GREENING SUMMER FALLOW: AGRONOMIC AND EDAPHIC IMPLICATIONS OF LEGUMES IN DRYLAND WHEAT AGROECOSYSTEMS

by

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DEDICATION

This thesis is dedicated to my parents, Denise and Kevin O'Dea, who have perpetually offered their unwavering support throughout my entire education career. Their support has been instrumental in helping me get to the level of Master of Science; they have always believed in my potential to get this far in school. Mom, Dad, you know better than anyone what a long road this has been for me. Thank you.

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ABSTRACT

Adopting nitrogen (N)-fixing legumes into crop rotations is an accessible, ecological practice capable of increasing agricultural sustainability. Nonetheless, in northern Great Plains (NGP) wheat systems, proper water use management and the realization of N benefits are barriers to legumes replacing summer fallow. Legumes should also be able to mitigate legacies of soil organic matter losses from summer fallow. We conducted a participatory field-scale study in north-central Montana, assessing the viability of no-till, early-terminated legume green manures (LGMs) as summer fallow replacements. Soil water and nitrogen were measured to evaluate LGM effects on subsequent wheat crops. Farmers were interviewed to elucidate perspectives and challenges of adopting LGMs. Compared to fallow, LGMs depressed subsequent wheat yields by 6% (0.24 Mg ha^{-1}), and lowered grain protein at sites where wheat was fertilized with N (9 g kg^{-1}); grain protein was increased at unfertilized sites (5 g kg^{-1}). Absent rotational benefits from LGMs were attributed to dry conditions in the LGM year leading to low LGM biomass N and reduced N mineralization potential in soils, rather than soil water limitation to subsequent wheat. Farmers were curious about possible long-term benefits from LGMs, but expressed that the economic viability of LGMs appeared tenuous in the short-term. We also examined attributes and processes in soils from an eight-year-old rotation study containing fallow-wheat, continuous wheat, and legume-inclusive no-till rotations. We examined potentially mineralizable C and N (PMC and PMN), microbial biomass-C and wet aggregate stability (WAS). Nitrogen fertilizer was also added to a duplicate set of soils, and effects on C and N mineralization were evaluated. Legume-inclusive systems generally had higher levels of soil parameters, and had 26-50% greater PMN than wheat-only systems. Systems returning the most crop residue C to the soils had higher WAS regardless of legumes. Nitrogen additions depressed C and N mineralization. Results of these studies suggest that in NGP agroecosystems, LGMs can avoid limiting soil water available to subsequent wheat when terminated early and managed as no-till crops, but that legumes should be viewed as an investment in soil quality which may precipitate rotational N benefits more reliably after three or more appearances in rotation.

CHAPTER ONE

INTRODUCTION

Approaching Sustainability in Agriculture

> "It was inevitable and no doubt desirable that the tremendous momentum of industrialization should have spread to farm life. It is clear to me, however, that it has overshot the mark, in the sense that it is generating new insecurities, economic and ecological, in place of those it was meant to abolish. In its extreme form, it is humanly desolate and economically unstable. These extremes will some day die of their own too much, not because they are bad for wildlife, but because they are bad for farmers"
> - *Aldo Leopold, 1945, from Meine* (1987)

Agriculture, Ecosystems, and Ecosystem Services.

Over the past 60 to 70 years, agriculture has been highly successful in sustaining food supplies for growing global populations, but issues concerning the environmental sustainability of agriculture have been largely overshadowed by this achievement (Pollock et al., 2008). Ecological conservation strategies that emerged after the 1930's dustbowl disasters were largely displaced by enthusiasm for the growing "green revolution", which emphasized productivity and development of industrial/technological approaches to management (Odum, 1984; Harwood, 1990; Robertson and Swinton, 2005; Drinkwater and Snapp, 2007). Industrial/technological strategies can help increase food production, support secondary agricultural economies, and theoretically may lower agricultural footprints by producing more food on less land. Notwithstanding this, these strategies may perpetuate inadvertent ignorance of agricultural impacts on ecosystems (Holling and Meffe, 1996), loss of local ecological knowledge (Altieri, 2004; Pilgrim et al., 2008), and may not be accessible in non-industrialized nations (Kanyama-Phiri et al.,

2008). The inertia of agricultural industry and advocacy of technological solutions to agricultural sustainability remains substantial, well illustrated by the current push to adopt genetically modified technologies as an approach to sustainability (Borlaug, 2007; Avery and Avery, 2008; Anonymous, 2011).

Nonetheless, with increasing support by growing sublimated counter-cultures in small-scale agricultural operations (Rigby and Caceres, 2001; Robertson and Harwood, 2001; Heckman, 2006), the late 1980's saw re-establishment of agroecology concepts and ecologically informed approaches as active research areas (Lowrance et al., 1984; Altieri, 1989; Jackson and Piper, 1989; Paul and Robertson, 1989; Gliessman et al., 1998). Agroecology has since then been espoused by some as a fundamental and globally accessible approach to agricultural sustainability (Matson et al., 1997; Altieri, 1999; Hanson et al., 2007; Pretty, 2008). With growing recognition and activity within research institutions and in professional societies such as the Ecological Society of America, ecologically informed management strategies are now repositioned to influence agricultural policy and institutions of large-scale commodity agriculture.

Ecologically Informed Management in Agriculture.

Natural ecosystems are generally recognized for their resource use efficiencies in producing biomass, stability, and sustainability, and have hence been used as models to inform agroecosystem management (Gliessman et al., 1998). Because the abiotic environment intrinsically limits a natural ecosystem, it serves as a benchmark for the long-term sustainable production of a given landscape and as a locally adapted, functioning, interdependent system (Odum, 1984; Gliessman, 2001; Drinkwater, 2009).

Understanding ecosystem limits and functions can inform land managers of functions that may be lost from disturbed ecosystems, and how those functions may be compensated for through best management of the modified ecosystem (Dale et al., 2000). Likewise, from a food production perspective, managing an agricultural system as an agroecosystem aims to sustainably economize the system through facilitating best use of localized resource opportunities and inherent environmental production capacities.

As problems related to resource depletion and ecological dysfunction mount, decision-making informed by ecological knowledge may be increasingly useful beyond agriculture (Odum, 1969; Palmer et al., 2005). But because agriculture is so intensively managed, land-use dominant, and ecologically disruptive, ecologically informed management has emerged as a particularly useful and fundamental approach to long-term agricultural sustainability.

Approaching Sustainability in Northern Great Plains Agroecosytems

> "[T]hat there must be a change in the system of cropping is admitted by all up-to-date farmers, for the growing of wheat alone and summer fallowing every third year, is too favourable to the introduction of weeds, the exhaustion of the soil fibre, and the depletion of fertility."
> - *Angus McKay, Indian Head Experimental Farm, SK, 1914, from Janzen* (2001)

> "…The main objection to summer fallowing and to the continued growing of cereal crops is, first the loss of one season's crop, and second the drain on the soil fertility, particularly on the nitrogenous compounds, which must finally result in soil depletion. That even the very fertile soils of the valleys of the arid region may be exhausted by continued grain growing has been demonstrated in many parts of the state of Utah after 30 to 40 years of farming…"
> - *F.B. Linfield, Montana Agricultural Experiment Station* (1902)

Ecologically Informed Management Approaches in Northern Great Plains Commodity Agriculture

In the semiarid northern Great Plains (NGP) region of North America, dryland monoculture small grain cropping with an alternating summer fallow season has been a conventional management approach for approximately a century (Ford and Krall, 1979; Larney et al., 1994; Janzen, 2001). In this region characterized by low and erratic rainfall, summer fallow practices were initially strongly encouraged to ensure adequate soil water storage for an economically stable dryland wheat (*Triticum aestivium* L.*)* crop every two to three years (Atkinson, 1907; Janzen, 2001; Tanaka et al., 2010). Despite this positive attribute, many researchers have noted negative/unsustainable aspects of summer fallow and approaches attempting to mitigate these since the early 1900s (Linfield, 1902; Atkinson and Nelson, 1911; Ford and Krall, 1979; Carlyle, 1997; Janzen, 2001; Karlen et al., 2011). A large majority of these negative effects were due to excessive tillage as part of summer fallow practices (Larney et al., 1994).

A major ecological management strategy currently being promoted and widely adopted in the NGP is no-tillage, including direct seeding and no-till summer fallow (i.e. "chem fallow"). No-till management is helping to protect soil from erosion and weathering, and effectively facilitating biologically-mediated changes in soil quality and water storage efficiency through reestablishment of beneficial soil structure and processes. Nonetheless, negative consequences of summer fallow are only partially ameliorated by widespread adoption of conservation tillage (Campbell et al., 2000; Sainju et al., 2009) and no-till practices in the region (Tanaka et al., 2010). Sub-optimal crop residue returns to soils (Campbell et al., 2000; Sainju et al., 2009), precipitation-use-

efficiency (Nielsen et al., 2005; Tanaka et al., 2005), and soil cover (Power et al., 1983; Tanaka et al., 1997), along with saline seepage (Black et al., 1981; Tanaka et al., 2010) and nitrate leaching (Campbell et al., 2006b; Jones and Olson-Rutz, 2011) remain issues in fallow-wheat systems, even under no-tillage summer fallow.

Consequently, it has been proposed that sustainability in these systems can be best approached through eliminating summer fallow by intensifying cropping systems (Peterson et al., 1996; Tanaka and Anderson, 1997; Zentner et al., 2001; Grant et al., 2002; Miller and Holmes, 2005; Nielsen et al., 2005). This is possible because of increased soil water storage efficiency in no-till managed systems, and consequently summer fallow acreage has steadily declined since the early 1970's (Carlyle, 1997; Tanaka et al., 2010). Cropping system intensification is an ecological management strategy which aims to increase precipitation use efficiency (PUE), effectively ameliorate soil degradation, and mitigate saline seeps and nitrate leaching resulting from excess water percolation through the soil profile during summer fallow. The push to intensify these systems has also prompted another ecological management strategy- diversification of crop rotations away from wheat monocultures (Miller et al., 2001; Gan et al., 2010). A wheat-only system has increased pest pressures in this agroecoregion, which may be partially mitigated through crop diversification (Smiley et al., 1996; Derksen et al., 2002; Krupinsky et al., 2002).

Importantly, these approaches must prove to be economically viable. Since the mid-1980's, pulse crops in rotation with small grains are an increasingly profitable crop replacing summer fallow, especially in the Canadian NGP region (Campbell et al., 2002;

Carlyle, 2002; Miller et al., 2002; Carlyle, 2004; Cochran et al., 2006). Recently, increases have also been reported in Montana acreage planted to pulse crops (Tanaka et al., 2010; Burgess et al., in review), particularly in the northeast portion of the state. Legume inclusion in wheat systems therefore holds considerable promise; legume crops not only increase the diversity of NGP agroecosystem species, but notably contribute ecological functional diversity (Tilman et al., 1997) into these N-intensive agroecosystems through biological N-fixation. Semiarid dryland wheat agroecosystems represent a major North American commodity cropping system that historically has not substantially benefited from biological N-fixation.

Importance of Legumes in Agroecosystems

> "The land is extremely fertile, but it is not so incapable of exhaustion as it is sometimes represented to be. Many of the crops… thrive only when a certain rotation is observed (such as wheat, followed by clover and beans)…"
> - *Karl Baedeker*, *remarking on Egyptian agriculture* (1885).

> "…If the producing capacity of soils is to be kept under any system of crop raising, some nitrogen gathering crops must be grown."
> - *Alfred Atkinson*, *Montana Agricultural Experiment Station* (1907)

The symbiotic relationship that nitrogen-fixing bacteria form with legumes is the single most important ecological interaction that transforms atmospheric N into plant usable nitrogen, and the most important in agroecosystems (Pierzynski et al., 2005). Global biological fixation of N is estimated to be in the order of 100-150 Tg yr^{-1}, roughly twice the amount produced industrially (Pierzynski et al., 2005). Of that amount, crop legumes are estimated to fix approximately 22-35 Tg (~ 90 to 140 kg ha^{-1}) of N globally per year (Brady and Weil, 2004; Peoples et al., 2009). In agriculture, legume cropping is

responsible for the only biological N fixation facilitated directly by management. All other natural inputs of N come through free-living bacteria or atmospheric deposition but are insignificant in comparison, and cannot meet the demands of annual cropping. While legumes have been used for centuries in agriculture for N fertility, synthetic N fertilizers have effectively antiquated legumes and other organic nutrient sources (Hargrove and Frye, 1987; Bullock, 1992; Crews and Peoples, 2004; Drinkwater and Snapp, 2007). Unfortunately, the synthesis of N fertilizer is a non-renewable resource dependent, energy intensive process (Smil, 2001), and losses following application of reactive N to agroecosystems are environment-polluting (Smil, 1999). These aspects present a sustainability issue, especially in N-intensive systems such as wheat (Piringer and Steinberg, 2006).

Importance of N in Northern Great Plains Wheat Systems and Ecological Ramifications of N Sources

> "If the high yielding dwarf wheat and rice varieties are the catalysts that have ignited the Green Revolution, then chemical fertilizer is the fuel that has powered its forward thrust...".
> - *Norman Borlaug*, *1970, from* Smil (2002)

Annual ecosystems in general are inherently N intensive, completing an entire life cycle's worth of resource acquisition in one year. Therefore, keeping soil N levels high is imperative to maintaining agroecosystems in a state suitable for annual crops. In the NGP, wheat dominates the annual crop economy and landscape and is well-adapted to climatic conditions that uniquely facilitate production of high-protein grain. In these systems though, N fertility is not only part of annual cropping, it is also directly related to grain protein levels. Since high grain protein demands price premiums in the market

(Grant et al., 2002) producers are encouraged to facilitate high N fertility. But since inherent soil fertility can decline after years of fallow-wheat cropping in the NGP, N fertilizer additions are increasingly compulsory for wheat producers to be competitive in the regional market. Nitrogen fertilizer is a considerable and volatile portion of wheat production costs (Walburger et al., 2004; Hoeppner et al., 2006; Piringer and Steinberg, 2006; Zentner et al., 2006), and since N fertilizer synthesis is fossil-fuel-dependent, it can also account for 66% or more of a farm's energy footprint in this region, depending on the amount of N added to reach yield goals (Zentner et al., 2004b).

Due to the added value of N in wheat cropping systems for high grain protein, it is economically beneficial to maximize N retention in the soil profile. Crop recovery of applied N fertilizer rarely exceeds 50% (Cassman et al., 2002; Crews and Peoples, 2004), and annual agroecosystems are often kept in a state of N saturation to assure desired crop uptake levels (Drinkwater and Snapp, 2007). Meanwhile, residual N not taken up by crops is vulnerable to losses to the environment through leaching or denitrification. Uptake is especially limited in monocultures by homogenous rooting depths and nutrient acquisition patterns, increasing the risk of N loss past the root zone (Janzen et al., 2003; Drinkwater and Snapp, 2007). During periods of fallow, the risk of N losses to groundwater increases with seasonal mineralization of soil organic matter (SOM) and lack of plant uptake (Campbell et al., 2006a; Tonitto et al., 2006). While nitrate leaching to groundwater is limited in the semiarid NGP, Bauder et al. (1993), Campbell et al. (2006b) report that summer fallow is a principal cause of nitrate leaching to groundwater in this region. With a continued focus on high-protein wheat and assumed increases in

worldwide food production demands (Smil, 2002), nitrate groundwater pollution could be a growing problem. Increasing N from legume sources in the NGP source and reducing summer fallowing may have promise for reducing N losses from these agroecosytems.

Expanding Legume Cropping in the Northern Great Plains

> "…The whole question of the proper cropping arrangement or crop rotation, for the-dry farm is of the highest importance to the dry-farm states. The plan of alternately cropping and fallowing, while indefinitely better than attempting to grow grain crops each year, and helpful to enabling men to get the crop with which to establish a home and meet their initial obligations, is not a system of permanent crop raising. Soil improving crops, like alfalfa and field peas, must be occasionally grown. These are the features of a permanent agriculture, and dryland agriculture must regard these essentials…"
> - *Atkinson and Nelson, Montana Agricultural Experiment Station* (1911)

Replacement of summer fallow with legumes in the NGP has historically faced apathy. With a growing affordable and abundant supply of synthetic N, legumes were obviated in many contemporary cropping systems, and further in the NGP by experiences of compromised stored soil water (Power et al., 1983; Power, 1990; Janzen, 2001). Since water is the main yield-limiting factor in dryland agriculture, conserving stored soil water remains paramount for successful dryland cereal production. With the help of 1) increased soil water storage under no-till managed soils, 2) a profitable market for pulse crop commodities, and 3) the allure of rotational benefits and a N-independent crop in the face of volatile N fertilizer prices (Hargrove and Frye, 1987; Peoples et al., 1995), pulse crops have considerable promise for adoption where precipitation conditions can support continuous cropping without compromising wheat yields. Yet, in the driest regions of the NGP, and particularly in north-central Montana (MLRA 52), summer fallow practice

remains well-entrenched; recent estimates suggest ~ 84% of cropped acreage remains in a fallow-wheat rotation (NASS, 2010). Since continuous cropping may considerably compromise wheat yields in this region (Miller and Holmes, 2005), legume green fallow crops (LGF's) consisting of a half-season forage or green manure (LGM) crop may be a less risky option for intensifying and diversifying these systems (Miller et al., 2002; Miller et al., 2006). These crops are grown in the early summer fallow year to produce N-rich biomass during the April to June peak precipitation period, using water otherwise vulnerable to losses during summer fallow (Tanaka et al., 2010; Karlen et al., 2011). Dry pea (*Pisum sativum* L.) and lentil (*Lens culnaris* Medik.) have particularly emerged as shallow rooted, water-efficient crops with indications of residual N and diversity benefits for wheat in rotation (Miller et al., 2001; Miller et al., 2002). These crops are likewise suitable when managed as LGF crops. Growing a partial forage or LGM crop is a practice that has yet to gain traction in conventional wheat rotations, but it may now be increasingly viable and appropriate in the driest regions of the NGP (Miller et al., 2006). Compared to summer fallow, these crops may be able to increase soil quality (Biederbeck et al., 1998), precipitation use efficiency (Tanaka et al., 2005), and soil cover (Tanaka et al., 1997), and reduce excess soil water percolation that leads to saline seepage and N leaching (Biederbeck and Bouman, 1994). They may also simultaneously offset N fertilizer inputs (Zentner et al., 2004a) and provide non-N rotational benefits (Smiley et al., 1996; Stevenson and van Kessel, 1996).

Legumes as Green Fallow Crops Replacing Summer Fallow.

> "Attempts to substitute for the bare fallow various leguminous crops, which have been plowed under, have decreased the yields of wheat. The

> lowered yields are evidently due to the drying out of the soil by the leguminous crop."
> - *Alway & Trumbull, Indian Head, SK, 1910 (from Janzen, 2001)*

Historical reports of wheat-yield-reducing water use from LGMs in the NGP were noted as early as the early 1900s, when LGMs were first being tested to reduce SOM loss and soil erosion from summer fallow (Janzen, 2001). Studies conducted through the mid-1900s likewise established that soil water use by LGMs compromised soil water available to subsequent wheat, and precluded rotational N benefits from LGMs (Army and Hide, 1959; Brown, 1964). In the early 1980s, high energy prices and increasing exploration of conservation techniques initiated a new push for alternate N sources from legumes (Power et al., 1983; Power, 1987; 1990; Biederbeck et al., 1993). Therefore, selecting legume species and management strategies that balance water use levels with biomass production and N-fixation benefits has been the challenge for most recent studies. The driest regions of the NGP have low and erratic precipitation, intensive spring-to-early summer precipitation patterns followed by late summer drought, and limited growing-degree days and instances of extreme winter temperatures. Consequently, early spring-sown legumes, especially dry pea and lentil, have been most ubiquitously studied and endorsed as suitable green fallow crops (Slinkard et al., 1987; Power, 1991; Townley-Smith et al., 1993; Biederbeck et al., 1996; Brandt, 1996; Pikul et al., 1997; Tanaka et al., 1997; Miller et al., 2006; Zentner et al., 2006). Growing regional seed supplies also enhances their potential as green manures. Pea particularly stands out as a relatively strong biomass producer with good N fixation ability, is competitive with weeds, but has relatively moderate tissue N concentrations and potentially higher relative seeding costs.

Compared with pea, lentil is a more affordable (low seeding cost) and highly labile green manure due to high tissue N concentrations, but is a lower biomass producer, and is less competitive with weeds (Biederbeck et al., 1993; Townley-Smith et al., 1993; Biederbeck and Bouman, 1994; 1996). In the NGP, these spring-sown green manures are intended to utilize early growing season precipitation and be terminated before water use compromises the yield potential of the following crop. Termination at later stages of maturity increases N contribution potential, but water use has been shown to be excessive at these stages (Townley-Smith et al., 1993; Biederbeck and Bouman, 1994; Aase et al., 1996; Zentner et al., 1996). Early LGM termination before full-bloom stage was suggested by Townley-Smith et al. (1993), Brandt (1996), and finally by Zentner et al. (2004a), who indicated agronomic and economic benefit thresholds were reached when termination timing was shifted from full-bloom to pre-full-bloom stage. To date, though, few studies further examining early-termination methods have been conducted.

Nitrogen benefits and resulting dynamics from pulses and LGF's in semiarid regions remain unclear, and crop responses may also be easily confounded by non-N factors (Miller et al., 2002). Variable reports may also be partly due to specific mineralization dynamics leading to low recovery of legume N from a single rotation. Bremer and van Kessel (1992) found that only 7% and 37% of N from lentil straw and green manure, respectively, was available to subsequent wheat. Janzen et al. (1990) found that 11 to 27% of N from lentil and tangier flatpea (*Lathyrus tingintanus* L.) green manure was recovered by subsequent wheat, and Rice et al. (1993) similarly found that ~11% of green manure N from the same two species was recovered by subsequent barley

(*Hordeum vulgare* L.). Interpreting legume N contributions as insubstantial from these and other reports of absent rotational benefits (Rice et al., 1993; Pikul et al., 1997; Tanaka and Anderson, 1997; Tonitto et al., 2006; Carr et al., 2008) may be due to a dearth of longer-term studies investigating perennial effects of legumes. Longer-term perspectives (3+ legume appearances in rotation) tell a contrary story of increasing wheat yields, quality, and N uptake over time from improved soil-N fertility from legumes in rotation (Campbell et al., 1997; Zentner et al., 2001; Zentner et al., 2004a; Walley et al., 2007; Allen et al., 2011).

Legume green manures have also historically been till-incorporated into the soil and very limited knowledge exists on no-till management of green manures; a few LGM studies have included no-till management components, but effects were not necessarily conclusive (Townley-Smith et al., 1993; Pikul et al., 1997; Tanaka et al., 1997; Miller et al., 2006). This is especially pertinent since till management is increasingly discouraged and unpopular among conventional producers in the NGP, and understanding the implications of no-till managed LGMs will be important for its adoption potential. Ultimately, combining early LGM termination at first-flower stage and enhanced water storage through no-till management may be a key strategy to reduce risks of stored water depletion for a subsequent wheat crop. Since eliminating summer fallowing also presents an economic risk to producers, participatory extension research may be able to inform researchers of critical challenges to producers adopting this practice across various site conditions. Although LGMs are an integral part of organic management for N fertility, it has not been a necessity for conventional growers, and adoption will benefit from

elucidating both immediate and long-term expectations from including legumes in rotation. This is especially necessary for green manures, which do not directly produce a harvestable market commodity. In this regard, dynamics of alternative green fallow methods for conventional producers such as early-terminated legumes for marketable forages should be explored (Miller et al., 2002).

Understanding Edaphic Changes from Cropping System Intensification and Legumes.

> "…the presence of moisture in the soil during the warm period makes favorable conditions for the activity of those organisms which make available the plant food in the soil. The crop after fallow, therefore, finds a large supply of moisture in the soil and ample plant food in a state to bring about rapid growth.
> - *Atkinson and Nelson, Montana Agricultural Experiment Station* (1911)

> "…when a field is cropped every year, the moisture is so fully utilized by growing plants that an insufficient amount is present for the bacteriological activities. As a consequence, the processes which have to do with bringing plant food into an available state are hindered, and useful food is not at hand for the development of large crops each year."
>
> - *Alfred Atkinson, Montana Agricultural Experiment Station* (1907)

In replacing summer fallow and intensifying cropping systems, shifts in the overall edaphology of NGP agroecosystems should be expected; these shifts should be particularly pertinent regarding introduction of legumes into the system (Biederbeck et al., 1998; Grant et al., 2002; Biederbeck et al., 2005; Lupwayi and Kennedy, 2007). Intensification with legumes should increase labile, N-rich residue contributions to soil SOM, leading to desirable changes in soil quality for agroecosystems. This includes increases in soil organic C that can precipitate desirable microbial, chemical, and physical changes in soil qualities (Sikora and Stott, 1996; Carter, 2002), and increased soil organic

N, which can lead to a robust and efficient N supply (Sikora and Stott, 1996; Robertson et al., 1999) for annual cropping. Because summer fallowing (especially tilled-fallow) has been widely reported to result in net losses of the organic matter (especially labile fractions) that sustains microbial activity aiding in maintaining soil quality (Monreal and Janzen, 1993; Aase and Pikul, 1995; Paustian et al., 1997; Doran et al., 1998; Janzen, 2001; Sainju et al., 2008), replacing summer fallow with legumes may be especially beneficial. Studies have shown that decreasing tillage, eliminating summer fallow, and increasing cropping intensity can lead to soil quality benefits (Campbell et al., 1999; Liebig et al., 2004; Campbell et al., 2005; Liebig et al., 2006). Both legume-amended and no-till soils can maintain higher microbial populations, have higher NH_4^+ to NO_3^- ratios, and higher indications of active SOM fractions (Doran, 1987; Drinkwater et al., 1995; 1998; Islam and Weil, 2000; Biederbeck et al., 2005).

Fertilization is also capable of building soil C and N in cereal grain systems through increasing residue production (Campbell and Zentner, 1993; Paustian et al., 1997; Varvel et al., 2002). But, legume-included rotations may likewise be capable of increasing C and N retention in soils (Drinkwater et al., 1998; Gregorich et al., 2001; Fortuna et al., 2008), without N fertilizer additions. Both fertilizer-N and legume-N sources have been reported to “prime” mineralization from SOM (Kuzyakov et al., 2000; Fontaine et al., 2003) and it remains unclear if N sources differ in this regard. Mitigating SOM loss with fertilizer inputs has been criticized for inconsistency and suspicion that N fertilizer may concomitantly incite organic matter decomposition (Khan et al., 2007; Mulvaney et al., 2009; Russell et al., 2009). In addition, N-fertilizer also has a “hidden C

cost" in its manufacturing process (Janzen et al., 1998; Schlesinger, 2000), which may negate soil C stored as a result of increased residue production in fertilized systems (Russell et al., 2005; DeLuca and Zabinski, 2011). These concerns are supported by the postulation that N fertilizer relieves stoichiometric N limitations for microbes to metabolize available C supplies. Reports of N fertilizer effects on SOM decomposition mostly indicate no priming effect on SOM (Jenkinson et al., 1985; Fog, 1988). Conversely, studies in the NGP illustrate that legume systems (including grain legumes and legume green manures) are apparently capable of maintaining soil C and N levels similarly to fertilized continuous wheat (Biederbeck et al., 1994; Campbell et al., 1997; Biederbeck et al., 1998; Campbell et al., 2001). This occurs even though 1) more abundant and recalcitrant shoot residue C returns from systems such as continuous wheat are expected to have a more profound effect on SOM accretion (Drinkwater et al., 1998; Gregorich et al., 2001), and that 2) labile legume residues are expected to contribute minimally to SOM buildup compared with high C:N residues (Curtin et al., 2000) and perhaps even induce priming effects on native SOM. Consequently, a fertilizer effect on organic matter decomposition of some nature is still suspect for this discrepancy in observations.

Legume-inclusive systems have also been purported to help re-synchronize soil C and N cycles, and stabilize a natural C:N ratio balance in SOM, while also improving N uptake synchrony through incremental release from residues and microbial biomass pools (Campbell et al., 1993; Drinkwater et al., 1998; Tilman, 1998; Crews and Peoples, 2005; Gardner and Drinkwater, 2009). However, Due to the cool dry conditions that

predominate in the semiarid NGP, shifts in agroecosystem equilibrium may be expected to be slow and gradual, as observed in aforementioned long term studies where increased soil N supplying capacities from legumes were evident only after several rotation cycles. Despite some reports of initially decreased N availability as a cost to investing in intensified cropping with legumes, long-term studies have also indicated that positive returns can be realized after several years, and sometimes concomitantly reduce nitrate leaching risks (Drinkwater et al., 1998; Zentner et al., 2001), if legume systems are managed with cognizance to increasing N-supplying capacities (Crews and Peoples, 2005; Campbell et al., 2006a; Gardner and Drinkwater, 2009). Soil physical properties, including soil aggregate stability (Biederbeck et al., 1994; Campbell et al., 1997; Biederbeck et al., 1998; Islam and Weil, 2000; Walley et al., 2007) can also be affected, leading to greater infiltration, aeration, resistance to erosion (Arshad et al., 1996), and protection of SOM (Six et al., 2000).

These aspects indicate potential for NGP cropping systems intensified with legumes to lead to long-term increases in soil fertility and ecosystem service potentials from agricultural soils. Since legumes and intensified cropping are increasingly common and no-till management is rapidly becoming conventional in these systems, understanding edaphic changes resulting from these management factors is imperative, and has been identified as a research need (Grant et al., 2002; Cochran et al., 2006; Lupwayi and Kennedy, 2007). This should lead to fostering appropriate expectations, and a better understanding of the potential of these management changes to result in more sustainable NGP cropping systems.

Research Objectives.

Contributing to a body of knowledge concerning viable summer fallow elimination and adoption of legume rotations in Montana and the NGP are paramount objectives of this thesis. Research objectives were twofold and concern unsettled questions of replacing summer fallow with legumes. The first objective largely focuses on an agronomic viability issue for farms where legume inclusion is most appropriate as green fallow (forages or LGMs) crops due to water use constraints. Past studies illustrated that the agronomic viability of LGM crops in these regions hinges on conservative crop water use management, and that early termination and no-tillage may be promising strategies for conserving critical soil water for subsequent wheat crops. However, these results were from carefully controlled plot-scale studies, and it remained unclear whether results would be consistent at larger field scales, and under farmer management. Additionally, LGM adoption appears to be inexplicably negligible in regions of the NGP that it may be most suited to, and understanding farmer perspectives would likely help inform future adoption/advocacy strategies. Therefore, Chapter Two addresses a two-year field-scale study of LGM-wheat vs. summer fallow-wheat rotations on five farmer-managed sites in the summer fallow-wheat dominated region of north-central Montana. To date, there has been minimal research on combining no-tillage and early LGM termination, and no investigation of field-scale, farmer-managed, LGM-wheat rotations.

The second objective concerns the inconsistency of perceived effects from legumes in rotation in dryland wheat agroecosystems, especially concerning benefits of

legume-fixed nitrogen. Benefits are inconsistently detected from short-term studies in this region, whereas long-term studies have detected positive legume influences on edaphic conditions that lead to wheat yield benefits. Understanding legume effects on a temporal scale will allow researchers to inform producers with appropriate expectations from legumes in rotation. Additionally, assessing edaphic conditions after several rotations with legumes increases chances of detecting other positive soil quality benefits that may result from eliminating summer fallow, and legume inclusion. Intensified cropping with legumes may have advantages over intensification with more wheat, including increasing various soil quality parameters and the N supplying capacity of soils, without the need for fertilizer N additions. If producers do not immediately perceive yield benefits from legumes in rotation, the incentive may be deterred and the practice stigmatized. Further evidence is needed to indicate that legume benefits in this region may begin to manifest after several rotations. Chapter Three therefore addresses an assessment of select soil attributes from an eight-year-old rotation study including wheat-only vs. legume-inclusive wheat rotations, and N fertilizer effects on mineralization dynamics in soils conditioned by different crop rotations. To date there has been little evaluation of legume effects on edaphic conditions in dryland wheat rotations, especially in the U.S. portion of the NGP. No studies were found assessing of N fertilizer effects on mineralization dynamics in soils in wheat-based NGP agroecosystems.

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CHAPTER TWO

GREENING SUMMER FALLOW WITH LEGUME GREEN MANURES: ON-FARM ASSESSMENT IN NORTH-CENTRAL MONTANA

Contribution of Authors and Co-Authors

Manuscript in Chapter 2

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Contributions: Managed/conducted research project, obtained partial funding for project, analyzed data with the assistance of of Ilai N. Keren, wrote the manuscript.

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Contributions: Assisted in designing study and obtaining main funding source for the project, advisement and authority on nutrient cycling/soil chemistry aspects of research, secondary editing and feedback on the manuscript.

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Greening summer fallow with legume green manures: On-farm assessment in north-central Montana

Abstract: Growing annual legumes as green manures (LGMs) may increase the sustainability of northern Great Plains fallow-wheat (*Triticum aestivum* L.) systems, though viability hinges on soil water management and realization of biologically fixed-N benefits. Plot-scale research in Montana has shown that managing LGMs with first-flower stage termination and no-till practices increases agronomic viability by conserving soil water, and that rotational N benefits can increase wheat grain quality. Nonetheless, farmer adoption of LGMs has been negligible. To better understand this practice and its regional adoption potential, we conducted a participatory on-farm assessment of no-till LGM vs. summer fallow – wheat rotations in north central Montana. Soil water and nitrate levels to 0.9 m, potentially mineralizable nitrogen (PMN) to 0.3 m, wheat yields, and producer adoption challenges were assessed at five farmer-managed, field-scale sites. Analysis across sites showed that compared to fallow, LGM treatment diminished average wheat yield by 6%, and diminished grain protein by 9 g kg^{-1} ($p = 0.01$) at sites where wheat was fertilized with N, and increased grain protein by 5 g kg^{-1} at unfertilized sites ($p = 0.08$). Small soil water depletions in LGM treatments below fallow (30 mm, ~17%) at wheat seeding and near record high rainfall during the wheat-growing season (280 to 380 mm) suggest that LGMs likely did not limit soil water available to wheat in this study. Soil nitrate levels following LGMs were 29 to 56% less than summer fallow at wheat seeding. Conversely, greater PMN was detected in LGM treatments at 3 of 5 sites. We theorize that N mineralization from LGMs may have been insubstantial by wheat

seeding due to dry soil conditions and low LGM biomass N contributions, consequently affecting wheat yield potential through early-season N limitation. LGMs increased average use-efficiency of available N by 24% during the wheat year, and increased total residue C by 12%, and N returned to soils by 26 kg ha^{-1} after two years. Our results also illustrated that farmers viably managed LGMs with early-termination and no-till practices, but that LGM adoption may be hindered by a lack of immediate wheat yield or protein benefits from legume-N and seed costs for LGMs. Appropriate incentives, management strategies, and yield benefit expectations (short vs. long-term) should be fostered to increase the adoption potential of this N-economizing soil and water conservation strategy.

Key words: dryland wheat–field scale–green fallow–no till–northern Great Plains

Cropping systems in the northern Great Plains (NGP) of North America are entering a post-summer fallow and wheat (*Triticum aestivum* L.) monocropping era. Pulse crops such as dry pea (*Pisum sativum* L.) and lentil (*Lens culnaris* Medik.) have become increasingly important summer fallow replacement crops, especially since the early 1990s (Miller et al. 2002; Carlyle 2004; Tanaka et al. 2010). Advances in water conservation resulting from conservation tillage and no-tillage adoption have allowed for this change (Cochran et al. 2006). Yet, in the driest regions of the NGP, and particularly in north-central Montana (MLRA 52), summer fallow practice has been more tenacious; recent estimates suggest ~ 84% of cropped acreage remains in a fallow-wheat rotation

(NASS 2010). Rotating wheat with early-terminated (anthesis stage, i.e., "first flower") annual legumes, termed "legume green manure" (LGM), may be a water-conservative way to realize rotational legume benefits in this region, particularly regarding fixed-N and mitigating negative effects of summer fallow that lead to soil degradation, nitrate leaching, and saline seeps (Tanaka et al. 2010).

Beginning in the early 1900s, research initiatives in the NGP on LGMs have fluctuated with trends in the availability of N fertilizer (Army and Hide 1959; Brown 1964; Janzen 2001), price, and sustainability initiatives (Hargrove and Frye 1987; Biederbeck et al. 1993; Peoples et al. 1995). In the NGP, LGM interest has been persistently tempered by water use constraints affecting wheat yield. Historically, studies established that excessive water use by LGMs have precluded wheat yield benefits from crop diversification or N-fixation (Brown 1964; Biederbeck et al. 1996; Zentner et al. 1996; Janzen 2001), and that biomass production and soil water conservation must be balanced for the practice to be viable (Zentner et al. 2004). Also, N fertilizer has generally been cost-effective and reliable, effectively replacing legumes as an N source (Bullock 1992; Drinkwater and Snapp 2007). Legume N contributions are a fundamental component of organic management, but this has also kept the practice associated with tillage, and relegated it to a fringe practice among conventional no-till producers. Despite potential conservation/sustainability benefits, mainstream LGM adoption is unlikely unless LGMs can be shown to: (1) conserve critical soil water levels for subsequent wheat, (2) exhibit fixed-N yield benefits that increase grain protein and/or offset N

fertilizer costs, and (3) be consonant with no-tillage management and contemporary soil conservation practices.

Historically, LGMs were terminated at full bloom stage or at predetermined dates generally coinciding with the former, and incorporated with tillage. Under this management, water use by LGMs was often excessive and prompted Townley-Smith (1993), Brandt (1996), and Zentner (1996) to suggest that LGMs be terminated before full-bloom stage. Zentner et al. (2004) demonstrated in a Saskatchewan study that critical soil water levels were maintained when LGMs were terminated before full-bloom stage. This management change also produced an unprecedented positive shift in yields and economic returns from LGM rotations. Understanding that tillage-based LGM management was not consistent with current soil and water conservation principles and practices, Miller et al. (2006) and Burgess et al. (n.d.) combined early LGM termination (first-bloom) with no-till management. They showed that wheat yield following LGMs was never less than those following summer fallow, and consistently had ~8 g kg^{-1} greater wheat grain protein than wheat following summer fallow, even in droughty conditions. But, due to the delicate nature of terminating LGMs at the proper time for conserving soil water, it was not known whether these results could be reproduced at the field scale under farmer management.

We enlisted five wheat producers from north-central Montana to collaborate in a participatory, field-scale study. We hypothesized that wheat following no-till LGMs would yield as well as wheat following no-till summer fallow, and fixed N benefits would increase grain protein. Our objectives were to assess treatment effects on soil

water, N availability, and wheat yield and protein. We also hoped to gain insight into the producer's experience of adopting LGM practices. We expect that this study will help further elucidate the agronomic viability of managing LGMs with no-till and early-termination, and adoption potential in north-central Montana and the NGP.

Materials and Methods

Producer Collaboration. Five producer collaborators were recruited with the assistance of the Great Falls, Montana Natural Resources Conservation Service office. Collaborators were required to (1) plant an annual LGM crop, (2) maintain an adjacent summer fallow (chemical fallow) strip as a control treatment, (3) use no-till practices on the field site, (4) terminate the LGM at first flower, (5) provide information about logistics of growing a LGM crop in rotation with wheat, and (6) communicate and coordinate with the research team so that data collection was timely and unobtrusive to farm operations. Otherwise, all management decisions were delegated to producers. See table 1 for site orientations and table 2 for specific site management details.

Field Sites, Experimental Design. Producers chose field sites and established treatments on their farms. They either planted a LGM strip within a fallow field (3 sites), left an unseeded strip (1 site), or sprayed-out a strip in a LGM field two weeks after emergence (1 site). Field sites were considered acceptable experimental units only if both treatment transects had highly similar topography and management histories.

A replicated-measurement paired t-test experimental design with 6 to 12 paired sampling points was established at each site depending on transect length. Transect lengths ranged from 550 to 1300 m (see table 1). Sampling points were established 5 to

10 m from either side of the fallow-LGM treatment interface, systematically spaced 100 m apart and at least 30 m from each end of the field site to avoid header areas. All sampling points were recorded with a Trimble Geo XT GPS unit (Trimble Navigation Limited, Sunnyvale, CA), and a Garmin Dakota 20 (Garmin International Inc., Olathe, KS) was used to re-navigate to points for sampling. See table 1 for specific field site metrics, and figures 1a and b for field site example.

Determining Site-Specific Characteristics. Baseline soil texture, pH, salts, levels of inorganic N, P, K, and soil organic C for the 0 to 15 cm depth were determined for each treatment transect at all sites using five, evenly spaced, hand-cored (1.7-cm diam.) soil samples per transect, sampled on June 11, 2009. These samples were then composited, and sent for analysis (Agvise, Northwood, ND; table 1). Precipitation data were recorded from rain gauges at each field site, and were augmented with data from the nearest Western Regional Climate Center weather station (WRCC, Reno, NV) in cases of missing or compromised rain gauge data (table 3). These stations were between 11 and 31 km (average = 19 km) from the sites. Temperature estimates were compiled solely from WRCC data.

Sampling Protocols. Samples for soil water and NO_3-N content were taken at two intervals; 3-7 d post-termination of the LGM, and 0-21 d before wheat seeding, depending on the producer's decision to plant winter or spring wheat (see table 2). Soil cores were taken to a depth of 0.9 m in 0.3-m increments, and stored in polypropylene-lined paper bags. At wheat seeding, an additional 0.3-m core adjacent to the main 0.9-m core was taken for potentially mineralizable nitrogen (PMN) analysis. A truck-mounted

hydraulic probe (Concord Equipment, Hawley, MN) with a 1 m x 3 cm diameter sample tube (Giddings Machine Company, Windsor, CO) was used for taking soil cores. Samples taken at wheat seeding were 1 to 3 m from the original post-termination samples to avoid the original sample point, where biomass had been removed. All sampled soils were stored in coolers until they could be returned to the lab (6 to 48 hr).

Legume green manure shoot biomass samples (1 m^2) were hand-harvested 3-7 d after herbicide application. Wheat shoot biomass samples (1 m^2) were likewise hand-harvested 0 to 7 d before producers harvested (approximately Zadoks stage 87 to 92). Weed biomass was also collected, but was largely insubstantial (< 10 % of crop biomass) except at Oilmont.

Laboratory Procedures. After returning from the field, all field-moist soil samples were immediately weighed, and placed in a dryer (4 d, 50°C), or frozen (-10°C) in a chest freezer until they could be dried. Soil bulk densities and gravimetric soil water contents were determined after taking dry weights, and used to calculate soil water levels in units of Equivalent Depth (Or and Wraith 2000). Dried soils were ground with a Dynacrush Soil Crusher (Custom Laboratory Equipment, Orange City, FL) to pass through a 2-mm sieve. From each sample, a 5-g subsample was extracted with a 1 *M* KCl solution as described by Bundy and Meisinger (1994) and analyzed for NO_3^-N by Cd reduction with a Lachat flow injection autoanalyzer (Lachat Instruments, Milwaukee, WI).

Each field-moist soil sample taken for PMN was homogenized by manual chopping (knife) to a 2 to 4-mm maximum aggregate size. PMN was then determined according to the method described by Bundy and Meisinger (1994); 10-g subsamples

were waterlogged, purged with N_2 gas, and incubated anaerobically (7 d, 40°C). Pre and post-incubation samples were extracted with a 2 *M* KCl solution and analyzed for NH_4^+-N with a Lachat autoanalyzer.

Biomass samples were oven dried (4-7 d, 40 to 50°C) and weighed 'hot' from the oven for total shoot biomass yields. Seeds were hand-threshed, separated if present, and weighed. LGM biomass, wheat straw/chaff, and weeds were ground with a Wiley Mill (Thomas Scientific, Swedesboro, NJ) and then fine ground (< 0.5 mm) with an Udy Cyclone Mill (Udy Corporation, Fort Collins, CO). Nitrogen content of LGM, weeds, and wheat straw biomass was analyzed from a 1-g subsample using a LECO CNS combustion analyzer (LECO Corp., St. Joseph, MI). Wheat grain protein and moisture were determined with an Infratec 1241 Grain Analyzer (Foss of North America, Eden Prairie, MN), with protein data standardized to 120 g kg^{-1} (12%) moisture. Wheat grain N content was determined by dividing protein concentrations by a factor of 5.7. All wheat grain yield values were also standardized to 12% moisture. Weed biomass was used in analyses only if it constituted 10% or more of the total biomass gathered at a given sample point.

Statistical Analysis. Data quality was examined with boxplots, and suspected outliers were reassessed by examining Jackknifed Mahalanobis distances of the differences between treatment values. Strategies for dealing with suspected outliers then generally followed those outlined by Ramsey and Schafer (2002). In cases of skewed-right data (overwhelmingly in soil N data only), it was decided to report more conservative estimates of the magnitudes of treatment effects by removing large outliers strongly influencing means, even if statistical conclusions were unchanged by their inclusion.

Treatment effect statistics are presented both at the individual site level, and across all sites. Despite low statistical resolutions (small *n*) and difficulty in examining test assumptions, individual site-by-site analyses are included because of different site conditions and management, and to aid in interpreting results across all sites. Differences between LGM and summer fallow treatments at individual sites were analyzed using paired t-tests. For analysis of treatment effects compared across all sites, a mixed-model ANOVA was constructed with treatments as fixed effects, and with site, and paired sample point (individual paired observations within sites) nested within site as random effects. The ANOVA test assumptions were evaluated with residual plots, histograms, and Q-Q-normal plots. Analyses were conducted with JMP 9 (SAS Institute, Cary, NC) for outlier screening and basic paired t-test analyses using the *Multivariate Methods> Multivariate> Jackknife Distances* and *Matched Pairs* platforms, respectively, or R (The R Foundation for Statistical Computing, Vienna, Austria), using the *nlme* statistical package for mixed-effects models (Pinheiro and Bates 2009; Pinheiro et al. 2011). Treatment effects were considered statistically significant when $p \leq 0.10$.

Results and Discussion

Shoot LGM Biomass, N Content. Legume biomass and biomass N ranged 2-fold over sites, respectively (table 4), due to differing site conditions and management choices (tables 2 and 3). At sites where pea was grown, LGMs generally yielded greater, averaging 0.97 Mg ha^{-1} biomass and 32 kg ha^{-1} biomass N, while lentil at Oilmont yielded nearly 50% less, with 0.55 Mg ha^{-1} biomass and 15 kg ha^{-1} biomass N. Legume green manure biomass N (table 4) correlated well with shoot biomass ($r = 0.85$). Box

Elder, Sunburst, and Oilmont had similarly low biomass N concentrations (data not shown), averaging 26 g N kg^{-1}, leading to lower relative biomass N contributions compared to Big Sandy and Joplin, which averaged 39 g kg^{-1} N. Nitrogen fixation was not measured in this study, but N-fixing nodules on LGM roots were clearly present and appeared active (distinctively reddish-pink hued) at all sites.

In two studies on LGMs biomass productivity, Biederbeck et al. (1993; 1996) respectively reported 1.5 and 2.6 Mg ha^{-1} biomass and 40 and 62 kg ha^{-1} N for lentil and pea in Saskatchewan, and Power et al. (1991) reported 3.9 Mg ha^{-1} biomass and 69 kg ha^{-1} N for pea in Nebraska. Our low biomass results are partly due to early termination (Brandt 1996), but our results were even low for early terminated legumes. In two early-terminated LGM studies from southern Saskatchewan (Brandt 1996; Zentner et al. 2004), the lowest LGM biomass and biomass N measures reported were 1.2 Mg ha^{-1} and 42 kg ha^{-1}, respectively, in dry years. Similarly, Miller et al. (2006) reported early-termination-managed pea biomass and biomass N measured 1.2 to 1.8 Mg ha^{-1} and 48 to 54 kg ha^{-1}, respectively, at sites in north-central Montana. In a northern Alberta study, Rice et al. (1993) reported low biomass and biomass N only in years when considerable drought occurred during the last month of full-bloom terminated LGM growth. Their LGM biomass and biomass N had 0.6 to 0.8 Mg ha^{-1} and 13 to 16 kg ha^{-1}, respectively, for lentil and 0.8 to 0.9 Mg ha^{-1} and 16 to 20 kg ha^{-1}, respectively, for Tangier flatpea (*Lathyrus tingitanus* L.). Tanaka et al. (1997) also reported low early-terminated pea LGM biomass and biomass N yields of 0.57 Mg ha^{-1} and 17 kg ha^{-1}, respectively, during only one dry year of five years in a North Dakota study. In our study, low LGM biomass

and biomass N was most likely caused by low/untimely precipitation during the LGM growing season at four of five sites (table 3), and/or late seeding dates leading to short, sub-optimal growth periods (Joplin and Oilmont, table 2). The aforementioned studies suggest that annual legume biomass responses are highly dependent on in-season precipitation. Also, N-fixation was reported to be negatively affected in droughty conditions in southeastern Alberta (Bremer et al. 1988), and likewise may have lowered biomass N concentrations in our study.

Soil Water. All sites, with the exception of the Joplin site, received very little rainfall during the LGM growth period (table 3) and presented a favorable opportunity for observing LGM effects on stored soil water under early-termination and no-till management. Total soil water to 0.9 m was 29 to 46 mm less under LGMs than under fallow at LGM termination (table 5). Legume green manures caused a mean 43 mm (22%) depletion ($p < 0.01$) below fallow to 0.9 m, with 25 mm (58% of total depletion) occurring in the top 0.3 m, and 38 mm (88% of total depletion) occurring in the top 0.6 m. At individual sites, soil water appeared unaffected by LGMs in the 0.6 to 0.9 m depth, although overall, a 5-mm mean depletion effect ($p = 0.02$) was detected.

Our results support conclusions by others that annual LGMs such as pea and lentil largely limit soil water use to the 0.6 m depth (Biederbeck and Bouman 1994; Miller et al. 2006). Our results approximated Aase et al.'s (1996) suggested threshold (50 mm) for LGM water use to not compromise availability to subsequent wheat. Early LGM termination likely abated excessive soil water use, even during a very dry spring.

At wheat seeding, total soil water to 0.9 m (table 5) under LGM soils ranged between 0 and 39 mm less than fallow, with a mean depletion effect of 30 mm. The Big Sandy site completely recovered to fallow values (all $p > 0.10$); this was evidently due to a single substantial July rainstorm event that deposited ~ 60 mm of rain at that site (as reported by producer). While the greatest soil water depletion at LGM termination occurred at Sunburst and Oilmont, their soil water depletions were similar to other sites at wheat seeding (April 2010).

For fall-measured soil water, Townley-Smith et al. (1993) reported a mean 46-mm depletion from full-bloom terminated LGMs (both tilled and no-till) in Saskatchewan. Brandt (1996) in Saskatchewan and Miller et al. (2006) in Montana reported full recovery of soil water to fallow values with early-terminated LGMs under a wide range of precipitation conditions. Biederbeck and Bouman (1994) importantly illustrated that soil water to 0.6 m may be equal by spring, but lower depths may still show effects of depletion under full-bloom LGM termination timing. Zentner et al. (2004) reported that after shifting to early-termination practices, mean spring soil water depletion levels from LGMs to the 1.2-m depth decreased from 53 mm to 22 mm. Miller et al. (2006) reported no differences in April plant-available soil water between LGM and fallow values in higher precipitation conditions. Overall, precipitation up to wheat seeding during our study appeared to limit soil water recharge potential compared to other studies, and illustrates the importance of early-termination in safeguarding against excessive LGM soil water use in this region.

Soil Nitrogen. Soil NO_3–N concentrations at sites were generally low at LGM termination, and despite biological-N fixation, LGMs apparently depleted soil NO_3–N (table 6). Nitrate to 0.9 m in LGM soils at LGM termination indicated a mean 12 kg ha^{-1} (55%) depletion below fallow values ($p < 0.01$). By site, LGM NO_3–N depletion occurred consistently in the 0 to 0.3-m depth (all $p < 0.10$), with this depth accounting for 79% of the total mean depletion ($p < 0.01$).

Soil NO_3–N depletion from legume crops is common despite their ability to fix N; legumes will preferentially use some available soil N before investing in symbiosis with rhizobia (Larue and Patterson 1981; Butler and Ladd 1985). This effect can be viewed positively from a conservation standpoint, where LGMs act as "catch crops" for soil N otherwise vulnerable to losses via leaching or denitrification in fallow treatments (where soil N and water conditions are concomitantly higher) as suggested by Biederbeck and Bouman (1994) and Miller (2006), respectively. This effect would also be most detectable just after cessation of plant growth and before any substantial mineralization of residues has occurred. Since this was the case in our study, depletion measured at termination is likely a good approximation of soil N sequestered by LGMs.

At wheat seeding, mean soil NO_3–N depletion from LGM treament was slightly greater than at LGM termination at 19 kg ha^{-1}, but the magnitude of the depletion below fallow values was less (34%). Values in both treatments again varied by site, but generally increased (table 6), with more consistent detection of differences in lower depths. Depletion in the 0.3 to 0.6 m depth at this timing was consistent at individual sites

(all $p < 0.10$), and mean depletion in the total 0.3 to 0.9 profile amounted to 8 kg ha^{-1} (44% of total).

Reports from other studies have likewise indicated that NO_3–N depletion can persist into the fall and/or spring following LGMs in some cases, and that short-term net gains in soil NO_3–N from LGMs are fairly uncommon. Biederbeck et al. (1996) and Tanaka et al. (1997) observed mostly no differences from fallow in fall-sampled soil NO_3–N following LGM treatments. Miller et al. (2006) observed equal fallow and LGM NO_3–N values in fall-sampled soils after LGM treatment; in spring, values were also equal, minus one instance where fallow values were considerably lower. This anomaly was speculated to be caused by denitrification that occurred in saturated fallow soils and not in unsaturated soils following legumes, since no evidence of leaching was found. In another Montana study, organic pea green manure produced equal or higher nitrate concentrations as summer fallow in late summer or fall to the 0.3-m depth, and generally equal values in the 0.3 to 0.6-m depth (Miller et al. 2011). Brandt (1996) and Pikul et al. (1997) both reported instances of lower spring or soil NO_3–N in soils following the first year of LGM treatment, but in spring after the second or third cycle of LGM treatment, LGM treatments began to exhibit higher or equal values, respectively, than fallow controls. Allen et al. (2011) reported in a follow up study to Pikul et al. (1997), that soil available N generally continued to be enhanced in LGM treatments compared to fallow after the third appearance of LGMs in rotation. Zentner et al. (2004) likewise showed that that soil NO_3-N following lentil green manure was consistently lower than fallow until

the spring after the second cycle of green manure, and then remained consistently higher than fallow for the next eight years of the study.

Measurements of potentially mineralizable nitrogen (PMN) at wheat seeding produced variable results, with greater values in LGM soils detected at three of five sites (table 6). Across sites, PMN measured in fallow soils at sites ranged from 5 to 15 kg ha^{-1}, and from 5 to 46 kg ha^{-1} in LGM soils, with LGM treatment causing a mean 9 kg ha^{-1} increase in PMN overall ($p < 0.01$). Soils that were sampled in spring (Sunburst, Oilmont) exhibited greater and more consistent positive responses from LGM treatments; only one of three sites sampled in fall had greater PMN in LGM soils compared to fallow.

Greater PMN detected in LGM treatments suggests that there was substantial legume-N not yet mineralized at wheat seeding, and is in agreement with results by Pikul et al. (1997) who likewise reported lower soil NO_3–N and higher soil PMN in LGM treatments compared to fallow. We theorize that lower NO_3–N and higher PMN in soils following LGM compared to fallow in our study were caused by three main factors: (1) unusually low precipitation during the LGM growing season which diminished mineralization potential; (2) low biomass N contributions from LGMs across all sites; and (3) no tillage treatment minimizing mineralization of LGM residues. Since LGMs dry the top layer of soils where the bulk of nutrient mineralization occurs, it is very likely that this top layer stayed consistently dry at all sites throughout that season, when very little precipitation occurred (table 3). Cassman and Munns (1980) derived an equation for estimating N mineralization potential as a function of soil gravimetric water content and

temperature; based on gravimetric water contents observed to 0.3 m in our LGM and fallow treatments at LGM termination (120 and 170 g kg^{-1}, respectively) and using a hypothetical soil temperature of 20°C, N mineralization potential in fallow would be 8.1 kg ha^{-1} every 14 d, while mineralization in LGM treatments would be negligible. Elliott et al. (1984) similarly showed, *in situ*, the pronounced effects that soil water content can have on mineralization potential during summer fallow. In a meta-analysis of cover crops as fallow replacements, Tonitto et al. (2006) showed studies with cover crops containing <110 kg ha^{-1} of shoot biomass N tended to correlate with 15% yield reductions in subsequent crops compared to fallow controls. Our measurements of biomass N from this study are far below 110 kg ha^{-1}, as are measurements commonly reported in studies in the NGP. This finding suggests that there is likely a critical threshold of contributions from LGM biomass N that must be met before a net gain of mineralized N is consistently attainable. This is not surprising considering that soil N sequestered and fixed in residues may remain in various organic N pools for indefinite periods before becoming plant available, and is supported by findings of Janzen et al. (1990) and Bremer and van Kessel (1992). Lack of apparent mineralization from green manure may also be due to a lack of LGM biomass soil incorporation in a no-tillage situation where residues remain aboveground (figure 1b and c). No-till management is generally acknowledged to delay nutrient recovery from residue compared to tillage (Schoenau and Campbell 1996; Triplett and Dick 2008), until after several years of residue accumulation on the soil surface. Pikul et al. (1997) showed that no tillage LGM and fallow treatments in two of four years had significantly lower soil NO_3^-N values than corresponding tilled controls,

and recent work by Vaisman (2011) and Burgess et al. (n.d.) similarly supports the conclusion that net N mineralized in no-till can be less than tilled treatments. While NH_3-N volatilization has been detected from green manure residues (Janzen and McGinn 1991; de Ruijter et al. 2010; Vaisman et al. 2011), Engel (personal communication, July 2009) found no evidence of this in an unreplicated trial at the Sunburst site. Additionally, very dry conditions and lack of LGM residues in contact with soils were not conducive to NH_3-N volatilization during this study.

Wheat Yield Response. Yields of wheat were similar across all sites despite differences in fertilization, with the exception of the Oilmont site, which overall yielded less than the rest (table 7). LGM treatment depressed mean yield by 0.24 Mg ha^{-1} (6%) compared to fallow. Total shoot biomass yields correlated strongly grain yields ($r = 0.99$). Grain protein responses were related to producers' N fertilizer decision for their wheat crop (table 3). Subset analyses by fertilizer decision (fertilizer or none) revealed that the fertilized sites (Box Elder, Joplin, and Sunburst) had diminished protein levels in LGM treatments (9 g kg^{-1}; $p = 0.01$), while the unfertilized sites (Big Sandy and Oilmont) had increased protein levels in LGM treatments (5 g kg^{-1}; $p = 0.08$). Mean grain N yield was depressed 7 kg ha^{-1} by LGM treatments, while grain density was increased 5 kg m^{-3} by LGM treatment over fallow across sites. Analyses of tiller density, seeds per head, and seed weight (not included in tables) were unhelpful in indicating factors driving spring or winter wheat yield responses. Although some differences in these components were observed within sites, patterns were inconsistent and analysis across all sites similarly indicated no treatment effects (all $p > 0.20$).

Despite soil water depletion effects detected at wheat seeding, we do not believe that soil water availability substantially limited wheat growth. This is due to three factors: (1) soil water depletion caused by early-terminated LGMs was low, (2) yield response at Big Sandy was similar to others despite a full soil water recharge to 0.9 m by wheat seeding, and (3) most importantly, each site received from 73 to 150 mm more rainfall than average from April to August. We theorize that wheat yield depression was the result of N depletion caused by LGM treatment. Wheat yields were uncorrelated with soil water at seeding ($p = 0.35$), but correlated moderately with soil NO_3–N at seeding ($r = 0.56$; $p < 0.01$). Pikul et al. (1997) attributed significant yield losses to N limiting conditions following LGM treatment, though this effect had changed by the time Allen et al. (2011) later reported on the same study, due to an accumulation of soil N from LGMs. This contradicts most aforementioned studies attributing reduced soil water availability from LGMs as the primary factor limiting subsequent wheat yields. Miller et al. (2006) and Zentner et al. (2004) concluded that better soil water conservation from early LGM termination eliminated wheat yield depressions following LGMs. Zentner et al. (2004) also reported though that by the time positive yield responses and economic returns had begun from LGMs, available soil N following LGM treatments had also begun to surpass fallow. A follow-up study by Campbell et al. (2006) on the experiment reported by Zentner et al. (2004) indicated that the N supplying power of LGM-amended soils was so greatly increased after 17 yr that it caused greater nitrate leaching than summer fallow. They suggested that legume N credits used in calculating fertilizer rates for this rotation were too conservative. A recent long term study in Bozeman, MT by Miller et al.

(personal communication, September 2010) also supports that the N supplying capacity of soils can be greatly increased by LGMs; after four rotation cycles, an unfertilized no-till LGM - wheat rotation produced spring wheat yields and protein values equal to a fertilized (N = 139 kg ha^{-1}) no-till summer fallow-wheat rotation.

According to estimates by Engel et al. (2006), protein levels in our study were near or below critical levels (121 and 135 g kg^{-1} for winter and spring wheat, respectively) indicating N-limited conditions for wheat yields in both fallow and LGM treatments. The only site that surpassed this critical level was Box Elder, which had the highest fertilization rate (table 2) and also had no difference in grain yield between treatments (p =0.88) or protein (p = 0.23). Comparatively, the Joplin site was fertilized at a lower rate (table 2) and also had no difference in wheat grain yield (p = 0.56), but had depressed grain protein in LGM treatments (p = 0.08), suggesting more N limited conditions. Further, the differing grain protein responses between unfertilized and N fertilized sites suggests that wheat yield potential was likely inhibited from early season N limiting conditions in LGM treatments, rather than in the late season, after more mineralization occurred. It was likely that late season mineralization from LGM residues during grain fill caused grain protein to be marginally increased at unfertilized sites, whereas this effect was overpowered by N fertilizer additions at the other sites, similar to effects observed in pulse-wheat rotations (Miller et al. 2002). The theory of early-season N limitation is also substantiated by the Box Elder producer, who observed wheat tissue chlorosis in early spring in the LGM treatment only. Nitrogen limited conditions were also corroborated by lowered grain N yields and higher grain densities detected in LGM

treatments across all sites. High grain density is a parameter that tends to be inversely related to N availability.

Conservation Parameters. Conservation parameters including use efficiency of available N (NUE) and residue C and N returned to soils, were favorable for LGM rotations compared to fallow (table 8). Mean NUE was 24% greater in LGM treatments. Values of 1 or above indicate that N removed in grain equaled or surpassed amounts of NO_3-N to 0.9 m measured at wheat seeding (table 6) plus N fertilizer added (table 2). As expected, the highest NUE values occurred at sites that were unfertilized since wheat growth was totally dependent on mineralized soil N (table 2). Analysis across all sites indicated 260 kg ha^{-1} (12%) greater residue C and 25 kg ha^{-1} (108%) greater residue N residue returned to soils (corresponding with 0.58 Mg ha^{-1} greater total residue yields) in LGM treatments.

The effect of LGMs on NUE and residue C and N returned indicate their potential to reduce N losses to the environment, and for increasing soil-building organic matter contributions to soils. Higher NUE may also indicate increased synchrony between soil N mineralization and plant demand (Crews and Peoples 2005), considering that LGM treatments apparently relied more heavily on in-season mineralization to meet plant demand. Miller (2006) observed higher NUE at one of three sites from LGM treatments, and in instances of lower fertilizer rates. Biederbeck (1998) reported more residue returned to soils in LGM-wheat treatments over fallow-wheat, which corresponded with increases in soil C, N, and other physical, chemical, and biological soil parameters. Increased protective soil cover was also visually obvious in LGM treatments (figures 1a and c) during our study. Considering that a mean yield depression of 0.24 Mg ha^{-1} (3.5 bu

ac^{-1}) was detected in our study, it is questionable whether producers will accept short-term losses for the sake of long-term conservation goals.

Producer Feedback. Four of the five producers claimed they would continue to experiment with LGMs, despite several challenges. Common concerns included: (1) LGM seed cost; (2) planting winter wheat crops into LGM-dried soil surface; (3) timing spring field operations so that LGMs can be planted early; (4) resisting the temptation to let LGMs grow past first-flower for more biomass accumulation; and (5) absent yield responses. While the last four issues may be rectified through awareness of appropriate expectations from LGMs and adapting operation routines, seed cost may be the most formidable barrier to LGM adoption. While all producers voiced a desire to increase their conservation efforts with LGMs, not all found it to fit within their economic means. Seed costs for LGMs are not a new concern in this region, and date back to early reports of trials with LGMs (Atkinson 1907). It is important to note though that all used top-grade pea or lentil seed for this study. Much cheaper low-grade pea (i.e. feed grade), and especially lentil (i.e. Extra No. 3 and feed grade), would help reduce seed cost. Often low grade pea and lentil seed is available and producers would be well advised to seek this out for LGM use. Growing a small acreage of pulse crops for seed may also be an economical way to procure seed for LGM cropping. Four of five producers interviewed after the project likewise endorsed this perspective, and some recommended that other producers interested in the practice start with small acreages to safeguard against potential economic failures. This approach may furthermore help producers unfamiliar with pulse cropping, or wary of re-cropping with pulses, get accustomed to appropriate

pulse crop management and rotational effects. All producers indicated an interest for future research to better clarify long-term benefits of LGMs in rotation (including economic assessments), and to better understand benefits of LGMs vs. pulse cropping for grain.

Summary, Conclusions

Results from this study confirm that early LGM termination is effective in limiting water use from LGMs, and that LGMs can be managed with no-till practices; importantly, these results occurred under farmer management at the field-scale. No-till management may moreover aid in conserving soil water and is consonant with current soil conservation paradigms. Nonetheless, our results suggest that LGM-N benefits may not be consistently or immediately realized in wheat yields or grain quality. Soil N use by LGMs may cause temporary soil N deficiencies for wheat depending on mineralization conditions following LGMs. These conditions may be related to soil water content, and whether enough N from LGM biomass has been contributed to soils to produce a net gain of plant available N over what may be retained in organic N pools. Further study is needed to determine how long it takes for the N supplying capacities of soils to be increased by LGMs in semiarid NGP agroecosystems, and under no-tillage management where N sequestered in residues may be recovered more slowly than with tillage. Legume green manure practices in this region may be appropriately viewed as an investment towards long-term conservation and economy rather than a practice reliably precipitating immediate yield benefits. Based on producer feedback, this sometimes fits within economic goals, but producers uniformly expressed an interest for future research to

further clarify long-term benefits (including economic assessments) that may result from LGM cropping. Furthermore, for LGM cropping to be economically viable, producers should be encouraged to source seed inexpensively, and/or conservation initiative program subsidies should be encouraged in order to overcome LGM seed costs during the adoption/transition period. The potential of this practice to mitigate negative effects of summer fallow and producer dependence on N fertilizer is unlikely to be realized unless appropriate LGM incentives, management strategies, and expectations are fostered.

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Table 1
Orientation, soil, and experimental characteristics of five experimental sites in north-central Montana.

	Site				
	Big Sandy	**Box Elder**	**Joplin**	**Sunburst**	**Oilmont**
Orientation					
Site location	47°54'50" N, 109°55'24" W	48°18'08" N, 110°05'55" W	48°44'56" N, 110°52'41" W	48°48'05" N, 111°38'30" W	48°48'07" N, 111°31'08" W
Elevation (m)	888	833	1059	1102	1090
Soils*					
Dominant soil classification	Aridic Argiborolls	Aridic Argiborolls	Aridic Argiborolls	Aridic Argiborolls	Aridic Argiborolls
Dominant soil texture	Sandy clay loam	Loam	Clay loam	Loam	Sandy clay loam
pH (saturated paste)	6.1	6.9	7.6	6.9	7.8
Soil organic C (g kg^{-1})	11.0	8.7	12.8	12.2	11.0
Salinity (dS m^{-1})	0.2	0.4	0.4	0.3	0.4
Fallow NO_3-N (kg ha^{-1})	16.0	10.1	11.2	37.0	12.3
LGM NO_3-N (kg ha^{-1})	10.6	7.8	15.7	16.8	11.2
Fallow Olsen P (mg kg^{-1})	23	19	16	12	9
LGM Olsen P (mg kg^{-1})	21	25	19	11	8
Fallow extractable K (mg kg^{-1})	340	422	319	599	355
LGM extractable K (mg kg^{-1})	433	403	451	519	507
Experimental Characteristics					
Transect length (m)	558	732	1288	671	732
Paired sampling points (*n*)	6	8	12	8	8

* All soil characteristics listed after "Dominant soil classification" refer to the 0-15 cm epipedon, sampled June 11, 2009.
† Soil Testing methods used: soil organic C- weight-loss-on-ignition (LOI); NO3-N: 2 *M* KCl extraction, Cd reduction determination; Olsen P: $NaHCO_3$ extraction, colorimetric determination; extractable K: 1 *M* NH_4OAc extraction; mass spectrometry determination. (Brown 1998)

Table 2
Crop management details and sampling dates for five experimental sites in north-central Montana.

	Site				
	Big Sandy	**Box Elder**	**Joplin**	**Sunburst**	**Oilmont**
Legume Green Manure					
Green manure crop	Semi-leafless pea	Forage pea	Semi-leafless pea	Semi-leafless pea	Lentil
Cultivar	Polstead	Sirius	Cruiser	Espace	Indianhead
Seeding date (2009)	Apr. 11	Apr. 21	May 11	Apr. 15	May 17
Seeding rate (kg ha^{-1})	168	186	135	168	39
Row spacing (cm)	31	31	31	19	23
Targeted plant density (plants m^{-2})	64	132	61	76	130
Fertilizer	0	0	0	0	0
Inoculant brand*	*NitraStik*	*NitraStik*	*NitraStik*	*Tag Team*	*NitraStik*
Termination date (2009)	June 18	June 23	June 26	June 27	July 09
Plant stage at termination‡	Late first bloom	Late first bloom	Early first bloom	50% bloom	Early first bloom
Termination herbicide	Glyphosate; 2,4-D; Dicamba	Glyphosate; 2,4-D amine	Glyphosate; Dicamba	Glyphosate	Glyphosate; 2,4-D
Respective rates, a.e. (g ha^{-1})	578; 504; 175	841; 399	709; 210	788	788; 284
Sampling date (2009)	June 23	June 29	June 30	July 01	July 15
Wheat					
Pre-seeding sample date†	Sep. 04, 2009	Sep. 03, 2009	Sep. 03, 2009	Apr. 03, 2010	Apr. 04, 2010
Wheat type	Winter	Winter	Winter	Spring	Spring
Cultivar	Genou	Genou	Genou	Corbin	Corbin
Wheat seeding date	Sep. 22, 2009	Sep. 22, 2009	Sep. 23, 2009	Apr. 25, 2010	May 05, 2010
Seeding Rate (kg ha^{-1})	67	67	67	84	78
Row spacing (cm)	30.5	30.5	30.5	19.1	22.9
Fertilizer	0	11-52-0; 46-0-0	11-52-0; 46-0-0	10-20-0; 46-0-0	0
Respective rates (kg ha^{-1})	–	86; 146	56; 62	56; 62	–
Wheat sampling date (2010)§	Aug. 05	Aug. 04	Aug. 16	Aug. 26	Aug. 27

* All inoculants used were peat-based, minus the Sunburst producer, who used a liquid form.
† Pre-seeding sampling dates were dependent on the producer's decision to plant a spring or winter wheat crop.
‡ Early first bloom = appearance of first flower observed in field, Late first bloom = one flower present on most plants in field, 50% bloom = halfway to full bloom.
§ Wheat crops harvested by producers within 0 to 7 days after the sampling date.

Table 3
Precipitation and average temperatures for five experimental sites in north-central Montana, from April 2009 to August 2010.

	Site				
	Big Sandy	**Box Elder**	**Joplin**	**Sunburst**	**Oilmont**
Nearest WRCC station*					
	Big Sandy (240770)	Big Sandy (240770)	Joplin (244512)	Sunburst 8E (247996)	Sunburst 8E (247996)
Precipitation (mm)					
Apr.-June '09	64 *(150)*†	33 *(150)*	140 *(120)*	61 *(157)*	64 *(157)*
July-Aug. '09	102 *(70)*	74 *(70)*	46 *(62)*	43 *(73)*	43 *(73)*
Sept. '09-Mar. '10	93 *(115)*	93 *(115)*	86 *(75)*	143 *(119)*	143 *(119)*
Apr.-Aug. '10	293 *(220)*	306 *(220)*	293 *(182)*	379 *(229)*	379 *(229)*
Apr. '09-Aug. '10	551 *(555)*	505 *(555)*	565 *(440)*	627 *(578)*	629 *(578)*
Annual Average†	*335*	*335*	*258*	*348*	*348*
Average Temperatures (C°)					
Apr.-June '09	11.9 *(12.8)*†	11.9 *(12.8)*	10.6 *(11.4)*	10.3 *(11.1)*	10.3 *(11.1)*
July-Aug. '09	20.0 *(20.8)*	20.0 *(20.8)*	18.8 *(19.7)*	17.9 *(19.0)*	17.9 *(19.0)*
Sept. '09-Mar. '10	0.0 *(1.0)*	0.0 *(1.0)*	-0.3 *(0.3)*	0.4 *(0.9)*	0.4 *(0.9)*
Apr.-Aug. '10	14.8 *(16.0)*	14.8 *(16.0)*	13.3 *(14.7)*	12.5 *(14.3)*	12.5 *(14.3)*
Apr. '09-Aug. '10	11.7 *(9.8)*	11.7 *(9.8)*	10.6 *(8.8)*	10.3 *(8.8)*	10.3 *(8.8)*
Annual Average†	*6.8*	*6.8*	*5.5*	*6.5*	*6.5*

* Precipitation was estimated from rain gauges on site and from data recorded at the nearest Western Regional Climate Center (WRCC) weather station in the case of missing on-site data. All temperatures are from WRCC station data.
† 30 yr averages *in parentheses* and "*Annual Average*" derived from 1980 to 2010 WRCC data.

Table 4
Treatment means and standard error of the means for LGM shoot biomass estimates across five sites in north-central Montana.

		Site				
Yield Component		**Big Sandy**	**Box Elder**	**Joplin**	**Sunburst**	**Oilmont***
Shoot biomass (Mg ha^{-1})						
	Mean	1.07	0.73	1.02	1.09	0.55
	SE mean	*0.04*	*0.04*	*0.04*	*0.08*	*0.05*
Shoot biomass N (kg ha^{-1})						
	Mean	44.2	19.3	37.8	28.4	14.5
	SE mean	*1.2*	*1.3*	*1.5*	*1.9*	*1.6*

*Weed biomass and biomass N at Oilmont amounted to 0.26 Mg ha^{-1} and 3 kg ha^{-1}, respectively.

Table 5
Treatment means, standard error of the difference between means, and two-sided *p*-values for Equivalent Depth total soil water content (mm) at LGM termination, and wheat seeding for specified soil depths across five sites in north-central Montana.

		Site					
Sampling Depth	**Treatment, *Statistics***	**Big Sandy**	**Box Elder**	**Joplin**	**Sunburst**	**Oilmont**	**Mean‡**
At LGM termination							
0-0.3 m							
	Fallow	77	63	79	76	75	74
	LGM	51	41	55	47	52	49
	SE difference	*2*	*1*	*3*	*3*	*7*	*2*
	p-value	*<0.01**	*<0.01**	*<0.01**	*<0.01**	*0.01**	*<0.01**
0.3-0.6 m							
	Fallow	65	48	77	52	64	61
	LGM	54	41	68	37	41	48
	SE difference	*4*	*7*	*2*	*4*	*7*	*2*
	p-value	*0.02**	*0.31*	*<0.01**	*0.01**	*0.02**	*<0.01*
0.6-0.9 m							
	Fallow	54	44	74	44	61	55
	LGM	53	40	72	36	49	50
	SE difference	*3*	*6*	*3*	*5*	*7*	*2*
	p-value	*0.87*	*0.51*	*0.55*	*0.12*	*0.14*	*0.02**
At wheat seeding†							
0-0.3 m							
	Fallow	64	56	64	80	83	70
	LGM	68	36	45	72	73	58
	SE difference	*5*	*3*	*2*	*3*	*4*	*2*
	p-value	*0.39*	*<0.01**	*<0.01**	*0.03**	*0.07**	*<0.01**
0.3-0.6 m							
	Fallow	67	54	74	58	72	65
	LGM	68	39	61	41	54	53
	SE difference	*7*	*5*	*3*	*4*	*7*	*2*
	p-value	*0.82*	*0.01**	*<0.01**	*<0.01**	*0.03**	*<0.01**
0.6-0.9 m							
	Fallow	62	49	72	50	62	59
	LGM	63	46	64	38	55	53
	SE difference	*5*	*5*	*4*	*3*	*7*	*2*
	p-value	*0.73*	*0.52*	*0.09**	*<0.01**	*0.33*	*<0.01**

* Differences at individual sites determined by paired t-tests and treatment means across all sites from mixed-effects ANOVA considered significant at $p \leq 0.10$.
† Wheat seeding sampling was in Sept. for Big Sandy, Box Elder and Joplin (winter wheat) and in April for Sunburst and Oilmont (spring wheat).
‡ Treatment grand means and statistics calculated across all sites. Note: "Mean" is not the mean of site means.

Table 6
Treatment means, standard error of the difference in means, and two-sided *p*-values for soil NO_3-N and Potentially Mineralizable N (PMN) content (kg ha^{-1}), measured at LGM termination and wheat seeding for specified soil depths across five sites in north-central Montana.

		Site					
Sampling Depth	**Treatment, *Statistics***	**Big Sandy**	**Box Elder**	**Joplin**	**Sunburst**	**Oilmont**	**Mean‡**
NO_3-N at LGM termination							
0-0.3 m							
	Fallow	21	15	9	26	8	15
	LGM	5	6	5	6	4	6
	SE difference	*4*	*2*	*2*	*3*	*1*	*1*
	p-value	*0.01**	*<0.01**	*0.07**	*<0.01**	*<0.01**	*<0.01**
0.3-0.6 m							
	Fallow	10	4	20	17	2	7
	LGM	3	3	5	8	1	4
	SE difference	*2*	*1*	*4*	*4*	*0*	*1*
	p-value	*0.01**	*0.18*	*0.13*	*0.41*	*0.13*	*<0.01**
0.6-0.9 m							
	Fallow	9	14	39	15	2	14
	LGM	4	13	24	13	2	10
	SE difference	*3*	*6*	*13*	*8*	*0*	*3*
	p-value	*0.20*	*0.91*	*0.25*	*0.83*	*0.48*	*0.26*
NO_3-N at wheat seeding†							
0-0.3 m							
	Fallow	47	29	24	54	16	30
	LGM	26	15	19	23	10	19
	SE difference	*6*	*5*	*2*	*9*	*4*	*2*
	p-value	*0.01**	*0.02**	*0.03**	*0.01**	*0.18*	*<0.01**
0.3-0.6 m							
	Fallow	20	7	11	24	6	13
	LGM	14	5	7	7	4	7
	SE difference	*2*	*1*	*1*	*3*	*1*	*1*
	p-value	*0.01**	*0.03**	*<0.01**	*<0.01**	*0.08**	*<0.01**
0.6-0.9 m							
	Fallow	10	24	29	15	2	13
	LGM	7	18	13	11	3	10
	SE difference	*1*	*5*	*9*	*3*	*1*	*1*
	p-value	*0.13*	*0.26*	*0.09**	*0.22*	*0.77*	*0.02**
PMN at wheat seeding							
0-0.3 m							
	Fallow	15	12	5	12	7	9
	LGM	5	13	17	46	23	18
	SE difference	6	6	6	10	6	3
	p-value	*0.14*	*0.91*	*0.07**	*0.03**	*0.02**	*<0.01**

* Treatment differences at individual sites determined by paired t-tests and treatment means across all sites from mixed-effects ANOVA considered significant at $p \leq 0.10$.
† Wheat seeding sampling was in Sept. for Big Sandy, Box Elder and Joplin (winter wheat) and in April for Sunburst and Oilmont (spring wheat).
‡ Treatment means and statistics as calculated across all sites. Note: "Mean" is not the mean of site means.

Table 7
Treatment means, standard error of the difference in means, and two-sided *p*-values for wheat yield component responses across five sites in north-central Montana.

		Site†					
Yield Component	**Treatment, *Statistics***	**Big Sandy**	**Box Elder**	**Joplin**	**Sunburst**	**Oilmont**	**Mean‡**
Grain Yield (Mg ha^{-1})							
	Fallow	4.76	4.48	4.05	4.83	1.69	3.94
	LGM	4.25	4.43	3.92	4.36	1.51	3.70
	SE difference	*0.36*	*0.26*	*0.22*	*0.26*	*0.18*	*0.11*
	p-value	*0.21*	*0.88*	*0.56*	*0.11*	*0.36*	*0.04**
Grain Protein (g kg^{-1})							
	Fallow	88	130	108	127	95	110
	LGM	94	123	99	117	99	106
	SE difference	*4*	*6*	*4*	*7*	*3*	*2*
	p-value	*0.26*	*0.23*	*0.08**	*0.24*	*0.24*	*0.13*
Grain N Yield (kg ha^{-1})							
	Fallow	65	90	72	99	25	69
	LGM	61	84	62	79	23	62
	SE difference	*5*	*5*	*5*	*7*	*2*	*2*
	p-value	*0.48*	*0.23*	*0.07**	*0.04**	*0.50*	*<0.01**
Grain Density (kg m^{-3})							
	Fallow	772	777	775	786	794	781
	LGM	776	788	770	796	800	786
	SE difference	*2*	*4*	*4*	*6*	*2*	*2*
	p-value	*0.05**	*0.03**	*0.28*	*0.15*	*0.01**	*0.04**

* Treatment differences at individual sites determined by paired t-tests and treatment means across all sites from mixed-effects ANOVA considered significant at $p \leq 0.10$.
† Big Sandy, Box Elder and Joplin grew winter wheat, Sunburst and Oilmont grew spring wheat.
‡ Treatment means and statistics as calculated across all sites. Note: "Mean" is not the mean of site means.

Table 8
Treatment means, standard error of the difference in means, and two-sided *p*-values for conservation parameters across five sites in north-central Montana.

		Site†					
Conservation parameters	**Treatment, *Statistics***	**Big Sandy**	**Box Elder**	**Joplin**	**Sunburst**	**Oilmont**	**Mean‡**
NUE§							
	Fallow	0.86	0.69	0.74	0.83	1.07	0.84
	LGM	1.37	0.77	0.87	1.05	1.32	1.04
	SE difference	*0.19*	*0.04*	*0.07*	*0.10*	*0.14*	*0.04*
	p-value	*0.04**	*0.10**	*0.07**	*0.05**	*0.12*	*<0.01**
Residue C Returned (kg ha^{-1}) §§							
	Fallow	2867	2482	2159	2687	811	2179
	LGM	2933	2709	2649	2918	909	2439
	SE difference	*182*	*183*	*121*	*125*	*106*	*65*
	p-value	*0.73*	*0.26*	*<0.01**	*0.15*	*0.39*	*<0.01**
Residue N Returned (kg ha^{-1}) §§							
	Fallow	26	33	20	33	8	24
	LGM	67	47	59	54	21	50
	SE difference	*2*	*2*	*3*	*2*	*2*	*2*
	p-value	*<0.01**	*<0.01**	*<0.01**	*<0.01**	*<0.01**	*<0.01**

* Treatment differences at individual sites determined by paired t-tests and treatment means across all sites from mixed-effects ANOVA considered significant at $p \leq 0.10$.
† Big Sandy, Box Elder and Joplin grew winter wheat, Sunburst and Oilmont grew spring wheat.
‡ Treatment means and statistics as calculated across all sites. Note: "Mean" is not the mean of site means.
§ Calculated as grain N yield (kg-ha^{-1}) divided by N fertilizer added plus pre-seeding 0 to 0.9 m soil nitrate (kg-ha^{-1}).
§§ Sum of residue C and N returned over both fallow/LGM and wheat years.

Figure 1
Example of field site during LGM stage (a) and subsequent wheat stage (b), and no-till LGM residue breakdown stages in September, 2009 (c) and the following August, 2010 (d).

Note: Photos a and b taken from the same vantage point at Box Elder, with LGM crop (a) at the appearance of first flowers (June 23, 2009), and wheat crop (b) on July 20, 2010. Box Elder was the only site with a visual treatment effect, attributed to slightly delayed maturity on the LGM side. Image c shows residue cover heading into winter, and c and d illustrate amounts of LGM residue not yet incorporated into soils by winter wheat seeding (c) and at wheat harvest (d).

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CHAPTER THREE

LEGUME, CROPPING INTENSITY, AND N-FERTILIZATION EFFECTS ON ATTRIBUTES AND PROCESSES IN SOILS FROM AN EIGHT-YEAR-OLD SEMIARID WHEAT SYSTEM

Contribution of Authors and Co-Authors

Manuscript in Chapter 3

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Contributions: Primary designer of project and experiments, conducted all experiments, analyzed data with assistance from Ilai N. Keren (co-author), wrote the manuscript.

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Contributions: Primary advisement and assistance in statistical analyses, particularly nonlinear modeling analyses illustrated in table 3, and figure 1.

Co-author: Perry R. Miller

Co-author: Designed study that experiments were conducted on, obtained funding that supports the study, reference for agronomic management of study, provided data that contributed to table 2 and 5.

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Legume, cropping intensity, and N-fertilization effects on attributes and processes in soils from an eight-year-old semiarid wheat system

Abstract

In the northern Great Plains (NGP) of North America, legumes are promising alternative crops replacing summer fallow. In the long term, legumes may decrease dependence on N fertilizer in wheat (*Triticum aestivum* L.) systems, and help mitigate effects of soil organic matter (SOM) losses from summer fallow. These longer-term implications of legumes and intensified cropping in this region remain unclear though, particularly in no-till managed systems. We compared effects of no-till summer fallow-wheat (F-W), continuous wheat (CW), legume green manure (pea, *Pisum sativum* L.)-wheat, and dry pea-wheat (P-W) cropping systems on select soil attributes in an 8-year-old rotation study. Potentially mineralizable carbon and nitrogen (PMC and PMN), microbial biomass carbon (MB-C), and wet aggregate stability (WAS) were examined. We also measured N fertilizer addition effects on C and N mineralization. Legume systems (LGM-W and P-W) generally resulted in higher PMC, PMN, and MB-C, while intensified systems (CW and P-W) had higher WAS. Our results are generally consistent with results from longer-term tillage-managed studies in the NGP with three or more legume appearances in rotation. Nitrogen fertilizer depressed C and N mineralization from soils, mostly in intensified systems, and particularly in CW. Legumes likely have an important role in more sustainable NGP agroecosystems by 1) increasing the N-supplying power of the soil (~26-50%) compared to wheat-only systems and reducing the need for N fertilizer inputs for subsequent wheat crops, and 2) having potential to mitigate negative effects of SOM losses from summer fallow, without N inputs.

Keywords

northern Great Plains • summer fallow • mineralizable • microbial biomass • aggregate stability

Abbreviations

NGP- northern Great Plains; OM- organic matter, SOM- soil organic matter, SOC- soil organic carbon; TN- soil total nitrogen; PMN- potentially mineralizable nitrogen; PMC- potentially mineralizable carbon; MB-C- microbial biomass carbon; WAS- wet aggregate stability; GWC- gravimetric water content

Introduction

Dryland agroecosystems in the northern Great Plains (NGP) of North America are primarily limited by low and erratic water availability. This has led to widespread promotion and use of summer fallow practices as a soil water accumulation strategy throughout the 20th century, helping to stabilize wheat (*Triticum aestivum* L.) yields (Karlen et al. 2011; Tanaka et al. 2010). Summer fallow serves this purpose well, but is not considered sustainable; negative summer fallow effects have been widely reported since the early 20th century (Atkinson and Nelson 1911; Carlyle 1997; Ford and Krall 1979; Gan et al. 2010; Janzen 2001; Larney et al. 1994; Linfield 1902; Tanaka et al. 2010). These effects include, but are not limited to, soil organic matter (SOM) losses and sub-optimal residue returns to soils (Campbell et al. 2000; Sainju et al. 2009), and nitrate leaching (Campbell et al. 2006; Jones and Olson-Rutz 2011). Reducing tillage in summer fallow mitigates some of these aspects, but eliminating summer fallow entirely may further increase sustainability in these systems (Gan et al. 2010; Tanaka et al. 2010). Recently, improved soil water storage efficiency in no-till systems has helped to eliminate summer fallow in some regions of the NGP (Tanaka and Anderson 1997; Tanaka et al. 2005).

Water-use-efficient annual legumes (i.e. pulse crops) such as dry pea (*Pisum sativum* L.) and lentil (*Lens culinaris* Medik.) are promising summer fallow replacements (Gan et al. 2010; Miller et al. 2002). Compared to intensification with more wheat, legumes can provide biologically fixed N to N-intensive wheat production, and contribute functional diversity to NGP agroecosystems. Pulse crop acreage replacing summer fallow has increased 10-fold in the NGP since the early 1990s, but summer fallow practice remains steadfast in north-central Montana, i.e. MLRA (Major Land Resource Area) 52 (Campbell et al. 2002; Tanaka et al. 2010). The MLRA 52 represents a region where continuous cropping is economically marginal due to precipitation constraints. In the MLRA 52, partial-season legume green fallow crops (forages or green manure crops) have been proposed to intensify and diversify cropping, while still conserving stored soil water (Miller et al. 2006).

Legumes are assumed to provide N benefits to subsequent wheat, but this has not been consistently detected in studies from the NGP (Lupwayi and Kennedy 2007; Miller et al. 2002; O'Dea et al. in preparation; Walley et al. 2007). Long-term studies on legume-wheat rotations suggest that N-benefits to wheat in this region may be realized only after multiple legume appearances in rotation (Allen et al. 2011; Campbell et al. 1992; Walley et al. 2007; Zentner et al. 2004). This delayed response may be a reality of cool, water-limited conditions in the NGP leading to low annual legume biomass contributions, slow breakdown of residues, and subsequent slow release of available N (Beckie et al. 1997; Bremer and van Kessel 1992; Janzen et al. 1990), especially in no-till systems (Schoenau and Campbell 1996; Triplett and Dick 2008). A lack of immediate benefits is potentially discouraging to producers expecting N fertilizer-type responses from legumes (O'Dea et al. in preparation),, while a more reasonable expectation may be a gradual buildup of the soil N pool (Janzen et al. 1990; Ladd et al. 1981).

An understanding of legume versus fertilizer N sources in agroecosystems, particularly in the NGP, remains limited, especially regarding SOC and N retention effects. Legume systems may help increase synchrony between N supply and crop demand (Crews and Peoples 2005) and help to reduce N losses. This may occur because legumes 1) contribute N in organic forms that require biologically-mediated slow release

of plant available N (Drinkwater and Snapp 2007); 2) > 50% of N taken up by crops can be derived from N mineralized from SOM (Cassman et al. 2002); and 3) greater proportions of legume N vs. fertilizer N may be retained in soils (Janzen et al. 1990). Questions also remain whether legumes, in addition to increasing the N-supplying capacities of soils, are capable of mitigating SOC losses as well or better than fertilized cereal systems, especially considering their labile residues (Curtin et al. 2000). Priming effects on SOM mineralization have been reported from both addition of N fertilizer and legume residues (Kuzyakov et al. 2000), although N fertilizer can also depress mineralization from SOM (Fog 1988). In cropping systems, reduced SOM losses have been attributed to both N fertilizer additions that increased crop residues (Campbell and Zentner 1993; Paustian et al. 1997; Varvel et al. 2002) and to legume inclusion (Drinkwater et al. 1998; Fortuna et al. 2008; Gregorich et al. 2001). Recent meta-analyses also highlighted however that N fertilizer can be inconsistently effective in mitigating SOM losses in agroecosystems, and may even lead to SOM losses in some cases (Khan et al. 2007; Mulvaney et al. 2009; Russell et al. 2009). Possible mechanisms of N source effects on SOC and N retention therefore remain unclear, especially in NGP agroecosystems. To date though, studies from the Canadian NGP region report that legumes (particularly) and intensified wheat cropping in comparison with systems with summer fallow can result in higher SOC, TN, and higher levels of several chemical, microbial, and physical soil parameters (Biederbeck et al. 1998; Biederbeck et al. 1994; Biederbeck et al. 2005; Campbell et al. 1997; Campbell et al. 2001; Lupwayi and Kennedy 2007). Nonetheless, published studies with legume-inclusive systems in longer-term experiments in the NGP are rare, particularly in the U.S. region. Since legumes and intensified cropping are increasingly common and no-tillage is rapidly becoming convention in these systems, understanding soil changes resulting from these management factors is increasingly relevant (Cochran et al. 2006; Grant et al. 2002; Lupwayi and Kennedy 2007).

Earlier studies on soil quality indices in the NGP identified several chemical, microbial, and physical soil parameters sensitive to management changes, and are associated with negative summer fallow effects on SOM (Biederbeck et al. 1998;

Biederbeck et al. 1994). Our objectives for this study were to examine potentially mineralizable soil C and N (PMC and PMN, respectively), microbial biomass-C (MB-C), and wet aggregate stability (WAS) in bulk soils from an eight-year-old dryland rotation study including no-till fallow-wheat, intensified, and legume-inclusive systems. We also aimed to better understand N fertilizer effects on C and N mineralization from soils conditioned by these different cropping systems. Understanding changes in soil parameters and soil processes associated with the use of legumes and intensified no-till wheat systems could lead to more appropriate expectations about the results of these management changes.

Materials and Methods

Site Description and Experimental Design

Soils used in this experiment were from a long-term study located at Montana State University's A. H. Post Agronomy Research Farm, located 10 km west of Bozeman, MT (45°40′ N, 111° 9′ W). Soils are a silt loam (fine-silty, mixed, superactive, frigid, Typic Haplustolls) with 88 g kg^{-1} sand, 825 g kg^{-1} silt, 86 g kg^{-1} clay in the surface 10 cm, (Dusenbury et al. 2008) and a pH of 7.2 to 7.7 in the surface 15 cm (Miller et al. 2008). The site receives 416 mm annual precipitation and has an annual mean temperature of 6.4°C (data from on-site *Bozeman 6 W* weather station, provided by Western Regional Climate Center, Reno, NV). The site is less arid than most Montana wheat-growing regions, but with similar late-spring to early-summer peak precipitation patterns followed by late-summer drought. This study was initially established in 2002 as a completely randomized split-plot design with four blocks (replicates). Additional site characteristics, experimental design, and some management information has been described in a previous publication by Dusenbury et al. (2008). The farm has highly variable cropping histories, and a ~30-y history of intensive tillage, but the study site had not been tilled since 1999.

We examined four no-till systems, including: fallow- wheat (F-W), legume (pea) green manure-wheat (LGM-W) systems, continuous wheat (CW), and pea-wheat (P-W).

A summary of cropping system history and N management is presented in Table 1; SOC, TN, and residue characteristics for each system are presented in Table 2. Additional management information is detailed in Burgess et al. (in preparation)

Soil Sampling

Soil sampling occurred in two phases during the 8th crop year; once in April 2010 prior to spring wheat planting (used for PMN and PMC experiments), and once in October 2010 after wheat harvest (used for MB-C and WAS experiments). Soils were systematically hand cored (1.7 cm diam. x 15 cm) from 10 points across each plot in a zig-zag pattern (avoiding plot edges by ~1 m), excluding loose surface residue. The ten cores from each plot were composited and stored at 2°C until processing.

Potentially Mineralizable C and N procedures

PMN and PMC measurements were determined over a 112-d incubation period at 30°C, following modified methods of Drinkwater et al. (1996). After 28 d of storage, soil samples were homogenized by sieving into two fractions (< 2.5-mm, 2.5 to 5-mm). A final homogenized sample consisted of 4 parts < 2.5-mm aggregates and 1 part 2.5 to 5-mm aggregates; this ratio included most of the original sample, and helped assure that soil aggregate surface areas would be standardized across samples. Roots and organic residues were not removed from samples if < 5 mm.

Twelve 10-g dry-soil-equivalent subsamples from each original sample were placed into 20-mL scintillation vials, tamped to a uniform bulk density (1.0 g cm^{-3}), and water contents adjusted to 50% water-filled pore space (WFPS). An equivalent of 35, 38, 23, and 36 mg kg^{-1} of N in the form of dissolved urea was added to six of twelve vials for W-F, CW, LGM-W, and P-W, respectively. These amounts correspond to 50% of the amount of N fertilizer added to plots in spring 2010, and were meant to approximate an amount of N fertilizer remaining in soils after some plant uptake and/or losses. The six vials from each N treatment were respectively placed in autoclaved 950-mL Mason jars containing 25 mL of water (to maintain 100% humidity) with lids modified to

accommodate a butyl rubber septum (Sigma-Aldrich Corp., St. Louis, MO) sealed with silicone.

Potentially Mineralizable Carbon

Soil incubation jars were aerated often due to the need to avoid headspace CO_2 concentrations over 10 mL L^{-1} causing oxygen-limiting conditions. Measurements of headspace CO_2 concentrations used to determine PMC were therefore taken every 3.5 d from time-zero to day 28, every 7 d from day 28 to 56, and every 14 d from day 56 to 112. Headspace CO_2 samples were taken with a 10-mL syringe, and injected directly into pre-evacuated 3.7 mL Exetainers® (Labco International Inc., High Wycombe, UK). Jars were aerated (5 min) in a running fume hood following each CO_2 sampling. CO_2 concentrations were determined using a Varian CP 3800 gas chromatograph (GC) with a CombiPal autosampler (Agilent Tech., Santa Clara, CA), equipped with a 0.5-mL sample loop, 0.5-m long x 3.175-mm inner diameter HayeSep N 80/100 backflush column (VICI Valco Corp., Houston, TX) and a 2-m long x 3.175-mm inner diameter PoraPak QS 80/100 analytical column (Waters Corp., Milford, MA) using He as a carrier gas (190 kPa, 40 mL min^{-1}). Oven and column temperatures were set at 40 and 120°C, respectively. Headspace CO_2 readings were adjusted by subtracting output values from blank values (x 4), dividing by the number of vials, and correcting for changing headspace volumes from evaporating water and vials removed for PMN measurements (described in following section). Adjusted CO_2 concentrations (µL L^{-1}) were then converted to mg kg^{-1} for reporting PMC as cumulative C mineralized over time using the equation modified from Robertson et al. (1999)

$$C-min = C * 12.01 \left(\frac{(P \times V)/(8.3145 \times T)}{SM}\right)$$

where *C-min* is mineralized C in mg kg^{-1}, *C* is the concentration of headspace CO_2 corrected for ambient chamber CO_2 (values from blanks), 12.01 is the molar mass of C, *P* is the atmospheric pressure (kPa) at a given elevation, *V* is the volume of the headspace chamber (L), 8.3145 is the universal gas constant in L kPa $K^{\circ -1}$ mol^{-1}, *T* is the ambient

temperature (°K), and *SM* is the sample mass (dry weight) in g. Only PMC values from days 7, 14, 28, 56, and 112 are presented in this paper.

Potentially Mineralizable Nitrogen

Potentially mineralizable N was measured at time-zero, and days 7, 14, 28, 56, and 112. For each measurement, one scintillation vial was removed from each incubation jar during aeration (described in previous section) and immediately placed in a refrigerator at 2°C. Soils were dissolved in 50 mL of 1 *M* KCl and were placed into 60 mL centrifuge tubes, shaken for 1 h at 250 rpm, centrifuged (5000 x g at 4°C, 10 min), and supernatants filtered with Whatman 42 (2.5 μm) ashless filter papers (Whatman plc., Maidstone, UK) for analysis. Nitrate-N and NH_4-N concentrations from filtered supernatants were measured through Cd reduction with a Lachat flow injection analyzer (Lachat Instruments, Loveland, CO; QuickChem methods 12-107-04 and 06-1B, respectively). Data output ($\mu L\ L^{-1}$) was converted to mg kg^{-1} for reporting PMN levels defined as net NO_3 + NH_4-N mineralized minus time-zero measurements.

Microbial Biomass and Aggregate Stability

Soil water contents of samples were equilibrated by adding amounts of deionized water based on GWC (20 g, 110° C, 24 h) to paper towels and placing them in the soil sample bags. Water was allowed to diffuse over 21 d (at 4°C), after which, GWC's of the samples were within 1% of each other. Soil cores were then fractured by splitting with an awl, or gently crumbled. Fractured cores were sieved (1 and 2-mm, nested sieves) until at least 100 g of 1 to 2-mm aggregates were recovered from the entire sample.

Microbial Biomass

Methods for determining MB-C via substrate induced respiration (SIR) were modified from Höper (2006). Soils were pre-incubated (21°C, 10 d), and a 10-g dry-equivalent soil subsample from the 1 to 2-mm fraction was tamped to a uniform bulk density (1 g cm^{-3}) in 20-mL scintillation jars. Substrate consisted of 1.5 g of glucose dissolved in a 100-mL solution, along with 5-mM NH_4^+ (as $(NH_4)_2SO_4$) and 1-mM PO_4^{3-}

(as KH_2PO_4 and K_2HPO_4) concentrations outlined in Bollmann (2006) as additional N, P, K, and S nutrient sources. One mL of substrate plus enough water to bring WFPS to 50% was added to each sample immediately prior to incubation. Soils were placed inside the same jars used in the PMC/PMN experiment, each containing 10 mL of deionized water for maintaining humidity. Soil incubations for SIR were carried out at 21°C; after a 2-h pre-incubation, jars were opened, aerated in a fume hood (5 min), resealed, and time-zero measurements of headspace CO_2 concentration taken immediately, and again after 4 h for SIR measurements. Sampling procedures followed those used in PMC experiments. Headspace CO_2 concentrations ($\mu L\ L^{-1}$) were then converted to mg kg^{-1} MB-C using the modified equation derived from calculations presented by Höper (2006) and Anderson and Domsch (1978)

$$MB\text{–}C = 30\left(\frac{C}{SM * H}\right)$$

where MB-C is microbial biomass C (mg kg^{-1}), 30 is the rate constant for the maximum initial CO_2 response of microbes to glucose addition, *C* is the measured headspace CO_2 ($\mu L\ L^{-1}$) concentration corrected for ambient CO_2 (as measured in four blanks), *SM* is the dry soil sample mass (g), and *H* is the incubation time (h).

Wet Aggregate Stability

Methods for measuring WAS were modified from Arshad et al. (1996) and Kemper and Rosenau (1986). Aggregate agitation in water was carried out with a mechanized device with a total up and down stroke measuring 2.6 cm (1.3 cm in each direction), at a speed of ~90 oscillations per min. 10-g dry equivalent subsamples from the 1 to 2-mm fraction were poured into 1-mm sieves (54-mm diam. x 30-mm deep) positioned at the surface of water in soil cans below them (76-mm diam. x 52-mm deep). Each can contained 100 mL of deionized water. Samples were allowed to moisten through capillary action for 5 min, then agitated in water for 1 min to dissolve unstable aggregates. A second set of cans with 100 mL of deionized water and 2 g of $(NaPO_3)_6$ was then used to dissolve remaining stable aggregates. Any sand/gravel or large organic matter particles remained on the sieve. Both sets of cans were placed in a drying oven

(110°C) until water was completely evaporated. Wet aggregate stability is presented as g kg^{-1} water-stable aggregates (WSA), calculated using the equation:

$$WSA = 10 * \left(\frac{SA}{UA + SA}\right)$$

where *SA* is mass stable aggregates (g) – 0.2 g $(NaPO_3)_6$, and *UA* is mass unstable aggregates (g).

Statistical Analysis

Potentially mineralizable N and C data were analyzed using two different approaches. We first used mixed-effects models to analyze PMN and PMC independently by day. This was done to assess data by individual measurement timing and to highlight when effects became apparent, in detail. This analysis was conducted using R (The R Foundation for Statistical Computing, Vienna, Austria) and the *nlme* software package for mixed-effects models (Pinheiro et al. 2011; Pinheiro and Bates 2009) with cropping system and fertilization treatment as fixed effects, and block (replicate) as a random effect, with correlations grouped by cropping system and fertilization level. To estimate an asymptote of PMN and PMC (not reached after 112 days) and relative rates of decay as a function of first-order kinetics in long-term incubations (Stanford et al. 1974; Stanford and Smith 1972) we also analyzed data with an asymptotic ("exponential decay") nonlinear mixed-effects model. Talpaz et al. (1981), Paustian and Bonde (1987), and Benedetti and Sebastiani (1996) assert that nonlinear exponential decay models are appropriate for modeling mineralization trends. This analysis was also constructed using R and the *nlme* statistical package using the two-parameter *SSasympOrig* self-starting model (y = asymptote, x = half-life) fit through the origin (x = 0, y = 0). Cropping system and fertilization treatment were considered fixed effects, and with day as a predictor, an asymptote and or half-life was fit to each block (replicate) as random effects, with correlations grouped by cropping system and fertilization level. Microbial biomass and WAS data were also analyzed with a mixed-effects model ANOVA using the *nlme* package, with cropping system as a fixed effect and block (replicate) as a random effect.

Data quality was examined graphically, usually using boxplots and residual vs. predicted plots; suspected outliers were further examined with Jackknifed Mahalanobis distance plots of residuals using the *Multivariate* platform in JMP 9 statistical software (SAS Institute Inc., Cary, NC) . Strategies for dealing with suspected outliers then generally followed those outlined by Ramsey and Schafer (2002). Blocks (replicates) were removed from the nonlinear PMN and PMC analysis if the model could not be fit to the data (i.e. lack of an asymptotic trend, or less than five data points per block) or if the confidence interval of a given random effect violated the homogeneity of variance assumption. All test assumptions were evaluated and confirmed by examining confidence intervals of random effects, residual vs. predicted plots, and QQ-normal plots. If the homogeneity of variance assumption for fixed effects was in question or heteroscedasticity was apparent, weighted variance structures using the *varPower* or *varIdent* functions from *nlme* were used to better meet the assumptions of the test.

Since cropping systems represent different combinations of residue quantities and qualities returned to soils (Table 2) and we hypothesized that effects would vary on both gross and fine levels. Pre-planned contrasts therefore were designed to compare grouped combinations of cropping systems (gross level) and all individual cropping system combinations (fine level). Grouped contrasts include: 1) wheat (WHT) vs. legume (LEG) rotations = F-W, CW vs. P-W, LGM-W; 2) low (LO) vs. high (HI) intensity systems = F-W, GM-W vs. CW, P-W; and 3) conventional fallow-wheat (F) vs. alternative-to-fallow systems (ALT) = F-W vs. CW, P-W, LGM-W. The LGM-W system could be considered "intensified" in terms of crop output and cropping frequency, but residue returns to this system differed minimally from the F-W system due to management (see Table 1, 2). The LGM-W system is contrasted with F-W in ALT because of a difference in quality of residues returned and the lack of summer fallow; both are expected to affect soils. The effect of fertilizer on C and N mineralized was evaluated through contrasting fertilized vs. unfertilized means; if there were significant interactions between cropping system and fertilization, fertilized treatments were contrasted only with their unfertilized control in a given system. All effects were considered significant at $P \leq 0.10$.

Correlation analyses were conducted between our results and on select soil and crop residue parameters listed in Table 2, again using the *Multivariate* platform in JMP 9. For PMN and PMC correlations, only data from day 112 were used. Significant correlations ($P \leq 0.10$) are reported as Pearson's correlation coefficient (r). If test assumptions were in question, results were tested against Spearman's non-parametric rank correlation results, and were rejected if the Spearman's test resulted in $\rho > 0.10$.

Results

For each soil parameter measured, gross effects of grouped treatments are presented first; the WHT vs. LEG contrast represents an effect of residue quality from legume presence, LO vs. HI contrast represents an effect of residue quantity from intensified cropping, and the F vs. ALT contrast represents a combined effect of changing residue quantity and/or quality when summer fallow is replaced with crops. Finer-scale differences among individual cropping systems are presented second to illustrate relative strengths of individual cropping systems on soil parameters.

Potentially Mineralizable C and N

Soil PMC and PMN are measurements of relatively finite, inherent mineralizable fractions of SOM. The nonlinear model-predicted asymptotes of PMC and PMN are best estimates of soil PMC and PMN. Measured PMC and PMN after 7, 14, 28, 56, 112 d are simply "snapshot" values after a given amount of time, presented to illustrate mineralization trends leading to an ultimate measurement of PMC and PMN. Any effects from added N fertilizer are referred to as effects on C and N mineralization.

Potentially Mineralizable Carbon

Analysis of PMC by day revealed cropping system and fertilizer effects from day 7 onward (Table 3). On days 7 and 14, a LO vs. HI system effect was prominent, with higher PMC values in the CW and P-W systems than in the F-W system on both days. By days 28 and 56, the prominent effect was between F and ALT systems; by day 56, PMC

values in the LGM-W system had increased to values approximating CW and P-W systems, where all three ALT systems individually had higher PMC values than the F-W system. By day 112, both F vs. ALT and WHT vs. LEG system effects were prominent ($P < 0.01$); individually, PMC values in the LGM-W system and the P-W system were higher than both WHT systems, and PMC values in each ALT system were higher than in the F-W system. Urea fertilizer addition slightly stimulated C-mineralization on day 7 (4 mg kg^{-1}), had no effect on day 14, and depressed C-mineralization from days 28 through 112, illustrating a transition from slightly stimulatory, to depressive mineralization effects overall. By day 112, fertilizer addition had depressed C mineralization by 94 mg kg^{-1} across all soils.

Analysis of model-predicted asymptotes of PMC (Table 4, Fig. 1) indicated that treatment effects differed slightly from day 112 results, likely due to an interaction between cropping system and fertilization treatment in this analysis. A prominent effect was still observed in the F vs. ALT contrast ($P = 0.08$), but the WHT vs. LEG system effect ($P = 0.02$) was stronger. The LGM system had the highest PMC (1325 mg kg^{-1}) which was 304 and 387 mg kg^{-1} higher than for the CW and F-W systems, respectively. The relative rate of decay of PMC was greater (shorter half-life) in HI systems compared to LO systems, with the CW system having the greatest rate overall (Table 4, Fig 1). This was also reflected in the by-day analyses where the LO vs. HI system effect was prominent on days 7 and 14, but the effect declined thereafter (Table 3). Effects of N fertilizer addition were greatest in the HI systems, depressing C mineralization by 247 and 229 mg kg^{-1} in the CW and P-W systems, respectively.

Potentially Mineralizable Nitrogen

Analysis of PMN by day also indicated cropping system and N fertilization treatment effects from day 7 onward (Table 3). No main effects were detected on day 7, but there was an interaction between cropping system and fertilization; mineralization was depressed in the CW system, and stimulated in the LGM-W system, but mean effects were small (0.9 and 2.2 mg kg^{-1}, respectively). On day 14, the F vs. ALT system effect was prominent, with greater PMN values in each ALT system than in F-W. From day 28

through 112, WHT vs. LEG system effects were prominent, with the LGM-W system having consistently higher PMN values than CW and F-W for each day. Fertilization treatment effects from day 14 to 56 indicated that N addition depressed N mineralization across soils. By day 112, N mineralization in the F-W and LGM-W was depressed by 7.5 and 6.8 mg kg^{-1}, respectively, while N mineralization in CW was depressed most, by 16.6 mg kg^{-1}.

Analysis of the model-predicted asymptotes of PMN (Table 4, Fig. 1) indicated that the WHT vs. LEG system effect was more pronounced than on day 112. Potentially mineralizable N in the two LEG systems were higher than both WHT systems by ~39 mg kg^{-1} (50%). The PMN status of the CW system differed most from day 112 results, where the model accounted for a declining mineralization trend in CW (Fig. 1) that led to PMN differing from the P-W system in this analysis. This trend was also illustrated by the CW system having a greater relative rate of decay (shorter half-life) of PMN than the two LEG systems, which reached their asymptotes at a slower relative rate (Table 4, Fig 1). The addition of N fertilizer caused N mineralization to be depressed by 13 mg kg^{-1} across all soils.

Microbial Biomass Carbon

Analysis of MB-C results (Table 5) indicated that the only grouped treatment effect observed was in the WHT vs. LEG systems contrast ($P = 0.03$). Individual system contrasts indicated that MB-C in the P-W system was approximately 123 mg kg^{-1} higher than in CW and F-W systems. Despite LGM-W being a LEG system, its MB-C exhibited no difference from the two WHT systems.

Wet Aggregate Stability

In the WAS analysis (Table 5), a LO vs. HI system effect was the most prominent effect, and contrary to the other parameters, WHT vs. LEG exhibited no effect ($P = 0.70$). Both CW and P-W systems had higher WAS than both LO systems. The F vs. ALT contrast also indicated a prominent treatment effect as well ($P = 0.01$), but inspection of the data revealed that the HI systems likely strongly biased the mean of ALT; the mean

WAS value in the LGM-W system was only 8 g kg^{-1} above than the mean F-W value, compared to WAS in the HI systems which was 101 g kg^{-1} above the mean F-W value. Additionally, the LGM-W and F-W systems individually exhibited no difference (P = 0.66).

Correlation Between Soil and Crop Residue Parameters

Soil quality parameters measured in this study and select parameters listed in Table 2 were subjected to correlation analysis (Table 6). Amongst soil parameters, SOC moderately correlated with PMC and WAS. PMC correlated more strongly with soil total N (TN) than SOC (P = 0.01 vs. 0.08, respectively), and PMN correlated moderately only with TN. Regarding crop residue quantities and qualities returns to soils, the strongest correlation was between WAS and residue C returned to soils, supporting aforementioned correlations between WAS, SOC, and PMC. There was a moderate correlation between MB-C and residue N and a moderately negative correlation with residue C:N. There was also a moderately negative correlation between residue C:N and PMN and PMC.

Discussion

In this study, changes in residue quality and quantity in systems where summer fallow was replaced with a crop both apparently affected soil parameters compared to the F-W system. The LEG systems generally had greater soil PMC, PMN, and MB-C than WHT systems, and particularly the F-W system, and indicated an effect of residue quality on these parameters. The CW system had higher PMC values than F-W in the by-day analyses, but did not differ from the F-W system in the asymptote analysis of PMC. The CW system had a much greater effect on WAS, along with the P-W system, compared to the low residue F-W and LGM-W systems, indicating an effect of residue quantity on this parameter. These treatment effects on soil parameters were similar to those observed in other tillage-managed studies from the Canadian region of the northern Great Plains, with a few notable exceptions. In two six-year studies in Saskatchewan, mineralizable C and N, MB-C, and WAS (to 10 cm) were higher in LGM-W rotations (including a pea green

manure) than in a F-W rotation (Biederbeck et al. (1998; 2005). Soil quality parameters (except PMN) in a CW system in these studies also were higher than F-W, although effects were often less than from LGM-W systems. In our study, MB-C in the CW system did not differ from F-W. Also, although our LGM-W system was part of LEG systems that had higher MB-C, alone it differed from no other system, including F-W. It is particularly unclear why the CW rotation did not have higher MB-C in our study since high residue C returns from CW are expected to support more microbial biomass. In Biederbeck et al.'s (2005) tillage-based study, differences in MB-C between CW and F-W systems appeared to be caused by differences in the bacterial fraction of MB-C. No-till systems may rely more heavily on fungal, rather than bacterial decomposers (Beare et al. 1992). The SIR method we used to estimate MB-C also may not detect slow-responding fungal MB-C fractions as well as the fumigation-extraction method (Wallenstein et al. 2006) used by Biederbeck et al., so treatment differences in MB-C overall may not have been as detectable in our no-till study. Our LGM-W system also may have not affected MB-C or WAS because it did not increase residues returned to the soil over F-W, as it did in the Biederbeck et al. (1998; 1994; 2005) studies. Our observations support this possibility because 1) the higher residue-producing P-W system was the LEG system that individually had higher MB-C than both WHT systems, and 2) because evidence suggests that higher residue returns to soils in HI systems supported higher WAS. Nonetheless, WAS may also be associated with saprotrophic Basidiomycete fungi linked to more recalcitrant residues (Caesar-TonThat et al. 2011), as expected in our CW and P-W systems which likely returned higher quantities of ligninaceous residue fractions (Lupwayi et al. 2006).

In a similar but much longer-term study, Biederbeck et al. (1994) and Campbell et al. (1993) also reported that a lentil (for grain)-wheat rotation had higher mineralizable C to 15 cm, higher mineralizable N in the 7.5-15 cm depth, and higher WAS to 5 cm over a F-W rotation, and that the lentil rotation often equaled effects of a CW rotation on these parameters. Their CW system was the only system that supported higher MB-C (to 7.5 cm); it also had higher mineralizable C and N in the top 7.5 cm than the lentil rotation, but it should be noted that mineralizable C and N levels may be misleading in Biederbeck

et al. (1998; 1994). Measurements of mineralizable C and N in Biederbeck et al. (1998; 1994) were from 30 and 112-day incubations, respectively, whereas results from our study indicated that mineralizable C and N measured after ~30 and 112 days, respectively, can differ from ultimate measurements (i.e. an asymptote) if mineralization trends are unaccounted for. Particularly, in the CW system that had the shortest half-life, the proportion of available C and N mineralized was greater earlier in the incubation and declined more rapidly relative to the other treatments over time (Table 4, Fig. 1). Despite indications that CW had higher mineralizable C and N than F-W earlier in the incubation (Table 3), by the time cumulative C and N mineralized (i.e. PMC and PMN) reached an asymptote, CW did not differ from F-W (Table 4). It is also worth noting that the CW system studied in Biederbeck et al. (1994) had been in place for 12 years longer than their lentil-wheat rotation, which was also previously a CW system.

Biederbeck et al. (1998; 1994) did find that legume rotations, along with a CW system, had higher SOC and TN than a F-W rotation, and in one study (1994) observed positive correlations similar to ours between PMC and SOC, and PMN and TN. We did not measure SOC and/or TN in 2010, though higher PMC and PMN may indicate that SOC and TN may be affected accordingly, to a degree. Positive correlations we observed between PMC and SOC, and PMN and TN suggest that these levels may be related, but that other factors play a role since PMN and PMC only represent a particular fraction of SOM. Also, detecting higher amounts of PMC and PMN compared to control treatments indicates a relative accumulation of these SOM fractions. Our results suggest that these fractions are unlikely to decay completely in the amount of time elapsed between annual crop residue additions (Fig. 1), especially in field conditions, but the greater time elapsed between residue additions in F-W systems highlight how mineralizable fractions could be more readily exhausted in summer fallow situations.

Adding N fertilizer to soils in our study ultimately depressed mineralization from SOM. An extensive review by Fog (1988) also concluded overwhelmingly that N fertilizer depressed SOM mineralization; this phenomenon appears to occur regardless of form of applied N (Ramirez et al. 2010). Results may differ when fresh residues are present though- in our incubation expereiment, surface crop residues were not included.

Green et al. (1995) observed that addition of increasing rates of N fertilizer to native soil SOM accordingly depressed C mineralization, but that C mineralization rates were conversely stimulated when fresh maize residue was added to these soils. Whether added N stimulates or depresses mineralization depends on the presence or absence of available polysaccharides in OM; this is the only fraction that N fertilizer stimulates decomposition of, particularly cellulose. After exhaustion of this fraction, added N fertilizer depresses mineralization of remaining recalcitrant compounds, including ligninaceous and humic substances. Secondary metabolism in microbes capable of breaking down these fractions is apparently inhibited when soil N availability is high (Fog 1988). Our results appear to agree with this phenomenon; when significant interactions allowed comparisons of N fertilizer effects on individual systems, the most depressive effects were in the HI systems (Table 3 and 4), which should return more ligninaceous and recalcitrant compounds to soils (Lupwayi et al. 2006). Also, if small amounts of un-decomposed polysaccharides were present in soil samples in our study, this may explain why we saw a small, but statistically significant stimulatory-to-depressive response shift in C mineralization between days 7 to 28, and stimulated N mineralization in the LGM-W system on day 7.

Despite out results, N fertilizer effects on SOM warrant examination with crop residues present to better understand mechanisms and implications of N fertilizer as a SOM building tool. For example, priming effects on SOM may occur when 1) high nutrient availability encourages rapid decomposition of labile fractions of fresh OM, and primes remaining OM for slow growing, secondary decomposers also capable of SOM breakdown, and 2) extracellular enzymes used in fresh OM decomposition are functionally redundant with SOM having similar chemical constitutions as the fresh OM (Fontaine et al. 2003). The latter may be pertinent in monocropped systems. These mechanisms may be supported by findings of Soon and Arshad (2002), where crop residues in fertilized plots decomposed more rapidly and mineralized more N than in unfertilized plots, and of Bell et al. (2003) where addition of wheat straw caused SOM priming in a CW system, and in accordance with increasing fungal to bacterial ratios. These mechanisms also give some insight into why legume-inclusive systems may

positively affect soil C and/or N retention equally well as systems that return more recalcitrant, high C:N residues in comparable or higher quantities (Biederbeck et al. 1998; Drinkwater et al. 1998; Fortuna et al. 2008; Gregorich et al. 2001). Fundamental differences exist between N availability in legume systems where N fertility is partially met by fixed-N in residues. Specifically, 1) N availability is more constrained to incremental release over a long period (Fig. 1) whereas in systems more reliant on N fertilizer, N availability is pulsed, and may encourage rapid residue breakdown; 2) legume residues may be able to sustain bacterial populations (Biederbeck et al. 2005) that competitively control populations of slower growing fungal communities capable of causing SOM priming; and 3) diversified residues in legume systems may not encourage SOM priming as much as in monocropped systems with chemically similar residue and SOM fractions.

The depressive effects of N fertilizer on SOM mineralization observed in our study and others should not be used as a rationale for the conservation of soil C and N, considering the possibility of stimulated residue decomposition and inciting priming effects on SOM. Nor should it obscure that for instance, 1) a depressive effect of 13 mg kg^{-1} on N mineralization in our study was caused by adding an average of 33 mg kg^{-1} of reactive N to soils, and that 2) the "hidden cost" in CO_2 emissions of N fertilizer synthesis (Janzen et al. 1998; Schlesinger 2000) may also negate any soil C sequestered from N fertilizer-increased residue production (DeLuca and Zabinski 2011; Russell et al. 2005). The former may also contribute to why N fertilizer synchrony with crop demand may be poor; N fertilizer is added in a pulse at the early stages of crop growth when plants too small to efficiently use the amount applied; meanwhile residual N fertilizer is vulnerable to leaching/denitrification/volatilization losses, and/or static N fertilizer in soils depresses mineralization potential from SOM for crop uptake at later stages. Soil OM derived-N constitutes a substantial if not a majority of N uptake, whereas fertilizer derived-N recovery rarely crests 50% of the amount of N applied (Cassman et al. 2002; Crews and Peoples 2005).

Our study illustrated that N mineralized in legume systems is sustained over a long period of time (Fig. 1), and appeared to be regulated by the C:N quality of residues

returned to soils (Table 2 and 4). The CW system was incapable of likewise sustaining this release of N, mineralizing (i.e. "decaying") available C and N at a faster rate (Table 4), and leading to an early pulse of mineralized N followed by apparent immobilization (Fig. 1). A CW system therefore theoretically requires N fertilizer additions to best increase residue C additions precipitating SOM changes, and to meet crop demands. Nonetheless, despite the fact that legume-N is released more slowly over a long period of time, the increase in N-supplying capacity of soils from legumes should not be underestimated. Indeed, researchers have cautioned that legume N needs to be managed properly in order to increase N synchrony with crop uptake demands (Crews and Peoples 2005; Gardner and Drinkwater 2009), and to improve legume-N retention (Hauggaard-Nielsen et al. 2009; Starovoytov et al. 2011). Even in semiarid systems, a Saskatchewan study by Campbell et al. (2006) reported that available N credits (fall NO_3-N + 20% of LGM shoot biomass N) applied to a 17-year old LGM (lentil) -W-W rotation were too conservative, and led to higher NO_3-N leaching than in the F-W-W control. Best management practices of spring soil sampling and subsequent soil N credits should be determinants of N rates applied to crops following legumes. Accordingly, in the current long-term study, data from Miller et al. (personal communication, September 2010) showed that after four legume rotations, the LGM-W rotation with no N fertilizer added was capable of producing yields and grain protein concentrations equal to the F-W system which received 139 kg ha^{-1} of N fertilizer. The effect of the LGM-W rotation on wheat yield was not equaled by any other legume system, including the P-W system or a pea hay-W system. This finding substantiates that increased PMN observed in the LGM-W system in our study was likely associated with increased wheat yield from increased soil N-supplying power. Additionally, if N fertilizer additions can stimulate residue decomposition and increase chances of negating soil C increases, implementing appropriate N credits from legumes should additionally aid in mitigating SOM related losses from agroecosystems.

Conclusions

Intensified and legume-inclusive cropping systems in our study generally had higher levels of measured soil parameters than summer fallow-wheat systems. Our soil parameters were most consistently higher when residue C returned to soils was high and average residue C:N ratios were lower, suggesting that residue quantity and quality both play a role. Compared to CW, legume-inclusive systems increased the N supplying capacity of soils, and generally increased the mineralizable fraction of soil C. A sustained slow-release of mineralized-N from legume-inclusive systems was observed in our study, and is indicative of a reduced need for N inputs; these attributes may also help increase plant-soil N synchrony and reduce N losses in soils compared to pulsed N fertilizer additions. Legume-inclusive systems also exhibited promise to have higher WAS and MB-C but only if they increase residue returns to soils over traditional F-W rotations. We found that N fertilizer has a depressive effect on mineralization from SOM, but that depressed N mineralization is trumped by the amount of N added (~3 fold) to cause that effect and therefore still led to high amounts of reactive N in soils vulnerable to losses. Also, the effects of N fertilizer on soil C and N retention needs further study in the presence of residues because 1) N fertilizer may stimulate fresh residue decomposition, and 2) stimulated residue decomposition may prime mineralization of SOM. This would help elucidate if reduced needs for N fertilizer in legume systems can help reduce levels of reactive N in soils vulnerable to losses, and decrease chances of priming effects on SOM mineralization. Even though our results and the discussed mechanisms behind legume and N fertilizer effects on soils highlight that further studies are needed, our results suggest that legumes warrant a more appropriate place as a soil fertility and soil-building management tool. Given the 1) development of profitable pulse commodity markets and the need for crop diversity in NGP, 2) the importance of N and efficient use of N in NGP agroecosystems, and 3) evidence to date suggesting that legumes are capable of mitigating some effects of SOM losses from summer fallow, legume crops may have a very critical place in increasing the sustainability of NGP agroecosystems.

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Table 1 Cropping system histories, soil available nitrogen to 0.6 m (kg ha^{-1}), and fertilizer nitrogen added to systems (kg ha^{-1}), 2003 to 2010.

Cropping System[a], *Nitrogen*	Year								*Average N, wheat years*[c]
	2003	2004	2005	2006	2007	2008	2009	2010	
F-W	Fallow	Win. wht	Fallow	Win. wht	Fallow	Win. wht	Fallow	Spr. wht	
Avail N (Fert N)[b]	*26 (0)*	*199 (88)*	*NA (0)*	*211 (156)*	*NA (0)*	*275 (233)*	*NA (0)*	*200 (145)*	*221 (78)*
CW	Spr. wht	Win. wht	Spr. wht	Win. wht	Spr. wht	Win. wht	Spr. wht	Spr. wht	
Avail N (Fert N)	*202 (176)*	*199 (88)*	*200 (160)*	*216 (96)*	*202 (179)*	*276 (220)*	*201 (189)*	*207 (166)*	*213 (159)*
LGM-W	Win. pea hay	Spr. wht	Win. pea hay	Spr. wht	Win. pea hay	Spr. wht	Spr. pea manure	Spr. wht	
Avail N (Fert N)	*37 (11)*	*164 (118)*	*NA (15)*	*168 (116)*	*NA (6)*	*150 (94)*	*NA (6)*	*184 (99)*	*167 (53)*
P-W	Win. pea	Win. wht	Win. pea	Win. wht	Win. pea	Win. wht	Spr. pea	Spr. wht	
Avail N (Fert N)	*37 (11)*	*178 (108)*	*NA (15)*	*191 (156)*	*NA (6)*	*255 (210)*	*NA (6)*	*191 (149)*	*204 (78)*

[a] Cropping systems are fallow-wheat (F-W), continuous wheat (CW), legume green manure-wheat (LGM-W), pea-wheat (P-W).

[b] Nitrogen rates (*Fert N*) determined as 5 kg N per 100 kg of targeted yield, minus available spring soil NO_3-N to 0.6 m (*Avail N)*. Lower available N and fertilizer rates in LGM-W and P-W reflect legume N credits alloted each wheat year. *NA*: Soil nitrogen data not available.

[c] Average annualized soil and fertilizer nitrogen avalable for wheat crops in each system from 2003-2010. The CW system is averaged over 8 wheat years while all other systems are averaged over 4 wheat years.

Table 2 Soil organic C (SOC) and total N (TN) to 20 cm as measured in 2008, and average annual cropping system residue amounts and qualities returned to soils, 2003-2010.

	Soil[b]			Residue returned[c]							
Cropping System[a]	SOC (g kg^{-1})	TN (g kg^{-1})	Soil C:N	Shoot (Mg ha^{-1})	Shoot C (kg ha^{-1})	Shoot N (kg ha^{-1})	Shoot C:N	Root[d] (Mg ha^{-1})	Root C[d] (kg ha^{-1})	Root N[d] (kg ha^{-1})	Root C:N[d]
F-W	19.1	2.26	8.4	3.51	1554	22	72	0.93	413	11	38
CW	20.5	2.38	8.6	4.77	2146	39	55	1.24	556	19	29
LGM-W	19.5	2.41	8.1	3.23	1433	42	34	1.06	468	23	21
P-W	20.9	2.40	8.7	4.40	1972	52	38	1.19	531	19	27

[a] Cropping systems are fallow-wheat (F-W), continuous wheat (CW), legume (pea) green manure-wheat (LGM-W), pea-wheat (P-W).

[b] Most recent measurements from 2008, SOC from Engel (unpublished data); TN from McCauley (2011). Treatment differences in SOC were not determined, and no differences in TN in the 0-10 or 10-20 cm depth were reported between treatments at $P \leq 0.10$.

[c] Data from Miller (unpublished).

[d] Root parameters are estimated. Root biomass calculated using shoot:root ratios used in Janzen et al. (2003) for wheat, and from Gan et al. (2009) for pea. Calculations for root C and N concentrations for wheat based on differences between root and shoot concentrations reported by Soon and Arshad (2002). Pea shoot C and N concentrations were used for root estimates based on findings by Wichern et al. (2007).

Table 3 Soil potentially mineralizable carbon (PMC) and nitrogen (PMN) values as measured by day, affected by cropping systems and urea fertilizer addition.

	PMC (mg kg^{-1})					PMN (mg kg^{-1})				
Cropping	Day					Day				
System[a]	7	14	28	56	112	7	14	28	56	112
F-W	68 C[b]	128 C	248 C	446 B	701 C	5.2 B	10.5 B	20.1 B	36.1 C	58.0 C
Fertilized[c]	*ns* –[b]	*ns* –	*ns* –	*ns* –	*ns* –	*4.8 b*	*ns* –	*ns* –	*ns* –	*50.5 d*
CW	98 AB	179 AB	316 AB	560 A	870 B	5.8 B	13.4 A	21.1 B	40.2 BC	60.2 BC
Fertilized	*ns* –	*ns* –	*ns* –	*ns* –	*ns* –	*4.9 c*	*ns* –	*ns* –	*ns* –	*43.6 d*
LGM-W	77 BC	150 BC	312 B	615 A	990 A	5.2 B	13.6 A	28.0 A	55.2 A	77.4 A
Fertilized	*ns* –	*ns* –	*ns* –	*ns* –	*ns* –	*7.4 a*	*ns* –	*ns* –	*ns* –	*70.6 b*
P-W	108 A	202 A	372 A	635 A	941 A	4.8 B	12.7 A	26.2 A	50.7 AB	71.2 AB
Fertilized	*ns* –	*ns* –	*ns* –	*ns* –	*ns* –	*4.7 b*	*ns* –	*ns* –	*ns* –	*67.9 ab*
Fertilization[c]										
– N	88 B	ns –	312 A	564 A	876 A	5.2 A	12.6 A	23.8 A	45.5 A	66.7 A
+ N	92 A	ns –	286 B	508 B	782 B	5.5 A	11.9 B	21.6 B	39.2 B	58.1 B
Grouped Contrasts[d]										
WHT – LEG =	-10	-23	-60	-122	-180	0.5	-1.2	-6.5	-14.8	-15.2
P-value	*0.38*[b]	*0.15*	*0.03*	*0.01*	*<0.01*	*0.38*	*0.08*	*0.01*	*0.01*	*0.01*
LO – HI =	-31	-51	-64	-67	-60	-0.1	-1.0	0.4	0.2	2.0
P-value	*0.01*	*0.01*	*0.02*	*0.12*	*0.05*	*0.81*	*0.13*	*0.83*	*0.97*	*0.70*
F – ALT =	-26	-49	-85	-158	-233	-0.1	-2.7	-5.0	-12.6	-11.6
P-value	*0.05*	*0.02*	*0.01*	*0.01*	*<0.01*	*0.91*	*<0.01*	*0.05*	*0.03*	*0.08*
ANOVA[b]										
Cropping System										
P-value	*0.07*[b]	*0.04*	*0.03*	*0.03*	*<0.01*	*0.27*	*0.03*	*0.04*	*0.03*	*0.04*
Fertilization										
P-value	*0.05*	*ns*	*<0.01*	*<0.01*	*<0.01*	*0.18*	*0.04*	*<0.01*	*<0.01*	*<0.01*
Cropping System x Fertilization										
P-value	*ns*	*ns*	*ns*	*ns*	*ns*	*< 0.01*	*ns*	*ns*	*ns*	*0.08*

[a] Cropping systems are fallow-wheat (F-W), continuous wheat (CW), green (pea) manure-wheat (LGM-W), pea-wheat (P-W). Means presented for treaments are least squares means.

[b] Effects from ANOVA and between treatments and treatment groups in contrasts were considered significant at $P \leq 0.10$ (ns = not significant). Treatments sharing the same letter do not significantly differ. Lower case letters should only be compared to thier unfertilized counterpart within a given treatment, and not against other fertilized treatments. All differences between treatments determined by single-degree-of-freedom contrasts.

[c] Means for individual fertilized treatments are only presented if a cropping system x fertilization interaction was significant in ANOVA.

[d] Grouped treatments contrasted refer only to unfertilized treatments, and include wheat systems (WHT) = F-W, CW; legume systems (LEG) = LGM-W, P-W; low intensity systems (LO) = F-W, LGM-W; high intensity systems (HI) = CW, PW; fallow-wheat (F) = F-W; alternative to fallow-wheat (ALT) = CW, LGM-W, P-W. Values presented in grouped contrasts are differences beween the first and second treatment group indicated.

Table 4 Nonlinear model results for asymptote and half-life (relative rate of decay) of soil potentially mineralizable carbon (PMC) and nitrogen (PMN) affected by cropping systems and urea fertilizer addition. Associated model results presented in Fig. 1.

	PMC		PMN	
	Asymptote (mg kg^{-1})	Half-life (days)	Asymptote (mg kg^{-1})	Half-life (days)
Cropping System[a]				
F-W	938 C[b]	62 AB	83 B	68 AB
Fertilized[c]	*757 c*	*ns –*	*ns –*	*ns –*
CW	1021 BC	47 C	74 B	52 B
Fertilized	*775 d*	*ns –*	*ns –*	*ns –*
LGM-W	1325 A	74 A	120 A	72 A
Fertilized	*1113 a*	*ns –*	*ns –*	*ns –*
P-W	1204 AB	52 BC	115 A	82 A
Fertilized	*974 c*	*ns –*	*ns –*	*ns –*
Fertilization[c]				
– N	1122 A	68 A	98 A	ns –
+ N	905 B	49 B	85 B	ns –
Grouped Contrasts[d]				
WHT – LEG =	-284	-8	-39	-18
P-value	*0.02*[b]	*0.20*	*<0.01*	*0.04*
LO – HI =	19	18	8	5
P-value	*0.87*	*0.01*	*0.08*	*0.56*
F – ALT =	-245	5	-20	1
P-value	*0.08*	*0.51*	*0.43*	*0.95*
ANOVA[b]				
Cropping System				
P-value	*<0.01*	*0.02*	*<0.01*	*0.05*
Fertilization				
P-value	*0.06*	*0.07*	*<0.01*	*ns*
Cropping System x Fertilization				
P-value	*<0.01*	*ns*	*ns*	*ns*

[a] Cropping systems are fallow-wheat (F-W), continuous wheat (CW), green (pea) manure-wheat (LGM-W), pea-wheat (P-W). Means presented for treaments are least squares means.

[b] Effects from ANOVA and between treatments and treatment groups in contrasts were considered significant at $P \leq 0.10$ (ns = not significant). Treatments sharing the same letter do not significantly differ. Lower case letters should only be compared only to thier unfertilized counterpart within a given treatment, and not against other fertilized treatments. All differences between treatments determined by single-degree-of-freedom contrasts.

[c] Means for individual fertilized treatments are only presented if a cropping system x fertilization interaction was significant in ANOVA.

[d] Grouped treatments contrasted refer only to unfertilized treatments, and include wheat systems (WHT) = F-W, CW; legume systems (LEG) = LGM-W, P-W; low intensity systems (LO) = F-W, LGM-W; high intensity systems (HI) = CW, PW; fallow-wheat (F) = F-W; alternative to fallow-wheat (ALT) = CW, LGM-W, P-W. Values presented in grouped contrasts are differences beween the first and second treatment group indicated.

Table 5 Soil microbial biomass carbon (MB-C) and wet aggregate stability (WAS) as affected by cropping systems.

Cropping System[a]	MB-C (mg kg^{-1})	WAS (g kg^{-1})
F-W	333 B[b]	101 B
CW	322 B	220 A
LGM-W	381 AB	109 B
P-W	450 A	192 A
Grouped Contrasts[c]		
WHT – LEG =	-88	-10
P-value	*0.03*[b]	*0.69*
LO – HI =	-29	101
P-value	*0.41*	*<0.01*
F – ALT =	-51	72
P-value	*0.22*	*0.01*
ANOVA[b]		
Cropping System		
P-value	*0.09*	*0.02*

[a] Cropping systems are fallow-wheat (F-W), continuous wheat (CW), legume (pea) green manure-wheat (LGM-W) pea-wheat (P-W). Means presented for treatments are least squares means.

[b] Effects from ANOVA and between treatments and treatment groups in contrasts were considered significant at $P \leq 0.10$ (ns = not significant). Treatments sharing the same letter do not significantly differ. All differences between treatments determined by single-degree-of-freedom contrasts.

[c] Grouped treatments contrasted include wheat systems (WHT) = F-W, CW; legume systems (LEG) = LGM-W, P-W; low intensity systems (LO) = F-W, LGM-W; high intensity systems (HI) = CW, PW; fallow-wheat (F) = F-W; alternative to fallow-wheat (ALT) = CW, LGM-W, P-W.

Table 6 Correlation (*r*) matrix for soil and residue data, and measured soil quality parameters.

Parameters[a]	PMC[c]	PMN[c]	MB-C	WAS
SOC	0.46[d]	*ns*	*ns*	0.54
TN	0.63	0.50	*ns*	0.47
Soil C:N	*ns*	*ns*	*ns*	*ns*
Residue C[b]	*ns*	*ns*	*ns*	0.77
Residue N[b]	*ns*	*ns*	0.47	*ns*
Residue C:N[b]	-0.59	-0.56	-0.52	*ns*
PMC[c]		0.75	*ns*	0.41
PMN[c]			ns	ns
MB-C				ns

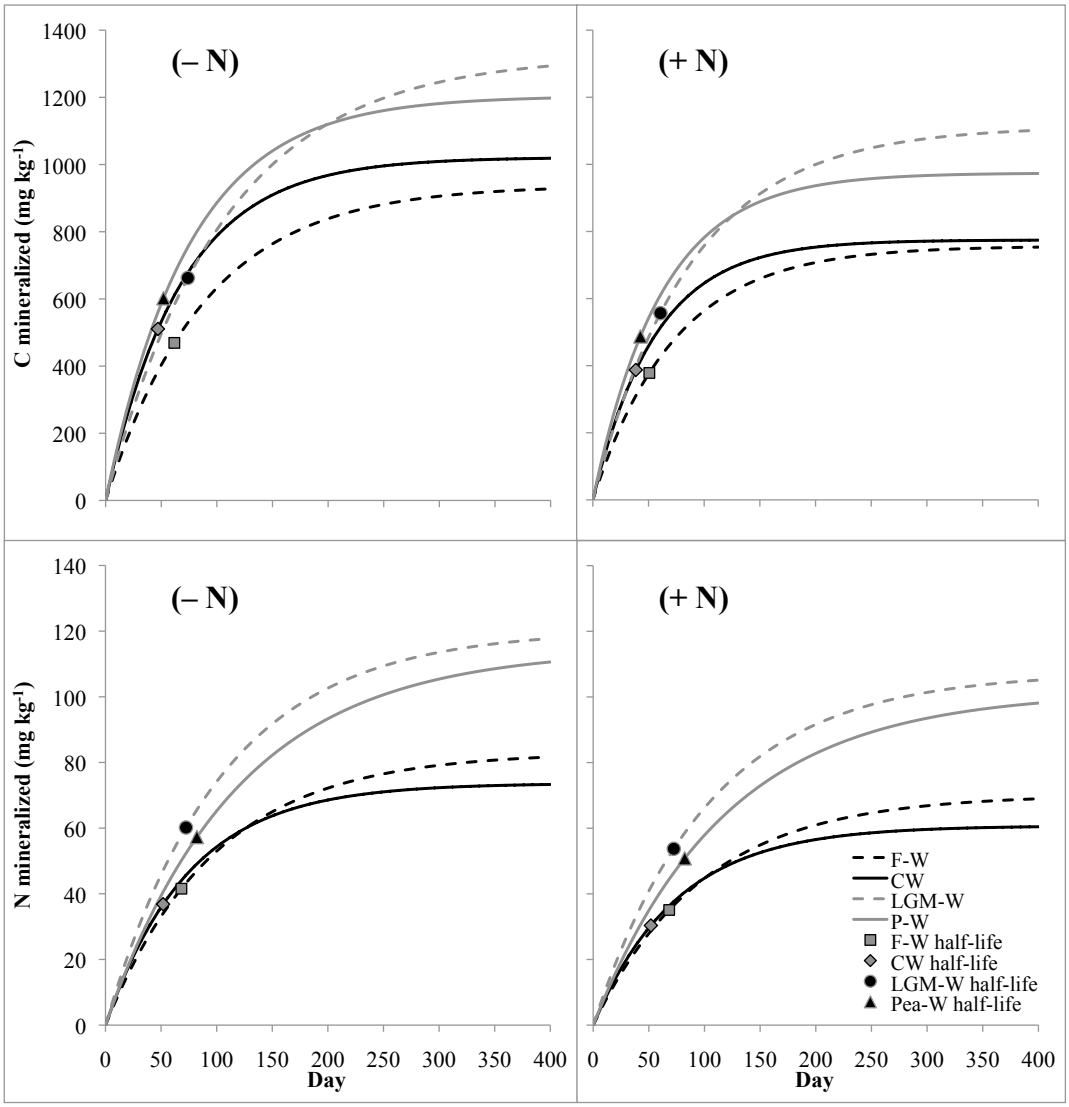
[a] Parameter abbreviations are as follows: SOC - soil organic carbon; TN- soil total nitrogen; PMC - potentially mineralizable carbon; PMN - potentially mineralizable nitrogen; MB-C; microbial biomass carbon; WAS - wet aggregate stability.

[b] Residue data is shoot + root.

[c] PMN and PMC at day 112 used for correlation analyses.

[d] Correlations were considered not significant (ns) if $P > 0.10$.

Fig. 1 Nonlinear modeled carbon and nitrogen mineralization as a function of time. The asymptote and half-life (relative rate of decay) of PMC and PMN as affected by cropping systems and urea fertilization are shown. Associated statistics presented in the Table 2.



Note: Cropping systems: fallow-wheat (F-W), continuous wheat (CW), legume (pea) green manure-wheat (LGM-W), pea-wheat (P-W); Fertilization treatments: no fertilizer added (–N) and urea fertilizer added (+ N). Models were developed from data collected on days 7, 14, 28, 56 and 112.

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CHAPTER FOUR

EPILOGUE

Considerations for Future Research

I was fortunate to bring both of my thesis projects to a successful close without any major failures, and to have found results of interest. Results presented in this thesis should help further understanding of agronomic and edaphic effects of legumes as summer fallow replacements in northern Great Plains (NGP) agroecosystems. Although I took great care to have confidence in the integrity of my measurements and few spontaneous problems arose beyond my control that could have substantially affected the quality of the results presented, a few should be noted for future reference.

Methodological Considerations from Chapter Two Study

In the field study presented in Chapter Two, we gave producers the responsibility of setting up rain gauges at sites. This was troublesome, and I sometimes had to rely on word-of mouth reports from producers for site-specific data if the rain gauge data were compromised. Although I ultimately believe I was able to best estimate precipitation at each site given the resources I had, I would have rather not augmented some data with word-of-mouth reports from producers and/or measurements from the nearest weather station.

Secondly, experimental sites in this study represented large areas that increased chances of capturing spatial variability. At times this variability appeared to be potentially confounding, and it illustrated to me that a larger sample size (perhaps 50%

more) might have served a study like this well. More replication of measurements could have increased statistical resolutions for evaluating treatment effects at individual sites in light of "data noise" caused by spatial variability issues. In addition, small sample sizes in our individual site analyses made it difficult to graphically assess whether statistical test assumptions were met for a valid analysis.

This study also highlighted that potentially mineralizable N (PMN) measurements seemed to have a variable relationship with the time when the sample was taken. Soils measured in spring after legume green manure (LGM) treatment seemed to have much more detectable treatment differences than soils sampled in fall. This may have been an artifact of the 7-d waterlogged incubation method methods used. Potentially mineralizable N detected in this method may be more indicative of aerobic microbial biomass N (Bundy and Meisinger, 1994; Drinkwater et al., 1996) where a nutrient flush comes from the turnover of highly labile aerobe biomass in anaerobic waterlogged conditions. More thorough breakdown of residues into soils overwinter may have presented an advantage to detecting PMN in spring-sampled soils, where substantial amounts of green manure derived-N may have moved in to a labile aerobic heterotroph biomass pool. In contrast, detecting PMN in fall-sampled soils would rely on plant residue N being mineralized in the absence of a functioning aerobic heterotroph community. Investigation into whether detection of PMN in the 7-d waterlogged incubation method is affected by these factors will help highlight when and how this particular method is most applicable.

Methodological Considerations from Chapter Three Study

In the plot study presented in Chapter Three, soils were sampled from an agricultural research farm with a long history (~30 y) of intensive and frequent management changes. Although experimentation is the purpose of these stations, detecting management effects on soils (which already respond slowly and variably to management) may be difficult due to inherent site variability/confounding artifacts of past management. In addition, classic agricultural designs with four replicates may make it additionally difficult to detect treatment effects on soils in light of inherent site variability (Kravchenko and Robertson, 2011). Although I made an effort to reduce spatial variability by homogenizing soils sampled across whole subplots, in retrospect, I also wished I'd taken duplicate measurements to better understand the inherent soil variability I was working with, and to help increase statistical power to detect differences. For example, removing a single data outlier derived from a traditional 4-replicate (block) design reduces a given treatment's sample size by 25%, substantially reducing the resolution for estimating the true mean for that treatment. To specifically increase chances of detecting management effects on soils in future studies I would encourage 1) experimental designs with more than 4 replicates, 2) establishing treatments on sites where management history has been relatively homogenous/consistent, and 3) duplicate measurements from each replicate.

On a more detailed methodological note, soils sampled in fall for microbial biomass C and wet aggregate stability measurements in this study were sampled under dry conditions; a downside to this circumstance is that when certain cropping systems dry surface soils more than others (i.e. use more surface soil water), "field-moist" conditions

can differ. When collected in fall for this study, most soils had comparable field-moist water contents, but the perennial legume/grass treatment (see Appendix B) was considerably drier. I consequently had to devise a way to equilibrate soil water contents without disturbing soils in a way that would affect soil aggregates (i.e. not make mud). Dryness of the soil also affects collection of aggregates, where soil cores fracture into aggregates less readily when too dry. Although it appeared that I was able to equilibrate soil water contents between samples with some success, it would have been more ideal to collect soils following a rain event when surface soils had more equal soil water contents. It is possible, but remains unclear to me whether the original dry condition of soils in the perennial legume/grass treatment might have ultimately affected results.

Lastly, the substrate induced respiration (SIR) method used to detect microbial biomass-C (MB-C) in this study may have limited application in detecting slower-growing fungal communities. Since these slower-growing fungal communities may represent a larger proportion of microbial biomass in no-till managed soils compared to tilled soils, the SIR method may have limited application in detecting treatment differences in MB-C in no-till systems. Whether the SIR method and the more conventional fumigation-extraction method detect MB-C differentially in no-till soils should be investigated further.

Novel/Important Contributions from Chapter Two Study

The study in Chapter Two revealed for the first time that ample amounts of soil water for wheat crops could be conserved when LGMs were terminated at first-flower stage and no-till practices were used at the field scale and under farmer management.

This finding has important implications for LGM adoption amongst conventional no-till wheat producers. Our study also revealed a limitation of LGMs that was previously under-represented in the literature, regarding the possibility of short-term sequestration of soil N in LGM biomass. While this possibility can be viewed positively in a context where legumes act as "catch crops" for residual soil nitrate, the dry, cool conditions prevailing in the NGP and slowed nutrient cycling rates from residues in a no-tillage system may temporarily limit nutrient recovery from LGM biomass to subsequent crops. This finding has important implications for expectations of rotational benefits from legume N, and may affect LGM adoption potential unless it is made clear that this is likely a transient effect. This study may also be the first record of producer concerns regarding LGM adoption in this region, and should help clarify steps that could be taken in order to encourage wide-scale LGM adoption.

Novel/Important Contributions from Chapter Three Study

The study presented in Chapter Three appears to be an original study examining legume-inclusive cropping system treatment effects on soil attributes in no-till systems and in the US region of the NGP. Contrary to past studies in tilled systems, our study indicated that continuous wheat systems might have less promise to mitigate mineralizable C, N, and MB-C lost as a result of summer fallow effects on soil organic matter (SOM). Also, unless legume-inclusive systems can return more residues to soils than summer fallow-inclusive systems, soil wet aggregate stability is unlikely to be affected by legume-inclusion alone. Our use of a nonlinear model which accounted for mineralization trends and predicted an asymptote of mineralizable C and N, indicated that

results presented in past studies from shorter-term incubations could be misleading if treatments exhibit effects that change over time. It was expected that the N-supplying power of the soil would be higher in legume-inclusive systems, and this study importantly confirmed that legume systems in the NGP might begin to reduce needs for N fertilizer after several legume appearances within a rotation. Overall these findings also have particular implications for whether SOM-related losses from summer fallow can be mitigated by legume crops as summer fallow replacements. In this study, legume systems exhibited the most promise to mitigate summer fallow-induced losses of mineralizable C, N, and MB-C from soils.

This study was also an original examination of N-fertilizer effects on SOM conditioned by wheat cropping systems in the semiarid NGP. We observed that N fertilizer depressed C and N mineralization from SOM in general, and that the strongest depressive effects appeared to be associated with systems returning higher amounts of recalcitrant residue fractions to soils. Nonetheless, the depressive effect on N mineralization was surpassed by the amount of N added to soils to cause the effect, and our literature review revealed that when fresh residues are present, N-fertilizer may conversely stimulate residue decomposition and prime SOM decomposition. These findings have implications for better understanding the dynamics of N-fertilizer effects on soils, and the ramifications of using N-fertilizer as a tool to increase SOM by increasing crop residue production.

Future Research Directions

Above all, more work is needed to understand the long-term effects of legumes on cropping systems in the northern Great Plains, particularly regarding rotational legume N benefits. Since studies to date seem to indicate that N benefits from legumes may only begin to manifest consistently after several legume cycles, this needs to be explicitly communicated to producers interested in adopting legumes into their wheat rotations. If producers expect immediate N fertilizer related responses from legumes, legumes may be increasingly stigmatized as an ineffective N source. This could severely hinder adoption trends, particularly regarding LGMs, which produce no harvestable commodity and must precipitate rotational N benefits to be economically viable. Ways to reduce seeding costs for green manures, including reduced seeding rates, and inexpensive ways to source seed should also be explored.

More work is also needed to ascertain whether legumes are sustainable summer fallow replacements capable of mitigating SOM related losses from summer fallow practices in the NGP. Studies focused on assessing mechanistic differences between legume derived-N and N-fertilizer on crop N use efficiency and C and N retention in soils should help further elucidate whether legumes are an ecologically sustainable source of N for NGP agroecosystems.

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APPENDICES

APPENDIX A

ADDITIONAL DATA FROM STUDY IN CHAPTER TWO: ALTERNATIVE SUMMER FALLOW REPLACEMENT TREATMENTS

Introduction:

Appendix A details additional data collected in the study outlined in Chapter Two. Because there is interest in different treatments of legumes as summer fallow replacements, producers at two of the five sites mentioned in Chapter Two elected to add additional treatments to their fields. At Box Elder, the producer alternatively harvested a pea crop for hay, while at Sunburst, the producer chose to grow a pea crop to maturity and harvest for seed and to have cattle graze their LGM crop in the fall of 2009. Additional background information is detailed in Chapter Two.

Materials and Methods

Experimental design information and materials and methods used for collecting biomass and soil data are outlined in detail in Chapter Two. At Box Elder, the pea for hay treatment was compared to the LGM treatment because it was closer (~33.5 m) than the summer fallow treatment (~ 53.5 m). Pea hay biomass was hand-harvested approximately 10 cm above the soil surface at first-flower stage, and the remaining pea stubble was collected separately 7 days later, after herbicide termination was complete. At Sunburst, the pea for seed treatment and a respective summer fallow control treatment were located approximately 120 m from the LGM treatment detailed in Chapter Two. Biomass in the pea for seed treatment was taken in mid-August 2009. In October 2009 grazing enclosures were erected at the Sunburst site to protect the LGM sampling points from which soil measurements presented in Chapter Two were taken. Samples from the grazed LGM and summer fallow treatments were collected approximately 3 m from the grazing

exclosures. Biomass and soil samples for the grazed treatments were not taken at LGM termination because the producer decided to cattle graze after this sample timing had already passed.

Results and Discussion

Both the pea for hay and pea for seed treatments had higher total biomass (Table 1) than the LGM treatments in Chapter Two, but returned similar amounts of residues as LGM treatments at each site respectively (Chapter 2, table 4). Higher biomass in the pea for hay treatment compared to LGM treatment at Box Elder occurred because crop stubble in the pea for hay treatment continued to grow until it was herbicide-terminated several days after the LGM treatment. Differences in soil water use (Table 2) between LGM and the pea hay treatments were not apparent at harvest/LGM termination, or at wheat seeding. By harvest at Sunburst, the pea for seed treatment had depleted soil water below fallow values to 0.6 m; at wheat seeding soil water in the pea for seed treatment was still lower than fallow to 0.3 m. Soil water in the grazed LGM treatment at Sunburst was also lower than fallow treatment to 0.3 m. Soil NO_3-N and potentially mineralizable nitrogen (Table 3) following LGM or pea for hay treatments did not differ at either sample timing. By harvest at Sunburst, the pea for seed treatment had depleted soil NO_3-N below fallow values to 0.9 m. At wheat seeding, soil NO_3-N to 0.3 was still lower in the pea for seed treatment compared to fallow; NO_3-N in the grazed LGM treatment was also lower than fallow at this timing. Wheat yields (Table 4) at Box Elder following the pea for hay treatment were lower than yields following LGM treatment. At Sunburst, wheat yields and grain protein following grazed LGM treatment were lower than in

grazed fallow. There was no difference in yields between the pea for seed and its respective fallow control treatment.

It is unclear why wheat yields in the pea for hay treatment at Box Elder were lower than in the LGM treatment since there were no differences detected in soil water or N between these treatments. Miller et al. (2006) observed that removing pea shoot biomass compared to leaving pea shoot biomass in place as green manure had no effect on subsequent wheat yields. Results presented in Chapter Two indicated that wheat following LGM treatments was likely more N limited than in fallow. In the pea for hay treatment, wheat grain N yields were lower than following LGM treatment, suggesting that N limitation may have also played a role in lowering wheat yields following pea for hay. Although we lack evidence, it is assumed that additional growth of pea stubble between swathing and herbicide termination could have affected critical amounts of soil water and/or N leading to lower wheat yields. At Sunburst, grain yields in grazed treatments were very similar to means in the un-grazed counterparts presented in Chapter Two (Chapter 2, table 7). Hence, no effect of grazing is suspected, and wheat yields are assumed to have been subject to very similar soil water and N environments. In the pea for seed treatment, it is unclear why wheat yields following pea grown to maturity did not differ from the fallow control, when it would be expected that soil water and N available to subsequent wheat would be compromised, especially since the pea year was very dry (Chapter 2, table 3). Mean wheat yields in the pea for seed and its fallow control treatment appeared lower overall than in the LGM, grazed LGM, and their respective

fallow control treatments though, suggesting that another unmeasured factor may have been limiting wheat yields overall on the pea-for-seed portion of the field site.

Conclusion

There appeared to be no clear advantage to alternate treatment of legumes replacing summer fallow on subsequent wheat. Wheat yields or grain protein were not increased by legume treatments compared to fallow controls, and in the case of the pea for hay treatment, yields were lower than in the LGM treatment. Although wheat following pea for seed treatment yielded no differently than wheat following its fallow control, other factors may have been limiting wheat yields in both of these treatments.

References:

Miller P.R., Engel R.E., Holmes J.A. (2006) Cropping sequence effect of pea and pea management on spring wheat in the northern Great Plains. Agronomy Journal 98:1610-1619. DOI: 10.2134/agronj2005.0302.

Table 1 Mean biomass yields of harvested and crop residue portions from alternative summer fallow replacements across two sites in north-central Montana.

Yield Component	Site	
	Box Elder (pea for hay)	Sunburst* (pea for seed)
Harvested biomass (Mg ha^{-1})		
Mean	0.69	0.77
Residue biomass (Mg ha^{-1})		
Mean	0.61	0.90
Harvested biomass N (kg ha^{-1})		
Mean	28	19
Residue biomass N (kg ha^{-1})		
Mean	15	22

*Weed biomass and biomass N at Sunburst amounted to 0.21 Mg ha^{-1} and 12.4 kg ha^{-1}, respectively, in addition to crop biomass reported above.

Table 2 Alternative summer fallow replacement treatment means for Equivalent Depth total soil water content (mm) at harvest, and wheat seeding for specified soil depths across two sites in north-central Montana.

Sampling Depth	Control, *Alternative* Treatment	Site†	
		Box Elder	Sunburst
At LGM termination			
0-0.3 m			
	LGM	41 a*	na‡ –
	Hayed	*43 a*	*na* –
	Grazed Fallow	na –	nd‡ –
	Grazed LGM	*na* –	*nd* –
	Fallow	na –	64 a
	Seed Peas	*na* –	*33 b*
0.3-0.6 m			
	LGM	41 a	na –
	Hayed	*50 a*	*na* –
	Grazed Fallow	na –	nd –
	Grazed LGM	*na* –	*nd* –
	Fallow	na –	58 a
	Seed Peas	*na* –	*33 b*
0.6-0.9 m			
	LGM	40 a	na –
	Hayed	44 *a*	*na* –
	Grazed Fallow	na –	nd –
	Grazed LGM	*na* –	*nd* –
	Fallow	na –	52 a
	Seed Peas	*na* –	*42 a*
At wheat seeding†			
0-0.3 m			
	LGM	36 a	na –
	Hayed	*36 a*	*na* –
	Grazed Fallow	na –	89 a
	Grazed LGM	*na* –	*75 b*
	Fallow	na –	80 a
	Seed Peas	*na* –	*69 b*
0.3-0.6 m			
	LGM	39 a	na –
	Hayed	*36 a*	*na* –
	Grazed Fallow	na –	69 a
	Grazed LGM	*na* –	*59 a*
	Fallow	na –	66 a
	Seed Peas	*na* –	*54 a*
0.6-0.9 m			
	LGM	46 a	na –
	Hayed	38 *a*	*na* –
	Grazed Fallow	na –	52 a
	Grazed LGM	*na* –	*49 a*
	Fallow	na –	53 a
	Seed Peas	*na* –	*51 a*

* Differences determined by paired t-tests considered significant at $P \leq 0.10$. Treatment means followed by the same letter do not singnificantly differ.

† Big Sandy, Box Elder and Joplin sampled Sept 2009, Sunburst and Oilmont sampled April 2010, in accordance with producer's decision to plant winter or spring wheat.

‡ na = Not applicable (treatment not present at site), nd = not determined.

Table 3 Alternative summer fallow replacement treatment means for soil NO_3-N (mg kg^{-1}) and potentially mineralizable nitrogen (PMN) post harvest and wheat seeding for specified soil depths at two sites in north-central Montana.

		Site†	
Sampling Depth	Control, *Alternative* Treatment	Box Elder	Sunburst
NO_3-N at harvest			
0-0.3 m			
	LGM	6 a*	na‡ –
	Hayed	*7 a*	*na* –
	Grazed Fallow	na –	nd‡ –
	Grazed LGM	*na* –	*nd* –
	Fallow	na –	30 a
	Seed Peas	*na* –	*5 b*
0.3-0.6 m			
	LGM	3 a	na –
	Hayed	*2 a*	*na* –
	Grazed Fallow	na –	nd –
	Grazed LGM	*na* –	*nd* –
	Fallow	na –	19 a
	Seed Peas	*na* –	*5 b*
0.6-0.9 m			
	LGM	13 a	na –
	Hayed	*5 a*	*na* –
	Grazed Fallow	na –	nd –
	Grazed LGM	*na* –	*nd* –
	Fallow	na –	29 a
	Seed Peas	*na* –	*8 b*
NO_3-N at wheat seeding†			
0-0.3 m			
	LGM	15 a	na –
	Hayed	*12 a*	*na* –
	Grazed Fallow	na –	55 a
	Grazed LGM	*na* –	*17 b*
	Fallow	na –	43 a
	Seed Peas	*na* –	*11 b*
0.3-0.6 m			
	LGM	5 a	na –
	Hayed	*3 a*	*na* –
	Grazed Fallow	na –	37 a
	Grazed LGM	*na* –	*15 b*
	Fallow	na –	24 a
	Seed Peas	*na* –	*12 a*
0.6-0.9 m			
	LGM	18 a	na –
	Hayed	*6 a*	*na* –
	Grazed Fallow	na –	18 a
	Grazed LGM	*na* –	*11 a*
	Fallow	na –	28 a
	Seed Peas	*na* –	*16 a*
PMN at wheat seeding			
0-0.3 m			
	LGM	13 a	na –
	Hayed	*15 a*	*na* –
	Grazed Fallow	na –	19 a
	Grazed LGM	*na* –	*28 a*
	Fallow	na –	43 a
	Seed Peas	*na* –	*41 a*

* Differences determined by paired t-tests considered significant at $P \leq 0.10$. Treatment means followed by the same letter do not singnificantly differ.

† Big Sandy, Box Elder and Joplin sampled Sept 2009, Sunburst and Oilmont sampled April 2010, in accordance with producer's decision to plant winter or spring wheat.

‡ na = Not applicable (treatment not present at site), nd = not determined.

Table 4 Means of yield components, for alternative summer fallow replacement treatments at two sites in north-Central Montana

Yield Component	Control, *Alternative* Treatment	Site† Box Elder		Site† Sunburst	
Grain Yield (Mg ha^{-1})					
	LGM	4.43	a*	na‡	–
	Hayed	*4.01*	*b*	*na*	–
	Grazed Fallow	na	–	4.80	a
	Grazed LGM	*na*	–	*4.24*	*b*
	Fallow	na	–	4.16	a
	Seed Peas	*na*	–	*3.96*	*a*
Grain Protein (g kg^{-1})					
	LGM	123	a	na	–
	Hayed	*118*	*a*	*na*	–
	Grazed Fallow	na	–	131	a
	Grazed LGM	*na*	–	*111*	*b*
	Fallow	na	–	131	a
	Seed Peas	*na*	–	*120*	*a*
Grain N Yield (kg ha^{-1})					
	LGM	84	a	na	–
	Hayed	*73*	*b*	*na*	–
	Grazed Fallow	na	–	97	a
	Grazed LGM	*na*	–	*72*	*b*
	Fallow	na	–	84	a
	Seed Peas	*na*	–	*74*	*a*
Grain Density (kg m^{-3})					
	LGM	788	a	na	–
	Hayed	*779*	*b*	*na*	–
	Grazed Fallow	na	–	785	b
	Grazed LGM	*na*	–	*795*	*a*
	Fallow	na	–	789	a
	Seed Peas	*na*	–	*798*	*a*

* Differences determined by paired t-tests considered significant at $P \leq 0.10$. Treatment means followed by the same letter do not singnificantly differ.

† Box Elder grew winter wheat, Sunburst grew spring wheat.

‡ na = Not applicable (treatment not present at site), nd = not determined.

APPENDIX B

DATA COLLECTED FROM ADDITIONAL TREATMENTS IN THE STUDY PRESENTED IN CHAPTER THREE

Introduction

Data presented in appendix B are from additional treatments that were sampled along with the treatments presented in the study described in Chapter Three. Additional introductory material and background information on this study is presented in Chapter Three.

Materials and Methods

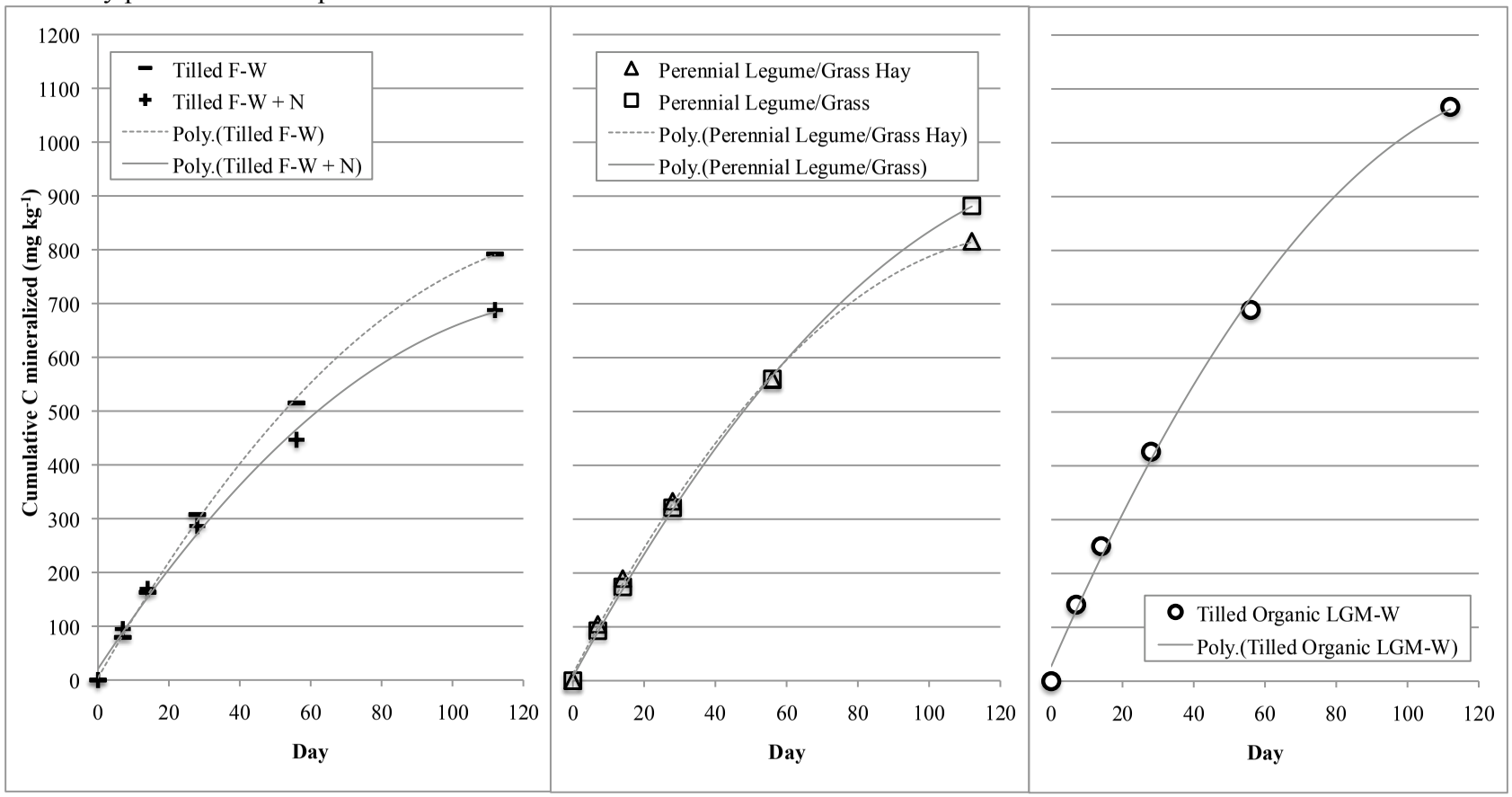
Experimental design and materials and methods used for collecting data in appendix B are presented in detail in Chapter Three. Samples were collected from three other treatments in addition to the ones presented in Chapter Three and included a 1) tilled summer fallow-wheat system (TF-W), 2) an organic legume (pea) green manure-wheat system (ORG), and 3) a perennial legume grass mixture (PER) where half of the main plot was harvested for hay. The ORG system had only two replicates and hence data presented for this system are derived from a lower sample size than the other treatments. As described in Chapter Three, urea fertilizer was added to a duplicate set of soils from the TF-W system; since nitrogen fertilizer is not a management component in the ORG and PER systems they were not included in the urea fertilizer treatments. Data are only presented graphically; these datasets were not statistically analyzed. Soil C and N mineralization trends (Figs. 1 and 2 respectively) are presented as plotted arithmetic treatment means from each day measured over the 112-day incubation described in Chapter Three. Arithmetic means and 90% confidence intervals are presented for potentially mineralizable carbon and nitrogen (PMC and PMN) values measured at day

112 (Fig. 3), and for microbial biomass C (MB-C) and wet aggregate stability (WAS) (Fig. 4).

Results

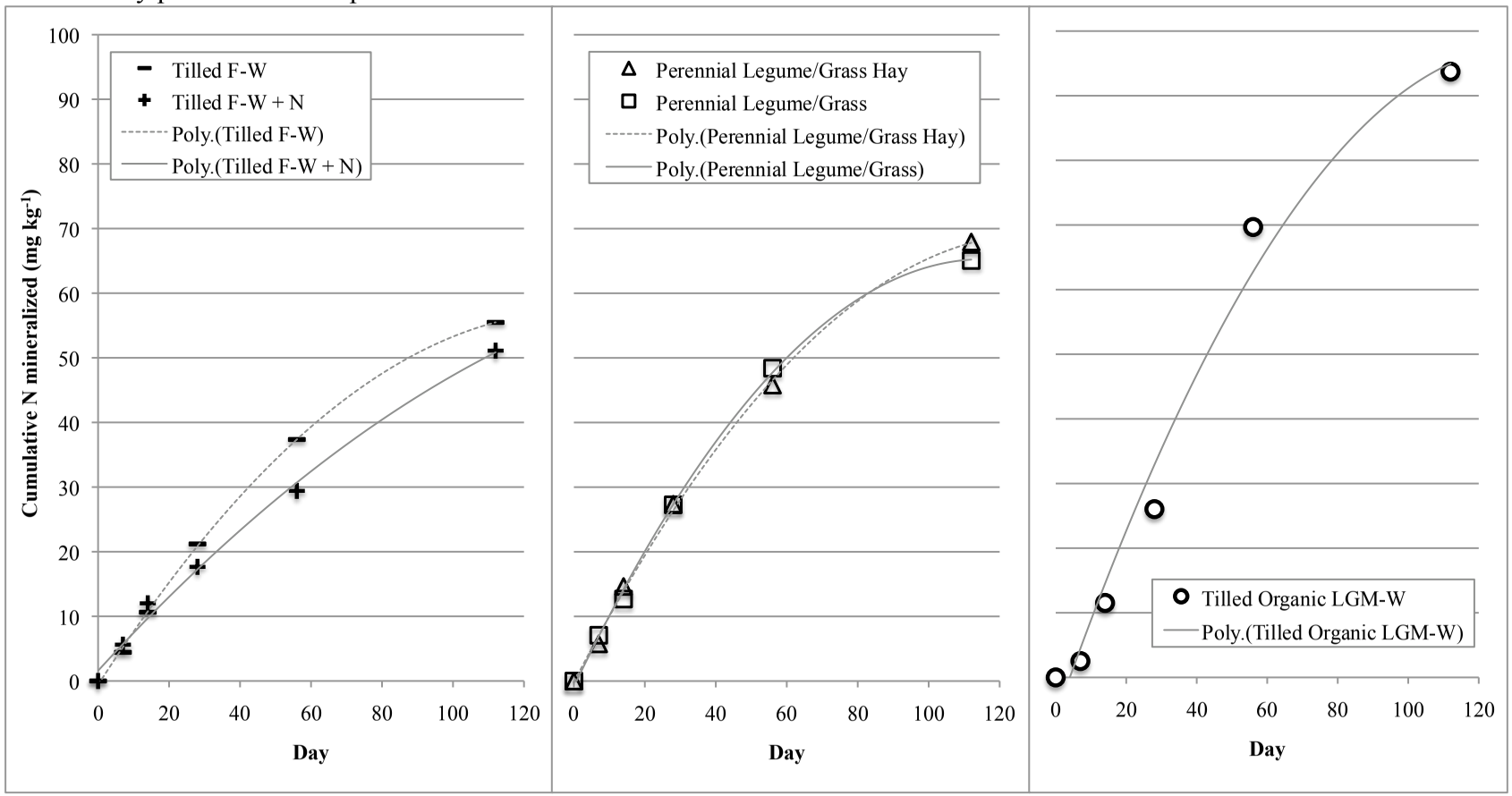
Since results were not statistically analyzed, the information presented is only illustrative of trends. Data presented below are therefore left open for the reader to interpret and compare this data to results from treatments presented in Chapter Three.

Figure 1 Mean cumulative soil carbon mineralization trends (mg kg^{-1}) over 112 days for three cropping systems not included in the study presented in Chapter Three.



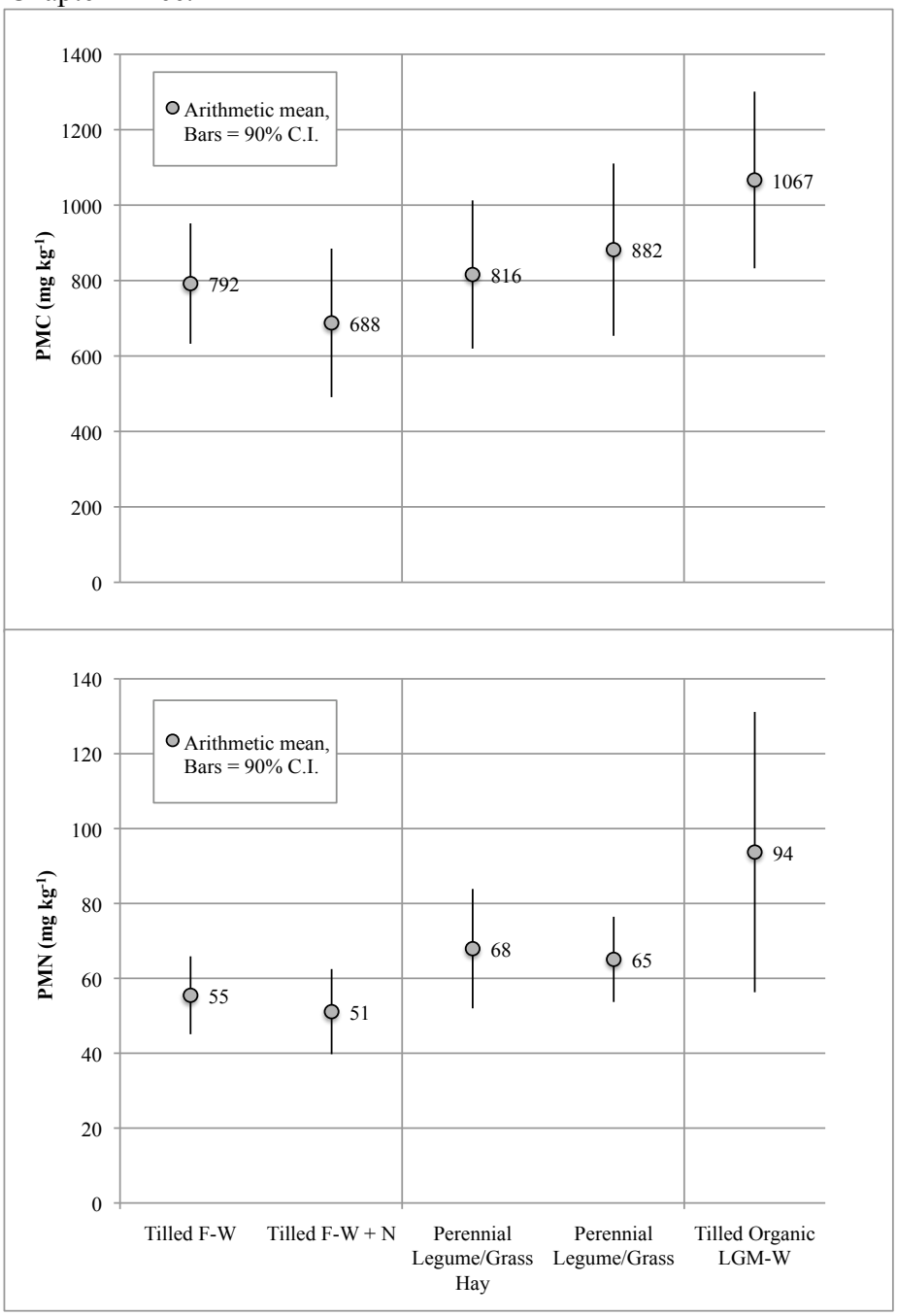
Note: Data points presented are arithmetic means from 4 observations in the Tilled F-W and Perennial legume/grass treatments; means in the Organic LGM-W system are from 2 observations x 2 duplicate measurements. Data trends are illustrated by a second- order polynomial ('Poly.') regression line.

Figure 2 Mean cumulative soil nitrogen mineralization trends (mg kg^{-1}) over 112 days for three cropping systems not included in the study presented in Chapter Three.



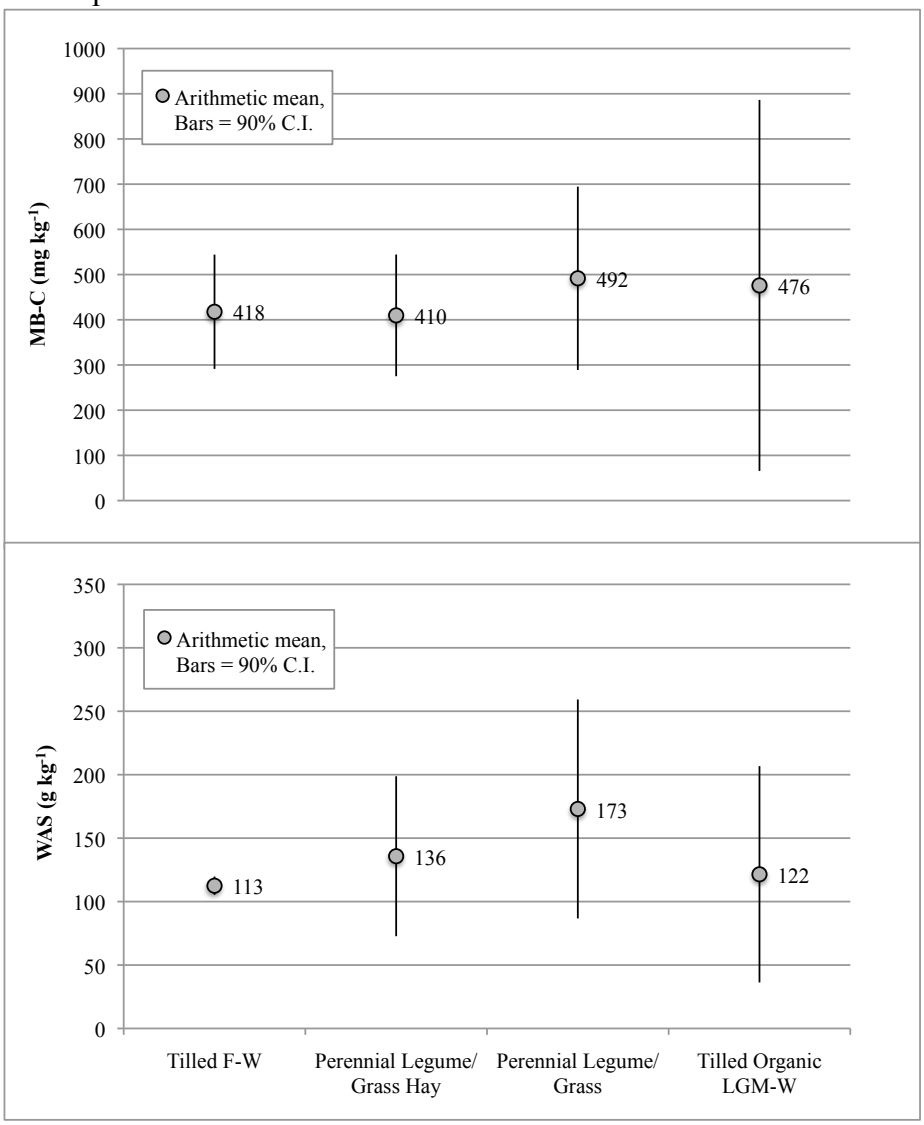
Note: Data points presented are arithmetic means from 4 observations in the Tilled F-W and Perennial legume/grass treatments; means in the Organic LGM-W system are from 2 observations x 2 duplicate measurements. Data trends are illustrated by a second- order polynomial ('Poly.') regression line.

Figure 3 Arithmetic mean values and 90% confidence intervals for soil potentially mineralizable C and N (PMC and PMN) as measured on day 112 in three cropping systems not included in the study presented in Chapter Three.



Note: Data points presented are arithmetic means from 4 observations in the Tilled F-W and Perennial legume/grass treatments; means in the Organic LGM-W system are from 2 observations x 2 duplicate measurements.

Figure 4 Arithmetic mean values and 90% confidence intervals for soil microbial biomass carbon (MB-C) and wet aggregate stability (WAS) in three cropping systems not included in the study presented in Chapter Three.



Note: Data points presented are arithmetic means from 4 observations in the Tilled F-W and Perennial legume/grass treatments; means in the Organic LGM-W system are from 2 observations.