculated with Nodulator® liquid inoculant at a rate of 3 ml kg seed^{-1}. At Lethbridge, peas were inoculated with Cell-Tech® liquid inoculant in 2010 at a rate of 3 ml per kg seed and with Soil Implant+® granular inoculant in 2011 at a rate of 5.7 kg ha^{-1} placed with the seed.

The green manure crop was terminated at pea full bloom and/or within 10 days post heading of barley, ranging from 47-64 days after planting. A description of termination dates and methods for Carman and Lethbridge are summarized in Table 3 and 4, respectively. In general, each operation date was comprised of two passes in opposite directions, except for wide blade cultivation in Carman and Lethbridge and discing at Lethbridge for which a single pass was deemed sufficient. Treatments were re-applied according to weed growth and re-growth of the cover crop.

Spring wheat was seeded into the green manure plots in spring of year 2. At Carman, wheat (cv. AC Waskada) was planted on May 19, 2011 and April 12, 2012 at 147 kg ha^{-1} and 142 kg ha^{-1}, respectively. Plots were seeded with a double disc zero till drill at a row spacing of 15 cm. Due to excessive weed pressure in all plots in 2011, the wheat was terminated with tillage on June 29, 2011 and re-planted to buckwheat (*Fagopyrum esculentum*). A roto-tiller was used to ensure all above-ground biomass remained in the plots. Buckwheat (cv. AC Manisoba) was planted at 58 kg ha^{-1} on June 29, 2011 using a double disc zero till drill. Buckwheat was chosen due to its rapid growth, competitiveness and short growing season. At Lethbridge, wheat (cv. AC Lillian) was planted on May 11, 2011 and May 8, 2012 at 99 kg ha^{-1} and 104 kg ha^{-1} in 2011, respectively, targeting 300 seeds m^{-2}. Plots were seeded with a double disc zero till drill at a row spacing of 22.5 cm.

In year 3, fall rye (cv. AC Hazelet) was seeded into the plots after buckwheat harvest in 2011 at Carman and after wheat harvest at Lethbridge in 2011. At Carman, plots were tilled with a roto-tiller and planted to fall rye at a rate of 100 kg ha^{-1} to a depth of 2.5 cm on September 2, 2011 using a double disc zero till drill. At Lethbridge, plots were planted to fall rye at a rate of 129 kg ha^{-1} on September 21, 201l using a double disc zero till drill. See Table 5 for harvest dates of wheat, buckwheat and fall rye.

Table 3. Description of green manure termination methods for each treatment in 2010[†] and 2011[‡] at Carman.

		Green Manure				Spring Wheat
Treatment	Year	July	August	September	October	May
Tillage	2010	Disced	Disced	-	Disced	Cultivated
	2011	-	Disced	Disced	-	Disced
Blade Roll	2010	Rolled	Rolled	-	Rolled	-
	2011	-	Rolled	Rolled	-	-
Blade Roll + Tillage	2010	Rolled	Rolled	-	Disced	Cultivated
	2011	-	Rolled	Rolled	Disced	Disced
Wide Blade	2010	Undercut	Undercut	-	Undercut	-
	2011	-	Undercut	-	-	-
Flail Mow	2010	Mowed	Mowed	-	Mowed	-
	2011	-	Mowed	Mowed	-	-
Fallow[§]	2010	Disced	Disced	-	Disced	Cultivated
	2011	-	-	-	-	-

† Initial termination was done on July 15, 2010.
‡ Initial termination was done on August 5, 2011.
§ The fallow treatment was tilled occasionally for weed control. In 2011, there was no fallow treatment included.

Table 4. Description of green manure termination methods for each treatment in 2010[†] and 2011[‡] at Lethbridge.

		Green Manure				Spring Wheat
Treatment	Year	July	Aug	Sept	October	May
Tillage	2010	-	-	Disced	-	-
	2011	-	Disced	-	-	-
Blade Roll	2010	-	-	Rolled	Rolled	-
	2011	-	Rolled 2x	Rolled	-	-
Blade Roll + Tillage	2010	-	-	Rolled	Cultivated 2x	-
	2011	-	Rolled 2x	Cultivated	-	-
Wide Blade	2010	-	-	Undercut	-	-
	2011	-	Undercut	Undercut	-	-
Flail Mow	2010	-	-	Mowed	Mowed	-
	2011	-	Mowed	Mowed	-	-
Fallow	2010	Cultivated	-	Cultivated	-	-
	2011	Cultivated	-	-	-	-

† Initial termination was done on September 3, 2010.
‡ Initial termination was done on August 22, 2011.

Table 5. Harvest dates for test crops at Carman and Lethbridge

Site-Year	Crop	Harvest Date
Carman 2011	Wheat †	June 29
	Buckwheat ‡	September 2
Carman 2012	Wheat	July 31
	Fall Rye	July 31
Lethbridge 2011	Wheat	September 16
Lethbridge 2012	Wheat	August 22
	Fall rye	August 22

† Due to excessive weed pressure, wheat was terminated at stem elongation using tillage and re-planted to buckwheat.
‡ Buckwheat yield samples were taken at 43% seed colour change. Plots were swathed and biomass removed prior to fall rye planting.

3.3 Data Collection

3.3.1 Data collection in the year 1 green manure crop

*Soil nitrate***.** Soil samples were taken at seeding of the green manure crop for Carman 2010 (0-120 cm in 30 cm increments) and Carman 2011 (0-15 cm and 15-60 cm). Six random samples were taken from across the entire field and bulked. Soil samples were taken again at termination of the green manure crop for Carman 2011 (0-120 cm in 30 cm increments) and Lethbridge 2011 (0-90 cm in 30 cm increments). Two samples were taken and bulked for each plot. Samples were taken using a hand auger in Carman (core diameter 4 cm) and a soil coring truck in Lethbridge (core diameter 4 cm). Samples were refrigerated until they were sent to Agvise laboratories (Northwood, ND) for soil nitrate-N analysis using the cadmium reduction method. Soil nitrate data below 30 cm from Lethbridge was not used in the analyses due to excessively high background concentrations (265 kg ha^{-1} from 30-90 cm), attributed to lateral flow from a nearby composting station.

Green manure biomass and biomass nitrogen. Biomass samples of each green manure plant species (pea, barley, oat and soybean) and weeds were taken immediately prior to termination of the green manure crop. Samples were taken from the alleyways to leave the plots undisturbed; the green manure crop growing in the alleyways was consistent with the crop growing in the plot area. At Lethbridge 2010 and 2011, three

0.25 m^2 samples were taken from the alleyways of each block. At Carman 2010, one sample of 1 m^2 was taken from the alleyway of each block. At Carman 2011, four 0.4 m^2 samples were taken from the alleyway of each block. Samples were dried at 60°C for at least 48 hours and then weighed. The samples from Carman were ground using a Wiley Mill No. 1 (Arthur H. Thomas Co., Philadelphia). The ground samples were subsampled for nitrogen concentration analysis using a LECO-FP-528 combustion analyser (LECO Corporation, St. Joseph, MI).

Gravimetric moisture content. At Carman 2010, Carman 2011 and Lethbridge 2010, field moist soil samples (subsamples from soil samples collected for soil nitrate) were weighed and placed in the oven at 60°C for at least 48 hours. Dried soil samples were weighed and gravimetric soil moisture content was calculated using the following formula;

$$\text{Gravimetric soil moisture (\%)} = \frac{\text{soil wet weight (g)} - \text{soil dry weight (g)}}{\text{soil dry weight (g)}} \times 100 \quad \text{[eq. 1]}$$

3.3.2 Data collection in the year 2 spring wheat crop

Green manure residue. As early in the spring as possible, samples of green manure surface residue were taken. For Carman 2011, Carman 2012 and Lethbridge 2011, two 0.0625 m^2 quadrats per plot were taken and combined. For Lethbridge 2012, two 0.25m^2 quadrats per plot were taken. Plant samples from both sites in 2011 (wet conditions) were washed due to a high proportion of soil adherence. Samples were dried at 60°C for at least 48 hours and weighed.

Soil nitrate. Soil samples were taken at wheat seeding for Carman 2011 and Carman 2012 (0-120 cm in 30 cm increments), and shortly after seeding (due to wet conditions) in Lethbridge 2011 (0-90 cm in 30 cm increments). Soil samples were taken at wheat termination/buckwheat planting at Carman 2011 (0-120 cm in 30 cm increments) and again at buckwheat harvest (0-120 cm in 30 cm increments), which also corresponded to fall rye planting. Soil samples were taken at wheat harvest at Lethbridge 2011 (0-90 cm in 30 cm increments), which also corresponded to fall rye planting, and Carman 2012 (0-120 cm in 30 cm increments). At all sampling times, two samples were taken from each plot and bulked. Soil cores were taken using a hand auger in Carman and a soil coring truck in Lethbridge. Samples were refrigerated until they were sent to Agvise laboratories (Northwood, ND) for soil nitrate-N analysis using the cadmium reduction method. Soil nitrate data below 30 cm from Lethbridge was not used in the analyses due to excessively high background concentrations, attributed to lateral flow from a nearby composting station.

Gravimetric soil moisture. At Carman 2010 and Carman 2011, field moist soil samples (subsamples from soil samples collected for soil nitrate) were weighed and placed in the oven at 60°C for at least 48 hours. Dried soil samples were weighed and gravimetric soil moisture content was calculated using equation 1.

Soil temperature. Tidbit v2 temperature data loggers (Onset Computer Corporation, Bourne, MA) were placed in the soil at a depth of 5 cm immediately after spring wheat seeding at the Carman location only. One temperature data logger was placed in the center of each plot in three blocks. Soil temperature was recorded every 4 hours for a period of three weeks after spring wheat planting. Average daily temperature was calculated by taking the average of 6 readings per day.

Wheat plant population and Haun stage. At approximately the 2 leaf stage of wheat at Carman and the 4 leaf stage at Lethbridge, plant density and wheat development was measured. At Carman 2011 and Carman 2012, all plants along one 1 m length of row were counted in two locations per plot (1 row x 1 m length x 2 locations). At Lethbridge 2011 and 2012, all plants along two 1 m lengths of row were counted in two locations per plot (2 rows x 1 m length x 2 locations). Wheat development was determined by measuring the Haun scale (Haun 1973) for ten wheat plants along a randomly selected 1 m length of row per plot at Carman 2011, Carman 2012 and Lethbridge 2012. At Lethbridge 2011, Haun scale was measured for five wheat plants along a randomly selected 1 m length of row per plot.

Weed density and composition. Weed density was determined at approximately the 3-4 leaf stage of wheat at all site-years. Individual weed species were counted in two randomly selected 0.25 m^2 quadrats per treatment for both years at Lethbridge. At Carman 2011, large broadleaf weeds were counted in two randomly selected 0.25 m^2 quadrats per plot and small broadleaves and grasses were counted in two randomly selected 0.0156 m^2 quadrats per plot. At Carman 2012, broadleaf weeds were counted in two randomly selected 0.25 m^2 quadrats and green foxtail was counted in two 0.0169 m^2 quadrats per plot. Weed densities were recorded by species.

Wheat biomass and biomass nitrogen. Wheat and weed biomass samples were taken at the stem elongation stage at all site-years by cutting all the above ground wheat and weeds using a sickle, approximately 2 cm from the soil surface. At Carman 2011, Lethbridge 2011 and Lethbridge 2012, two 0.5 m rows of above ground wheat and weed biomass were sampled in two areas per plot. At Carman 2012, three 0.5 m rows of above ground wheat and weed biomass were sampled in two areas per plot. Wheat and weed samples were dried at 60°C for at least 48 hours and weighed. Wheat and weed biomass samples were also taken at the wheat hard dough stage. At Carman 2012, Lethbridge 2011, and Lethbridge 2012, two 0.5 m rows of above ground wheat and weed biomass were sampled in two areas per plot. At Carman 2011, buckwheat and weed biomass was sampled at harvest; three 0.5 rows of above ground buckwheat and weed biomass were sampled in two areas per plot. All crop and weed samples at hard dough/harvest were dried at 60°C for at least 48 hours and weighed. All samples from Carman were subsampled and ground using a Wiley Mill No. 1 (Arthur H. Thomas Co., Philadelphia). The ground samples were subsampled for nitrogen concentration analysis using a LECO-FP-528 combustion analayser (LECO Corporation, St. Joseph, MI).

3.3.3 Data collection in the year 3 fall rye crop

Fall rye biomass and biomass nitrogen. Fall rye biomass was sampled at stem elongation at Lethbridge 2012 by cutting all the above ground fall rye and weeds using a sickle, approximately 2 cm from the soil surface. Two 0.5 m rows were sampled in two areas per plot. Samples were dried at 60°C for at least 48 hours and weighed. Fall rye biomass was sampled at the hard dough stage at Lethbridge 2012 and Carman 2012. At Lethbridge, two 0.5m rows were sampled in two areas per plot and fall rye and weeds were separated. At Carman, two 1 m rows were sampled in two areas plot. Weeds were estimated visually to account for <5% of total biomass at Carman and therefore fall rye and weed biomass was combined. Samples were dried at 60°C for at least 48 hours and weighed. Samples from Carman were subsampled and ground using a Wiley Mill No. 1

(Arthur H. Thomas Co., Philadelphia). The ground samples were subsampled for nitrogen concentration analysis using a LECO-FP-528 (LECO Corporation, St. Joseph, MI).

Soil nitrate. Soil samples were taken after fall rye harvest at Carman 2012 from 0-120 cm in 30 cm increments using a hydraulic Giddings® soil auger (Giddings Machine Company, Windsor, CO). Two samples were taken per plot and bulked. Samples were refrigerated until they were sent to Agvise laboratories (Northwood, ND) for soil nitrate-N analysis using the cadmium reduction method.

Grain yield and grain protein. At Lethbridge, wheat grain yield was collected with a Wintersteiger Delta combine. A 250 g subsample was cleaned and tested for protein using Foss Near Infrared (NIR) Technology. Nitrogen uptake was calculated by multiplying % protein by a factor of 5.6 (Tkachuk 1969). At Carman 2011, buckwheat grain yield was collected by hand harvesting three 1 m rows in two areas per plot. The samples were air dried on drying beds and threshed using a stationary Wintersteiger combine. At Carman 2012, wheat grain yield was harvested from each plot with a Massey Ferguson 80XP plot combine.

3.6 Statistical Analysis

Treatment effects were tested using analysis of variance (ANOVA) for all measurements. Data was analyzed as one-way randomized complete block design using PROC Mixed procedure with the Statistical Analysis Software Program (SAS Institute 2001), with treatment as fixed effect and block as a random effect. Green manure management method was considered significant at $P < 0.05$. Means within treatments were compared using Tukey's HSD at the 5% level of significance. Assumptions of ANOVA were tested by using the PROC Univariate procedure to test for normality of the residuals and by using PROC Print to identify outliers based on critical values of internal studentized residuals of Lund's test (Lund 1975). When data did not conform to normality, appropriate transformations were conducted for analysis. In these cases, untransformed data are presented with statistical analysis based on transformed data. Site and years were analyzed separately due to the different cropping history and growing conditions at each site-year.

4. RESULTS AND DISCUSSION

4.1 Green Manure Biomass

Producing high biomass green manure cover crops is important for providing nitrogen to subsequent crops and to provide a thick mulch for weed suppression. At Carman, the average green manure biomass was 4700 kg ha^{-1} over the two years. The Lethbridge site produced more biomass in both years, averaging 5700 kg ha^{-1}. Total biomass production amounts from a spring seeded annual green manure on the Canadian prairies ranges from 3499-7566 kg ha^{-1} for a pea-oat intercrop at Carman, MB (Natural Systems Agriculture 2011) and 863-2520 kg ha^{-1} for a monoculture legume in central Saskatchewan (Sullivan 2012). Estimates of total nitrogen content in the above ground green manure biomass ranged from 115-162 kg ha^{-1} (Table 6).

Table 6. Green manure biomass and biomass nitrogen at the time of termination at **Carman** (2010, 2011) and **Lethbridge** (2010, 2011).

Site-year	Biomass			Biomass Nitrogen		
	Green manure	Weeds	Total	Green manure	Weeds	Total†
	-------------- kg ha^{-1}	--------------		----------------- kg ha^{-1}	----------------	
Carman 2010	3877	729	4606	-	-	115
Carman 2011	3094	1656	4751	97	36	134
Lethbridge 2010	-	-	4955	-	-	124
Lethbridge 2011	6472	29	6501	-	-	162

† For Carman 2010, Lethbridge 2010 and Lethbridge 2011, total biomass nitrogen was estimated based on 2.5% nitrogen content for green manure biomass.

4. 2 Green Manure Residue

Green manure residue was sampled in early spring to determine if green manure management method affected the amount of mulch present at planting the following year. The amount of surface residue or mulch present at spring wheat planting the year after termination is indicative of weed suppression potential and erosion risk.

At Carman, all reduced tillage treatments (blade roll, blade roll + tillage, wide blade cultivation and flail mowing) increased surface residue significantly compared to the tillage treatment in both years (Table 7). The blade roll treatment resulted in the greatest surface residue present in spring before wheat planting (3112-3276 kg ha^{-1}).

At Lethbridge, residue amounts tended to be greater than Carman as can be expected due to higher initial green manure biomass (Table 6). In 2011, the blade roll, blade roll + tillage and wide blade cultivation treatments resulted in residue amounts greater than 4000 kg ha^{-1} and were significantly greater than all other treatments. In 2012, residue amounts were smaller and there were no differences between the green manure treatments, which all had significantly more surface residue than the fallow treatment.

Green manure managed with wide blade cultivation (3030 kg ha^{-1}) resulted in similar residue levels as the blade roller (3630 kg ha^{-1}) in all 4 site-years. Despite similar residue levels as wide blade cultivation, it should be noted that the blade roller left a more uniform seedbed. The wide blade cultivator left standing residue that was not spread evenly across the soil surface. Flail mowed green manure left less residue than the roller in 2 of 4 site-years. The flail mower chopped the residue into smaller pieces; more surface area and closer contact with soil microorganisms can lead to more rapid decomposition (Creamer and Dabney 2002) and thus less residue at spring planting.

Green manure treatments always had more residue present at spring planting compared to the fallow treatment. Although still practiced in the drier regions of the Northern Great Plains, fallow practices increase risk of soil erosion and degradation.

In the present study, green manure biomass at termination ranged from 4600-6500 kg ha^{-1} (Table 6) and residue levels in spring were greatest following blade rolled green manure (3112-5210 kg ha^{-1}). Residue levels reported in the literature required for weed suppression range from 2-4 times the natural rate, corresponding to 4900 kg ha^{-1} to potentially limit weed emergence (Teasdale and Mohler 1993), to up to 9000 kg ha^{-1} for good weed control and no effect on main crop yield (Smith et al. 2011). The present study suggests limited potential to produce sufficient biomass from an annual pea-barley green manure for weed suppression the following year; however, reduced tillage management is important to optimize this opportunity. Averaged across site-years, blade rolling and flail mowing resulted in losses of approximately 45 and 48% of the original biomass from termination to spring the following year, respectively, compared to 80% for the tillage treatment. Higher decomposition with flail mowed residue is a potential downfall for weed suppression (Teasdale and Mohler 1993; Creamer and Dabney 2002) but may increase nitrogen availability. On the other hand, Smith et al. (2011) reported similar decomposition between rolled and mowed rye.

Another important aspect of the amount of green manure residue present is its nitrogen content. Greater surface residue in zero till treatments represents a portion of nitrogen that is less available for mineralization by soil microorganisms. Although the nitrogen content of the residue in the current study was not measured, Drinkwater et al. (2000) compared till vs. no-till hairy vetch and found that four times as much residue remained on the soil surface in the no-till treatment and the residue contained up to 60 kg N ha^{-1}.

Table 7. Effect of green manure management on surface residue in spring the following year at **Carman (2011, 2012)** and **Lethbridge (2011, 2012).**

	Carman		Lethbridge	
Treatment	2011	2012	2011	2012
	------------------ kg ha^{-1} ------------------			
Tillage	562 **c**†	629 **c**	1158 **c**	2126 **a**
Blade Roll	3112 **a**	3276 **a**	5210 **a**	2934 **a**
Blade Roll + Tillage	1462 **b**	2582 **ab**	4254 **a**	1515 **ab**
Wide Blade	2382 **a**	2493 **ab**	4242 **a**	3004 **a**
Flail Mow	2528 **a**	1934 **b**	2748 **b**	2612 **a**
Fallow	417 **c**	-	74 **d**	335 **b**
P>F	<0.0001	0.0003	<0.0001	0.0002

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

4.3 Soil Microclimate

Tillage practices and crop residue management influence both soil temperature and soil moisture. Zero tillage practices have been found to lower soil temperature compared to conventional tillage practices (Gauer et al. 1982; Bortslap and Entz 1994). Additionally zero tillage and mulching is known to decrease water evaporation and increase soil moisture (Gauer et al. 1982; Bullied and Entz 1999). Gauer et al. (1982) identified that the main factor contributing to lower soil temperature and higher moisture content was the presence of straw cover on zero-tilled fields. Thus, it is expected that cover crop termination method, which influences the amount of residue present at spring wheat planting, would also influence the soil microclimate in which spring wheat is planted. The soil microclimate beneath green manure residue in turn can affect wheat development and potentially weed germination. In the present study, soil temperature at 5 cm was monitored in Carman at spring wheat planting and gravimetric soil moisture was taken at all site-years in late fall after green manure termination and again in spring at wheat planting.

4.3.1 Soil Temperature

At Carman 2011, excess moisture in spring led to late planting. Wheat was planted on May 19 into warm soil. Daily soil temperature on May 21 ranged from 13.8-14.8°C. For three weeks after planting, there were no significant differences in average daily soil temperature (May 21 to June 10) among termination treatments.. This is not surprising since the effect of tillage and residue management on soil temperature has been shown to diminish as the growing season progresses (Gauer et al. 1982) and residue decomposes (Teasdale and Mohler 1993).

At Carman 2012, spring wheat planting took place on April 12 when soil temperature was markedly cooler compared to May. Daily soil temperature on April 18 was 4.6-5.7°C. Average daily soil temperature was significantly higher in the tillage and blade roll + tillage treatment compared to all other treatments on 8 out of the 22 dates sampled from April 18 to May 9 (Figure 2). Pre-seeding tillage, which was conducted in the tillage and blade roll + tillage treatment, has been shown to promote soil warming

(Gauer et al. 1982). Soil temperature in the flail mower treatment tended to be lower than the tillage treatments but higher than the blade roll and wide blade cultivation treatments, but this trend was not significant. This tendency for intermediate temperatures in the flail mower treatments may be due to residue levels that were also intermediate, less than blade rolling or wide blade cultivation but more than the tillage treatments (Table 7).

The largest differences in soil temperature occurred on April 24th (6 days after planting) where the tillage treatments were 2.1-2.8°C warmer ($P<0.05$) than all other treatments. In the present study, a tillage pass in late fall of the green manure year and prior to planting wheat was able to promote soil warming to the same degree as standard tillage practices. Soil temperature has a significant influence on rate of leaf appearance (Miralles and Slafer 1999); therefore, consistently cooler soil temperatures in the reduced tillage treatments in 2012 could result in delayed plant development (Section 4.4).

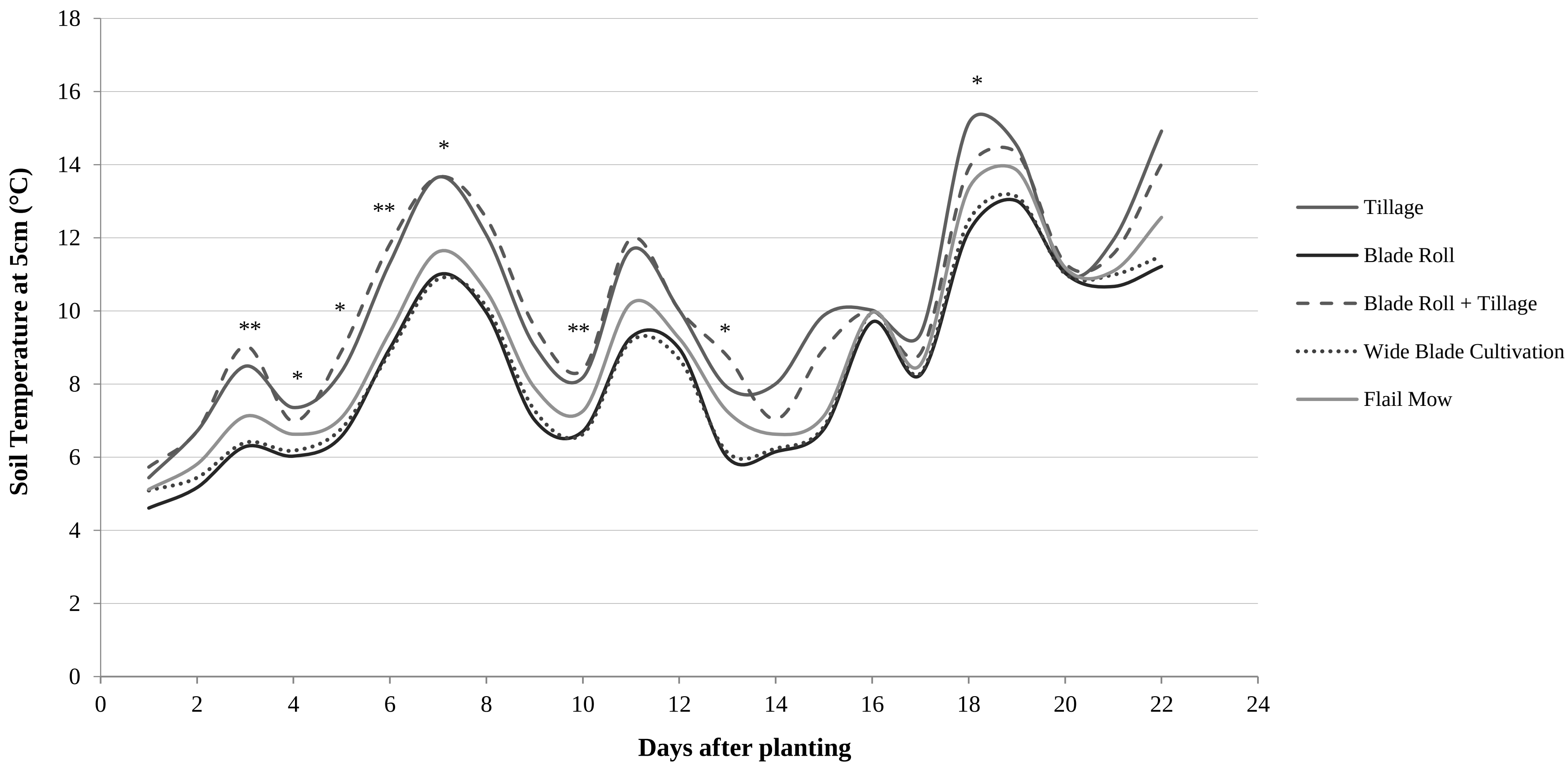


Figure 2. Effect of green manure management on average daily soil temperature at 5 cm for three weeks after spring wheat planting from April 18 to May 9 at Carman 2012. Green manure management effect significant at *P<0.05* (*) and *P<0.01* (**).

4.3.2 Soil Moisture

Reduced tillage practices and mulching conserve soil moisture (Gauer et al. 1982; Teasdale and Mohler 1993; Bullied and Entz 1999). In the present study, gravimetric soil moisture was measured in fall after green manure termination and in spring before planting.

There were no significant differences in gravimetric soil moisture content detected at any site-year. The fall of 2010 and spring of 2011 at both locations had above average precipitation. For example from April to May 2011, Carman and Lethbridge received 127% and 208% of long term average precipitation (Table 1), respectively. These large precipitation amounts contributed to overall high soil moisture content and possibly masked treatment effects. Average gravimetric soil moisture in fall of 2010 at Lethbridge was 22% from 0-30 cm across all treatments; field capacity (33 kPA) is estimated to be 27%, based on a sandy clay loam texture and 2.5% organic matter (Saxton and Rawls 2006). In spring of 2011 at Carman, gravimetric soil moisture was 26% from 0-30 cm across treatments. The estimated field capacity (33 kPA) and saturation (0 kPa) at Carman is 18 and 48%, respectively based on a sandy loam texture and 2.5% organic matter (Saxton and Rawls 2006).

The effect of surface mulch on soil moisture content is often dependent on incident precipitation. In years of excessive precipitation, soil moisture benefits may not be observed (Sullivan 2012) while during dry periods, surface mulch prevents soil moisture decline (Teasdale and Mohler 1993). The fall of 2011 and spring of 2012 were normal in terms of precipitation for both locations, thus differences in soil moisture would have been anticipated. However, the water conserving benefits of reduced tillage cover crop management were not evident in the present study. Gravimetric soil moisture in fall 2011 was 22 and 16% at 0-30 cm for Lethbridge and Carman, respectively with no response to green manure management. Fall plant growth after termination in the blade roll and flail mow treatments, from re-growth of green manure and weeds, may have reduced the effects of moisture conservation. Above average rainfall in the month prior to sampling may have also provided sufficient water recharge.

4.4 Wheat Plant Population

Plant population is important to achieve optimum yield potential and can be affected by surface residue and tillage practices. The current recommended plant population for spring wheat is 250-300 plants m^{-2} (Manitoba Agriculture, Food and Rural Initiatives). Wheat plant population density was significantly affected by green manure management method in 2 out of 4 site-years and responses were variable (Table 7).

At Carman 2011, plant population density ranged from 96-185 plants m^{-2}. The only significant difference at this site was a lower plant density in the flail mowed green manure (96 plants m^{-2}) compared to tillage (185 plants m^{-2}). Flail mowing also tended to have the highest weed density (Table 10); poor weed control following flail mowed green manure may be one reason for poor wheat establishment. At Lethbridge 2012, treatments with some degree of soil disturbance (tillage, blade roll + tillage, wide blade cultivation and fallow) resulted in a higher plant stand than treatments without soil disturbance. Surface residue has been found to be the main factor affecting soil temperature and moisture in zero till systems (Gauer et al. 1982); which can sometimes lead to reduced crop establishment (Borstlap and Entz 1994). In the present study, soil disturbance had little effect on surface residue present in spring at Lethbridge in 2012.Therefore, other factors may have been involved.

Of note, is that all site-years and all treatments had plant populations lower than those currently recommended. This was most evident in 2011 at both locations, where excessively wet soil conditions could have led to seed and seedling diseases. At Carman, high weed pressure at seeding (Figure 3) would have also reduced wheat stand. The poor plant stand at Carman 2011 supported the decision to terminate the spring wheat crop and re-plant to buckwheat. While wheat plants have the ability to compensate for low plant populations by producing more tillers (Satorre 1999), adequate plant density is important for early season weed competition. High planting densities are often recommended in organic cropping systems to improve crop competitiveness against weeds. In the present study, plant stand was sometimes reduced in zero till treatments; therefore consideration should be given to increase seeding rate in reduced tillage organic systems compared to those with conventional tillage. In contrast, Vaisman et al. (2011) reported wheat populations between 237-407 plants m^{-2} across all treatments, which compared the blade roller and various frequencies of tillage involved in green manure termination the previous year; with no overall treatment effect.

Table 8. Effect of green manure termination method on wheat plant population at **Carman (2011, 2012)** and **Lethbridge (2011, 2012).**

	Carman		Lethbridge	
Treatment	2011	2012	2011	2012
	------------------------ plants m^{-2}			------------------------
Tillage	185 **a**†	167	146	243 **a**
Blade Roll	109 **ab**	167	155	212 **bc**
Blade Roll + Tillage	136 **ab**	155	156	220 **abc**
Wide Blade	107 **ab**	153	130	223 **ab**
Flail Mow	96 **b**	152	155	200 **c**
Fallow	161 **ab**	-	140	235 **a**
P>F	0.0265	0.2415	0.3578	<0.0001

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

4.5 Wheat Development

Wheat development is affected by environmental factors, which can differ between tillage systems and surface residue. When crop residue is left on the soil surface, tillage promotes soil warming which can improve crop establishment, although not always materially (Gauer et al. 1982). The Haun scale provides a visual assessment method that is convenient and accurate for monitoring crop development and relating it to environmental factors (Haun 1973).

The wheat development response to green manure termination method was variable among site-years (Table 9). At Carman 2011, there was no response at the 2 leaf stage (Date 1) but significant differences were detected at the 3 leaf stage (Date 2). The lack of response at Date 1 is supported by soil temperature data which was monitored for 3 weeks after planting, and showed no significant differences among green manure management methods. At Date 2, wheat in treatments with some degree of soil disturbance (tillage, blade roll + tillage, wide blade cultivation and fallow) was more advanced than those without (blade roll, flail mow). For example, the wheat in the tillage and blade roll +

tillage treatment was at Haun stage 4.1 while wheat in the blade roll and flail mow treatment was at 3.1, with wide blade cultivation in between at 3.5. Temperature is the major component of environmental factors affecting plant development; however, other factors such as level of nutrition, plant density and water availability may have an effect when treatments are extreme (Miralles and Slafer 1999). Important differences in soil nitrogen availability were detected at time of wheat planting in 2011 (Table 18) and may explain differences detected at Date 2. A similar trend occurred at Lethbridge 2011; however, differences were larger; especially between fallow (Haun stage 6.7) and the blade roll treatment (Haun stage 4.3). Soil temperature was not monitored at Lethbridge, but it is possible that high residue levels in the zero till treatments reduced soil temperature and delayed wheat development.

At Carman 2012, the treatments with spring soil inversion (tillage and blade roll + tillage) resulted in significantly faster wheat development. This corresponds to higher daily average soil temperature at 5 cm on 8 out of 22 days for these two treatments compared to the rest (Figure 2). Vaisman et al. (2011) also reported faster development in wheat following tillage, compared to blade rolled green manure. In their study, one tillage pass in spring eliminated wheat plant development delays. The blade roll + tillage treatment in the present study also tended to be more advanced than the blade roll treatment in all site-years, although differences were not always significant.

Table 9. Effect of green manure management on wheat Haun stage at **Carman (2011, 2012)** and **Lethbridge (2011, 2012).**

	Carman			Lethbridge	
	2011		2012	2011	2012
Treatment	Date 1	Date 2	Date 1	Date 1	Date 1
	----------	----------	Haun stage	----------	----------
Tillage	2.1	4.0 **a**†	2.3 **a**	5.7 **ab**	3.7
Blade Roll	2.1	3.1 **c**	1.8 **b**	4.3 **b**	3.6
Blade Roll + Tillage	2.1	4.1 **a**	2.1 **ab**	4.9 **ab**	3.8
Wide Blade Cultivation	2.2	3.5 **abc**	1.7 **b**	5.1 **ab**	3.5
Flail Mow	2.0	3.1 **bc**	1.7 **b**	4.8 **b**	3.7
Fallow	2.0	3.8 **ab**	-	6.7 **a**	3.8
P>F	0.8900	0.0003	0.0007	0.0052	0.0688

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey’s HSD.

4.6 Weeds

Weeds are an important limiting factor in reduced tillage organic systems; cultural practices are utilized to promote crop competitiveness and surface mulch is relied on for weed suppression. In the present study, individual weed counts were taken at the wheat 3-4 leaf stage to determine if weed density and/or composition were affected by green manure management.

4.6.1 Weed Density

Carman

At Carman, broadleaved weeds were the most abundant and important in terms of competitiveness. The effect of green manure management on total broadleaved weed density was variable. In 2011, the tillage and fallow treatments had a lower broadleaf weed density compared to wide blade cultivation, which had the highest weed density (Table 10). Wide blade cultivation appears to have stimulated smartweed (*Polygonum sp.*) germination, which comprised over 50% of the weed density for that treatment in 2011. In 2012, there was no significant green manure management effect on total broadleaf weed density at Carman (Table 11). Despite variable effects on total broadleaf weed density, there were many important effects of green manure management among individual weed species.

Dandelion, Canada fleabane (*Conyza canadensis*) and prickly lettuce (*Lactuca serriola*) were the most important weed species at Carman (Table 10 and 11). Green manure managed with the blade roller (20-45 plants m^{-2}) and flail mower (25-61 plants m^{-2}) had significantly higher dandelion density compared to tillage (0-3 plants m^{-2}) and blade roll + tillage (2-4 plants m^{-2}) in both years. Leaf proliferation of dandelion has been found to increase between periods of mowing (Sawada et. al 1982 cited in Stewart-Wade et al. 2002), partly due to increased light availability (Von Hofsten 1954 cited in Stewart-Wade et al. 2002). This may be an important reason for high dandelion populations in the flail mow and blade roll treatments. Canada fleabane density was also significantly higher in both years with the flail mower and in 1 of the 2 years with the blade roller, compared to tillage and blade roll + tillage. In 2011, prickly lettuce density was significantly higher in the flail mow treatment compared to all other treatments except the blade roller which was no different than any other treatment.

The flail mow and blade roll treatments confirm that eliminating tillage completely during green manure management can increase perennial and winter annual weed pressure. Alternatively, the wide blade cultivation treatment with an intermediate degree of soil disturbance tended to decrease dandelion, Canada fleabane, and prickly lettuce density. Although this trend was not always significant, the differences were important for agronomic productivity. All three weed species (dandelion, Canada fleabane, and prickly lettuce) were prolific and competitive. In 2011, most weeds were established before the wheat (Figure 3). According to Teasdale et al. (2007) cover crop residue has no potential impact on perennial structure survival and low impact on the growth of established weeds. Therefore, an overall trend was apparent at Carman - increasing soil disturbance decreased dandelion, Canada fleabane and prickly lettuce density. Dandelion has become the most important weed in long-term organic no-till trials (established 2008) being conducted at the same experimental farm as the present study, in Carman, MB (Caroline Halde, personal communication, February 13, 2013).

Some annual broadleaves also responded to green manure management method at Carman. In 2012, wild buckwheat (*Polygonum convolvulus*) density was significantly lower in the blade roll, flail mow and wide blade cultivation treatments (3-14 plants m^{-2}) compared to tillage (90 plants m^{-2}). A similar but non-significant trend was evident for wild mustard (*Sinapis arvensis*). Wild mustard and wild buckwheat are summer annual weeds whose germination is known to be stimulated by tillage (Ominski and Entz 2001) and were the #2 and #5 most abundant weeds, respectively, in an on-farm survey of organic farms in Saskatchewan (Knight and Shirtliffe 2003).

The effectiveness of cover crop mulch for weed management depends on the weed species present and quantity of cover crop residue. Cover crop mulches are generally more effective at suppressing small-seeded summer annual weeds and largely ineffective at suppressing perennial weeds (Mirsky et al. 2012). In non-organic cropping systems, some perennial weeds have been shown to be associated with reduced and zero tillage systems compared to conventional tillage (Blackshaw et al. 1994; Thomas et al. 2004). Therefore it can been anticipated that reducing tillage in long-term organic cropping systems which rely on cover crop mulches for weed suppression, can lead to a shift in the weed community from annual to perennial plants. Evidence of such a shift was observed in the present study and also at the Rodale Institute after just one year of organic no-till (Ryan et al. 2009). In contrast, Vaisman et al. (2011) did not report weeds as a major limiting factor in wheat following green manure termination with a blade roller, despite having relatively low cover crop biomass. Aside from quantity of cover crop residue, other factors such as field history, cultural practices and weed seed bank may also determine the type of weed species present and extent of weed competition in the year following cover crop termination.

Table 10. Effect of green manure management on total broadleaf weed density and the four predominant weed species in the spring wheat at **Carman (2011).**

Treatment	Total	Dandelion‡	Canada Fleabane‡	Prickly Lettuce	Smartweed‡
	plants m^{-2}				
Tillage	59 **b**†	3 **bc**	5 **b**	2 **b**	25 **ab**
Blade Roller	121 **ab**	20 **a**	23 **ab**	15 **ab**	18 **ab**
Blade Roll + Tillage	74 **ab**	2 **bc**	2 **b**	4 **b**	20 **ab**
Wide Blade Cultivation	154 **a**	9 **ab**	6 **ab**	5 **b**	79 **a**
Flail Mower	122 **ab**	25 **a**	38 **a**	29 **a**	2 **b**
Fallow	58 **b**	1 **c**	1 **b**	0 **b**	32 **ab**
P>F	0.0050	<0.0001	0.0067	0.0010	0.0381

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

‡ Reported means of untransformed data. Analysis performed on log10(x)+0.1 transformed data.

Table 11. Effect of green manure management on total broadleaf weed density and the four predominant weed species in the spring wheat at **Carman (2012).**

Treatment	Total	Dandelion	Canada fleabane	Wild mustard‡	Wild buckwheat
	plants m^{-2}				
Tillage	100	0 **b**†	0 **b**	42	90 **a**
Blade Roller	68	45 **a**	42 **a**	7	3 **b**
Blade Roll + Tillage	65	4 **b**	0 **b**	17	45 **ab**
Wide Blade Cultivation	44	8 **b**	34 **ab**	1	14 **b**
Flail Mower	68	61 **a**	52 **a**	4	5 **b**
Fallow	-	-	-	-	-
P>F	0.1123	<0.0001	0.0033	0.1989	0.0075

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

‡ Reported means of untransformed data. Analysis performed on log10(x) + 0.1 transformed data.

Figure 3. Carman (2011) 15 days after spring wheat seeding; green manure managed with (clockwise): tillage, blade roller, blade roll + tillage, wide blade cultivation, flail mower and fallow with no cover crop.

Lethbridge

At Lethbridge, weed dynamics were markedly different than at Carman. Total weed density, including grasses, was hardly affected by green manure management (Table 12). In 2012, the only difference in total weed density was between the tillage treatment and fallow treatment, with fallow experiencing lower weed density. The most prevalent and problematic weed at Lethbridge was volunteer barley. Volunteer barley density tended to be greater in the blade roll (12-14 plants m^{-2}) and blade roll + tillage treatments (10-25 plants m^{-2}) compared to all other treatments (0-10 plants m^{-2}) although the differences were not always significant. Other weeds present were mainly summer annuals such as round leaved mallow (*Malva pusilla*), redroot pigweed (*Amaranthus retroflexus*) and wild oat (*Avena fatua*).

The treatments which involved blade rolling at initial termination (blade roll and blade roll + tillage) resulted in more volunteer barley present in the spring wheat. It is possible that the blade rolling operation was not completely effective at killing the barley in the green manure crop at initial termination. If the barley did not desiccate and die rapidly, it is possible that the seeds matured on the rolled plant, leaving viable seed to germinate and become a weed the next year. Previous research has considered the efficacy of various mechanical methods for effectively killing cover crops (Creamer and Dabney 2002; Ashford and Reeves 2003; Kornecki et al. 2009). Roller design and plant growth stage have been identified as key factors in success of termination. The roller at Lethbridge was smaller and lighter than the roller used at Carman which may have resulted in less effective crimping of the stems. Visual notes also confirmed that the blade roll treatments took longer to desiccate than the other treatments. The presence of volunteer barley in all treatments except fallow also suggests that plant staging at termination may have been a factor. In cereal crops, use of the blade roller at the early milk stage or later has been found to achieve a kill rate similar to that of herbicide termination (Ashford and Reeves 2003). Results from Lethbridge highlight the importance of effective termination to avoid volunteer weed pressure in subsequent crops.

Overall, weed pressure at Lethbridge did not appear to be a limiting factor to wheat performance. Prior to implementation of this experiment, the Lethbridge site was under long-term conventional management with herbicide use. Herbicide use and inclusion of glyphosate tolerant crops tends to lower the weed seed bank while organic management tends to increase seed bank numbers (Gulden and Shirtliffe 2009). Significantly greater grass and broadleaf weed seedbank densities were observed in organic rotations in Nebraska compared to conventional rotations (Wortman et al. 2010). Thus it is possible that a low weed seed bank relative to the Carman site and differences in prior management contributed to low overall weed pressure at Lethbridge. Green manure residue levels were higher at Lethbridge compared to Carman (Table 7). This may have improved weed suppression although they still did not exceed those reported in the literature required for complete weed suppression. Therefore, lower weed seed bank may have been the most important factor affecting weed density in wheat the year following green manure termination at Lethbridge.

The Lethbridge site provides evidence for the use of these implements in conventional cropping systems or those in transition to organic, with a history of herbicide use and lower weed seed banks. Results from Lethbridge suggest that in these circumstances cover crops can be grown and managed periodically without tillage or herbicide, with no significant increase in weed pressure the following year.

Table 12. Effect of green manure termination method on total weed density and volunteer barley density during the wheat production year at **Lethbridge (2011, 2012).**

	2011		2012	
Treatment	Total weeds	Volunteer Barley	Total Weeds	Volunteer Barley
	---- plants m^{-2} ----			
Tillage	43	10 **ab**†	49 **a**	2 **b**
Blade Rolling	33	14 **ab**	26 **ab**	12 **a**
Blade Roll + Tillage	56	25 **a**	35 **ab**	10 **b**
Wide Blade Cultivation	40	3 **b**	22 **ab**	2 **b**
Flail Mower	37	6 **b**	17 **ab**	1 **b**
Fallow	38	0 **b**	9 **b**	0 **b**
P>F	0.5304	0.0011	0.0158	0.0002

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

4.6.2 Wheat and Weed Biomass

Weed biomass measurements were taken in addition to weed density because the relative size and staging of individual weed species present in the experiment have important implications for competitive ability, regardless of population density. For example, the perennial and winter annual weed species present at the time of density sampling were well established and more competitive with the wheat relative to the annual species in the seedling stage. Weed biomass measurements indicate the outcome of weed suppression potential and crop-weed competition. In organic systems, where weeds co-exist with the crop, weed biomass plays an important role in nutrient uptake and partitioning (Section 4.7).

Weed biomass measurements were taken at wheat stem elongation: at this development stage, there is a sharp increase in demand for assimilates and nutrients and the maximum number of kernels per head is determined (Miralles and Slafer 1999). Therefore, inter-and intra-plant competition for nutrients is important and will affect final yield.

At Carman 2011, green manure management had a significant effect on wheat biomass, weed biomass and percent weed biomass (Table 13). Total weed biomass at stem elongation far exceeded total wheat biomass in all treatments, ranging from 73-98% of total biomass. This level of weed competition was evident throughout the growing season as a result of an extremely wet spring and delayed seeding that favoured established perennial and winter annual weeds (Figure 3). It is of particular interest to note that a record 2.9 million acres went unseeded in Manitoba in 2011 due to excess moisture, up from the previous record of 1.5 million acres in 2005 (source: Manitoba Agricultural Services Corporation). The wet conditions also allowed for a wide window for weeds to get established. Perennial weeds pose a particular challenge in organic zero till since it is unlikely that any amount of crop residue mulch can suppress them (Carr et al. 2011). Total weed biomass was considered large, ranging from 1077-2845 kg ha^{-1}. Total weed biomass was greatest in the flail mow and blade roll treatments. Although weed biomass in these treatments was not significantly greater than for the other green manure treatments, these were the only treatments that resulted in greater weed biomass than in the fallow treatment. Lower weed densities have been found in fallow-wheat rotations compared to continuous cropping (Blackshaw et al. 1994). The extreme weed pressure at Carman 2011 across treatments supported the decision to terminate the wheat crop and re-plant the plots to buckwheat.

At Carman 2012, weed biomass was numerically and proportionately lower compared to 2011. A warmer, drier winter and spring enabled the wheat to be planted earlier and the crop was able to establish and compete better with the weeds. At stem elongation, green manure managed with the flail mower had significantly greater % weed biomass (72%) compared to all other treatments (14-38%), except the blade roller (62%). This trend was also evident at the hard dough sampling time (Table 16). Wheat following green manure managed with wide blade cultivation also tended to have high weed biomass, but had significantly more wheat biomass at hard dough (6567 kg ha^{-1}) than wheat following blade rolled (2546 kg ha^{-1}) or flail mowed (2916 kg ha^{-1}) green manure. This is likely due to greater nitrogen availability in the wide blade treatment (Table 19) which allowed the wheat to be more competitive. The predominant weed species at Carman 2012 was Canada fleabane which persisted competitively throughout the growing season, especially in the flail mow treatment (Figure 4).

In contrast to the findings at Carman, Vaisman (2010) found no overall effect of green manure tillage regime on weed biomass at the soft dough stage of wheat the following year. However, in a Pennsylvania study, total biomass in organic no-till corn was predominately weeds at maturity following a hairy vetch cover crop (Drinkwater et al. 2000). In that study, tillage at cover crop termination and in row cultivation was required to maintain corn yields and low weed biomass, but tillage was successfully eliminated at corn planting. More recent studies have found that optimal biomass levels of >9000 kg ha^{-1} can provide excellent weed control but substantial year to year variation in biomass production suggests that supplementary weed control may be needed in some years (Reberg-Horton et al. 2011).

Table 13. Effect of green manure management on wheat and weed biomass at the stem elongation stage of wheat during the wheat production year at **Carman (2011, 2012).**

Treatment	2011 Wheat	2011 Weed	Weed %	2012 Wheat	2012 Weed	Weed %
	-------- kg ha^{-1} -------		--- % ---	--------- kg ha^{-1} ------		--- % ---
Tillage	531 **a**†	1537 **ab**	73 **a**	1701 **a**	283 **c**	14 **c**
Blade Rolling	53 **c**	2845 **a**	98 **b**	422 **b**	723 **b**	62 **ab**
Blade Roll + Tillage	408 **a**	1353 **ab**	77 **a**	1317 **a**	396 **bc**	23 **c**
Wide Blade Cultivation	144 **bc**	2515 **ab**	93 **b**	718 **b**	431 **bc**	38 **bc**
Flail Mower	77 **c**	2790 **a**	97 **b**	456 **b**	1145 **a**	72 **a**
Fallow	401 **ab**	1077 **b**	74 **a**	-	-	-
P>F	<0.0001	0.0036	<0.0001	<0.0001	<0.0001	<0.0001

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

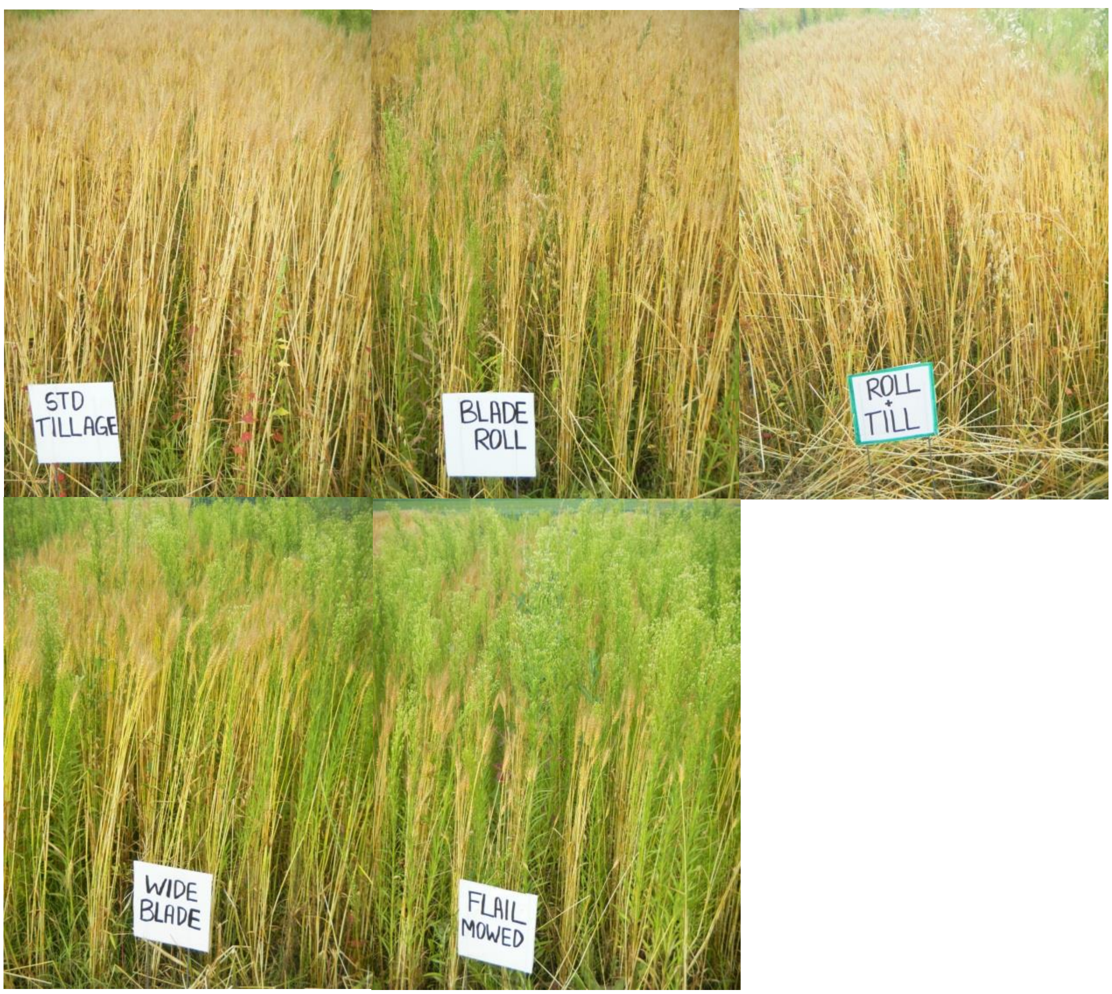


Figure 4. Carman (2012) at hard dough stage of wheat; Canada fleabane in wheat following green manure managed with (clockwise): tillage, blade roller, blade roll + till, wide blade cultivation and flail mower.

At Lethbridge, weed biomass as a percent of total biomass at stem elongation was low relative to Carman (Table 14). In 2011, weed biomass in the blade roll + till treatment was 58% of total biomass; significantly higher than all other treatments (20-27%), and likely attributable to volunteer barley as discussed previously. In 2012, % weed biomass in the blade roll treatment was 35%, significantly higher than all other treatments (7-17%) and likely attributable once again to volunteer barley.

Total wheat biomass at stem elongation tended to be higher in the tillage and fallow treatments in 2011 at Lethbridge (Table 14). This is likely due to higher soil nitrogen availability at 0-30 cm (Figure 5). In 2012, tillage treatments (tillage, blade roll + tillage and fallow) had significantly higher wheat biomass compared to the blade roller at stem elongation. This can be attributed to the significantly higher volunteer barley density in the blade roll treatment in 2012 (Table 12). Differences in wheat biomass between green manure treatments were not significant at the hard dough stage of wheat in both years (Table 16).

The lack of green manure management effect on wheat biomass at hard dough is similar to the findings of Vaisman (2010), in which perennial and winter annual weed pressure was not a major limiting factor. Results from Lethbridge support the observation from Teasdale et al. (2012); maintaining a low weed seed-bank should be a priority for the success of organic roll-killed grain production systems.

Table 14. Effect of green manure termination method on wheat and weed biomass at the stem elongation stage of wheat during the wheat production year at **Lethbridge (2011, 2012).**

Treatment	2011 Wheat	2011 Weed	2011 Weed %	2012 Wheat	2012 Weed	2012 Weed %
	--------- kg ha^{-1} -------		--- % ---	--------- kg ha^{-1} -------		--- % ---
Tillage	555 **ab**†	122	20 **b**	2299 **a**	161 **b**	7 **b**
Blade Rolling	280 **b**	110	25 **b**	1623 **c**	907 **a**	35 **a**
Blade Roll + Tillage	319 **b**	326	58 **a**	2184 **ab**	261 **b**	11 **b**
Wide Blade Cultivation	318 **b**	103	24 **b**	1775 **bc**	305 **b**	14 **b**
Flail Mower	297 **b**	77	27 **b**	1861 **bc**	370 **b**	17 **b**
Fallow	703 **a**	254	24 **b**	2402 **a**	122 **b**	5 **b**
P>F	0.0030	0.1548	0.0128	<0.0001	0.0020	0.0009

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

The effect of green manure management method was also measured in the buckwheat crop seeded after the failed wheat crop at Carman in 2011. The tillage treatment produced the greatest buckwheat biomass (8421 kg ha^{-1}) and was significantly higher than the zero till treatments (2911-3095 kg ha^{-1}) but similar to the blade roll + tillage treatment (5840 kg ha^{-1}) (Table 15). Differences in biomass correspond well to the total soil and plant nitrogen present at wheat termination/buckwheat planting (Table 22). Despite substantial differences in buckwheat biomass, grain yields were similar among tillage and reduced tillage treatments (Section 4.8). Weed biomass was not significantly affected by green manure management, likely due to the tillage at planting and because buckwheat is a fast growing crop that competes well with weeds (Clark 2007).

Overall, the response of weed biomass in spring wheat to green manure management across site-years was variable. Aside from producing high biomass cover crops for weed suppression, results from the present study emphasize the effect of the cropping system and the need to maintain low weed populations. The Lethbridge site, with long term intensive herbicide use, we presume to have a lower weed population compared to the Carman site under organic management. Use of a killed cover crop mulch will not be a panacea for weed control but rather one tool along with crop rotation and other strategies (Carr et al. 2011a).

Table 15. Effect of green manure management on buckwheat and weed biomass, following wheat termination, in year 2 at **Carman (2011)**.

	Biomass	
Treatment	Buckwheat	Weed
	--------- kg ha^{-1} -------	
Tillage	8421 **a**†	707
Blade Rolling	3095 **bc**	1629
Blade Roll + Tillage	5840 **ab**	1158
Wide Blade Cultivation	4537 **bc**	1738
Flail Mower	2911 **c**	1686
Fallow	5523 **abc**	1442
P>F	0.0001	0.2331

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

Table 16. Effect of green manure termination method on wheat and weed biomass at the hard dough stage of wheat during the wheat production year at **Carman (2012)** and **Lethbridge (2011, 2012).**

	Carman			Lethbridge					
	2012			2011			2012		
Treatment	Wheat	Weed	Weed %	Wheat	Weed	Weed %	Wheat	Weed	Weed %
				-------- kg ha^{-1} --------		--- % ---	-------- kg ha^{-1} -------		--- % ---
Tillage	9014 **a**†	1249 **c**	13 **c**	10082	1648 **b**	15 **ab**	11978 **ab**	1140	9
Blade Rolling	2546 **c**	2858 **ab**	55 **a**	9614	1828 **ab**	17 **ab**	9265 **b**	2536	22
Blade Roll + Tillage	7039 **ab**	2391 **bc**	26 **bc**	6726	3900 **a**	36 **a**	9079 **b**	1791	16
Wide Blade Cultivation	6567 **b**	3149 **ab**	34 **b**	10662	757 **b**	8 **b**	11093 **ab**	703	6
Flail Mower	2916 **c**	3657 **a**	59 **a**	9769	1158 **b**	11 **b**	9814 **ab**	2183	18
Fallow	-	-	-	9261	1886 **ab**	19 **ab**	13151 **a**	25	<1
P>F	<0.0001	0.0006	<0.0001	0.1155	0.0072	0.0020	0.0067	0.1035	0.0864

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

4.7 Nitrogen Dynamics

Synchronizing green manure nitrogen release to match crop uptake remains an important goal of organic systems. Achieving adequate nitrogen supply with low disturbance termination techniques for cover crops is proving markedly more difficult (Peigne et al. 2007; Carr et al. 2011b) compared to systems with tillage. However, manipulation of green manure residue management may better synchronize green manure nitrogen release with subsequent crop demand (Cherr et al. 2006). An important objective of this experiment was to determine the effect of green manure management on nitrogen dynamics. To achieve this, soil nitrate-N samples and crop biomass nitrogen samples were taken throughout the duration of the experiment.

4.7.1 Green Manure Year 1

4.7.1.1 Soil Nitrogen

Residual soil nitrate levels at the time of planting the green manure in Carman would be considered high in 2011 (74 kg ha^{-1} from 0 to 60 cm) and very low in 2012 (20 kg ha^{-1} from 0 to 60 cm), according to the Manitoba Soil Fertility Guide. In Lethbridge, anecdotal reports suggest that underground lateral movement of nitrate-rich groundwater from a neighbouring beef cattle composting site was responsible for an excessive level of residual nitrate in 2012 (Table 17). Although soil tests were not taken in 2011, we assume the entire site has high residual soil nitrate levels. In spite of being very high from an agronomic perspective, these residual nitrate levels were less than the regulatory threshold of 157 kg ha^{-1} from 0-60 cm according to Manitoba Water Stewardship. A survey of 5% of organic farms in Saskatchewan showed median soil nitrogen levels (nitrate and ammonium) ranging from 37 to 49 kg ha^{-1} from 0-45 cm. A higher median soil nitrogen level was reported by Entz et al. (2001) for organic farms in Manitoba and North Dakota (92 kg ha^{-1} for nitrate-N only from 0-60 cm).

Table 17. Soil nitrate-N at the time of seeding the green manure at different depths for **Carman** and **Lethbridge**.

Site-year	0-30	30-60	60-90	90-120	0-60	Total‡	Rating§
	---------------- kg ha^{-1} ----------------				------ kg ha^{-1} -----		
Carman 2010	36	38	22	18	74	114	High
Carman 2011†	-	-	-	-	20	-	Very low
Lethbridge 2010	-	-	-	-	-	-	-
Lethbridge 2011	43	81	184	-	124	308	Very High

† At Carman 2011, soil was sampled from 0-15 and 15-60 cm.
‡ Total soil nitrate calculated from 0-120cm for Carman 2010 and 0-90 cm for Lethbridge 2011.
§ Rating based on soil test nitrate-N in top 0-60 cm according to the Manitoba Soil Fertility Guide.

In temperate humid regions, the greatest potential for leaching of nitrate-N occurs during the fall and winter and before planting of the main crop in spring (Brady and Weil 2008). Moreover, leaching is affected by water volume and concentration of nitrate, since this is the period when there is not plant uptake of water or nitrate. Soil nitrate-N was measured in late fall of the green manure year at Carman 2011 to determine if green manure management affected leaching potential. Results indicate that green manure management did not significantly affect soil nitrate-N present in the soil profile in the fall after green manure termination (Table 19). However, soil nitrate-N tended to be higher in treatments that involved soil disturbance at initial termination (tillage and wide blade cultivation). For example, nitrate-N from 0-120 cm was 80 and 81 kg ha^{-1} for the tillage and wide blade treatments compared to 59 and 74 kg ha^{-1} for the blade roll and flail mow treatments, respectively. The elevated levels of nitrate-N in the soil disturbance treatments may increase leaching risk. The tillage pass for the blade roll + tillage pass did not occur until after soil sampling; therefore, soil nitrate-N levels were similar. Across all treatments, nitrate-N levels would be considered low to moderate, and well below Manitoba's regulatory threshold. Vaisman et al. (2011) consistently found higher levels of nitrate-N present following tilled green manure compared to blade rolled. Soil nitrate-N levels in their study ranged from 101-264 kg ha^{-1} in fall after green manure termination.

4.7.2 Spring Wheat Year 2

4.7.2.1 Soil Nitrogen

Carman 2011

At Carman 2011, the green manure crop managed with tillage alone provided significantly more soil nitrate-N from 0-120 cm (190 kg ha^{-1}) at spring seeding compared to all other green manure treatments (Table 18). Tillage has been shown to increase soil nitrate-N concentrations following green manure incorporation as compared to no-till (Drinkwater et al. 2000; Vaisman 2010; Sullivan 2012). A 2695 kg ha^{-1} wheat crop will take up 85-105 kg ha^{-1} of nitrogen (Manitoba Soil Fertility Guide); therefore, prior to planting, the wide blade cultivation (98 kg ha^{-1}) and blade roll + tillage (127 kg ha^{-1}) treatments appear to have already produced adequate levels of nitrogen to meet crop demand. The three green manure treatments with soil disturbance (tillage, blade roll + tillage and wide blade) had similar levels of nitrate-N within the 0-30 cm soil depth, and were greater than the blade roll and flail mow treatments ($P<0.01$). This is likely due to faster mineralization of the green manure residue where it has been stimulated by soil disturbance, due to increased exposure to soil microorganisms (Cogle et al. 1987). However soil nitrate-N levels from 30-60, 60-90 and 90-120 cm were also elevated in the tillage treatments, indicating potential downward movement between fall and spring.

The differences in total soil nitrate-N (0-120 cm) between treatments remained similar from wheat seeding to wheat termination at Carman 2011. For example, total soil nitrate at wheat termination/buckwheat planting in the tillage treatment (189 kg ha^{-1}) remained 2-3x greater than the blade roll treatment (63 kg ha^{-1}) and flail mow treatment (70 kg ha^{-1}) despite no significant difference in wheat biomass N uptake (Table 20). Therefore it appears that mineralization occurred too readily in the tillage treatment; in advance and in excess of crop demand and leaving nitrate susceptible to denitrification and leaching losses. Drinkwater et al. (2000) also found that green manure incorporated with primary tillage prior to corn planting increased season long mineral N concentration from 5-20 cm compared to mowed green manure, and peaked long before corn reached its exponential growth phase.

Following buckwheat harvest, total soil nitrate-N levels (0-120 cm) were not significantly different across treatments, ranging from 34-55 kg ha^{-1}. This also corresponds to the time of fall rye planting. Despite no differences in soil nitrate-N availability at fall rye planting, delayed mineralization in the reduced tillage treatments may result in higher biomass nitrogen uptake in year 3 (Section 4.7.2.2). Total soil nitrate-N (0-120 cm) at fall rye harvest was very low across all treatments, ranging from 11-16 kg ha^{-1}.

Carman 2012

Prior to spring wheat production at Carman 2012, soil nitrate levels were measured in fall of 2011 after green manure termination. There was no significant effect of green manure management on soil nitrate-N at any depth (Table 19).

The following spring in Carman 2012, soil nitrate-N levels from 0-120 cm in the blade roll + tillage (93 kg ha^{-1}), wide blade cultivation (94 kg ha^{-1}) and tillage (126 kg ha^{-1}) treatments were greatest and not significantly different from each other. A combination of rolling plus tillage (Vaisman et al. 2011), as well as undercutting (Wortman et. al 2012) have been shown to provide similar or higher nitrate-N levels compared to tillage (with a disc) for green manure management. However, significantly greater nitrate-N was detected from 60-90 cm and 90-120 cm in the tillage treatment, indicating downward movement and higher risk of leaching below the root zone.

Reasons for less soil nitrate-N in the zero till treatments (blade roll and flail mow) at spring wheat planting in both years at Carman could include delayed mineralization of the green manure residue (Peigne et al. 2007), due to less soil contact and lower soil temperature (Figure 2), reduced mineralization of soil organic matter in absence of tillage (Drinkwater et al. 2000) and ammonia volatilization from surface applied green manure residue (Janzen and McGuinn 1991). A recent investigation by Engel et al. 2013 under dry field conditions, typical of summer in the Northern Great Plains, found that volatilization losses after a mowed field pea green manure are small, representing only 0.3-0.5% of the plant biomass N. The wide blade cultivation treatment could also be considered to have a ‘surface applied residue’ since the green manure was not

Table 18. Effect of green manure termination method on soil nitrate-N in the depths 0-30 cm, 30-60 cm, 60-90 cm, 90-120 cm and total (0-120 cm) during the wheat crop production year at **Carman (2011).**

	May					June					August				
	Wheat					Wheat/Buckwheat					Buckwheat/Fall Rye				
	Seeding					Harvest/Planting					Harvest/Planting				
Treatment	0-30	30-60	60-90	90-120	Total	0-30	30-60	60-90 ‡	90-120	Total	0-30	30-60	60-90	90-120	Total
	------- kg ha^{-1} -------														
Tillage	76 a†	49 a	37 a	29 a	190 **a**	83 a	45 a	37 a	25 a	189 **a**	20	14	11 a	16	55
Blade Rolling	28 b	21 c	15 b	13 c	78 **cd**	28 c	12 c	11 d	11 b	63 **d**	14	8	6 ab	6	35
Blade Roll + Tillage	48 a	31 bc	25 ab	24 abc	127 **bc**	56 ab	27 b	21 b	18 a	123 **b**	17	9	7 ab	10	42
Wide Blade	37 ab	22 c	22 ab	16 bc	98 **cd**	34 bc	19 bc	19 bc	18 a	90 **bcd**	14	8	6 b	8	34
Flail Mower	17 b	18 c	16 b	15 bc	66 **d**	30 c	12 c	13 cd	15 ab	70 **cd**	15	9	6 ab	8	39
Fallow	61 ab	39 ab	31 a	25 ab	156 **ab**	49 abc	24 b	30 ab	22 ab	108 **bc**	14	8	7 ab	12	41
P>F	0.0037	<0.0001	0.0012	0.0023	<0.0001	0.0007	<0.0001	<0.0001	0.0152	<0.0001	0.0802	0.1308	0.0509	0.1589	0.2096

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

‡ Reported means of untransformed data. Analysis performed on log10(x) transformed data.

Table 19. Effect of green manure termination method on soil nitrate-N in the depths 0-30 cm, 30-60 cm, 60-90 cm, 90-120 cm and total (0-120 cm) during the wheat crop production year at **Carman (2012).**

	October 2011					May 2012					August 2012				
	Green Manure					Wheat					Wheat				
	Fall					Seeding					Harvest				
Treatment	0-30	30-60†	60-90	90-120	Total	0-30	30-60	60-90	90-120	Total	0-30	30-60§	60-90§	90-120	Total
	------- kg ha^{-1} -------														
Tillage	39†	17	11	15	81	60 **a**‡	31	19 **a**	17 **a**	126 **a**	4.5	2.8 **ab**	3.4	3.4	14
Blade Rolling	22	17	9	12	58	26 **c**	19	9 **b**	10 **b**	63 **b**	2.8	2.2 **b**	3.4	3.9	12
Blade Roll + Tillage	32	11	7	8	59	47 **b**	26	11 **b**	10 **b**	93 **ab**	5.0	4.5 **a**	3.4	4.5	17
Wide Blade	38	25	9	8	80	44 **b**	26	15 **ab**	10 **b**	94 **a**	5.6	2.8 **ab**	2.2	3.9	15
Flail Mower	34	20	9	10	74	26 **c**	17	9 **b**	11 **b**	62 **b**	3.4	2.8 **ab**	2.8	3.9	13
P>F	0.4097	0.7972	0.6331	0.3272	0.5142	<0.0001	0.0461	0.0022	0.0044	0.0006	0.0562	0.0262	0.5437	0.7087	0.1951

† Reported means of untransformed data. Analysis performed on sin(x) transformed data.

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

§ Data would not conform to normality.

incorporated into the soil. The greater mineralization following wide blade cultivation as compared to blade rolled or flail mowed can likely be explained by stimulated decomposition of root tissue and mineralization of indigenous soil organic matter. Substantial amounts of legume N are allocated to the below-ground biomass (Biederbeck et al. 1995).

Differences between treatments were no longer significant following harvest of the spring wheat in 2012 (Table 19). In fact, total soil nitrate-N levels (0-120 cm) were very low across all treatments (12-17 kg ha^{-1}). In organic cropping systems, green manure crops are generally expected to provide nitrogen to two subsequent cash crops (Natural Systems Agriculture 2010). Vaisman (2010) measured soil nitrate-N and found that total soil nitrate-N increased from 48 to 131 kg ha^{-1} and from 87 to 159 kg ha^{-1} in the blade rolled treatment and tilled treatments respectively, from the soft dough stage of wheat in year 2 to spring of year 3. Thus, in her study, mineralization increased soil nitrate-N levels sufficiently to meet demands of the second cash crop. In the present study, a fall rye crop was successfully established and harvested in year 3 after the green manure crop for the first replication of the experiment at both locations (Section 4.10).

Lethbridge 2011

At Lethbridge, soil nitrate-N samples were taken during the wheat production year in 2011 only (Figure 5). At stem elongation, the fallow treatment (with no green manure) had significantly more soil nitrate-N (104 kg ha^{-1}) from 0-30 cm compared to all other treatments (33 kg ha^{-1}), except tillage (63 kg ha^{-1}). Standard fallow practices are known to stimulate mineralization of indigenous soil organic matter and increase available soil nitrogen, which has also led to increased leaching compared to continuous cropping (Campbell et al. 2006). Land area reported to be in summerfallow has declined from 2001 to 2011 on the Canadian prairies (Statistics Canada 2006 and 2011), since alternatives such as the inclusion green-manure legumes in rotation (Biederbeck et al. 1995) or continuous cropping are more sustainable and economical alternatives to fallow-wheat cropping systems in the Northern Great Plains.

The greater soil nitrate-N in the fallow and tillage treatments corresponded to greater wheat biomass at stem elongation (Table 14) but no significant difference in biomass was observed at the hard dough stage (Table 16). The lack of significant difference in wheat biomass at the hard dough stage of wheat could be due to increased mineralization in low disturbance green manure treatments throughout the growing season. Sullivan (2012) took soil samples from this same experiment at the stem elongation stage and measured the amount of N mineralized (N_{min}) from 0-15 cm over a 4 week period. Sullivan (2012) found that N_{min} was significantly greater in the rolled treatment (18.1 kg ha^{-1}) compared to the tillage treatment (7.6 kg ha^{-1}). Similarly, a study in Pennsylvania found that N-mineralization potential at 0-5 cm was two to threefold greater in soils where green manure residue was left on the soil surface compared to intensive tillage (Drinkwater et al. 2000). Increased mineralization potential following zero till green manure represents an important source of nitrogen that could be synchronized with crop uptake during the growing season. This would be reflected in substantial biomass accumulation and N content but not necessarily with high concentrations of nitrate-N in soil samples. Achieving synchrony between nitrogen release and crop uptake provides both agronomic and environmental benefits.

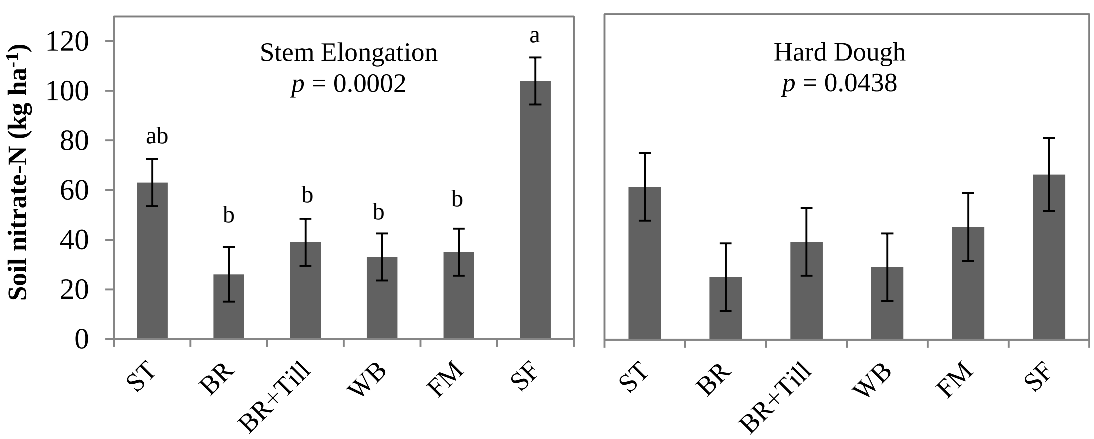


Figure 5. Effect of green manure termination method on soil nitrate-N from 0-30 cm during the wheat crop production year at **Lethbridge (2011).** Error bars indicate standard error of the mean. ST=standard tillage, BR=blade roll, BR+Till=blade roll plus tillage, WB=wide blade cultivation, FM=flail mow, SF=standard fallow.

4.7.2.2 Wheat and Weed Biomass Nitrogen

Total biomass nitrogen uptake values observed at Carman are within the range reported in previous studies examining organic wheat following a green manure. Total biomass (main crop + weeds) nitrogen uptake at Carman ranged from 41-70 kg ha^{-1} for spring wheat and 37-129 kg ha^{-1} for buckwheat (Table 20 and 21). Sullivan (2012) reported wheat nitrogen uptake values from 38-90 kg ha^{-1} in Saskatchewan while Vaisman (2010) reported higher values in Carman, ranging from 95-205 kg ha^{-1}. In contrast to these previous studies, weed competition was an important factor in this study and thus competition for nitrogen between crop and weeds was also important. Biomass nitrogen was not measured at Lethbridge due to the excessively high quantities of soil nitrate-N levels observed at depth (data not reported), which likely masked the nitrogen contribution of the green manure and subsequent response in the main crop.

Carman 2011

At Carman 2011, total N uptake in wheat at stem elongation ranged from 47-82 kg ha^{-1} (Table 20) and was greatest in the tillage treatment. Total nitrogen uptake in wheat and weeds for the tillage treatment was significantly greater than the blade roll + tillage treatment, but similar to all other treatments. The lower N uptake in the blade roll + tillage treatment can be explained by the relatively smaller weed biomass and weed biomass N uptake compared to the rest. A more profound response is the allocation of biomass nitrogen between wheat and weeds. Percent weed biomass nitrogen was significantly greater in the blade roller, flail mower and wide blade cultivation treatments compared to the tillage and blade roll + tillage treatments. The latter two treatments included spring tillage, suggesting that spring tillage is an important tool to manage weeds which compete for available nitrogen. It could be anticipated that a spring tillage pass in the flail mow and wide blade cultivation treatments would have reduced weed growth and subsequent nitrogen capture, as observed in the blade roll + tillage treatments. That being said, in April and May, Carman received 27% more precipitation than normal. This extended wet period led to early weed growth and subsequent nitrogen uptake. In all treatments, weeds captured more than half of total biomass nitrogen (63-98%), which supported the decision to terminate the wheat and re-plant to buckwheat.

The effect of green manure management with tillage persisted in the buckwheat crop. The effect of green manure management on buckwheat biomass and total biomass (buckwheat + weeds) N uptake was highly significant ($P<0.0001$); green manure managed with tillage alone resulted in 192-350% more nitrogen uptake in the buckwheat crop compared to all other treatments (Table 20). Drinkwater et al. (2000) also observed significantly greater nitrogen uptake in above ground corn biomass following vetch incorporated with tillage compared to mowed vetch. In the present study, treatments with intermediate soil disturbance (blade roll + tillage, wide blade and fallow) also tended to have greater buckwheat and total N uptake compared to zero till treatments, although differences were not significant.

Of note, is that the wheat and weed biomass, terminated by roto-tilling, was mixed with soil and left in the plots. Differences in residue quality between treatments, as a result of varying ratios of wheat and weeds, may also have affected mineralization rate. For example, a recent study of three weed species found that tall weeds (20 cm) with a C:N ratio of ~20 may initially immobilize N when mixed with soil (Lindsey et al. 2013).

Carman 2012

At Carman 2012, zero till green manure management (blade roll and flail mow) significantly reduced total biomass N uptake (wheat + weeds) compared to tillage at stem elongation (Table 21). Additionally, the majority of the nitrogen in the zero till treatments was taken up by weeds (61-69%). The blade roll + tillage (27 kg ha^{-1}) and wide blade cultivation (23 kg ha^{-1}) treatments significantly increased wheat N uptake compared to zero till treatments (10-11 kg ha^{-1}), but still lagged behind the tillage treatment (41 kg ha^{-1}). The maximum rate of uptake of nitrogen in spring wheat occurs during flowering (Malhi et al. 2006); therefore, differences in biomass N may be overcome if delayed mineralization in reduced tillage treatments results in greater nitrogen availability between stem elongation and flowering.

At the hard dough sampling stage, total N uptake was not affected by green manure management. However, the allocation of biomass nitrogen between wheat and weeds remained important. Wheat N uptake was significantly greater in the tilled treatment (60 kg ha^{-1}) compared to all other treatments (13-30 kg ha^{-1}). Wheat N uptake was reduced by 50 and 75% in the reduced tillage (blade roll + tillage and wide blade cultivation) and zero tillage (blade roll and flail mow) treatments, respectively. The reduction in wheat N uptake can be attributed to increased competition with weeds; weeds captured 45 and 71% of total biomass N in the reduced tillage and zero tillage treatments, respectively. Similarly, in the Eastern USA, the fate of available N following till vs. zero till termination of hairy vetch also varied; weed N uptake accounted for greater than 40% of above ground nitrogen uptake in the zero till treatments (Drinkwater et. al 2000).

Results from both years at Carman showed that weed competition for nitrogen uptake was an important factor. Other studies investigating reduced till organic systems in Canada have not reported differences in nitrogen uptake between weeds and the main crop. For example, Vaisman (2010) reported that weed biomass (and biomass N) accounted for only 6-14% of total biomass (and biomass N) in 1 of 3 site-years but was not affected by blade rolling or tilling the green manure. In their study, weed biomass was not measured separately in the other years because it was estimated to comprise <10% of total biomass. Likewise, weeds were not an important factor in the Saskatchewan study comparing the blade roller and flail mower with tillage, but all treatments received spring tillage prior to wheat planting (Sullivan 2012). Results from the present study and previous studies suggest that the impact of weed competition in organic reduced tillage systems is related to differences in weed seed bank as well as cultural practices such as management history and time of seeding. Data from the present study provides important information on the impact of weed competition on nitrogen dynamics in reduced till organic systems that have not previously been reported in Canada.

Table 20. Effect of green manure termination method on wheat biomass nitrogen at stem elongation and buckwheat and weed biomass nitrogen at harvest during year 2 at **Carman (2011).**

	Wheat				Buckwheat		
Treatment	Wheat	Weeds	Total	% Weeds	Buckwheat	Weeds	Total
	--------------- kg ha^{-1}	--------------		----%----	--------------- kg ha^{-1}	--------------	
Tillage	25 **a**†	56	82 **a**	68 **b**	115 **a**	13	129 **a**
Blade Rolling	1 **d**	48	49 **ab**	97 **a**	22 **b**	15	37 **b**
Blade Roll + Tillage	14 **b**	33	47 **b**	71 **b**	43 **b**	13	55 **b**
Wide Blade Cultivation	5 **cd**	55	60 **ab**	92 **a**	35 **b**	19	55 **b**
Flail Mower	2 **cd**	47	49 **ab**	96 **a**	18 **b**	19	38 **b**
Fallow	11 **bc**	34	51 **ab**	63 **b**	52 **b**	16	67 **b**
P>F	0.0037	0.0674	0.0294	<0.0001	<0.0001	0.8321	<0.0001

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

Table 21. Effect of green manure termination method on wheat and weed biomass nitrogen at the stem elongation and hard dough stage of wheat in the wheat production year at **Carman (2012)**.

	Stem elongation				Hard Dough			
Treatment	Wheat	Weeds	Total	% Weeds	Wheat	Weeds	Total	% Weeds
	-------------- kg ha^{-1}	--------------		----%----	----------- kg ha^{-1}	---------		----%----
Tillage	41 **a**†	6 **c**	46 **a**	13 **c**	60 **a**	11 **b**	70	18 **b**
Blade Rolling	11 **c**	16 **ab**	25 **b**	61 **ab**	13 **b**	30 **a**	43	71 **a**
Blade Roll + Tillage	27 **b**	9 **bc**	36 **ab**	24 **c**	29 **b**	23 **ab**	51	43 **ab**
Wide Blade Cultivation	23 **b**	12 **bc**	35 **ab**	34 **bc**	30 **b**	25 **ab**	55	46 **ab**
Flail Mower	10 **c**	22 **a**	32 **b**	69 **a**	14 **b**	27 **ab**	41	65 **a**
Fallow	-	-	-	-	-	-	-	-
P>F	<0.0001	0.0010	0.0021	<0.0001	0.0008	0.0471	0.0918	0.0006

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

4.8 Nitrogen Availability

To elicit the effect of green manure management on nitrogen availability, regardless of sink (crop, weeds or soil), a nitrogen availability index was calculated. Nitrogen availability was calculated as total soil nitrate from 0-120 cm plus biomass nitrogen at each sampling period for Carman 2011 and Carman 2012 (Table 22).

At Carman 2011, the tillage treatment had significantly more nitrogen present in the system compared to all other treatments. At wheat termination, the tillage treatment had 271 kg ha^{-1} of nitrogen, followed by the fallow system (182 kg ha^{-1}), which was not significantly different than blade roll + tillage (169 kg ha^{-1}), wide blade cultivation (151 kg ha^{-1}) or flail mower (119 kg ha^{-1}) treatments. The blade roller (100 kg ha^{-1}) had significantly less nitrogen than the tillage and fallow treatments. At buckwheat harvest, tillage again had significantly more nitrogen present in the system (199 kg ha^{-1}), compared to all other treatments (72-108 kg ha^{-1}). However, greater nitrogen availability in the tillage system did not result in greater grain yield (Section 4.9). Consistently greater nitrogen availability in the tillage treatment can be attributed to higher mineralization of the incorporated green manure and indigenous soil organic matter, stimulated by repeated tillage operations. Reducing tillage intensity with green manure management through a combination of blade rolling + tillage or wide blade cultivation reduced nitrogen availability by 62 and 56%, respectively, compared to tillage. Conversely, nitrogen availability was increased by 69 and 51% with these methods, compared to blade rolled green manure.

In the fallow treatment, favorable conditions in year 1 (soil moisture retention, repeated tillage) were conducive to rapid mineralization of indigenous soil organic matter. Evidently, this can lead to a short term increase in nitrogen availability, but fallow practices can lead to long term soil degradation. In a survey of organically managed farms in Saskatchewan, 18 of 60 fields were reported to be in a fallow rotation (Knight et al. 2010).

At Carman 2012, total nitrogen was not significantly affected by green manure management (Table 22). However, treatments with soil disturbance tended to have greater nitrogen availability compared to zero till treatments. While green manure biomass production was similar for both 2010 and 2011 experiments (Table 6), total nitrogen during the 2012 wheat crop year was markedly lower than 2011. Reasons for this are as follows. First, background soil nitrogen levels were lower in this field compared to 2011 (Table 17). Second, dry conditions prevailed from fall 2011 to fall 2012 (Table 1), thus reducing mineralization.

Results from both years at Carman showed that although differences were not always statistically significant, green manure managed with tillage always tended to have greater nitrogen availability during the time frame of this study than less tillage intensive systems. Green manure managed without any soil disturbance (the blade roller and flail mower), always tended to have the least available nitrogen. Moderate levels of soil disturbance (blade roll + tillage and wide blade cultivation) had intermediate levels of nitrogen. These findings are consistent with previous studies investigating surface applied legume residue. For example, Vaisman et al. (2011) found less available N following green manure terminated with a blade roller compared to tillage in 2 years at Carman. Mohr et al. (1999) also observed less available N following herbicide terminated alfalfa compared to tillage at 4 site-years in Manitoba. These differences persisted until the second spring after alfalfa termination at one site-year. In the present study differences in nitrogen availability were no longer evident by the end of the second growing season (Section 4.10).

It is a general consensus that annual green manure legumes can provide adequate N for at least one subsequent cash crop under conventional tillage practices (Drinkwater et. al 1999); however the challenge remains on how best to strategically reduce tillage and maintain adequate levels of nitrogen availability. In the present study, managing an annual green manure with blade rolling + tillage or wide blade cultivation appears most promising. One of the reasons for this is that despite sometimes less soil nitrogen availability in these treatments, nitrogen uptake (Table 20 and 21) and yield (Table 23) in subsequent crops is similar compared to the standard practice of tillage. Thus, managing green manure with these reduced tillage strategies ensures that nitrogen requirements of the crop are met and risk of highly mobile nitrate-N being lost to the environment is minimized.

Table 22. Effect of green manure termination method on total plant and soil nitrogen† in year 2 and 3 at **Carman (2011)** and year 2 at **Carman (2012)**.

Treatment	2011			2012
	Year 2		Year 3	Year 2
	Wheat termination	Buckwheat harvest	Fall Rye Harvest	Wheat Harvest
	---------------------- kg ha^{-1}	----------------------		--- kg ha^{-1} ---
Tillage	271 **a** ‡	199 **a**	52	84
Blade Roller	100 **c**	72 **b**	43	55
Blade Roll + Tillage	169 **bc**	97 **b**	52	69
Wide Blade Cultivation	151 **bc**	89 **b**	38	70
Flail Mower	119 **bc**	76 **b**	41	53
Fallow	182 **b**	108 **b**	42	-
P>F	<0.0001	<0.0001	0.3068	0.0874

† Total nitrogen was calculated by adding total soil nitrate (0-120cm from Tables 18 and 19) and above ground crop biomass nitrogen at harvest (From Tables 20 and 21).
‡ Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

4.9 Grain Yield

Ensuring the short term economic success of green manure systems is an important goal and will likely remain this way regardless of additional long term soil benefits achieved with reduced tillage management. Measuring main crop yield and making comparisons between green manure management treatments provides one way of measuring the economic viability of reduced tillage green manure management and subsequently the likelihood of adoption by farmers. Other considerations should include labour and energy requirements.

Buckwheat yield at Carman 2011 ranged from 566-792 kg ha^{-1} following green manure managed with soil disturbance (Table 23), comparable to the provincial average for 2011 of 775 kg ha^{-1} (source: Manitoba Crop Insurance Corporation). The buckwheat was harvested at only 43% color change, suggesting that yield would have likely been greater given a longer maturity period. Buckwheat following green manure managed with blade rolling and flail mowing yielded 331 and 400 kg ha^{-1}, respectively and was significantly less than the tillage treatment. Weed biomass at buckwheat harvest was not significantly affected by green manure management. The average 54% buckwheat yield loss with zero till management may be related to the average 65% reduction in soil nitrogen availability at planting, compared to green manure managed with tillage.

Wheat yield at Carman 2012 was greatest in the tillage (2599 kg ha^{-1}) and blade roll + tillage treatment (2250 kg ha^{-1}). These yields are slightly lower than the overall 10 year provincial average of 2979 kg ha^{-1} for conventional production (source: Manitoba Agricultural Services Corporation), but higher than the average spring wheat yield reported by 14 organic farms (1701 kg ha^{-1}) in Manitoba and North Dakota (Entz et al. 2001). The wide blade cultivation treatment (1582 kg ha^{-1}) had a similar yield to the blade roll + tillage (2250 kg ha^{-1}) and blade roll treatment (1039 kg ha^{-1}). Wheat following green manure managed with the flail mower had the lowest yield (558 kg ha^{-1}) but was not significantly different from the wheat following blade rolled green manure. The lower wheat yields in the zero till treatments can be attributed to two major factors; a 2x increase in weed biomass (Table 16) and 50% reduction in soil nitrogen at planting (Table 19), compared to tillage.

In the present study, wheat yields were consistently greater in Lethbridge compared to Carman (Table 23), which is consistent with long term averages comparing Alberta and Manitoba. Wheat yields in Lethbridge 2011 ranged from 3884-4530 kg ha^{-1} and were not affected by green manure management. In 2012, wheat yield was highest in the fallow (4636 kg ha^{-1}) and wide blade cultivation treatment (4255 kg ha^{-1}). Wheat following green manure managed with tillage (4065 kg ha^{-1}) and flail mowing (4035 kg ha^{-1}) was not significantly different from wide blade cultivation. The largest differences were observed with the treatments that involved blade rolling. The blade roll + tillage and blade roll treatment yielded 13 and 35% less than the tillage treatment, respectively. This can likely be explained by the presence of volunteer barley. These two treatments had the highest volunteer barley density (Table 12) at the 3-4 leaf stage and a decrease in wheat biomass was observed at hard dough (Table 17), likely a result of competition from volunteer barley. Residual nitrate-N levels was rated as very high for all treatments at the onset of the experiment and was not likely a limiting factor.

In summary, green manure managed with blade rolling + tillage and wide blade cultivation produced similar yields to tillage at 3 of 4 site-years (Table 23). In green manure termination, replacing one tillage operation with blade rolling can reduce energy requirements and erosion risk while maintaining crop yield.

In the year that crop yield was reduced in the blade roll + tillage treatment compared to continuous tillage in Lethbridge, volunteer barley density was higher in the blade roll plots. This likely contributed to reduced yield and can be avoided with proper termination timing.

Table 23. Effect of green manure termination method on main crop grain yield at **Carman (2011, 2012)** and **Lethbridge (2011, 2012).**

	Carman		Lethbridge	
	2011	2012	2011	2012
Treatment	Buckwheat	Wheat	Wheat	Wheat
	---------	kg ha^{-1}	---------	
Tillage	792 **a**†	2599 **a**	4489	4065 **b**
Blade Rolling	331 **c**	1039 **cd**	4413	3001 **d**
Blade Roll + Tillage	635 **abc**	2250 **ab**	3884	3594 **c**
Wide Blade Cultivation	566 **abc**	1582 **bc**	4275	4255 **ab**
Flail Mower	400 **bc**	558 **d**	4551	4035 **b**
Fallow	725 **ab**	-	4530	4636 **a**
P>F	0.0026	<0.0001	0.2589	<0.0001

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

4.10 Fall Rye Biomass, Grain Yield and Nitrogen

The effect of alfalfa termination method on nitrogen dynamics has been observed to persist for two subsequent growing seasons (Mohr et al. 1999). Previous studies looking at the effect of annual green manure management have only considered the nitrogen dynamics of the first year after green manure termination (Vaisman et al. 2011), and have recommended longer term studies to better understand green manure N release (Sullivan 2012). Thus, in the present study, fall rye was planted after main crop harvest in 2011 at both locations and monitored in year 3. Since nitrogen availability in the second year was reduced with zero till green manure management and potentially mineralizable N has been shown to be greater under zero till compared to tillage, it was hypothesized that nitrogen availability would be greater in the zero till treatments compared to the tillage control treatment in year 3.

Green manure managed with tillage produced the greatest fall rye biomass (11264 kg ha^{-1}) at Carman 2012 and was significantly greater than the flail mow treatment (8510 kg ha^{-1}). However, fall rye following green manure managed by blade rolling, blade roll + tillage and wide blade cultivation produced comparable biomass to tillage (Table 24). Fall rye biomass was greater at Lethbridge (12353-15018 kg ha^{-1}) than at Carman and was not affected by green manure management.

Fall rye biomass nitrogen uptake was measured at Carman was not significantly affected by treatments ($P>0.05$), although the tillage (38 kg ha^{-1}) and blade roll + tillage (37 kg ha^{-1}) treatments tended to have more nitrogen uptake compared to the other treatments (25-30 kg ha^{-1}). Grain protein was converted to nitrogen uptake for the fall rye at Lethbridge and ranged from 57-64 kg ha^{-1}.

Fall rye grain yield was not significantly affected by green manure management at either location (Table 24). Yields ranged from 3214-4339 kg ha^{-1} at Carman and 4986-5271 kg ha^{-1} at Lethbridge. In all cases, grain yields were lower than the 10 year average fall rye grain yield on conventional farms in Manitoba, which is 2834 kg ha^{-1} (source: Manitoba Agricultural Services Corporation).

Results from Carman and Lethbridge demonstrate that the residual effects of green manure management on nitrogen dynamics did not persist into year 3. While some differences in biomass were significant at Carman, nitrogen uptake and crop yield among green manure treatments was not significant at either location. This leads us to reject our hypotheses and conclude that nitrogen availability in the second growing season is not greater following zero till green manure management compared to the standard practice of tillage. Mohr et al. (1999) also reported no significant effect of alfalfa termination method on spring wheat yield in the second growing season following alfalfa termination with herbicide or tillage.

In the present study, managing the green manure without tillage (blade roll, flail mow) reduced soil nitrate-N and yield in year 2 and was not followed by increased soil nitrate-N or yield in year 3. Thus suggesting that zero till green manure management is not fully utilizing the potential nitrogen contribution of a green manure over this two year period. Managing the green manure with a combination of blade rolling + tillage or wide blade cultivation ensured both subsequent cash crops (2011 - spring wheat or buckwheat, 2012 – fall rye) yielded the same as tillage alone at both locations.

Table 24. Effect of green manure management in year 1 on fall rye biomass, grain yield and nitrogen components in year 3 at **Carman (2012)** and **Lethbridge (2012).**

Treatment	Carman			Lethbridge		
	Biomass	Yield	Biomass N uptake	Biomass	Yield	Grain N uptake
	-------------- kg ha^{-1} -----------			------------- kg ha^{-1} ------------		
Tillage	11264 **a**†	4239	38	14573	5271	60
Blade Rolling	9492 **ab**	3325	30	13824	4986	57
Blade Roll + Tillage	11080 **ab**	3906	37	12353	5057	61
Wide Blade Cultivation	9038 **ab**	3293	26	15018	5609	57
Flail Mower	8510 **b**	3214	25	13873	5458	60
Fallow	8726 **ab**	3392	28	13097	5970	63
P>F	0.0102	0.0592	0.1799	0.3492	0.5712	0.6762

† Means within a column followed by the same letter are not significantly different at $P<0.05$ according to Tukey’s HSD.

5. SUMMARY AND CONCLUSIONS

The objective of this study was to compare the standard practice of tillage with other mechanical implements for management of a pea-barley green manure on the Canadian prairies in an effort to reduce tillage in organic cropping systems. The findings of this study highlight important agronomic effects of these management methods that should be considered before being adopted in cropping systems. Markedly different results from Carman and Lethbridge also confirm that the suitability of reduced tillage green manure management is site-specific due to differences in cropping history and climate.

1) The effect of green manure management on nitrogen dynamics.

At Carman, managing green manure with tillage consistently increased soil nitrate as compared to blade rolling and flail mowing. Zero till management of green manure reduced soil nitrate the following spring by at least one half. In 2012 (the early seeding year), blade rolling plus tillage and wide blade cultivation provided similar soil nitrate availability as tillage. Nitrogen uptake by the main crop was always significantly greater in the tillage treatment compared to all other treatments. However, total biomass nitrogen uptake (crop + weeds) was often similar among treatments. This suggests that supplemental weed control in the reduced tillage treatments may increase nitrogen uptake by the crop. In conclusion, reducing tillage intensity associated with green manure management significantly reduced total soil nitrate the following spring but this did not necessarily affect total biomass nitrogen uptake. This may be due to differences in mineralization potential throughout the growing season.

At Lethbridge, high background soil nitrate levels masked the effects not only of the green manure itself, but also the effect of green manure termination method. Therefore, the two site-years at Lethbridge did not provide meaningful information about the effect of green manure management on nitrogen availability.

2) The effect of green manure management on weed composition and density.

At both locations, mulch levels in the zero till treatments at the time of spring wheat seeding averaged 3044 kg ha^{-1}. Therefore, the pea-barley green manure was not able to produce sufficient biomass for mulch-based weed control on the Canadian prairies.

At Carman, the predominant weed species were dandelion and Canada fleabane. The density of these weeds was significantly greater in the zero till treatments, especially the flail mower, compared to tillage. A combination of blade rolling + tillage and wide blade cultivation, both with intermediate soil disturbance, proved to be effective methods to reduce perennial and winter annual weed establishment. Large amounts of weed biomass prohibited wheat production in 2011 in all treatments, accounting for greater than 73% of total biomass at wheat stem elongation. This was due to excess moisture and delayed seeding. In 2012, seeding early in the growing season increased crop competitiveness; however, weed pressure remained an important issue in the zero till treatments.

Results from Carman demonstrate that zero till management of green manure without sufficient mulch can lead to economic losses due to weeds, especially in a long term organic system where resident weed seed bank numbers can build to high levels. Early seeding to minimize the window between green manure termination and main crop planting is important to improve crop competitiveness against weeds and increase the success of reduced tillage systems.

At Lethbridge, weed dynamics showed little response to green manure management. The primary weed of interest was volunteer barley which tended to be greater in the blade roll and blade roll + tillage treatment. Timing and efficacy of green manure termination is important to prevent volunteer crop problems.

3) The effect of green manure management on soil microclimate.

At both locations, gravimetric soil moisture was not affected by green manure management at any sampling time. Since moisture conservation benefits are dependent on incident precipitation, in years of adequate or excess moisture, moisture conserving benefits of zero till green manure management may not be evident.

At Carman, soil temperature in the spring following spring wheat planting was affected by green manure management in 2012 only; the early seeding year. Over a three week period, the average daily soil temperature at 5 cm was significantly higher in the tillage and blade roll + tillage treatment compared to all other treatments on 8 out of 22 sampling dates. Thus, larger amounts of surface residue following zero till green manure and lack of pre-seeding soil disturbance can sometimes lead to lower soil temperature in spring. Lower soil temperatures may delay plant development and nitrogen mineralization. A tillage pass in late fall of the green manure year and pre-seeding promoted soil warming similar to standard tillage practices.

4) The effect of green manure management on main crop yield

Main crop yield was significantly affected by green manure management method in both years at Carman. Buckwheat (2011) and wheat (2012) yield in the second year following green manure managed with tillage or a combination of blade rolling + tillage produced the greatest yields, followed by wide blade cultivation. Crop yield following zero till green manure was 50-80% less than following tillage. Due to the combined influence of management method on mineralization of the green manure residue and indigenous soil organic matter, and weed establishment, it is difficult to speculate with certainty which factor had a more profound influence on crop yield. Total nitrogen uptake (crop + weeds) was not affected by green manure management at the hard dough stage of wheat in 2012, suggesting that if weeds were adequately controlled nitrogen would not have been a yield limiting factor. This conclusion is supported by the fact that the correlation between weed biomass and crop yield ($r^2=0.8093$) is larger than the correlation between total soil nitrate in spring and crop yield at Carman 2012 ($r^2=0.5488$).

At Lethbridge, spring wheat yield was significantly affected by green manure management in 2012 only, with no distinct trend except that yields were lower in the treatments involving the blade roller at initial termination which had higher density of volunteer barley. This site is characterised by previous intensive herbicide and fertilizer use. Broadly speaking, nitrogen and weed dynamics were not profoundly affected by green manure management. In conclusion, without significant nitrogen or weed limitations, a green manure crop can be periodically managed without tillage or herbicide with no negative impact on subsequent crop yield.

5) The overall system performance of each mechanical implement compared to tillage for management of a green manure in an organic cropping system

To systematically evaluate the overall performance of each implement, six key parameters were evaluated (Table 25). Erosion protection, weed control, nitrogen availability and main crop yield for each implement were evaluated based on the results from this study. Efficacy/usability was evaluated based on experiences using the implements to terminate the green manure and observations made after termination. Energy savings were evaluated based on the estimated fuel required to use each implement. This table can assist farmers in making decisions on which management system is suitable for them based on the goals and limitations of their system. A holistic approach that considers the importance of each parameter is recommended.

Table 25. Strengths and weaknesses of each management system as deduced from results and experiences of the present study at Carman from 2010-2012.

	Efficacy/ Usability	Erosion protection	Weed control	Nitrogen availability	Main crop yield	Energy Savings
Tillage	★★★★	★	★★★★	★★★★	★★★★	★
Blade roll + tillage	★★★½	★★	★★★★	★★★	★★★½	★★
Blade roll	★★★	★★★★	★★	★★	★★	★★★★
Flail mow	★★★	★★★½	★½	★★	★★	★
Wide blade cultivation	★★	★★★½	★★★	★★★	★★★	★½

At Carman, tillage or a combination of blade rolling + tillage for managing the pea-barley green manure were not significantly different from one another for the majority of agronomic parameters. Substituting the blade roller for one tillage pass reduces energy use and erosion risk.

In contrast, results from the flail mower and blade roller treatments were often significantly different from the tillage treatments, but similar to one another. These differences are expected due to distinct differences in soil disturbance (or lack thereof). An advantage of the blade roller is that it requires less energy and also tended to have less weed pressure than the flail mower. The wide blade cultivation treatment often provided intermediate effects on agronomic parameters between the tillage and zero till treatments, but can be difficult to use for terminating high biomass cover crops.

The success of each management system was also dependant on spatial and temporal factors. At Carman, we learned that early seeding is necessary for the zero till systems. At Lethbridge, low weed populations and no limitation of N supply allowed zero till green manure management to be equally successful as green manure managed with tillage. Therefore timing of seeding, weed populations and residual nitrogen supply should also be considered.

Overall, this research demonstrates that eliminating tillage with pea-barley green manure management can compromise yield; however several options exist to successfully reduce tillage while maintaining yield and achieving soil conservation benefits.

6. GENERAL DISCUSSION

The window of time between green manure termination and main crop planting

The window of time between green manure termination and main crop planting proved to be an important factor in this experiment at Carman. For 2010-2011, from the date of green manure termination (July 15, 2010) to date of main crop planting (May 19, 2011), 1156 growing degree days (GDD) accumulated and 430 mm of precipitation (rain + snow) fell. This is compared to 2011-2012, when 840 GDD accumulated and 126 mm of precipitation fell from the date of green manure termination (August 5, 2011) to main crop planting (April 12, 2012). Greater thermal time and precipitation accumulation between these two dates increased green manure decomposition and weed establishment. This time period should be an important consideration in organic zero till systems, especially in the Northern Great Plains where seeding directly into fall seeded-spring terminated cover crops is less feasible.

At Carman, reduced tillage green manure management was successful only in 2012, when spring wheat was planted early (less GDD accumulation) and weeds were not fully developed. This is particularly important for a summer annual green manure, such as pea-barley, which was unable to produce sufficient biomass for mulch-based weed suppression. To achieve organic zero till management in our Northern climate, alternative green manure crops should also be considered. For example, recent investigation by Caroline Halde has demonstrated that spring planted hairy vetch, a winter annual legume, produces sufficient biomass to provide a weed suppressive mulch and nitrogen for subsequent crops following zero till termination with the blade roller (Caroline Halde, personal communication).

Alternatively, the main crop could also be modified. For example, winter wheat was compared to spring wheat for planting after flail mowed and blade rolled pea-barley green manure at Carman. Winter wheat performed superior to spring wheat when the green manure was planted early, in June compared to July. These two strategies, namely; 1) late planting of green manure and 2) planting the main crop in fall, minimize the window between green manure termination and main crop planting. This system warrants further consideration in the Northern Great Plains. However, the market for organic spring wheat is generally more desirable than for winter wheat.

Long term studies to examine the nitrogen dynamics of reduced till organic systems

A common question throughout the literature on reduced tillage organic green manure systems is “where is the nitrogen?”. Nitrogen behaviour in agro-ecosystems is complex and dynamic, making this question difficult to answer. In the present study and others, soil tests show reduced levels of nitrate-N following surface applied legume residue as compared to incorporated. However, in these same studies, biomass nitrogen uptake and yield has been shown to be statistically similar in the main crop following surface applied green manure as compared to incorporated (Mohr et al. 1999; Vaisman et al. 2011). Thus, it seems that mineralization during crop growth in zero till systems is occurring in synchrony with crop uptake. Mineralization potential has been shown to be higher in zero till green manure as compared to incorporated (Drinkwater et al. 2000; Sullivan 2011).

Future work should investigate the nitrogen balance of long term reduced till organic green manure systems. Previous studies have considered nitrogen immobilization and mineralization during initial decomposition of ^{15}N-labelled pea and barley residue (Jensen 1997), but have not considered the long-term fate of immobilized and mineralized N.

In conventional zero till systems, which have been studied more extensively, net N immobilization may occur during the transition period from conventional to conservation tillage. Do organic zero till systems also go through a transition period in which net N immobilization occurs? If so, how long does this period last? Reduced till green manure systems reviewed in this study have considered only a 1-3 year period. Furthermore, the C:N ratio of green manure residues is generally lower than crop residues. Therefore, immobilization may not be as important in organic zero till compared to conventional zero till systems. Reported volatilization losses from surface applied green manure range from only 0.3-14% (Janzen and McGinn 1991; Vaisman et al. 2011; Engel et al. 2013). Therefore, it is unlikely that volatilization losses account for substantial differences in nitrogen availability between zero till and tilled green manures.

It would be useful to employ ^{15}N- labelling studies and to monitor changes in soil nitrogen pools over time, to help answer these questions. Provided that legume green manure crops biologically fix large amounts of N, weeds are managed either with mulches or supplementary weed control, and nitrogen losses to the environment are no greater than tilled systems, reduced till green manure systems may reach an equilibrium between immobilization and mineralization over time.

Alternative uses of reduced tillage implements

In the present system, the wide blade cultivator could be used prior to seeding the main crop to manage perennial and winter annual weeds that establish following zero till green manure termination the previous year. The soil disturbance would also stimulate microbial activity and mineralization of green manure residue. Alternatively, the wide blade cultivator provides a means for conventional producers to manage weeds without herbicide or inversion tillage. This is particularly desirable as herbicide resistant weeds are an endemic problem.

In the present study, we tested a combination of blade rolling + tillage as well as strictly blade rolling and flail mowing. The flail mower exacerbated winter annual and perennial weed problems compared to rolling. However, a combination of flail mowing + tillage in late fall may address the weed problems associated with strictly flail mowing alone, and produce similar results to blade rolling + tillage. Alternatively, both flail mowing and blade rolling provide a viable option for conventional producers to manage cover crops without tillage or herbicide. With the option to use fertilizer and herbicides for the main crop, nitrogen and weed limitations are easier to overcome compared to organic systems.

This research has demonstrated several challenges of reduced till organic systems: weed control, nutrient availability, crop establishment and yield. This is particularly challenging in our Northern climate where we are limited by the length of our growing season to produce sufficient mulch with traditional annual green manures. Other high producing green manure crops (i.e. hairy vetch), which provide more mulch and nitrogen, should be considered for use with these implements. It is important that we think critically and innovatively, to adapt strategies that enhance profitability and environmental sustainability. Each of these mechanical methods offers organic and conventional producers alike, options to simultaneously reduce tillage and herbicide use.

7. LITERATURE CITED

Addae P. C. and C. J. Pearson. 1992. Thermal requirements for germination and seedling growth of wheat. Aust. J. Agric. Res. 43: 585-594.

Agehara S. and D. D. Warncke. 2005. Soil moisture and temperature effects on nitrogen release from organic nitrogen sources. Soil Sci. Soc. Am. J. 69: 1844-1855.

Ashford D. L. and D. W. Reeves. 2003. Use of a mechanical roller-crimper as an alternative kill method for cover crops. Am. J. Alternative Agric. 18: 37-45.

Biederbeck V. O., O. T. Bouman, C. A. Campbell, L. D. Bailey and G. E. Winkleman. 1995. Nitrogen benefits from four green-manure legumes in dryland cropping systems. Can. J. Plant Sci. 76: 307-315.

Blackshaw R. E., F. O. Larney, C. W. Lindwall, and G. C. Kozub. 1994. Crop rotation and tillage effects on weed populations on the semi-arid Canadian prairies. Weed Technol. 8: 231-237.

Blackshaw R. E., L. J. Molnar and J. R. Moyer. 2010. Sweet clover termination effects on weeds, soil water, soil nitrogen and succeeding wheat yield. Agron. J. 102: 634-641.

Borstlap S. and M. Entz. 1994. Zero-tillage influence on canola, field pea and wheat in a dry sub-humid region: agronomic and physiological responses.

Borghi B. 1999. Nitrogen as a determinant of wheat growth and yield. Pgs. 67-84 *in* E.H. Satorre and G. A. Slafer, eds. Wheat: ecology and physiology of yield determination. New York: Food Products Press.

Brady N. C. and R. R. Weil. 2008. The nature and properties of soils. 14th ed. New Jersey: Pearson Education.

Bullied W. J. and M. H. Entz. 1999. Soil water dynamics after alfalfa as influenced by crop termination technique. Agron. J. 91: 294-305.

Campbell C. A., F. Selles, R. P. Zentner, R. De Jong, R. Lemke and C. Hamel. 2006. Nitrate leaching in the semi-arid prairie: effect of cropping frequency, crop type and fertilizer after 37 years. Can. J. Soil Sci. 86: 701-710.

Canadian General Standards Board (CGSB). 2006. Organic production systems- general principles and management standards. Publication CAN/CGSB-32.310-2006. [Online] Available: http://www.tpsgc-pwgsc.gc.ca/ongc-cgsb/programme-program/normes-standards/internet/bio-org/documents/032-0310-2008-eng.pdf [21 Feb 2013].

Carr P. M., R. L. Anderson, Y. E. Lawley, P. R. Miller and S. F. Zwinger. 2011a. Organic zero-till in the northern US Great Plains region: opportunities and obstacles. Renew. Agric. Food Syst. 27: 12-20.

Carr P. M., P. Mäder, N.G. Creamer and J. S. Beeby. 2011b. Overview and comparison of conservation tillage practices and organic farming in Europe and North America. Renew. Agric. Food Syst. 27: 2-6.

Cherr C. M., J. M. S. Scholberg, and R. McSorley. 2006. Green manure approaches to crop production: a synthesis. Agron. J. 98: 302-319.

Clark A. 2007. Managing cover crops profitably. 3rd ed. United States: Sustainable Agriculture Research and Education (SARE) program.

Cogle A. L., W. M. Strong, P. G. Saffigna, J. N. Ladd and M. Amato. 1987. Wheat straw decomposition in subtropical Australia. II. Effect of straw placement on decomposition and recovery of added ^{15}N-urea. Aust. J. Soil Res. 25: 473-9.

Conservation Technology Information Center. 2008. National crop residue management survey. [Online] Available: http://www.ctic.purdue.edu/CRM/ [2013 Feb 25].

Coppens F., P. Garnier, A. Findeling, R. Merckx, and S. Recous. 2007. Decomposition of mulched versus incorporated crop residues: modelling with PASTIS clarifies interactions between residue quality and location. Soil Biol. Biochem. 39: 2339-2350.

Creamer N. G., Plassman B., Bennett M. A., Wood R. K., Stinner B. R. and Cardina J. 1995. A method for mechanically killing cover crops to optimize weed suppression. Amer. J. Alt. Agric. 10: 157-162.

Creamer N. G. and S. Dabney. 2002. Killing cover crops mechanically: review of recent literature and assessment of new research results. Amer. J. Alt. Agri. 17: 32-40.

Crews T. E. and M. B. Peoples. 2004. Legume versus fertilizer sources of nitrogen: ecological tradeoffs and human needs. Agric. Ecosyst. Env. 102: 279-297.

Dennett M. D. 1999. Effects of sowing date and the determination of optimum sowing date. Pgs 123-140 *in* E.H. Satorre and G. A. Slafer, eds. Wheat: ecology and physiology of yield determination. New York: Food Products Press.

Drinkwater L. E., R. R. Janke and L. Rossoni-Longnecker. 2000. Effects of tillage intensity on nitrogen dynamics in legume-based grain systems. Plant and Soil 227: 99-113.

Engel, R., C. Jones and R. Wallander. 2013. Ammonia volatilization losses were small after mowing in field peas in dry conditions. Can. J. Soil Sci. 93: 239-242.

Entz M. H., R. Guilford and R. Gulden. 2001. Crop yield and nutrient status on 14 organic farms in the eastern portion of the northern Great Plains. Can. J. Plant Sci. 81: 351-354.

Froud-Williams R. J. 1999. Wheat yield as affected by weeds. Pgs 161-182. *In* E.H. Satorre and G. A. Slafer, eds. Wheat: ecology and physiology of yield determination.. New York: Food Products Press.

Gauer E., C. F. Shaykewich and E. H. Stobbe. 1982. Soil temperature and soil water under zero tillage in Manitoba. Can. J. Soil Sci. 62: 311-325.

Geddes C. M., A. Cavalieri, and R. H. Gulden. 2012. Allelopathic potential of hairy vetch, fall rye and winter wheat. Poster session presented at the Canadian Weed Science Society, Winnipeg, MB.

Gulden R. H. and S. J. Shirtliffe. 2009. Weed Seed Banks: Biology and Management. Prairie Soils and Crops Journal 2:46-52.

Halde, Caroline. Personal communication, February 13, 2013. University of Manitoba, Canada.

Haun J. R. 1973. Determination of wheat growth-environmental relationships. Agron. J. 65: 813-816.

Janzen H. H. and S. M. McGinn. 1991. Volatile loss of nitrogen during decomposition of legume green manure. Soil Biol. Biochem. 23: 291-297.

Jensen E. S. 1997. Nitrogen immobilization and mineralization during initial decomposition of ^{15}N-labelled pea and barley residues. Biol. Fertil. Soils 24:39-44.

Knight J. D. and S. Shirtliffe. 2003. Saskatchewan organic-on farm research: Part 1: Farm survey and establishment of on-farm research infrastructure. [Online] Available: http://organic.usask.ca/Farm%20Survey%20and%20On-Farm%20Research.pdf [2013 Feb 25]

Knight J. D., R. Buhler, J. Y. Leeson, and S. J. Shirtliffe. 2010. Classification and fertility status of organically managed fields across Saskatchewan, Canada. Can. J. Plant Sci. 90: 667-678.

Kornecki T. S. A. J. Price, R. L. Raper and F. J. Arriaga. 2009. New roller crimper concepts for mechanical termination of cover crops in conservation agriculture. Renew. Agric. Food Syst. 24: 165-173.

Krafft, Guido (ed.). 1918. Ackerbaulehre. Berlin: Verlagsbuchhandlung Paul Parey.

Kumar K. and K. M. Goh. 2003. Nitrogen release from crop residues and organic amendments as affected by biochemical composition.

Lal R., D. C. Reicosky, and J. D. Hanson. 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil Till. Res. 93: 1-12.

Lal R. 2009. Laws of sustainable soil management. Agron. Sustain. Dev. 29: 7-9.

Lindsey, L. E., K. Steinke, D. D. Warncke, and W. J. Everman. 2013. Nitrogen release from weed residue. Weed Science 61:334-340..

Lund R. E. 1975. Tables for an approximate test for outliers in linear-models. Technometrics 17: 473-476.

Lynch D. 2009. Environmental impacts of organic agriculture: A Canadian perspective. Can. J. Plant Sci. 89: 621-628.

Macey, A. 2010. Certified organic production statistics for Canada 2009. [Online] Available: https://www.cog.ca/our-work/organic-statistics/ [2013 February 25]

Malhi S. S., A. M. Johnson, J.J. Schoenau, Z. H. Wang and C. L. Vera. 2006. Seasonal biomass accumulation and nutrient uptake of wheat, barley and oat on a Black Chernozem soil in Saskatchewan. Can. J. Plant Sci. 86: 1005-1014.

Manitoba Agriculture, Food and Rural Initiatives (MAFRI). Soil Quality. [Online] Available: https://www.gov.mb.ca/agriculture/crops/cropproduction/faa01s02.html [2013 Feb 25]

Manitoba Agriculture, Food and Rural Initiatives (MAFRI). Spring wheat production and management. [Online] Available: http://www.gov.mb.ca/agriculture/crops/cereals/bff01s01.html [2013 Feb 19]

Miller P. R., E. J. Lighthiser, C. A. Jones, A. Holmes, L. Rick and J. M. Wraith. 2011. Pea green manure management affects organic winter wheat yield and quality in semiarid Montana. Can. J. Plant Sci. 91: 497-508.

Miralles D. J. and G. A. Slafer. 1999. Wheat development. Pgs. 13-44. *In* E.H. Satorre and G. A. Slafer, eds. Wheat: ecology and physiology of yield determination. New York: Food Products Press.

Mirsky S. B., M. R. Ryan, W. S. Curran, J. R. Teasdale, J. Maul, J. T. Spargo, J. Moyer, A. M. Grantham, D. Weber, T. R. Way and G. G. Camargo. 2012. Conservation tillage issues: cover crop-based organic rotational no-till grain production in the mid-Atlantic region, USA. Renew. Agric. Food Syst. 27 (1); 31-40.

Mischler R., S. D. Duiker, W. S. Curran, and D. Wilson. 2010. Hairy vetch management for no-till organic corn production. Agronomy Journal 102: 355-362.

Mohr R. M., M. H Entz, H. H. Janzen and W. J. Bullied. 1999. Plant-available nitrogen supply as affected by method and timing of alfalfa termination. Agron. J. 91: 622-630.

Moyer J. R., R. E. Blackshaw, and H. C. Huang. 2007. Effect of sweetclover cultivars and management practices on following weed infestations and wheat yield. Can. J. Plant Sci. 87: 973-983.

Natural Systems Agriculture. 2010. Grazed green manures. [Online] Available: http://www.umanitoba.ca/outreach/naturalagriculture/articles/grazed_green_manures.html [2013 April 11].

Natural Systems Agriculture. 2011. Organic field crops laboratory, Carman, Manitoba. [Online] Available: http://umanitoba.ca/outreach/naturalagriculture/articles/fieldlab.html [2013 February 13].

Nelson, A. G., J. C. Froese and M. H. Entz. 2010. Organic and conventional field crop soil and land management practices in Canada. Can. J. Plant Sci. 90: 1-5.

Ominski P. D. and M. H. Entz. 2001. Eliminating soil disturbance reduces post-alfalfa summer annual weed populations. Can. J. Plant Sci. 81: 881-884.

Parr J. F. and R. I. Papendick. 1978. Factors affecting the decomposition of crop residues by microorganisms. Pgs. 101-129 *in* W. R. Oschwald, ed. Crop residue management systems. Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Peigne J., B. C. Ball, J. Roger-Estrade and C. David. 2007. Is conservation tillage suitable for organic farming? A review. Soil Use Manage. 23: 129-144.

Pikul J. L., J. K. Aase and V. L. Cochran. 1997. Lentil green manure as a fallow replacement in the semiarid Northern Great Plains. Agron. J. 89: 867-874.

Reberg-Horton S. C., J. M. Grossman, T. S. Kornecki, A. D. Meijer, A. J. Price, G. T. Place and T. M. Webster. 2011. Utilizing cover crop mulches to reduce tillage in organic systems in the southeastern USA. Renew. Agric. Food Syst. 27: 41-48.

Reicosky D. C. and R. R. Allmaras. 2003. Advances in tillage research in North American cropping systems. J. Crop Prod. 8: 75-125.

Rochette P. 2008. No-till only increases N_2O emissions in poorly-aerated soils. Soil Till. Res. 101: 97-100.

Ryan M. R., D. A. Mortenson, R. Seidel, R. G. Smith, A. M. Grantham. 2009. Weed community response to no-tillage practices in organic and conventional corn. Proceedings of the Northeastern Weed Science Society 63: 94. [Online] Available: http://www.newss.org/proceedings/proceedings_2009.pdf [2013 Jan 9].

SAS Institute. 2001.

Satorre 1999

Saxton, K. E. and W. J. Rawls. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70: 1569-1578.

Sayre L. 2003. New tools for organic no-till. [Online] Available: http://www.rodaleinstitute.org/introducing_a_cover_crop_roller. [3 March 2011].

Shirtliffe S. J. and E. N. Johnson. 2012. Progress towards no-till organic weed control in western Canada. Renew. Agric. Food Syst. 27:60-67.

Smith A. N., C. Reberg-Horton, G. T. Place, A. D. Meijer, C. Arellano, and J. P. Mueller. 2011. Rolled rye mulch for weed suppression in organic no-tillage soybeans. Weed Sci. 59: 224-231.

Statistics Canada. 2006. Techniques and technologies, Canada and provinces: census years 1991-2006. [Online] Available: http://www.statcan.gc.ca/pub/95-632-x/2007000/t/4129758-eng.htm [2013 Feb 25].

Statistics Canada. 2011. Land use as a proportion of total farm area, Canada, 2006-2011. [Online] Available: http://www.statcan.gc.ca/pub/95-640-x/2012002/figs/figure9-eng.htm [2013 April 11]

Statistics Canada. 2012. Field and special crops area. [Online] Available: http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/prim11a-eng.htm [2013 Feb 26]

Stewart B. A., R. L. Baumhardt and S. R. Evett. 2010. Major advances of soil conservation in the U.S. Southern Great Plains. Pgs. 103-182 *in* T. N. Zobeck and W. F. Schillinger, eds. Soil and water conservation advances in the United States. Madison, WI: Soil science society of America, special publication No. 60.

Stewart-Wade S. M., S. Neumann, L. L. Collins and G. J. Boland. 2002. The biology of Canadian weeds. 117. *Taraxacum officinale*. G. H. Weber ex Wiggers. Can. J. Plant Sci. 82: 825-853.

Stopes C., S. Millington and L. Woodward. 1996. Dry matter and nitrogen accumulated by three leguminous green manure species and the yield of a following wheat crop in an organic production system. Agr. Ecosyst. Environ. 57: 189-196.

Subbarao G. V., O. Ito, K. L. Sahrawat, W. L. Berry, K. Nakahara, T. Ishikawa, T. Watanabe, K. Suenaga, M. Rondon and I. M. Rao. 2006. Scope and strategies for regulation of nitrification in agricultural systems- challenges and opportunities. Crit. Rev. in Plant Sci. 25: 303-335.

Sullivan, C. Reduced tillage in organic cropping systems on the Canadian prairies. MSc thesis, University of Saskatchewan, Saskatoon, 2012. Print.

Teadsale J. R. and C. S. T. Daughtry. 1993. Weed suppression by live and desiccated hairy vetch (*Vicia villosa*). Weed Science 41: 207-212.

Teasdale J. R. and C. L. Mohler. 1993. Light transmittance, soil temperature and soil moisture under residue of hairy vetch and rye. Agron. J. 85:673-680.

Teasdale J. R. 1996. Contribution of cover crops to weed management in sustainable agricultural systems. J. Prod. Agric. 9: 475-479.

Teasdale J. R. and C.L. Mohler. 2000. The quantitative relationship between weed emergence and the physical properties of mulches. Weed Science 48: 385-392.

Teasdale J. R., L. O. Brandsaeter, A. Calegari, and F. Skora Neto. 2007. Chapter 4. Cover crops and weed management. Pgs 49-64 *in* M. K. Upadhyaya and R. E. Blackshaw. Non chemical weed management principles, concepts and technology. Wallingford, UK: CAB International Press.

Teasdale J. R., S. B. Mirsky, J. T. Spargo, M. A. Cavigelli and J. E. Maul. 2012. Reduced-tillage organic crop production in a hairy vetch cover crop. Agron. J. 104: 621-628.

Thomas A. G., D. A. Derksen, R. E. Blackshaw, R. C. Van Acker, P. R. Watson, and G. C. Turnbull. 2004. A multistudy approach to understanding weed population shifts in medium- to long-term tillage systems. Weed Sci. 52: 874-880.

Tkachuk R. 1969. Nitrogen-to-protein conversion factors for cereals and oilseed meals. Cereal Chem. 46:419-425.

Townley-Smith L., A. E. Slinkard, L. D. Bailey, V. O. Biederbeck and W. A. Rice. 1993. Productivity, water use and nitrogen fixation of annual legume green manure crops in the Dark Brown soil zone of Saskatchewan. Can. J. Plant Sci. 73: 139-148.

Triplett Jr. G. B. and W. A. Dick. 2008. No-tillage crop production: A revolution in agriculture! Agron. J. 100:153-165

Vaisman I. 2010. Investigation of the blade roller for organic green manure management. MSc Thesis, University of Manitoba, Winnipeg, Print.

Vaisman I., M. H. Entz, D. N. Flaten, and R. H. Gulden. 2011. Blade roller-green manure interactions on nitrogen dynamics, weeds and organic wheat. Agron. J. 103:879-889.

Van Doren D. M. and R. R. Allmaras. 1978. Effect of residue management practices on the soil physical environment, microclimate and plant growth. Pgs. 49-83 *in* W. R. Oschwald, ed. Crop residue management systems. Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Wortman S. E., J. L. Lindquist, M. J. Haar, and C. A. Francis. 2010. Increased weed diversity, density and above-ground biomass in long-term organic crop rotations. Renew. Agric. Food Syst. 25: 281-295.

Wortman S. E., C. A. Francis, M. L. Bernards, R. A. Drijber and J. L. Lindquist. 2012. Optimizing cover crop benefits with diverse mixtures and an alternative termination method. Agron. J. 104: 1425-1435.

APPENDIX

Table 1. Effect of green manure management on gravimetric soil moisture in the depths 0-30 cm, 30-60 cm, 60-90 cm and 90-120 cm in fall of the green manure year at **Carman (2011)** and spring of the wheat crop production year at **Carman (2011, 2012).**

	Spring 2011				Fall 2011				Spring 2012			
Treatment	0-30	30-60	60-90	90-120	0-30	30-60	60-90	90-120	0-30	30-60	60-90	90-120
	%											
Tillage	26.5†	26.0	24.5	26.0	15.2	17.8	23.0	25.6	18.5	18.9	19.3	23.3
Blade Rolling	26.3	25.3	24.5	25.5	16.0	18.2	21.3	26.7	19.3	19.3	18.8	24.0
Blade Roll + Tillage	25.8	25.5	24.3	27.0	15.7	15.3	22.0	24.2	18.8	18.8	20.8	24.3
Wide Blade Cultivation	24.5	23.5	23.5	28.0	15.6	15.8	20.9	25.0	18.8	18.0	18.8	23.8
Flail Mower	25.5	24.0	23.8	26.0	15.6	17.0	20.9	27.1	19.3	18.3	19.0	23.8
Fallow	25.8	24.5	25.0	25.8	-	-	-	-	-	-	-	-
P>F	0.4262	0.3188	0.7484	0.5347	0.8537	0.1456	0.8057	0.5989	0.2859	0.7049	0.0756	0.9622

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

Table 2. Effect of green manure management method on gravimetric soil moisture in the depths 0-30 cm, 30-60 cm and 60-90 cm in fall of the green manure year at **Lethbridge (2010, 2011).**

	Fall 2010			Fall 2011		
Treatment	0-30	30-60	60-90	0-30	30-60	60-90
	%					
Tillage	22.3†	23.0	24.3	21.8	23.1	25.0
Blade Rolling	22.3	23.3	23.2	22.6	23.0	24.6
Blade Roll + Tillage	22.0	23.4	25.3	22.3	22.7	24.8
Wide Blade Cultivation	21.5	22.7	24.5	21.9	23.5	23.6
Flail Mower	22.5	23.3	24.5	22.3	22.8	24.5
Fallow	22.3	23.2	24.0	22.0	23.6	23.4
P>F	0.2583	0.9827	0.4244	0.4776	0.9183	0.4990

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

Table 3. Effect of green manure management on average daily soil temperature for three weeks after spring wheat planting from May 21 to June 9 at **Carman 2011**.

	Day of Month (May-June)																			
Treatment	21	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5	6	7	8	9
ST	14.3†	15.1	12.9	10.4	11.3	11.2	10.7	12.6	11.8	11.2	12.3a	13.8	13.2	16.8	15.1	17.3	18.8	13.4	13.9	14.6
BR	14.9	15.6	13.0	10.2	11.4	11.4	10.6	13.0	11.9	11.3	13.1ab	14.4	13.3	17.3	15.4	18.6	20.9	13.3	14.9	16.6
BR+Till	14.4	15.3	12.7	10.1	11.0	11.0	10.6	12.7	11.6	11.1	12.4a	14.1	13.2	17.2	15.1	18.0	19.5	12.9	14.3	15.4
WB	13.8	14.5	12.5	9.9	10.6	11.3	10.7	12.5	11.6	11.0	12.0b	13.2	13.0	16.3	14.9	16.8	18.5	13.7	14.0	14.8
FM	14.4	15.4	13.0	10.4	11.6	11.7	10.8	13.0	12.0	11.4	12.6a	14.3	13.4	17.4	15.3	18.1	19.6	13.2	14.7	15.5
SF	14.3	15.2	12.9	10.2	11.3	11.3	10.6	12.8	11.8	11.2	12.4a	14.0	13.1	17.1	15.2	17.7	19.3	13.2	14.4	15.3
P>F	0.2109	0.1361	0.5162	0.4363	0.3578	0.4547	0.9000	0.1217	0.5090	0.2057	**0.0277**	0.1601	0.2201	0.1648	0.8828	0.0589	0.0970	0.8876	0.5846	0.3552

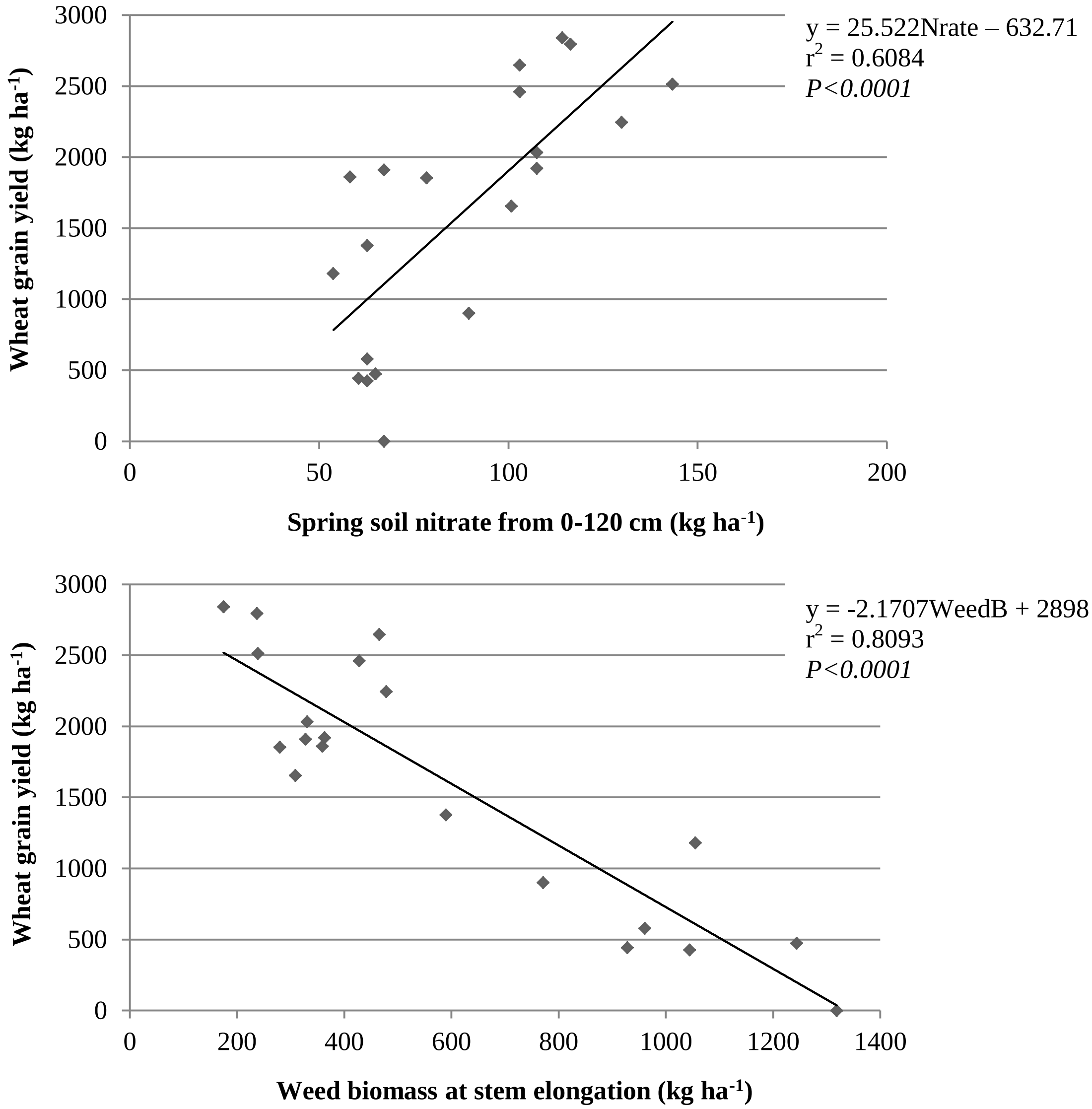
† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

Table 4. Effect of green manure management method on wheat grain protein at **Lethbridge (2011, 2012).**

Treatment	2011	2012
	----------- % -----------	
Tillage	14.6 b†	17.0
Blade Rolling	15.6 a	17.1
Blade Roll + Tillage	15.6 ab	17.1
Wide Blade Cultivation	15.7 a	17.1
Flail Mower	15.4 ab	17.0
Fallow	15.9 a	16.9
P>F	**0.0137**	0.7486

† Means within a column followed by the same letter are not significantly different at P<0.05 according to Tukey's HSD.

a)



b)

Figure 1. Relationship between wheat grain yield in 2012 and a) total soil nitrate availability from 0-120 cm in spring 2012 and b) total weed biomass at the stem elongation stage of wheat in 2012.