SEEKING SUSTAINABILITY FOR ORGANIC CROPPING SYSTEMS IN THE NORTHERN GREAT PLAINS: LEGUME GREEN MANURE MANAGEMENT STRATEGIES

by

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ABSTRACT

Soil fertility in organic cropping systems of the northern Great Plains (NGP) is most often achieved through inclusion of leguminous green manures. The objectives in this study were to evaluate the efficacy of pea as green manure; and more specifically, measure the effects of pea green manure type, termination timing and method for soil water use and soil N contribution. A study consisting of winter pea, spring pea, mustard, buckwheat and fallow was conducted at Big Sandy Montana. In Bozeman, MT, termination methods of winter and spring pea were compared. Green manures were terminated at one of two timings, first bloom or first pod. Winter pea was the superior annual green manure in this study, optimizing the soil water conservation and N fertility goals of organic dryland growers in the NGP. Winter pea terminated at bloom also provided the greatest soil N at the end of the green fallow period relative to other green manures. However, pod-terminated winter pea may enhance soil N fertility due to greater N fixation over the long-term. Although a N advantage of pod-termination was not illustrated in soil NO_3-N data, greater shoot biomass N may eventually contribute greater soil N to the cropping system.

Additionally, this study compared two experimental termination strategies, crimp-rolling and vinegar desiccation, with standard disk-tilling in attempt to reduce tillage in organic systems. The efficacy of termination strategy was dependent on pea growth stage. At first bloom, disk-tillage was the only method that effectively terminated pea growth. When terminating pea at pod, both disk-tillage and crimp-rolling were effective. Crimp-rolling at pod eliminated up to three tillage operations, while maintaining comparable soil water use and subsequent wheat yields to disk-tillage. Although the advantage of reducing tillage operations by crimp-rolling could not be directly measured in a 2-yr cropping sequence, longer-term tillage reduction may reveal multiple soil quality benefits for organic growers.

CHAPTER 1

PROJECT BACKGROUND AND OBJECTIVES

Introduction

The world's population has more than doubled in the past half-century, and is still growing at an annual rate of 1.2% (UN, 2001). The production capability of agricultural systems have, in general, paralleled increased demand (Tilman et al., 2002; Trewavas, 2002). Modern agriculture feeds roughly 6 billion people (Tilman et al. 2002). In terms of providing an inexpensive, abundant food source for a growing population, U.S. agriculture in particular has been an unparalleled success. The scientific advances and technological innovations of the agricultural revolution have provided farmers with new tools with remarkable efficiency, resulting in astonishing yields and increasing the global per capita food supply (FAO, 2001). As a result, agriculture is the largest industry on the planet.

Aside from meeting global food demands, modern agriculture is not sustainable. The American Society of Agronomy defined sustainable agriculture as one that over the long term (1) enhances environmental quality and the resource base on which agriculture depends, (2) provides for basic human food and fiber needs, (3) is economically viable, and (4) enhances the quality of life for farmers and society as a whole (Hatfield and Karlen, 1994). The techniques, innovations, practices, and policies that have provided an abundance of low-cost food have also undermined the basis for that productivity.

Practices such as intensive tillage, monoculture, irrigation, application of inorganic fertilizer, chemical pest control, and genetic manipulation of crop plants have become the mantra of modern agriculture (Gliessman, 1998). Although each has individually contributed to productivity, the sum of these habitudes has created a system of farmer dependence on external inputs. These current agricultural practices have cumulatively resulted in soil and water contamination, food-borne diseases, and erosion (Tilman, 1999; van der Werf and Petit, 2002).

The burgeoning food demand of a growing and developing world population has increased the need for nitrogen-N to be added to farmlands (Tilman et al., 2002). Globally, anthropogenic sources of N now exceed 'natural' sources (Vitousek et al., 1997a; 1997b; Leigh, 2004a; 2004b). Fertilizer N has produced astonishing increases in food production; without it, crop yields would eventually diminish as soil N reserves subsided (Tilman et al., 2002; Janzen et al., 2003). However, this unprecedented food production is at the cost of human health and the environment. Nitrate fertilizer can be used directly by plants or soil microorganisms (immobilization) or lost from the crop rooting zone by denitrification, leaching or runoff (Janzen et al., 2003). Lost N can cause eutrophication of surface water, increased concentrations of greenhouse gases, contamination of drinking water, and reduced biodiversity of native ecosystems, among other consequences (Socolow, 1999). Management of N in agroecosystems, therefore, is critical to maintain food production without undermining environmental quality.

A bifurcation of perspectives has inspired research on finding alternative cropping systems that reduce the dependence on inorganic fertilizer N, while sustaining yields. On

one hand, there is increasing public demand for certified ‘organic’ food, which does not allow for applications of inorganic N fertilizers. Soil fertility by organic farmers is often generated with legume-rich pastures or cover crops, a necessity that may consume 25% or more of a farmer’s land annually. Diverse cropping systems with legumes in rotation may reduce fertilizer N costs and increase nitrogen use efficiency (Biederbeck et al., 1996). Some scientists contend that the unprecedented human population exceeds the potential productivity of legume-based agriculture (Smil, 1997; Sinclair and Cassman, 1999; Cassman et al., 2002). However, the long-standing assumption that organic farming would yield just one-third or one-half of current conventional practices has come under recent scrutiny. Developing nations specifically have repeatedly shown yield increases with organic management (Halweil, 2006).

Despite the differing opinions as to how to sustain food production for a growing world population, increasing numbers of farmers are completing the 3-yr USDA organic certification transition period in part because it provides access to premium markets (Dimitri and Greene, 2002). Organic foods are one of the fastest growing sectors of the U.S. agricultural economy. In 2005, retail sales of Organic commodities topped US$13.8 billion and markets continue expanding at a rate of 20% annually (Winter and Davis, 2007). As organic agriculture is emerging from a fringe production method, mainstream academic research is increasingly engaging this topic (Winter and Davis, 2007).

The state of Montana is leading the trend in organic wheat (*Triticum aestivum* L.) production, with 20% of the total acreage in the United States (Greene, 2006). The semiarid northern Great Plains (NGP) is an especially challenging environment for

dryland crop production with highly variable precipitation and temperature being the most common constraints affecting crop production and quality. For example, a drought cycle from 2000 to 2004 in the main wheat-growing region of north central Montana included three years where rainfall was less than 80% of normal, and one year where it was less than 50% of normal (Miller, unpublished data, 2004). The increasing demand for organic products, daunting climate challenges of the semi-arid northern Rocky Mountain states, and lack of current research are three motivating factors why organic growers in the NGP need new knowledge to flexibly manage their systems.

USDA organic certification standards do not permit the use of synthetic fertilizers to maintain soil fertility. Therefore, nutrient management in organic systems is often accomplished by broadcasting animal or plant manures. In the NGP, using animal manures is typically not feasible due to farm size and distance from concentrated manure sources. Instead, dryland organic growers in the NGP use legume or 'green' manures (LGM) because of their ability to fix atmospheric N_2, which may provide N to subsequent crops.

The use of different legume species depends on various climate-specific factors. Whereas a clover (*Trifolium subterraneum* L.) understory or cover-crop mixture may provide a more continuous N supply to a cereal crop in subhumid regions, perennial or annual legumes are often grown and terminated prior to senescence in semiarid regions (Clapperton et al., 2004). In semiarid conventional cropping systems of Saskatchewan, the use of biennial and perennial LGM crops has been shown to be impractical because LGM water-use can depress subsequent crop yields (Campbell et al., 1986). However,

perennial and biennial LGM crops such as alfalfa (*Medicago sativa* L.) or yellow sweet clover (*Melilotus officinalis* L.) are often used in organic systems of the NGP. Research has shown that annual LGM crops are a good alternative in Saskatchewan, especially if they are efficient water users and are managed to conserve water (Biederbeck et al., 1993). Due to the moderate climatic similarities between southwestern Saskatchewan and Montana, annual LGM crops might represent a viable option for organic growers in Montana.

Organic cropping systems require additional tillage for weed management and LGM termination. Interest in reduced-tillage or conservation tillage practices has increased correspondently with the sustainable agriculture movement. No-till systems have been shown to increase crop productivity by capturing a greater proportion of incident precipitation (Peterson et al., 1996; Nielsen et al., 2005). Implementation of tillage-reducing strategies may help organic growers become more economically competitive and environmentally sustainable. This study aimed to identify management strategies to increase the sustainability of dryland organic agriculture in the NGP.

Literature Review

Historical Significance of Legume Green Manures

Legumes differ markedly from grasses, cereals, and other non-legume crops because they fix atmospheric nitrogen. Dinitrogen (N_2) fixation is accomplished through a symbiotic relationship with rhizobia bacteria residing in root nodules of these plants (Biederbeck et al., 2006). Historically, the primary approach for maintaining soil fertility

in intensive cropping systems was to incorporate legumes within field crop rotations (Cherr et al., 2006). After World War II, farming was rapidly mechanized and traditional "legume-cereal" rotations were abandoned as relatively cheap nitrogen fertilizers became widely available with the advent of the Haber-Bosch process (Smil, 1997). For semiarid regions such as the NGP, deep-rooted forage legumes were found to depress subsequent grain crop yields by depleting soil moisture reserves. This, in addition to affordable inorganic N sources, encouraged many farmers to adopt summerfallow to replace legumes in cropping systems.

Today, one of many unsustainable aspects of conventional farming systems in the semiarid NGP is fallow frequency. Summerfallow has been referred to as the single most devastating cause of soil degradation through soil nutrient and organic matter depletion, erosion, salinization, and inefficient use of precipitation (Dumanski et al., 1986; Monreal and Janzen, 1993; Larney et al., 1994). Wheat-fallow cropping practices on the prairies have been implicated as the cause of serious declines in soil organic matter (Monreal and Janzen, 1993). As a result, LGM research in conventional systems has focused on finding ‘green’ fallow alternatives to plant-free or ‘bare’ summerfallow. This green fallow research in conventional farming presents relevant insights for organic agriculture. This literature review examines both published and unpublished research pertaining to benefits and management strategies of LGM in cropping systems.

Benefits of Legume Green Manures

A significant advantage of legume versus fertilizer forms of N is the long-term replenishment of stable organic N reserves in the soil. As compared with fertilizer N

which is susceptible to nitrate leaching and denitrification, plant-derived N is relatively more recalcitrant (Muller and Sundman, 1988; Drinkwater et al., 1998). An experiment conducted in Alberta quantified the N contribution of lentil (*Lens culinaris* Medik.) to subsequent crops and organic matter reserves (Janzen et al., 1990). Compared with 36% recovery from ammonium fertilizer, subsequent wheat crops recovered only 14% of green manure N. However, the contribution of the green manure to the organic N pool in the surface soil layer was approximately twice that of inorganic fertilizer. The organic N pool is relatively recalcitrant, and remains a long-term source of potentially mineralizable nitrogen (PMN) for subsequent crops. A study in Denmark echoed this result, showing that after 3 yr of subsequent crops, 45% of the original pea (*Pisum sativum* L.) LGM N remained present in organic forms in the topsoil (Jensen, 1994). These findings agree with various early studies from diverse climatic contexts, suggesting N mineralization from decomposing legume residues may be largely independent of soil-climatic conditions (Amato et al., 1987).

LGM crops may improve a variety of soil properties. When properly managed, legumes will enhance the N-supplying power of soils, increase soil organic matter, stimulate soil biological activity, improve soil structure, reduce wind and water erosion, increase soil aeration, and improve soil water holding capacity (Biederbeck et al., 2006). For example, in subtropical rice (*Oryza sativa* L.) - wheat cropping systems of India, organic matter and total nitrogen concentrations were higher under LGM crops when compared to monsoon-season summerfallow (Mandal et al., 2003). Incorporation of mung bean (*Vigna radiate* L.) and *Sesbania* (*Sesbania rostrata*, and *Sesbania aculeata*)

manures in the clay loam increased total pore space, thus decreasing bulk density, an effect that persisted through subsequent rice and wheat crops. Green manuring also improved the soil physical growing environment as evidenced by higher values of mean aggregate weight diameter and higher saturated hydraulic conductivity than fallow. These improved soil properties due to green manuring resulted in greater root length density, and thus yields of subsequent rice and wheat crops. In clay-containing soils of the NGP, soil properties could be improved in a similar way to increase tilth.

In subhumid regions of the midwestern and eastern United States, various studies have shown that the use of green manures and cover crops between growing seasons of principal crops may reduce leaching in conventional cropping systems. A meta-analysis of studies that replaced fallow periods with cover crops was conducted in fertilizer-intensive cropping systems in various agroecoregions (Tonitto et al., 2006). That meta-analysis found that nitrate leaching in legume-based systems was reduced by 40%, relative to bare fallow systems due to scavenging of soil N by cover crops. These results demonstrated the potential for diversified rotations using both N- and non-N-fixing cover crops to maintain crop yields while reducing N leaching.

Nitrate leaching may also be reduced in areas of low annual precipitation. In a semiarid region of Saskatchewan, Zenter et al. (2001) further elucidated the environmental benefits of LGM crops. Of the four conventional cropping systems evaluated in a long-term crop rotation study at Swift Current, Saskatchewan (fallow-wheat, fallow-wheat-wheat, continuous wheat, and wheat-lentil), nitrate leaching was lowest with a legume in the rotational sequence (in this case, wheat-lentil). In addition,

soil organic carbon, mineralizable N and C, light fraction organic C, and water stable aggregates was greatest in the wheat-lentil system. Other environmental benefits of adding a legume in rotation were lower energy requirements for N fertilizer and an overall 19% reduction in CO_2 emissions (Zentner et al., 2001). The researchers concluded that extending and diversifying crop rotations to reduce fallow and include pulse crops will improve the sustainability of agricultural production in semiarid regions of the NGP.

Management of Legume Green Manures

Precipitation and soil fertility are yield-limiting factors of organic farming systems in the semiarid NGP. Thus, assessing LGM management strategies for maximum N_2 fixation and minimal water use represents a logical starting point in the examination of LGM management strategies. There has been a resurgence of research on LGM crops in conventional cropping systems due to increasing environmental and economic costs of inorganic N fertilizer, as well as renewed interest in developing sustainable agricultural systems. This review will focus on literature applicable to dryland organic cropping systems.

Despite the numerous benefits of LGM crops as fallow replacement, many studies in the semiarid NGP have reported lower or similar yield of cereal grains that follow LGM compared to those following tilled fallow (Brandt, 1996; Zentner et al., 1996; Vigil and Nielsen, 1998). Generally, yields of cereals following LGM were depressed because the legume reduced available spring soil water thereby putting the subsequent cereal crop

at a disadvantage in comparison to fallow (Zentner et al., 1996; Brandt, 1999). To maintain competitive yields, organic LGM crops must use soil water efficiently.

In the semiarid central Great Plains, most LGM crops grown full season deplete soil water from the 0-1.2 m soil depth (Nielsen and Vigil, 2005). Among pulse crops, pea has been shown to confer stronger rotational benefits to wheat by conserving greater soil water (Miller et al., 2001; Miller et al., 2003). To reduce water use by LGM crops, one approach is to grow a LGM early in the summer fallow period and to terminate the crop prior to maturity (Pikul et al., 1997). When allowed to reach maturity, Aase et al. (1996) determined that no more than 50 mm of soil water should be sacrificed by growing a lentil green manure if wheat is to be seeded the following year.

A variety of studies have estimated the optimal plant growth stage as bud or prior to full-bloom for LGM crops in fallow-replacement experiments (Townley-Smith et al., 1993; Zentner et al., 2004; Miller et al., 2006). In two sites in Montana, 19-39 mm more water was available for a subsequent wheat test crop when LGM growth was terminated at early bloom (Miller et al., 2006). In addition, LGM height has been suggested as an indicator of termination timing because plant height relates positively to both cumulative evapotraspiration and growing degree days. Terminating lentils before they reached a height of 0.35 m left sufficient water for subsequent crops in one study at Sidney, MT (Aase et al., 1996). However, using a standard height as a water usage indicator may be inappropriate, for lentil height varies with genetics and the environment as observed by Miller (personal correspondence, 2006).

A key 12-yr study illustrated that stage-specific management of lentil green manure is critical to managing soil water use (Zentner et al., 2004). During the first six years of a study researchers allowed lentil to grow to full bloom to maximize N_2 fixation. By allowing lentil to reach a later stage of development, water usage by the LGM proved detrimental to subsequent wheat crops. During ensuing years of the study, the researchers recommended that lentil be seeded as early as possible (late April to early May) and growth be terminated at the bud stage (by the first week in July), even if it meant limiting N_2 fixation. This later management resulted in the first favorable economic assessment of a LGM in a conventional cropping system.

Several studies in the NGP recommend recharging crop-consumed soil water using some sort of snow-trapping technique, however few reported effective results (Brandt, 1990; Townley-Smith et al., 1993; Brandt, 1999; Zentner et al., 2004). Some of the practices referred to included: using herbicides to halt the growth of the LGM thus eliminating the need for soil incorporation, planting mustard (*Sinapis alba* L.) strips after incorporation, and leaving standing strips of non-incorporated lentil green manure *in situ*. Brandt, (1999) concluded that a combination of early incorporation and leaving desiccated strips *in situ* can be effective at augmenting over-winter soil water. Another prospective snow-trapping technique not evaluated in these studies is to seed LGM crops in early autumn so considerable biomass is present prior to winter.

Late-incorporated green manures use considerable water (20-30 mm in a subhumid region of Canada), but also have lower levels of NO_3-N following termination when compared to fallow (Rice et al., 1993). Soil N availability for subsequent crops

may also decrease (30-39 kg NO_3-N ha^{-1}) when LGM growth is terminated at maturity (Miller et al., 2006). In fertilized cropping systems of northeastern Saskatchewan and northeastern Montana, incorporation at early budding reduced dry matter and N accumulation to half that obtained at full bloom (Townley-Smith et al., 1993; Pikul et al., 1997). In the NGP, optimal uptake of soil nitrate N by subsequent fall-sown crops occurred when manures were terminated at early bloom (Miller et al., 2006).

Although early-terminated green manures optimize N recovery by subsequent crops, the large size and dynamic nature of the soil organic N pool makes N added or removed by LGM crops difficult to quantify. Various studies in conventional cropping systems have failed to establish a relationship between LGM shoot biomass and soil N dynamics. These results indicate that in the short term, soil NO_3-N tests are not very sensitive to differences in LGM residue N content or presence. In contrast to NO_3 tests, ^{15}N-labeled legume residues have added new insights to LGM N cycling. Janzen et al. (1990) noted that 14% of N applied as green manure (pea and lentil) was recovered by a subsequent wheat crop. Increasing application rates of forage pea green manure result in an increased crop uptake of manure-derived N (Rees et al., 1993). Therefore, LGM crops producing greater biomass should increase soil N inputs.

The volatile loss of NH_3 following LGM termination has been found to consistently follow the same pattern: a large flush of NH_3 within 14 d of termination, followed by a much slower rate of volatilization (Sarrantonio and Scott, 1988; Janzen and McGinn, 1991). This initial flush of NH_3(g) has been attributed to LGM tillage and the rapid ammonification of soluble organic-N. The much slower stage, conversely, reflects the

volatilization of NH_4^+ generated by the mineralization of more recalcitrant N fractions in the LGM residue. Legume derived N was separated from soil N because of NH_3 volatilization. Although volatilization may only remove a small proportion of the LGM N, 14% as observed by Janzen and McGinn, (1991), this fraction represents the most labile N and that which is most critical to subsequent crop fertility in the short term.

Other studies have shown the release of organic ^{15}N to be very fast during the initial 3 mo of decomposition (Jensen, 1994). The amount of pea residue N in successive autumn-sown crops of barley (*Hordeum vulgare* L.), oilseed rape (*Brassica napus* L.) and wheat was twice as high as spring-sown. If the soil was left uncropped during the autumn, winter and early spring, the recovery in the spring-sown oilseed rape crop was only 1% of the residue N. Jensen (1994) suggests that the lower recovery of labeled N in spring-sown crops was probably due to leaching of the mineralized residue N during the autumn, winter, and early spring. However, N leaching in the semiarid NGP is not as probable due to relatively low precipitation. Subsequent fall-sown crops are seeded approximately 3 mo after early to mid-season termination; optimal timing to use available soil N to promote vigorous winter crop establishment.

The method by which LGM is incorporated may affect N recovery by subsequent crops, as well as volatile N losses. Unpublished data have indicated that termination of a green manure crop by herbicide application, which retains surface residue, may reduce subsequent wheat yield by 22% as compared with termination by tillage (Biederbeck and Slinkard, 1988). This yield reduction was attributed to higher mineralization from incorporated materials. However, Janzen and McGinn (1991) suggested volatile loss

from surface applications as an alternative mechanism. In controlled experiments, appreciable ammonia volatilization may occur when a LGM is applied to the soil surface. Incorporating LGM materials prevents volatile loss of NH_3; an observation also reported for fertilizers (Russelle et al., 1983). Unfortunately, immediate incorporation of LGM material into the soil greatly reduces its effectiveness as a measure for indigenous soil water conservation, erosion control, and snow trapping (Janzen and McGinn, 1991). Therefore, the optimum use of LGM residues may require a compromise between retaining surface cover and maximizing fertility benefits.

Several annual legume species present potential for use as green manure crops. A study conducted at Swift Current, SK compared four annual legume species for green manure effects and concluded that pea effectively fixed N_2 and contributed the greatest N response to spring wheat (Biederbeck et al., 1993; Biederbeck et al., 1996; Tanaka et al., 1997). Pea is also a suitable green manure crop because it has a high degree of decumbency which provides good ground cover for soil protection against wind and water erosion.

Planting and harvest dates, and cultivars of Austrian winter pea (AWP) have been evaluated as an annual LGM in the Palouse region of northern Idaho (Auld et al., 1982; Mahler and Auld, 1989) where precipitation averages 610 mm annually. Fall-planted AWP cultivars averaged 13.0 Mg ha^{-1} of shoot biomass as compared to 12.1 Mg ha^{-1} for spring pea lines. The AWP cultivar *Melrose* produced the highest yields of organic matter and vine N as compared with other cultivars (*Fenn,* common, *ID 89-1,* and *Romack*). Early September seeding was critical for maximum LGM potential because

delaying seeding until early October reduced shoot biomass production and vine N by over 50%. Winter pea produced 6.9 Mg ha^{-1} of shoot biomass when spring planted (Auld et al., 1982). The spring pea cultivars accumulated an average of 359 kg ha^{-1} of vine N compared to 280 kg ha^{-1} for the winter-planted AWP cultivars. Although greatest shoot biomass yield was obtained from pea harvested at pod, percent vine N declined with later harvest. The total vine N increased only 28 kg ha^{-1} as harvest was delayed from 6 June to 6 July. Most of the N in pea vines was already stored in the crop canopy shortly after the initiation of flowering. Therefore, Auld et al. (1982) suggested that AWP can be turned down immediately after flowering without greatly reducing the amount of N returned to the soil. Conversely, total vine N increased by 50 and 81 kg ha^{-1} between first bloom and plump pod in Montana (Miller P.R., unpublished data). Mahler and Auld (1989) found AWP to be most economically efficient when used as a seed pea because income can be generated annually, and harvested pea plots had comparable inorganic N levels to peas used as green manure. However, their justification for this assertion was based on soil nitrate-N, which provides an incomplete picture of N contribution from legumes. Conversely, Miller et al. (2006) found markedly higher crop N uptake following pea terminated for green manure vs. pea harvested for grain during drought conditions.

The autumn growth habit of winter pea is better suited for green manure than the spring growth due to earlier flowering date which better matches the growing season climate in Montana (Chen et al., 2006). Short-season spring annual crops such as mustard, however, may also be terminated early. Although crops in the mustard family do not fix N_2, several other benefits from brassica green manure have been reported

including suppression of weeds (Al-Khatib et al., 1997) and soil-borne pathogens (Fenwick et al., 1989; Kirkegaard et al., 2000). Brassica species contain glucosinolates, which are not phytotoxic themselves, but as the plant tissues break down glucosinolates are sometimes converted to isothiocyanates which contribute to allelopathic effects (Chew, 1988; Kirkegaard et al., 2000). In cropping systems that rely heavily on herbicides, Brassica crops have been suggested as an alternative weed control strategy. In a study by Al-Khatib et al. (1997), brassica green manures suppressed weeds in subsequent green pea crops. In a greenhouse experiment, mustard added to the soil at 20 g per 400 g of air-dry soil reduced emergence of shepherd's purse (*Calsella bursa-pastoris* L.), kochia (*Kochia scoparia* L.), and green foxtail (*Setaria viridis* L.) by 97, 54, and 49% respectively. Similarly, oilseed rape suppressed the emergence of the same weeds by 76, 25, and 25% respectively. This response was likely exaggerated, however, by the exorbitant mustard application rate, roughly equivalent to a field application rate of 112 Mg ha^{-1}.

A weed-inhibitory response was also found for buckwheat (*Fagopyrum esculentum* Moench) in subhumid-field studies in Japan (Iqbal et al., 2003). Allelochemicals such as alkaloids and simple phenolics were found in decaying buckwheat plant tissue. However, it was not determined whether weed growth inhibition was related to the production of allelopathic compounds released by buckwheat residues or to the reduction of light, moisture, or nutrients at the soil surface. Buckwheat grown in dryland conditions in Montana will not produce comparable biomass to these temperate-

region studies, however buckwheat has other benefits, including a high capacity to take up phosphorus (P) from calcium-bound sources inherent to NGP soils (Zhu et al., 2002).

Although P is a macronutrient in terms of plant demand, it is one of the least available nutrients in soils (Barber et al., 1963). In one pot-experiment, total P uptake by buckwheat plants from rock phosphate with nitrate as the only N source was 10-fold higher than that by spring wheat (Zhu et al., 2002). In response to P deficiency, buckwheat absorbs cations which result in a locally acidic rhizosphere just behind the root tip (Haynes, 1992) Calcareous soils inherent to many organic systems in the NGP may benefit from buckwheat release of rock-bound P. However, its warm-season nature may be susceptible to spring frost damage in northern climates (personal observation).

Project Justification and Objectives

Anecdotally speaking, I have observed organic farmers to be very interested in aligning with the principles of sustainable agriculture. Despite this enthusiasm, organic research represents a small proportion of the agricultural literature. Many organic growers rely heavily on personal experience to successfully manage their crops. However, as the astonishing growth trend in this sector continues, inevitably new farmers will make the conversion to organic. These farmers may require new knowledge and tools to be competitive in a constantly changing climate. By researching organic agriculture scientifically, organic farmers can rely on repeatable recommendations while focusing on what they do best, growing food.

There is still a long way to go in the pursuit of a more sustainable system of agriculture, and the development of appropriate scientific research programs will be critical to this aim. Although the focus of scientific research is often necessarily small in scale, the collaborative efforts and communication of members of the scientific community make the achievement of broad goals possible. By using sustainability as a general direction, as opposed to a clearly defined objective, farmers, researchers and policy makers can make reasonable improvements on a local or on-farm basis. Continuing to focus efforts locally may eventually reverse the unsustainable agricultural practices and collectively benefit humanity.

With change towards greater sustainability as the goal, there are three overlapping levels of progress. In a gradient from 'low sustainability' to 'high sustainability', progress can be characterized as going from *efficiency* changes, to *substitution* changes and last to *redesign* changes (MacRae et al., 1990). Using this framework as a guide, the goal of this research, which focuses on organic dryland cereal cropping systems of the NGP, is to generate management tools that will move our agricultural practices towards sustainability. The objectives of this study were to compare the efficacy of winter and spring pea as green manure with fallow; and more specifically, to measure the effects of pea green manure termination timing and method for soil water use and soil N contribution. Locally, these project findings will provide applicable information for organic growers in regard to the effects of different green manure management strategies.

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CHAPTER 2

EFFECTS OF GREEN MANURE GROWTH HABIT AND HARVEST TIMING ON NITROGEN CONTRIBUTION AND SOIL WATER USE

Introduction

Dryland organic production is increasing steadily throughout the NGP (USDA, 2001) and maintaining soil fertility is one of the major challenges facing organic farmers (R. Quinn, personal correspondence, 2004). Nitrogen (N) and phosphorus (P) are the two most important nutrients that limit yield and affect crop quality (Campbell et al., 2005). Organic matter levels in the soils of Montana are low in comparison to sub-humid regions to the east. Hence, soil reserves of N rapidly become depleted if not fertilized. Although animal manures can be an excellent organic fertilizer source for N (and P), cropland in the NGP is generally too remote and extensive to enable reliance on animal manures.

Nitrogen fertility in organic systems of this region is most often achieved through inclusion of leguminous green manures, often sweet clover (*Melilotus officinalis* L.) or alfalfa (*Medicago sativa* L.). One predicament with this approach is that biennial and perennial legumes that maximize N fixation also maximize soil water use (Nielsen et al., 2005). This is particularly important in the NGP where yield is typically constrained by water availability. Similarly, green manure intercrops also use soil water required for crop production, and thus not well-suited for semiarid regions. Based on findings on the semiarid Canadian prairies, annual legume species such as pea (*Pisum sativum* L.) may

provide a better trade-off between N_2 fixation and water use than biennial or perennial LGMs (Biederbeck et al. 1993; Zentner et al. 2004). Further, winter-seeded varieties of pea may better optimize N_2 fixation with soil water use than spring-seeded LGMs due to early spring growth habit (Chen et al., 2006).

It is often assumed that as a legume matures, increasing amounts of N will be available for subsequent crops. In a study by Pikul et al. (1997), researchers terminated lentil growth shortly after pods were set in the lower portion of the plant, which averaged an additional 101 kg ha^{-1} N in lentil phytomass than when terminated at full bloom. However, despite the increases in shoot N, differences in soil NO_3-N were not apparent at spring wheat seeding. As a LGM matures, the carbon to nitrogen (C:N) ratio increases, also potentially slowing decomposition. Because of the large size and dynamic nature of the soil organic N pool, N added or removed LGM crops can be difficult to quantify. A labeled ^{15}N study in a subhumid Danish agroecoregion demonstrated that after pea is terminated with tillage, mineralization of N occurs within 3 mo (Jensen, 1994). Therefore, subsequent fall crop seeding (i.e. winter wheat, *Triticum aestivum* L.) may best coincide with early-terminated LGMs, providing a longer period to decompose.

In addition to meeting crop nutrient demands, dryland organic farmers in the semiarid NGP must choose LGM crops that do not excessively use soil water required for subsequent crops. Studies in summerfallow cropping systems of the NGP report depressed cereal yields following LGM because the legume reduced available spring soil water thereby putting the subsequent cereal crop at a disadvantage in comparison to bare fallow (Zentner et al., 1996; Brandt, 1999). To reduce water use by LGM crops, one

approach is to grow an LGM early in the summer fallow period and terminate the crop prior to maturity (Pikul et al., 1997). A long-term economic assessment of green fallow at Swift Current, Saskatchewan estimated the optimal plant termination stage as bud or prior to full-bloom (Zentner et al., 2004). Based on green-fallow research, an important consideration for organic growers in the NGP is to choose early-maturing green manures that can be terminated early to conserve soil water, even if it may forego some N_2 fixation. Differences in green manure species, growth habit, and harvest timing will likely result in variable soil N contribution and water use, two aspects that must be balanced to sustain organic farm viability. The objectives of this study were to compare the relative efficacy of spring and winter pea as organic green manures with bare fallow. To do so, we measured the relative importance of N fixation (legume vs. non-legume) in providing nutrients for subsequent crops and the effect of green manure growth habit (spring vs. winter pea), and termination timing (bloom vs. pod) on soil water use and N contribution.

Materials and Methods

Field Site Description

The dryland field site at Big Sandy selected for this study is located in north central Montana, the primary wheat growing region in the state. Big Sandy lies within Agroecoregion 12, climatically drier than adjoining regions to the north and east (Padbury et al., 2002). For 16 yr prior to initiation of this research, the field site was managed according to international organic certification standards and used a crop

rotation of various annual crops grown for grain, annual legume green fallow, or alfalfa harvested for forage one year and terminated as green fallow the following year. Site characteristics for this 2-yr study are summarized in Table 2.1. Monthly growing season precipitation (Table 2.2) was collected using an on-site 3 x 30 cm manual rain gauge. Over-winter precipitation and average monthly maximum temperatures (Table 2.3) were obtained from the nearest meteorological station located 19 km from the farm. Missing temperature data were supplemented with results from the MSU-Northern Agricultural Research Center near Havre, located approximately 70 km from the farm. Annual rainfall totals were similar to the 30-yr average but the monthly distribution in 2005 was quite different, with June rainfall accounting for 52% of the annual total.

Experimental Design

The experimental design was a randomized complete block, with a split-plot treatment arrangement and four replications (Appendix figures A.1 and A.2). The main plot factor was green manure species and subplot treatment factors were green manure termination timings. Plot size was 9.7 x 18.2 m in 2005 and 10.9 x 27.4 m in 2006. Subplot size was 4.9 x 18.2 m in 2005 and 5.5 x 27.4 m in 2006. The green manure species were winter pea (cv. *Melrose*), yellow mustard (*Sinapis alba* L. cv. *AC Base*), spring pea (cv. *Arvika*), and buckwheat (*Fagopyrum esculentum* L. cv. *Mancan*). A tilled bare fallow control (4.9 or 5.5 x 18.2 m) was randomized within each block. Termination timings occurred at bloom (at least half of plants with one open floret) or at pod (at least half of plants with one full length pod) for winter and spring pea. Two non-legume green manures, mustard and buckwheat, were chosen as crop controls. Yellow mustard

flowering corresponded to winter pea, and therefore, both were terminated on the same date. Similarly, buckwheat termination dates coincided with spring pea. Pod stage for winter pea and mustard coincided with the flower stage for spring pea and buckwheat, and therefore all these treatments were terminated on the same day both years. Agronomic factors such as plant cultivars, seeding rates, and dates are summarized in Table 2.4.

A winter wheat test crop was planted perpendicularly to green manure plots on 6 Sep 2005 and 28 Sep 2006. Although this study did not include subsequent crop management, unpublished data from 2006 are included in the discussion, and thus follows a brief summary of methods. The winter wheat test crop was used to determine the cropping sequence effect (i.e.; LGM) on grain yield, grain protein concentration, and grain N yield of a subsequent crop. At seeding, all possible combinations of one genetic and two agronomic factors (2 x 2 x 2 full factorial) were included in the management of the winter wheat. For the genetic factor, two contrasting cultivars were used: Norstar and Pryor. Norstar is a very winter-hardy cultivar developed in Alberta, Canada in 1977, and is characterized by maximum winter dormancy, long straw, and limited yield potential, that was expected to compete well with weeds. Pryor is a modern (2003), semi-dwarf wheat well adapted to traditional winter wheat regions in Montana, and has a high yield potential, but was not expected to compete strongly with weeds due to its short stature. Agronomic factors included row spacing (0.15 m and 0.30 m) and seeding rate (200 seeds m^{-2} and 400 seeds m^{-2}).

Field Operations

For the 2005 trial, seeding was accomplished using a 2.4-m John Deere hoe drill with 0.18-m row spacing. For the 2006 trial, a 1.8-m Fabro no-till plot-scale disc seeder using 0.15-m row spacing was used. Winter pea was seeded directly into standing kamut (*Triticum turgidum* L.) stubble in both years, whereas spring pea, mustard, and buckwheat were sown into tilled kamut stubble. In 2005, a high-speed 3-pt hitch mounted rotary tiller was used to terminate the green manures, while in 2006 a 4-m heavy duty tandem disk was used. Fallow plots were rotary tilled three times to coincide with each green manure termination stage in 2005, and disked twice in 2006 coinciding with spring pea pod termination and on 18 July, when all plots were cultivated. In 2006, buckwheat was frost-killed and so was omitted from 2006 analyses. Table 2.5 further illustrates the green manure termination schedule and subsequent tillage operations at Big Sandy for the 2005 and 2006 growing seasons.

Data Collection

Soil cores were taken from each plot at fall or spring seeding, immediately prior to green manure termination, and in all plots at the end of the fallow period (i.e., just prior to seeding winter wheat for a subsequent related study). The tilled fallow control was sampled at all dates to provide a baseline chronosequence of soil water and N status throughout the green fallow phase. Soil cores (diameter 30.3 mm) were extracted to a depth of 1.2 m and split into four 0.3-m increments. Two cores were taken per plot at each sampling date, duplicates for each depth composited in plastic-lined paper sample bags or in plastic freezer bags, and placed in storage coolers for transport from the field

to the laboratory. At the laboratory, bags were weighed 'wet', opened, and placed upright in a drying oven. When the drying oven was not available, bags were placed in a freezer (-20 °C) after obtaining wet weights, and 'dry' weights were obtained at a later date. Gravimetric water content was determined by taking a subsample from each of the 0 to 0.3-m and 0.3 to 0.6-m increments, and the entire core sample from the 0.6 to 0.9-m and 0.9 to 1.2-m increments, and weighing before and after drying in an oven for at least 72 h at 105 ºC. The remaining subsamples from the 0 to 0.3-m and 0.3 to 0.6-m increments were dried at 50 ºC, ground to pass a 2-mm sieve, and analyzed for NO_3-N using the cadmium reduction method (Huffman and Barbarick, 1981). Bulk density values for the sampling depths were determined by dividing the oven-dried soil mass values by volumes of soil cores. Site bulk densities by depth were determined by averaging values for all blocks. Volumetric water content (cm water^3 cm oven-dry soil^{-3}) was determined by multiplying the mass water content obtained by oven drying (g water g oven-dry soil^{-1}) by the ratio of bulk density (g oven-dry soil cm bulk soil^{-3}) over water density (g water cm water^{-3}). The product of volumetric water content and the corresponding soil depth (cm) of water per unit area (cm water^3 cm soil^{-2}) was cm soil water. Soil NO_3-N (kg ha^{-1}) was determined similarly, also using the bulk density.

Shoot biomass samples were collected prior to each green manure termination by removing a representative 2-m^2 sample by hand with a sickle. Weed and green manure biomass were separated and dried at 50 ºC before weighing to determine crop and weed biomass per unit area. After weighing, weed and green manure biomass were recombined, milled, and analyzed for total N using a LECO CNS combustion analyzer

(LECO Corporation, St. Joseph, MO) to estimate the amount of shoot biomass N returned to plots. Root biomass was not measured owing to the difficulty and expense involved.

Statistical Analyses

Analysis of variance (ANOVA) was performed to examine treatment differences using JMP statistical software (SAS Institute, 2005). Treatment means were evaluated using the Protected LSD test (Steel and Torrie, 1980). Blocks (replicates) were considered a random effect while green manure variety and termination timing were considered fixed. Buckwheat was removed from the experimental design in 2006 due to heavy frost damage, so years were analyzed independently. Analyses used block x crop interaction, when significant ($P < 0.10$), to test 'crop' effect, otherwise residual error was used to test significance among crop and termination timing effects. For soil water and N analyses, tilled bare fallow treatments were used to calculate 'marginal' values by subtracting soil water and N values under tilled fallow from green manure treatments on the same dates. Thus, bare fallow treatments were not included directly in green manure analyses. Pre-planned orthogonal contrasts were used to test pea management effects. Effects were indicated as significant at $P \leq 0.10$ unless otherwise noted.

Results and Discussion

Green Manure Productivity

Averaged over the 2-yr study, total biomass treatment variance was best accounted for by crop (76%), and then by harvest timing (14%). In both site-years, pea had the greatest biomass yield ($P < 0.01$, Appendix Table A.3). Spring pea biomass

averaged approximately 88% of winter pea, while mustard averaged only 28% of winter pea during the 2-yr study (Table 2.6). Pea averaged four times greater shoot N yield than mustard (69 and 16 kg ha^{-1}, data not shown). The greater pea biomass and shoot N production at corresponding termination stages (bloom and pod) highlights a growth advantage to N-fixing legumes in this N-constrained environment. 'Weed' biomass was most affected by crop type (74% of total variance) and specifically the fall versus spring seeded contrast (29%); with winter-seeded pea plots containing the least weed biomass ($P < 0.01$, Appendix Table A.3). This result echoes earlier studies in conventional no-till systems of the NGP, where it has been shown that fall-planted winter pea competes sufficiently well without herbicide (Sooby et al., 1997). Relative proportions of weed to total biomass averaged at bloom were: 47% in buckwheat plots (2005 only), 35% of mustard, 23% of spring pea, and 8% of winter pea. Weed relative abundance ranged from 8-25% greater in 2006 due to an infestation of Russian thistle (*Salsola pestifer* Nels.), with the greatest increases in weed density occurring in mustard ($P < 0.1$, data not shown).

Winter pea produced greater shoot biomass at pod (3.4 Mg ha^{-1}) than spring pea (2.8 Mg ha^{-1}) in 2005, but did not differ in 2006 (Table 2.6). Biomass N yield at the pod stage did not differ between spring and winter pea in 2005, but was 25 kg ha^{-1} less for spring pea in 2006. Biomass C:N ratios were narrowest for bloom-terminated spring pea (13:1) in 2005, and bloom-terminated winter pea (17:1) in 2006. Compared to the 30-yr average, 116 mm greater precipitation (287% of average) fell in June 2005 (Table 2.2). Pea has been shown to have a greater growth response to in-season precipitation than

other annual legumes (Biederbeck et al., 1993), and it is likely that the considerable June precipitation was better timed for winter pea growth response. In addition, the 2005 site was inaccessible for a 2-wk period due to wet soil conditions which made 'bloom' termination 15 d later (16 June) than in 2006 (1 June) and 'pod' termination 10 d later (1 July in 2005; 21 June 2006). The combination of timely precipitation and delayed harvest dates accounted for the differences in winter and spring pea shoot biomass at pod observed in 2005. The precipitation pattern was closer to the 30-yr average in 2006.

Shoot biomass N was greater ($P < 0.1$) in pod-terminated winter pea in 2006 (91 vs. 66 kg ha^{-1} for spring pea), indicating superior N fixation for winter pea. Different biomass N accumulation patterns were likely a result of varying soil water conditions. Superior N fixation in winter versus spring pea has been observed previously in the NGP, evidenced by increased grain or forage N (P.R. Miller, personal communication, 2007). Soil water conditions in 2006 were less favorable for spring pea N_2 fixation, as rainfall was scarce between bloom (21 June) and pod (10 July) termination stages. Therefore, spring pea N fixation, and ultimately shoot N, was probably limited by water in 2006. During the two crop cycles of this study, bloom-terminated pea averaged approximately 66% of biomass and 77% of N yield when compared to the pod stage. In general, shoot C:N ratios widened between bloom and pod for the spring crops, while winter pea retained a low C:N at pod. The significant interaction between crop type and termination timing (C x T) (Appendix Table A.3) indicated that the combination of early maturing crops (C) and early termination (T) resulted in the lowest C:N ratio (Table 2.6). Because growing season precipitation was closer to the 30-yr average (149 mm from 1 May to 31

July; 30-yr average =162mm, Table 2.2), green manure productivity in 2006 was likely more typical than in 2005. Therefore, winter pea was a superior green manure in terms of biomass N production.

Green Manure Effects on Soil Nitrogen

Initial soil N differed between years with twice the NO_3-N available at winter pea seeding in the first year (27 and 14 kg NO_3-N ha^{-1}; Table 2.1), but both sites could be considered low. Under tilled fallow, soil N followed roughly the same pattern in both years (Table 2.7). In general, NO_3-N was higher at the end of the green fallow period than the preceding fall. Unusually high (178 mm) precipitation occurred in June 2005 (Table 2.2). Between 16 June (bloom winter pea) and 22 Aug (the end of the green fallow period), bare fallow gained 20 kg ha^{-1} soil NO_3-N in 2005 (Table 2.8) suggesting soil water was sufficient to mineralize soil organic matter over the same period. Conversely, soil N did not differ 2006 when growing season precipitation was less than the 30 yr average.

Bloom green manure termination was accomplished on 16 June, 2005, 10-d after first bloom due to very wet soil conditions. A rotary-tiller was used to terminate green manures, and the viney growth habit of pea, combined with wet conditions, impeded plow-down. Wet soil clogged winter pea between tiller blades and tractor tire treads. Because some pea biomass was thereby removed, the total shoot N incorporated in plots was decreased by an unknown amount, but certainly less than half. Green manure biomass removed during termination was returned by hand to plots, but the large plot size

made even distribution problematic. Photographs illustrating these potentially confounding occurrences are presented in the appendix (Figures A.4 and A.5).

Between bloom termination and the end of the green fallow period, soil NO_3-N under winter and spring pea increased in 2006 (47, 30 kg NO_3-N ha^{-1}). In 2005, incorporated green manures provided lesser of a soil NO_3-N advantage over bare tilled fallow (16, 16 kg NO_3-N ha^{-1}; Tables 2.8 and 2.9). Mustard breakdown augmented soil-NO_3-N in 2006 only. The greatest increases in NO_3-N occurred within the 0-0.3 m soil layer, the area of the soil profile most affected by green manure plow-down. Winter pea terminated at bloom surpassed bare fallow at the end of the green fallow period in 2006, but it did not differ from most other green manures (Table 2.9). This observation indicates that decomposing green manures contributed to the soil N pool in 2006. Air temperatures during the green fallow period were approximately 2 ºC warmer in 2006, which likely correlated with higher soil temperatures that promote mineralization of green manures (Table 2.3). In 2005, the abundant organic matter, above-normal growing season precipitation, and finer textured soils created conditions favorable for N mineralization in all treatments, including tilled fallow. These factors, in addition to biomass removal during plow-down, combined to limit the apparent soil N benefit from green manuring in 2005.

Additional N_2 is fixed by allowing LGM crops to mature later in the green fallow period, however, subsequent fall-sown crops have been shown to recover a lesser percentage of plant-derived N when termination is delayed (Jensen, 1994). Therefore, we hypothesized that soil NO_3-N at the end of the green fallow period would be greatest for

early terminated legume green manures, based on a narrower C:N ratio and a longer period for biomass decomposition. Soil tests taken at the end of the green fallow period, partially confirmed this hypothesis. In 2005, soil N contribution was lower under pod-terminated green manures at the end of the green fallow period with the exception of spring pea (Table 2.9). Differences among treatments were only apparent in the top 0-0.3 m of the soil profile. Soil N contribution did not differ between bloom and pod in 2006. As expected, pea contributed more to the soil-N pool as compared to non-legumes in 2005 (41% of within crop variance) (Appendix Table A.8). However, mustard NO_3-N did not differ from pea in 2006 partly due to a very high LSD value (Table 2.9). Minimal biomass N was present in mustard (10 kg ha^{-1}; Table 2.6), so it is probable that mustard behaved similarly to bare fallow.

Pod-terminated pea began decomposing 2 + weeks later than bloom-pea, and therefore the snapshot of soil NO_3-N taken at the end of the green fallow period did not fully account for N fixation potential. Superior N fixation by LGM crops sustains crop yields over the long-term, and is an important consideration in choosing when to terminate green manure growth. Nitrogen fixation potential can be estimated as the sum of N uptake (N shoot and root biomass N) and marginal soil N (soil N_{Final} – soil $N_{Initial}$). For example, bloom-winter pea had equal or greater soil N present at the end of the green fallow period, but pod-winter pea fixed twice the N (120 – 19 = 100, 77 – 26 = 51 kg ha^{-1}; data not shown). Possible errors in this estimation of N fixation include different mineralization and or N loss rates between green manure and tilled fallow (control), root biomass N factor (factor estimated), and unmeasured soil N below 0.6 m deep. If this

estimation of N fixation is adequate, organic producers in nutrient-constrained systems should terminate annual green manures at pod to maximize N fertility in the long-term.

Green Manure Effects on Soil Water

Patterns in soil water content under tilled fallow differed between years. In 2005, soil water content under tilled fallow did not differ between the three sequential green manure termination stages (winter pea bloom, pod, and spring pea pod; Table 2.10). Green manure soil water content at termination was similar to tilled fallow, with the exception of pod spring pea in 2005 (Table 2.11). June precipitation was abnormally high in 2005 (178 mm in 2005, 76 mm in 2006, long term average 62 mm), and well timed for spring pea usage (Table 2.2). Bloom winter pea terminated on 16 June did not fully use this moisture, most of which accumulated after winter pea commenced flowering. At the end of the green fallow period (approximately 3-mo after termination), crop type did not affect marginal soil water content in 2005 (Table 2.12). In 2006, when conditions were drier, soil water content under tilled fallow was greater (57, 73 mm) at the pod winter pea stage (21 June) than other termination stages (Table 2.10). Termination date was closer to the experimental protocol in 2006, and fewer tillage operations followed green manure termination (Table 2.4). By the end of the green fallow period in 2006, differences in soil water content between green manures were still evident. Bloom-terminated pea and mustard managed soil water similarly to tilled fallow, while pod-terminated pea treatments used more water than fallow (Table 2.12). Although bloom-terminated pea and mustard had similar soil water content at crop termination, mustard had minimal biomass (0.4 Mg ha^{-1}, Table 2.6) and therefore was an ineffective

green manure. Winter pea terminated at bloom used less water than most green manure treatments in both years, especially in the 0.6 – 1.2 m depth. The shallow rooting depth of pea has been shown to conserve soil water for subsequent crops in previous studies in the NGP (Miller et al., 2002; Miller et al., 2003; Miller and Holmes, 2005).

Although winter and spring pea are the same species, the fall seeding date drastically affected the way each variety used soil water, especially in the first year of our study (i.e., in 2005, accounted for 96% of within crop variance; Appendix Table A.10). Pea planting date effect on marginal soil water was smaller in 2006 (16% of within crop variance). At crop termination that year, bloom-winter pea had 33 mm greater soil water than bloom-spring pea (Table 2.11). By the end of green fallow, bloom-terminated peas did not differ, but pod-terminated winter pea had greater (25 mm) soil water content than pod-spring pea (Table 2.12). The interval between bloom and pod stage termination in 2006 was 19 d for both winter and spring pea. In this 19-d period, spring pea used 97 mm compared with winter pea using 6 mm net soil water to grow from bloom to pod (data not shown). Because spring pea did not reach pod until 10 July, higher midsummer temperatures (maximum average daily temperature = 31 °C in July, over the 84-yr of climate data collection, Western Regional Climate Center) likely resulted in greater evapotranspiration, hence increased soil water usage by spring pea to meet climatic demands. Spring pea reached the pod stage in mid-July in both years, forcing growth during this period of high evapotranspirative demand.

Winter pea showed excellent promise based on relative N contribution and water use parameters, and thus it should not be surprising that preliminary wheat recrop data

indicated the winter pea – winter wheat cropping sequence resulted in the greatest yield and grain quality (unpublished data). Winter pea terminated at bloom equaled the tilled fallow in the following test parameters: grain yield (Mg ha^{-1}), test weight (kg m^{-3}), seed weight (mg $seed^{-1}$); and exceeded tilled fallow for grain N yield by 5 kg ha^{-1} ($P < 0.10$, data not shown). Grain N yield is the single most important parameter in this study because it integrates both grain yield and grain protein into one value that reflects crop N uptake from the soil.

Winter pea green manure terminated at the pod stage represented the second most valuable green manure treatment, equaling the tilled fallow control in two winter wheat parameters, test and seed weight, and exceeding the tilled fallow control for grain protein concentration by 15 g kg^{-1} ($P < 0.01$, data not shown). This indicates that meaningful N cycling occurred from winter pea, despite the contribution of green manure N being lower during the green fallow period in 2005. Relevant differences did not occur among spring pea and mustard. Despite the ability of spring pea to fix atmospheric N_2, minimal mustard biomass did not use as much water and NO_3-N as spring pea. In addition, soil NO_3-N (Table 2.9) and water content (Table 2.12) at the end of the green fallow period were similar under mustard and spring pea, leading to a prediction of no difference in the subsequent wheat crop.

Although winter pea terminated at bloom was the best yielding annual green manure in this study, it is noteworthy that none of the annual legumes supplied sufficient N to the subsequent winter wheat crop. This is evidenced by poor protein values (8-10%) in the 2006 winter wheat test crop. Part of the justification of this research was to

determine how soil N contribution and water use differed between annual and 'standard' (biennial or perennial) green manures. Unfortunately, our inability to establish sweet clover limited the management decisions that can be based on this research. It will be interesting to see whether the additional soil NO_3-N supplied by green manures in 2006 results in greater grain protein in the 2007 winter wheat recrop. Because 2006 was a more 'typical' green fallow year, perhaps this will facilitate a more definitive conclusion about the performance of annual green manures.

Conclusions

Winter-seeded pea used as a green manure best achieved the goals of organic dryland growers in conserving greater soil water while contributing greater soil N relative to other green manures. The optimal termination timing for winter pea was first bloom based on the measurable soil N and water use parameters in this 2-yr study. However, over longer-periods, pod-terminated pea may enhance soil N fertility due to superior N fixation potential. The occurrence of spring precipitation followed by hot dry summers characteristic of the NGP highlighted the ability of early-terminated manures such as winter pea to conserve soil water required for subsequent crops. Preliminary test crop data confirmed the results of this study, lending further promise to the winter pea.

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Tables: Big Sandy

Table 2.1. General site and soil characteristics at Big Sandy, MT, 2004-2006.

Location	48° 9’ N, 110° 4’ W
Elevation (m)	834
Soil classification (USDA Soil Survey)	Degrand loam (2005) Telstad-Joplin loam (2006)
Soil texture (USDA Soil Survey)	Sandy loam (2005) loamy sand (2006)
Soil organic matter	1.9-2.3%
Soil pH	7.9 - 8.2
Initial soil NO_3-N (kg ha^{-1} to 0.6 m depth)	27 (Sep 2004) 14 (Sep 2005)
Crop stubble	kamut

Table 2.2. Precipitation at Big Sandy, MT, 2005-2006.

	2005	2006	*LTA*‡
	---------- mm ----------		
Sep-Apr†	116	119	*135*
May	18	53	*59*
June	178	76	*62*
July	8	20	*41*
Aug	22	33	*33*
Crop Year	342	301	*330*

† Over-winter precipitation preceding the growing season.
‡ LTA = long-term average at Big Sandy, 1971-2000 average annual precipitation as reported by Western Regional Climate Center, Desert Research Institute, Reno, NV.

Table 2.3. Average maximum air temperature at Big Sandy, MT, 2005-2006.

	2005	2006	*LTA*‡
	---------- Temperature °C ----------		
Sep-Apr†	10	10	*9*
May	20	22	*21*
June	24	26	*26*
July	32	34	*30*
Aug	29	30	*30*
Crop Year	15	16	*15*

† Over-winter air temperature averages preceding the growing season.
‡ LTA = long-term average at Big Sandy, 1971-2000 average annual air temperature as reported by Western Regional Climate Center, Desert Research Institute, Reno, NV.

Table 2.4 Agronomic factors for green manure study at Big Sandy, MT. 2004-2006.

Green Manures	Cultivars
Winter pea†	*Melrose*
Mustard†	*AC Base*
Spring Pea	*Arvika*
Buckwheat	*Mancan*
Seeding Dates	
Winter pea	15 Sep 2004, 6 Sep 2005
All spring crops	21 Apr 2005, 12 Apr 2006
Seeding Rates	-------- target seeds m^{-2} ------
Winter pea	120
Mustard	200
Spring Pea	120
Buckwheat	200

† *Nitragin Soil Implant* granular inoculant (Milwaukee, WI), strain ‘C’ was used to provide rhizobia for pea.

Table 2.5. Green manure termination schedule and subsequent tillage operations for Big Sandy, MT. 2005-2006.

Green manure	Timing	2005			2006		
Winter pea	Bloom	*16*	*June*	Rotary tiller	*1*	*June*	Tandem disk
		1	July	Rotary tiller	10	July	Chisel plough
		12	July	Rotary tiller	18	July	Tandem disk
		5	Aug	Tandem disk	4	Sept	Tandem disk, cultivator#
		25	Aug	Tandem disk†			
	Pod	*1*	*July*	Rotary tiller	*20*	*June*	Tandem disk§
		12	July	Rotary tiller	18	July	Tandem disk
		5	Aug	Tandem disk	4	Sept	Tandem disk, cultivator#
		25	Aug	Tandem disk†			
Mustard	Bloom	21	Apr	Rotary tiller ¶	12	Apr	Tandem disk, cultivator#
		16	*June*	Rotary tiller	*1*	*June*	Tandem disk
		1	July	Rotary tiller	10	July	Chisel plough
		12	July	Rotary tiller	18	July	Tandem disk
		5	Aug	Tandem disk	4	Sept	Tandem disk, cultivator#
		25	Aug	Tandem disk†			
	Pod	21	Apr	Rotary tiller ¶	12	Apr	Tandem disk, cultivator#
		1	*July*	Rotary tiller	*20*	*June*	Tandem disk
		12	July	Rotary tiller	18	July	Tandem disk
		5	Aug	Tandem disk	4	Sept	Tandem disk, cultivator#
		25	Aug	Tandem disk†			
Spring pea	Bloom	21	Apr	Rotary tiller ¶	12	Apr	Tandem disk, cultivator#
		1	*July*	Rotary tiller	*20*	*June*	Tandem disk
		12	July	Rotary tiller	18	July	Tandem disk
		5	Aug	Tandem disk	4	Sept	Tandem disk, cultivator#
		25	Aug	Tandem disk†			
	Pod	21	Apr	Rotary tiller ¶	12	Apr	Tandem disk, cultivator#
		12	*July*	Rotary tiller	*10*	*July*	Tandem disk
		5	Aug	Tandem disk	18	July	Tandem disk
		25	Aug	Tandem disk†	4	Sept	Tandem disk, cultivator#
Buckwheat‡	Bloom	21	Apr	Rotary tiller ¶	12	Apr	Tandem disk, cultivator#
		1	*July*	Rotary tiller	*10*	*July*	Tandem disk
		5	Aug	Tandem disk	18	July	Tandem disk
		25	Aug	Tandem disk†	4	Sept	Tandem disk, cultivator#
	Pod	21	Apr	Rotary tiller ¶	N		NA
		12	*July*	Rotary tiller	A		
		5	Aug	Tandem disk			
		25	Aug	Tandem disk†			
Fallow		21	Apr	Rotary tiller ¶	12	Apr	Tandem disk, cultivator#
		16	June	Rotary tiller	10	July	Tandem disk
		1	July	Rotary tiller	18	July	Tandem disk
		12	July	Rotary tiller	4	Sept	Tandem disk, cultivator#
		5	Aug	Tandem disk			
		25	Aug	Tandem disk†			

Italicized dates indicate green manure initial termination date

† Tillage performed on 25 Aug 2005 and 4 Sept 2006 was perpendicular to plots with a tandem disk

‡ Buckwheat plots omitted from 2006 analysis due to frost kill.

§ Winter pea –pod plots terminated 10 July 2006 were disked twice

¶ Tillage performed on 21 Apr 2005 was perpendicular to plots with a rotary tiller

Cultivator equipped with spring tine harrows

Table 2.6. Means for green manure biomass, weed biomass, and green manure total N content and C:N ratio at Big Sandy, MT, 2005-2006.

Green manure and harvest timing		Biomass yield weight	Weed yield weight	Biomass N yield	Biomass C:N ratio
		-------- Mg ha^{-1} --------		kg ha^{-1}	
		2005			
Winter pea	Bloom	2.5	0.1	64	17
Mustard	Bloom	0.9	0.1	19	19
Spring pea	Bloom	2.1	0.5	71	13
Buckwheat †	Bloom	0.5	0.4	17	11
Winter pea	Pod	3.4	0.1	83	18
Mustard	Pod	0.9	0.2	17	24
Spring pea	Pod	2.8	0.5	71	18
Buckwheat †	Pod	0.9	0.9	27	13
LSD‡		*0.5*	*0.3*	*16*	*4*
		2006			
Winter pea	Bloom	1.9	0.3	58	17
Mustard	Bloom	0.4	0.6	10	19
Spring pea	Bloom	1.9	0.7	47	25
Winter pea	Pod	3.5	0.2	91	19
Mustard	Pod	0.9	0.6	18	28
Spring pea	Pod	3.1	0.5	66	28
LSD		*0.7*	*0.3*	*18*	*NS*

† Buckwheat means were collected in 2005 only

‡ Fisher's Protected LSD ($P < 0.10$) for comparing means within a column.

Table 2.7. Mean soil N in two depth increments and the total soil column in tilled fallow plots on sequential sampling dates at Big Sandy, MT, 2004-2006.

Soil sampling date			0 – 0.3 m	0.3 - 0.6 m	**Total 0.6 m**
2004 -2005			---------- kg NO_3-N ha^{-1} ----------		
9	Sep	2004	16	9	**25**
21	Apr	2005	25	12	**37**
16	June	2005	19	17	**36**
1	July	2005	34	24	**58**
12	July	2005	27	20	**47**
22	Aug	2005	36	20	**56**
		LSD†	*7*	*4*	***11***
2005 - 2006					
2	Sep	2005	9	6	**15**
12	Apr	2006	11	9	**20**
2	June	2006	18	10	**28**
21	June	2006	12	11	**23**
10	July	2006	7	7	**14**
27	Sep	2006	21	8	**29**
		LSD†	*3*	*3*	***6***

† Protected least significant difference within a column according to Fisher's Protected LSD ($P < 0.10$).

Table 2.8. Treatment means for marginal† soil NO_3-N content at crop termination in a green manure study at Big Sandy, MT, 2005-2006.

Green manure treatment		---------- soil depth increment ----------		
		0 - 0.3 m	0.3 - 0.6 m	**Total 0.6 m**
		---------- kg NO_3-N ha^{-1} ----------		
		2005		
Winter pea	Bloom	-5	-2	**-7**
Mustard	Bloom	0	-5	**-5**
Spring pea	Bloom	-20	-12	**-32**
Buckwheat	Bloom	-16	-11	**-27**
Winter pea	Pod	-15	-13	**-27**
Mustard	Pod	-16	-7	**-22**
Spring pea	Pod	-18	-10	**-28**
Buckwheat	Pod	-16	-8	**-24**
LSD		*NS*	*NS*	***11***
		2006		
Winter pea	Bloom	-12	-5	**-17**
Mustard	Bloom	-12	-5	**-17**
Spring pea	Bloom	-9	-10	**-19**
Winter pea	Pod	-10	-9	**-19**
Mustard	Pod	-11	-10	**-21**
Spring pea	Pod	-2	-4	**-6**
LSD		*4*	*NS*	***5***

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.

† Protected least significant difference within a column according to Fisher's Protected LSD ($P < 0.10$).

Table 2.9. Treatment means for marginal† soil NO_3-N content at the end of the green fallow period‡ in a green manure study at Big Sandy, MT, 2005-2006.

Green manure treatment		soil depth increment		
		0 - 0.3 m	0.3 - 0.6 m	**Total 0.6 m**
		kg NO_3-N ha^{-1}		
		2005		
Winter pea	Bloom	12	-3	**9**
Mustard	Bloom	-5	-3	**-8**
Spring pea	Bloom	-10	-6	**-16**
Buckwheat	Bloom	-10	-5	**-15**
Winter pea	Pod	0	-6	**-6**
Mustard	Pod	-13	-6	**-20**
Spring pea	Pod	-10	-5	**-14**
Buckwheat	Pod	-18	-8	**-26**
LSD§		*10*	*NS*	***12***
		2006		
Winter pea	Bloom	28	2	**30**
Mustard	Bloom	17	2	**19**
Spring pea	Bloom	10	1	**11**
Winter pea	Pod	18	-2	**15**
Mustard	Pod	8	0	**8**
Spring pea	Pod	-3	-4	**-7**
LSD§		*24*	*NS*	***27***

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.
‡ The end of the green fallow period coincides with winter wheat seeding after one green manure cycle (22 Aug, 2005, 27 Sep 2006)
§ Protected least significant difference within a column according to Fisher's Protected LSD ($P < 0.10$).

Table 2.10. Mean soil water content in four depth increments and the total soil profile in tilled fallow plots on sequential sampling dates at Big Sandy, MT, 2004-2006.

Soil sampling date			0 – 0.3 m	0.3 - 0.6 m	0.6 – 0.9 m	0.9- 1.2 m	**Total 1.2 m**
			---------- mm soil water ----------				
2004 -2005							
9	Sep	2004	39	42	40	44	**166**
21	Apr	2005	69	56	46	45	**216**
16	June	2005	77	78	52	50	**257**
1	July	2005	68	70	66	45	**249**
12	July	2005	63	68	62	44	**237**
22	Aug	2005	54	54	54	48	**210**
		LSD†	*6*	*8*	*7*	*NS*	***23***
2005 - 2006							
2	Sep	2005	40	32	37	56	**164**
12	Apr	2006	78	72	64	54	**268**
2	June	2006	77	75	53	58	**263**
21	June	2006	81	81	79	79	**320**
10	July	2006	46	58	74	68	**247**
27	Sep	2006	70	67	62	64	**265**
		LSD†	*5*	*6*	*10*	*8*	***16***

† Protected least significant difference within a column according to Fisher's Protected LSD ($P < 0.10$).

Table 2.11. Treatment means for marginal† soil water content at crop harvest in a green manure study at Big Sandy, MT, 2005-2006.

Green manure treatment		soil depth increment				
		0 - 0.3 m	0.3 - 0.6 m	0.6 - 0.9 m	0.9 - 1.2 m	**0 - 1.2 m**
		mm of soil water				
		2005				
Winter pea	Bloom	-4	9	19	13	**37**
Mustard	Bloom	-19	-1	-3	-2	**-24**
Spring pea	Bloom	-21	-15	-6	2	**-39**
Buckwheat	Bloom	-8	-1	-7	11	**-5**
Winter pea	Pod	-19	-5	3	17	**-4**
Mustard	Pod	-12	-2	-9	1	**-22**
Spring pea	Pod	-23	-25	-16	0	**-64**
Buckwheat	Pod	-20	-19	-9	-6	**-53**
LSD‡		*NS*	*NS*	*15*	*NS*	***53***
		2006				
Winter pea	Bloom	-15	-9	1	8	**-15**
Mustard	Bloom	-4	-25	15	-2	**-16**
Spring pea	Bloom	-11	-18	-12	-6	**-48**
Winter pea	Pod	-21	-18	-24	-16	**-78**
Mustard	Pod	-5	-9	-10	-16	**-40**
Spring pea	Pod	-11	-22	-26	-16	**-72**
LSD		*7*	*NS*	*23*	*NS*	***16***

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.
‡ Fisher's Protected LSD ($P < 0.10$) for comparing means within a column.

Table 2.12. Treatment means for marginal† soil water content at the end of green fallow period‡ in a green manure study at Big Sandy, MT, 2005-2006.

Green manure treatment		soil depth increment				
		0 - 0.3 m	0.3 - 0.6 m	0.6 - 0.9 m	0.9 - 1.2 m	**0 - 1.2 m**
		mm of soil water				
		2005				
Winter pea	Bloom	0	1	0	2	**3**
Mustard	Bloom	0	-4	-8	-10	**-22**
Spring pea	Bloom	-10	-11	-15	-14	**-50**
Buckwheat	Bloom	-1	-4	2	-4	**-7**
Winter pea	Pod	-13	-14	-1	0	**-28**
Mustard	Pod	-7	-14	-16	-15	**-51**
Spring pea	Pod	-13	-21	-12	-14	**-60**
Buckwheat	Pod	-12	-18	-13	-13	**-56**
LSD§		*5*	*NS*	*NS*	*NS*	***NS***
		2006				
Winter pea	Bloom	2	-6	-4	-4	**-12**
Mustard	Bloom	2	-1	2	-5	**-2**
Spring pea	Bloom	-3	-8	-5	-4	**-19**
Winter pea	Pod	-5	-20	-15	-7	**-47**
Mustard	Pod	-1	-6	-4	-8	**-19**
Spring pea	Pod	-10	-31	-18	-13	**-72**
LSD§		*5*	*7*	*7*	*NS*	***22***

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.
‡ The end of the green fallow period coincides with winter wheat seeding after one green manure cycle (22 Aug, 2005, 27 Sep 2006)
§ Fisher's Protected LSD ($P < 0.10$) for comparing means within a column.

CHAPTER 3

EFFECTS OF TERMINATION METHOD AND HARVEST TIMING ON SOIL WATER USE AND NITROGEN CONTRIBUTION BY PEA GREEN MANURE

Introduction

Successful dryland crop production in the semiarid NGP must make efficient use of growth-limiting precipitation that varies spatially and temporally. In regions where water is generally the yield-limiting factor, research has focused on residue management practices that reduce or eliminate tillage. Tillage is culpable for degrading crop residues, making them less effective for reducing evaporation and leaving the soil vulnerable to wind erosion (Nielsen et al., 2005). There is a direct correlation between precipitation storage efficiency and reduction in tillage intensity. Conventional growers have been able to adopt reduced or no-till practices with the aid of herbicides such as glyphosate to effectively kill weeds and green fallow crops, thus increasing soil water available for subsequent crops. USDA organic Certification regulations prohibit the use of synthetic herbicides, which thereby restricts organic growers to tillage if they choose to terminate green manure growth prior to maturity (Patriquin, 1988; USDA, 2003).

Tillage is used in organic systems for weed control and seedbed preparation (Patriquin, 1988). However, integrated crop management strategies such as diverse crop rotations, competitive crop cultivars, increased crop seed rates, and reduced row spacing may also decrease weed biomass (Blackshaw et al., 2001; Liebman and Staver, 2001).

For organic grain growers to adopt no-till practices, they would have to eliminate tillage during weed control, green manure termination, and seedbed preparation. Although total elimination of tillage may be unrealistic, new strategies such as crimp-rolling and vinegar desiccation have been suggested as possible alternatives to tilling green manure crops (Derpsch, 2003). The elimination of tillage may have multiple benefits in terms of available soil water and N for subsequent grain crops; however, these strategies have not been evaluated in the semiarid NGP.

The crimp-roller was promoted by the Rodale Institute in an attempt to apply no-till principles to organic corn and soybean production (Sayre, 2005) (See Appendix B.1). Their front-mounted crimp- roller was designed for cover crop termination. The 'crimp' blades are welded on to a cylindrical 'drum' in a chevron pattern to avoid bouncing and facilitate steering. They are angled back from the direction of travel to reduce soil disturbance (Frick, 2006). The drum can be filled with water to increase its weight, particularly useful in dry soil. A front-mounted crimp-roller also avoids the difficulty of obtaining good crop-soil contact in compacted tire tracks, and allows seeding equipment to follow the roller in a single pass.

According to Frick (2006), one of the major objections to organic farming is the amount of tractor passes. By using the crimp roller, Rodale was able to reduce several tractor operations for corn by rolling and planting simultaneously in one pass. Because green manures in the NGP must be terminated early in the fallow season to conserve soil water, rolling and seeding cannot be accomplished in one tractor pass.

In preliminary trials at the Rodale Institute, the crimp-roller terminated growth most effectively (90% kill) when cover crops were flowering (preferably 50-75% bloom) (Frick, 2006). This stage also corresponded with the greatest nitrogen benefit from a LGM at the subhumid Pennsylvania farm (Frick, 2006). Crimp-rolled crops create a prostrate layer that may suppress or delay weed germination and reduce evaporation from the soil surface. The technology will require further fine-tuning and region-specific testing, but may reduce water loss associated with tillage of green manures on organic farms in the NGP.

Synthetic herbicides are not permitted by USDA organic regulations (USDA, 2003), but preliminary studies have demonstrated vinegar made from fruits or grains may be effective at killing weeds, which is allowable within the program standards (Radhakrishnan et al., 2002). While anecdotal reports of success with vinegar have been published in the popular press and on the internet, research to substantiate these claims is limited. The most frequently cited greenhouse and field studies from Beltsville, MD indicated that solutions of 10, 15, and 18% acetic acid provided 80-100% control of annual weeds such as giant foxtail (*Setaria faberi* L.), common lambsquarters (*Chenopodium album* Moq.), smooth pigweed (*Amaranthus hybridus* L.), and velvetleaf (*Abutilon theophrasti* Medic.) (Radhakrishnan et al., 2002). Application rates in the USDA-ARS study were not reported, but a subsequent study recommended a spray volume of 562 litres ha^{-1} with 20% (112 kg ha^{-1}) acetic acid (Curran et al., 2005).

Acetic acid terminates plant growth by deteriorating the waxy leaf cuticle, causing plant desiccation (Smith, 2004). Therefore, vinegar efficacy is dependent on coverage.

Some studies suggest adding 2% citrus oil and 1% liquid dish soap as an adjuvant to increase coverage (Guerena and Born, 2007). The most successful weed kill reported by Radhakrishnan et al. (2002) was for newly germinated or rapidly growing (such as after a precipitation event) seedlings, which have a thinner waxy cuticle. If vinegar is demonstrated as successful in weed control and is permitted by USDA organic regulations, replacing non-selective chemical herbicides like glyphosate with vinegar to kill LGM growth could potentially reduce tillage in organic systems.

One possible constraint to using vinegar to terminate green manure growth in the semiarid NGP is cost. In corn-soy production systems that use 20% acetic acid for between-row weed control, ARS researchers estimated a cost of \$161 ha^{-1} (Coffman et al., 2005). This would be cost-prohibitive for dryland organic growers in Montana. Climate-specific research is required for both vinegar and crimp-rolling termination of green manures, both of which may promise alternatives to tillage in organic systems.

Research on alternative green manure termination methods has not indicated how crimp-rolling and vinegar desiccation affect soil N contribution and water use. However, various studies in conventional systems have investigated the use of broad-spectrum herbicides to terminate green manure growth. Termination of a green manure crop by herbicide application, which retains surface residue, may reduce subsequent wheat yield by 22% as compared with termination by tillage (unpublished data, Biederbeck and Slinkard). The observed yield reduction was attributed to higher mineralization from incorporated materials. However, Janzen and McGinn (1991) suggested volatile loss from surface applications as an alternative mechanism. Volatile NH_3 losses (35 mg N

chamber^{-1} d^{-1} representing 3.6% of the N applied) were reported when lentil manures were left to decompose on the soil surface in sealed-chamber labeled ^{15}N experiments (Janzen and McGinn, 1991). Incorporation of LGM material into the top 5 cm of the soil, conversely, prevented volatile loss of NH_3. In another controlled experiment, incorporation of alfalfa residues resulted in more rapid N release from alfalfa residues and a larger short-term supply of plant-available N than where residues were retained on the soil surface (Mohr et al., 1999). If tillage accelerates N release, however, accumulations of excess inorganic N may be prone to leaching or denitrification (Firestone, 1982). Leaching losses of legume-derived N may also occur under dryland conditions in semiarid areas when legume plow down is followed by a fallow period (Campbell et al., 1984; Campbell et al., 1994). Leaching may result during the fallow period if copious net N mineralization coincides with increased soil water percolation. Despite the reported nutrient benefits, however, tillage incorporation of LGM material into the soil greatly reduces its effectiveness as a measure for soil water conservation and erosion control (Janzen and McGinn, 1991).

Nutrient cycling in agroecosystems is also dependent on biological factors such as earthworms. Considered ‘ecosystem engineers’, their burrows may affect green manure mineralization by increasing soil porosity, burying plant litter, and augmenting microbial habitat (Satchell, 1967; Brown, 1995). Additionally, worm castings (egested material) may enhance water retention and bacteria to fungi ratio, which may result in increased mineralization (Satchell, 1967; Swift, 1979). Therefore, organic growers may wish to adopt diversified and reduced tillage systems which have been shown to encourage

greater earthworm populations (Edwards and Lofty, 1982; Parmelee et al., 1990; Nuutinen, 1992; Clapperton et al., 1996; Pulleman et al., 2003).

Reducing tillage contributes part of the solution for increasing agricultural production in precipitation-limited agroecoregions (Nielsen et al., 2005). However, water use-efficiency in organic systems also varies with green manure crop type and termination timing. Organic systems of the NGP often rely on inclusion of leguminous green manures such as sweet clover (*Melilotus officinalis* L.) or alfalfa (*Medicago sativa* L.) for nitrogen (N) fertility. One predicament with this approach is that biennial and perennial legumes that maximize N fixation also maximize soil water use (Nielsen et al., 2005). Therefore, annual green manures, terminated early in the fallow period, have been recommended for soil water conservation (Pikul et al., 1997; Zentner et al., 2004).

We hypothesized that the fall-seeded, annual growth habit of winter pea would contribute sufficient nitrogen, while maximizing soil water conservation for subsequent crops. Based on successes in subhumid regions, we hypothesized that crimp-rolling could reduce tillage associated with green manure plow-down. Relative to tillage, we were uncertain whether crimp-rolling would conserve soil water because efficacy was previously achieved at late bloom (Frick, 2006). In the NGP, soil water conservation under green manure depends on early bloom termination (Zentner et al., 2004). Although the cost-effectiveness of vinegar application is currently questionable, we were interested to see if the concept of a broad-spectrum contact herbicide replacement could be effective in terminating green manure in an organic cropping system. The objectives of this study were to compare the relative water use and nitrogen contribution of annual and biennial

organic green manures with bare fallow. More specifically, we evaluated how alternative green manure termination strategies (crimp-rolling and vinegar), and termination timing (bloom vs. pod) affect soil water use and N contribution as compared to tillage-based termination.

Materials and Methods

Field Site Description

The dryland field site used for this study is located at the MSU Arthur H. Post agricultural experiment station in southwestern Montana (Table 3.1). Climatically, Bozeman is located in a wetter agroecoregion than adjoining agroecoregions due to higher annual precipitation, much of which accumulates as winter snowfall (Table 3.2). Monthly precipitation was collected from a meteorological station located at the experiment station. In 2005, annual precipitation was 54 mm less (364 mm) than the 30-yr average due to limited over winter precipitation, an effect that persisted through May. Annual precipitation in 2006 was similar to the 30-yr average (418 mm). Bozeman sits in a headwater valley (Missouri River), where typical soils consist of loess-deposited silt loams. Prior to the initiation of this research, the field sites had been conventionally managed with (2006) and without (2005) tillage, producing various annual crops. The 2005 site was preceded by an alternating broadleaf-cereal crop rotation which was initiated in 1999. Unfertilized winter (blocks 1 and 2) and spring wheat (blocks 3 and 4) were present in 2004. The 2006 site was preceded by 2 yr of bare fallow, followed by organically grown spring wheat in 2005.

Experimental Design

The experimental design was a randomized complete block with four replications (plot maps are in Appendix Figures B.1 and B.2). Plot size was 4 x 10 m. We aimed to evaluate differences in water use between biennial and annual growth habits, and thus chose sweet clover (yellow blossom, variety not specified) and winter pea (cv. *Melrose*). For the 2005 site, both green manure crops were seeded 1 Sep 2004 directly into standing wheat stubble using a 1.8-m wide no-till plot-scale seeder with 0.15-m row spacing. The sweet clover emerged well in the fall but had low winter survival. For the 2006 site, sweet clover seed was surface-broadcast 6 June 2005 in specified plots within the seedling wheat field to provide more time for sweet clover to establish prior to winter. Emerged sweet clover seedlings died due to drought stress under the competing spring wheat crop, and so failed again in 2006. On 11 Apr 2006, spring pea (cv. *Arvika*) was seeded as a replacement for sweet clover into a tilled seedbed using the same seeder. Thus, differences between annual and biennial green manure growth habits were not evaluated. A tilled bare fallow control was randomized within each block. Details of agronomic factors such as plant cultivars, seeding rates, and dates appear in Table 3.3.

Field Operations

Each block contained the treatments detailed in Table 3.4 plus a bare tilled fallow control. Termination timings occurred at bloom (at least half of plants with one open floret) or at pod (at least half of plants with one full length pod) for winter and spring pea. Tillage termination was accomplished with a 2-m wide tandem disk (2005: 380 mm disks, 2006: 460-mm diam. notched disks). For vinegar treatments, we used 30% (acetic

acid) white grain vinegar from Fleischmann's Vinegar (Cerritos, CA) diluted with tap water to an 10% concentration of acetic acid (93 kg ha^{-1}), so we added 2.5 L of water and 1.3 L of vinegar to a 3.8 L container. The vinegar solution was applied with a backpack sprayer with a 3.7-m boom in 2005. We used an application rate of 514 liters ha^{-1} to ensure adequate coverage (Curran et al., 2005). In 2006, we modified the vinegar solution (total 3.8 L) to include 76 ml (2% by volume) of organic citrus-based solvent and 38 ml L (1%) of organic dish soap. A 1.8-m wide boom was used in 2006. For crimp-rolled treatments, the roller drum was approximately 70% filled with water; enough to add approximately 360 kg of weight to a 527 kg roller (Appendix Figure B.3).

Details of post-treatment tillage operations are illustrated in Table 3.5. Vinegar and crimp-rolled plots were monitored closely to determine efficacy of the treatments. In 2005, we observed both treatments to be ineffective at the bloom stage, so the bloom plots were further subdivided on 26 June (2-wk after termination). In crimp-rolled plots, half of the area was re-treated with the vinegar solution (containing soap and citrus oil adjuvant) at 514 L ha^{-1}. In the vinegar plots, foliage was desiccated except for 10-20 cm of the shoot apex. Thus, these plots were bisected so that one half of the plot was mowed with a sickle mower to sever the shoot apex from the otherwise leafless stem. In 2005, two 1.2 –m soil samples were taken randomly from the subdivided plots, thus that soil data represents an average of both subtreatments. At the pod stage, there were two winter pea plots per block terminated with a crimp-roller. Of the two, the plot with the lesser weed biomass was chosen to remain no-till to minimize weed pressure in the winter wheat test crop. Throughout the summer season, plots were disked or cultivated as

necessary to combat prevalent prickly lettuce weed populations (Table 3.5). Seedbed tillage prior to winter wheat seeding was performed using a field cultivator with 0.17-m wide shovels and a trailing basket roller for soil packing.

Data collection

Soil samples were taken in each plot at fall or spring seeding, immediately prior to green manure termination, and in all plots at the end of the fallow period (i.e., just prior to seeding winter wheat for a subsequent related study). The tilled fallow control was sampled at all dates to provide a comparative chronosequence of soil water and N status throughout the green manure phase. Soil cores (diameter 30.3 mm) were extracted to a depth of 1.2 m and split into four 0.3-m increments. Two cores were taken per plot at each sampling date, composited by depth in plastic-lined paper sample bags or in plastic freezer bags, and placed in storage coolers for transport from the field to the laboratory. At the laboratory, bags were either weighed "wet", opened, and placed upright in a drying oven, or placed in a freezer (-20 °C) until recording wet weights and placing in the drying oven. Gravimetric water content was determined by taking subsamples from the 0 to 0.3-m and 0.3 to 0.6-m increments, and the entire core sample from the 0.6 to 0.9-m and 0.9 to 1.2-m increments, and weighing before and after drying in an oven for at least 72 hr at 105 ºC. The remaining subsamples from the 0 to 0.3-m and 0.3 to 0.6-m increments were dried at 50 ºC, ground, and analyzed for NO_3-N using the cadmium reduction method (Huffman and Barbarick, 1981). Additionally, at winter wheat seeding, two 0 - 0.15-m deep (30.3 mm diameter) cores were taken and composited from all plots at Bozeman. These latter samples were sealed in plastic-lined

bags and kept at 5 °C for approximately four months before processing commenced. The soil samples for ech plot were thoroughly mixed, bisected, and used to indicate potentially mineralizable N (PMN) using a 7-d, 40 ºC waterlogged incubation (Waring and Bremner, 1964) and to measure soil phosphorus (Olsen P) by sodium bicarbonate (Olsen et al., 1954). Bulk density values for the sampling depths were determined by dividing the oven-dried soil mass values by volumes of soil cores. Site bulk densities by depth were determined by averaging values for all blocks. Volumetric water content (cm $water^3$ cm oven-dry $soil^{-3}$) was determined by multiplying the mass water content obtained by oven drying (g water g oven-dry $soil^{-1}$) by the ratio of [bulk density (g oven-dry soil cm bulk $soil^{-3}$) over water density (g water cm $water^{-3}$). The product of volumetric water content and the corresponding soil depth (cm) of water per unit area (cm $water^3$ cm $soil^{-2}$) was cm soil water. Soil NO_3-N (kg ha^{-1}) was determined using bulk density and N concentration of dry soil.

Shoot biomass samples were collected prior to each green manure termination by removing a representative 2-m^2 sample by hand with a sickle. Weed and green manure biomass were separated and dried at 50 ºC before weighing to determine crop and weed biomass per unit area. After weighing, weed and green manure biomass were recombined, milled, and analyzed for total N using a LECO CNS combustion analyzer (LECO Corporation, St. Joseph, MI) to estimate the amount of shoot biomass N returned to plots. Root biomass was not measured because of the difficulty and expense involved.

Statistical Analyses

Analysis of variance (ANOVA) was performed to examine treatment differences using JMP statistical software (SAS Institute, 2005). Treatment means were evaluated using the Protected LSD (Steel and Torrie, 1980). Blocks (replicates) were considered a random effect while green manure treatment was considered fixed. Years were analyzed independently because of changes made to the experimental design in 2006. Randomization was partially restricted because vinegar + mow and crimp-roll + vinegar plots were necessarily adjacent. Analyses used residual error to test significance among green manure treatments. For soil water and N analyses, tilled bare fallow treatments were used to calculate 'marginal' values by subtracting soil water and N values under tilled fallow from green manure treatments on the same dates. Thus, bare fallow treatments were not included directly in green manure analyses. Pre-planned orthogonal contrasts were used to test major green manure treatment effects such as growth habit (winter vs. spring pea), termination timing, and termination method. Effects were indicated as significant at $P \leq 0.10$ unless otherwise noted.

Results and Discussion

Green Manure Productivity

Winter and spring pea biomass were equal at corresponding growth stages (Table 3.6), but pea biomass doubled between the bloom and pod stages ($P < 0.01$). . , Non-crop, or 'weed' biomass was lowest under the winter pea, especially at bloom. Winter and spring pea terminated at the bloom stage averaged 51 and 86% of shoot N yield at the

pod stage, respectively. Shoot C:N ratios in spring pea biomass were narrower at the bloom than the pod stage while winter pea C:N did not differ by termination stage. N uptake in spring pea was 27 kg N ha^{-1} greater at bloom than winter pea ($P \leq 0.1$). However, by pod, winter pea had 23 kg ha^{-1} greater shoot biomass N, indicating superior N fixation (Table 3.6) as observed previously in Bozeman (P.R. Miller, personal communication, 2006).

Green Manure Effects on Soil Nutrients

Spring NO_3-N under tilled fallow was three times greater (60 kg ha^{-1}) in 2005 than in 2006 (21 kg ha^{-1}) (Table 3.7). Spring data may have been affected by site history and over-winter precipitation. The 2005 site year was preceded by 7 yr of no-till management which likely accumulated active fraction soil organic matter (SOM) which could be readily mineralized. The mineralizable N fraction of SOM increases under long-term no-till conditions (Arshad et al., 1990). In contrast, the 2006 site had a multi-decadal tillage history. Green manures were planted into wheat stubble in both years; however, the 2006 site had been fallowed for 2 yr prior to the preceding spring wheat crop grown in 2005. It is likely that the active fraction SOM was highly mineralized by 2005, and therefore the preceding spring wheat crop at the 2006 site removed a large amount of readily available soil NO_3-N in its grain, or that considerable N was lost during the double fallow phase due to leaching or denitrification.

In addition to previous management differences between site-years, precipitation may have influenced mineralization of N in tilled fallow. Although we can not directly measure N losses, NO_3-N leaching may have occurred in 2006. Fall soil N levels in tilled

fallow were similar in both years (25 and 22 kg ha^{-1}); however, they differed greatly in spring (60 and 21 kg ha^{-1}, Table 3.7). Nitrogen is typically mineralized over-winter (Pierzynski et al., 2005); however, no apparent change in soil NO_3-N occurred from 15 Sep to 26 Apr under tilled fallow in 2006. Over-winter precipitation was unusually high (263 mm) in 2006 (Table 3.2) compared to below-average precipitation in 2005 (188 mm), which may indicate the discrepancy was partially a result of NO_3-N losses due to leaching or denitrification out of the upper 0.6-m.

Post-termination soil NO_3-N was considerably lower (by 17-32 kg N ha^{-1}) under pea plots than under tilled fallow in 2005 (Table 3.8). By the end of the green fallow period, soil NO_3-N levels had increased proportionately more under the cropped areas than under fallow. This observation indicates that decomposing green manures contributed to the soil N pool relative to fallow.

Green manure termination method did not affect soil NO_3-N at the end of the green fallow period in 2005 (Table 3.9). However, preliminary winter wheat test crop results indicate biomass-N (which corresponds with grain protein) differed among termination methods. Greatest biomass N yields followed tilled fallow (60 kg ha^{-1}), winter pea tilled at both bloom and pod stages (57 and 50 kg ha^{-1}), and the vinegar + mowing method (57 kg ha^{-1}) (Miller, unpublished data, 2006). Lowest biomass N followed crimp-rolling termination methods such as roll-bloom and roll-pod, no-till (30 and 40 kg ha^{-1}, respectively). This result did not correspond with soil NO_3-N present at the end of the green fallow period in 2005. A possible explanation for this apparent discrepancy is that soil water was more yield-limiting than soil NO_3-N, especially after

many years of no-till management. In treatments with the greatest soil water content at the end of the green fallow period, over-winter mineralization was presumably higher, which resulted in increased biomass N yields in the winter wheat test crop. Previous no-till management likely provided enough organic matter to decrease the relative soil N benefit from pea.

In 2006, soil NO_3-N content differed by pea type and termination stage; bloom-terminated pea had greater soil N at crop termination than at the pod stage, especially in the 0 - 0.3 m soil layer (Table 3.8). Soil N at the end of the green fallow period was greater under winter pea than spring pea in the three termination treatments (bloom-till, pod-till, pod-roll) common to both pea types (Table 3.9).

Termination strategy further affected soil NO_3-N at the end of the green fallow period in 2006. Disk-terminated winter pea had greater soil N than tilled fallow and all other strategies at bloom (Table 3.9). Vinegar and crimp-rolled treatments, including double treatments (crimp-rolled/vinegar and vinegar/mow) were relatively ineffective at contributing NO_3-N to the soil N pool. At the pod stage, tilled winter pea strategies had 9 kg greater NO_3-N ha^{-1} when compared to non-tillage strategies (i.e., crimp-roll, no-till). Since the two crimp-roll treatments (i.e. with and without subsequent disk tillage) were managed identically for 36 d after termination, and differed only by disk tillage for 12 d prior to soil sampling during hot dry surface soil conditions, we cannot explain the 9 kg difference.

Concentrations of PMN at winter wheat seeding were insensitive to differences among treatments due to high variability in both years (Table 3.10). However, some

differences emerged when contrasting tilled vs. untilled terminated pea ($P < 0.1$; Appendix table B.8). Winter pea plots that had been tilled at bloom had the least PMN (1 mg kg^{-1}), suggesting that a majority of the narrow C:N shoot biomass had already mineralized. The winter pea treatments with high PMN at the end of the 2006 cropping season were bloom-roll and pod-till (16 mg N kg^{-1}), but these treatments did not differ significantly from any treatment including bloom-till. A lack of correlation between over-winter NO_3-N changes and PMN was observed previously at Bozeman, suggesting PMN anaerobic incubation may not be a good indicator of aerobic field N mineralization at this site (C.A. Jones, unpublished data).

Increases in soil phosphorus fertility following green manures are notoriously difficult to detect since conventional soil P tests do not assess mineralizable organic forms (Campbell et al., 1984). However, P is often a yield-limiting nutrient in calcareous soils, and decomposing green manures have been shown to enhance P nutrition of succeeding crops by mineralizing relatively unavailable inorganic P forms to more available forms (Cavigelli and Thien, 2003; Randhawa et al., 2005). When green manure residues decompose, they release organic acids which increase P availability for a number of reasons including: (1) decreased pH , (2) decreased sorption (due to competition with HPO_4^{-2}), and (3) decreased rates of P precipitation (Grossl and Inskeep, 1991). Olsen P tests taken after one green manure cycle indicate that P availability varied by pea termination timing ($P < 0.1$) in 2006 (See Appendix Table B.8). However, pea growth habit (winter vs. spring) did not affect soil test P and no differences occurred with respect to termination method.

The optimal range for Olsen P fertility is 16-20 mg P kg^{-1} (Pierzynski et al., 2005). Treatments in the 2005 site, with previous no-till history ranged from 9 to 13 mg P kg^{-1}. In contrast, all treatments in the double fallowed, long-term tillage 2006 site were in the optimal range (Table 3.10). Previous studies have shown that tillage history does not affect P uptake in wheat (Lupwayi et al., 2006; Schwab et al., 2006). However, plowing has been shown to redistribute P in the top 0.15 m of soil (Schwab et al., 2006).

In this study, we did not assess C:P ratio in shoot biomass, and therefore cannot accurately predict whether net P mineralization or immobilization occurred at different termination timings. Pod-terminated winter pea had a higher soil test P at the end of the green fallow period in 2006 than bloom-terminated (Table 3.10; Appendix Table B.8). Because greater conversion of inorganic to organic P occurs in the presence of green manures (Cavigelli and Thien, 2003; Randhawa et al., 2005), terminating pea later presumably mineralized more P. Nitrogen mineralization was also high during the green fallow phase following pod 2006 (Table 3.9), indicating there was still time for substantial mineralization between pod and the end of the green fallow period. However, differences between Olsen P values were relatively small, and may not be appropriate to make specific conclusions about termination timing.

Termination method may have affected P availability. Among the pod-termination methods, lowest Olsen P (9 mg P kg^{-1}) values occurred under crimp-rolled, no-till plots in 2005. Retaining pea residue on the soil surface likely slowed decomposition and thus the release of organic acids. However, in 2006, the no-till termination method had the highest Olsen P (21 mg P kg^{-1}) after many decades of tillage.

Immobilization under tillage-incorporated pea may have advantaged no-till plots in 2006. Olsen P results were more likely affected by previous management history than green manure termination strategy.

To summarize, optimal termination strategies for maximizing yield-limiting nutrients (N and P) for subsequent crops are specific to green manure type, termination timing, and previous crop management. Our findings suggest that fall-seeded green manures such as winter pea can be terminated effectively at either stage with tillage, or by crimp-rolling at pod. Disk tillage was the only effective method for bloom-terminated spring and winter pea. Because spring pea matures later in the growing season, early termination will provide additional time for N residue breakdown by the end of the green fallow period.

Green Manure Effects on Soil Water

Soil water content under tilled fallow was used as a reference to compare relative water usage for green manure termination strategies (Table 3.11). Pea green manure used more soil water than tilled fallow, regardless of termination strategy or timing. Among pea treatments, termination at bloom used less soil water than at pod in both years (Table 3.12). For example, winter pea tilled at bloom used 21 (2005) and 32 mm (2006) less soil water than when tilled at pod. As observed in previous studies, early green manure termination was essential for conserving soil water (Pikul et al., 1997; Zentner et al., 2004).

Although winter and spring pea are the same species, the fall seeding date of winter pea was more conservative with soil water, especially when terminated at bloom

(Table 3.13). Winter pea used 23, 9, and 8 mm less soil water than spring pea in common termination treatments (bloom-till, pod-roll, pod-till, respectively). The earlier planting date of winter pea allows for early June termination as compared to spring pea which reaches first bloom in July, a period of higher evapotranspirative demand.

Among all the termination strategies, tillage at bloom conserved the most (22-50 mm) soil water for subsequent crops (Table 3.13). Winter pea tilled at bloom conserved soil water because disk-tillage effectively stopped winter pea maturation at bloom whereas alternative strategies did not immediately kill pea. When winter pea was terminated at bloom by vinegar and crimp-rolling, 40 and 50 mm of additional soil water were lost by the end of the green fallow period compared with tillage-based strategies performed on the same date. These differences in soil water usage likely occurred immediately after bloom 'termination' when vinegar and crimp-rolled pea recovered and continued transpiring soil water. After crimp-rolling, pea partially reoriented vertically and continued growing. Spraying pea with vinegar desiccated the stem, but the shoot apex remained green, presumably transpiring. The bloom vinegar-mow combination was the only split-plot combination that conserved soil water compared to the vinegar-only treatment (9 mm). Mowing severed green growing tips from the vinegar-senesced stem immediately stopped transpiration, conserving more soil water than the vinegar-only treatment.

Pod-terminated pea used more soil water than bloom. All winter pea (2005) and spring pea (2006) pod-termination strategies had equivalent soil water content by the end of the green fallow period. Tillage-terminated winter pea used slightly less (9 mm) water

than crimp-rolling in 2006. Water use did not differ between crimp-roll tilled and no-till winter pea treatments. Soil water content was similar in spring pea crimp-rolling and tillage treatments, both of which used considerably more soil water than winter pea (10 and 25 mm, respectively). Therefore, crimp-rolled may provide a useful alternative to tillage termination for annual pea green manures when performed at pod.

Preliminary wheat recrop data from 2006 indicate that pea water use appeared to be the chief yield-limiting factor. Pea termination strategies with greater soil water content at the end of the 2005 green fallow period generally had higher mean yields. Subsequent wheat yields (4.7, 4.9 Mg ha^{-1}) and biomass N (57, 60 kg ha^{-1}) were equivalent following winter pea tilled at bloom and tilled fallow, both of which were conservative of soil water (data not shown). Although vinegar was ineffective at killing pea, the vinegar-mowing combination was an effectual kill strategy, and this water savings was reflected in preliminary winter wheat yield data, 4.4 as compared to 3.3 Mg ha^{-1}. Subsequent crop yields following pod till and no-till (crimp-rolling) termination strategies did not differ (4.4, 4.2 Mg ha^{-1}), which again compared with soil water content at the end of the green fallow period. Surprisingly, termination timing between bloom and pod tillage treatments did not affect yields of the subsequent winter wheat test crop (4.7 and 4.4 Mg ha^{-1}, respectively), despite important differences in soil water content (32 mm) at the end of the green fallow period.

Conclusions

As compared with spring pea, winter pea green manure best achieved the goals of organic dryland growers such as conserving soil water while contributing soil N, especially when growth was terminated at bloom. Termination at bloom was only effective if accomplished with disk-tillage in this study. Vinegar was unable to effectively kill pea without subsequent mowing, and due to the additional management and exorbitant cost, we do not recommend using as a green manure termination strategy. Crimp-rolling at pod has the ability to eliminate up to three tillage operations, while maintaining comparable soil water use and subsequent wheat yields to tillage at pod. Subsequent crop and longer-term cropping sequence data should further elucidate how crimp-rolling compares with tilled green manure termination.

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Tables: Bozeman

Table 3.1. General site characteristics for Bozeman, MT, 2004-2006.

Location	45° 47’ N, 111° 9’ W
Elevation (m)	1463
Soil Classification (USDA Soil Survey)	Frigid Typic Calciustoll
Soil Texture (USDA Soil Survey)	Amsterdam silt loam
Initial soil NO_3-N (kg ha^{-1} to 0.6 m depth)	13 (Sep 2004)
	12 (Sep 2005)
Soil pH	7.2 - 7.7
Soil Organic Matter	25 g kg^{-1}

Table 3.2. Precipitation at Bozeman, MT, 2005-2006.

	2005	2006	*LTA*†
	---------- mm ----------		
Sep-Apr ‡	188	263	*210*
May	29	44	*71*
June	76	78	*64*
July	27	16	*38*
August	44	17	*35*
Total	364	418	*418*

† LTA = long-term average, 1971-2000 average annual precipitation as reported by Western Regional Climate Center, Desert Research Institute, Reno, NV.
‡ Over-winter precipitation preceding the growing season

Table 3.3 Agronomic factors for green manure termination study at Bozeman, MT. 2004-2006.

	Green manure crops		
	Winter pea	Spring pea	Sweet clover†
Cultivars	*Melrose*	*Arvika*	Common yellow
Seeding dates	1 Sep 2004 9 Sep 2005	-- 11 Apr 2006	16 Sep 2004 6 June 2005
Seeding rates (Target seeds m^{-2})	120	120	400
Equipment	Plot seeder	Plot seeder	Plot seeder 2004 ‡ Hand spreader 2005
Depth	2.5 cm	2.5 cm	1.3 cm 2004 Surface 2005

† Sweet clover failed to establish in this study

Table 3.4. Green manure treatments at Bozeman, 2005-2006.

Timing	Termination method	Green manure 2005	Green manure 2006	Additional subtreatments
Bloom	Till	Winter pea	Winter pea	
			Spring pea	
	Crimp-roll	Winter pea	Winter pea	Vinegar
	Vinegar	Winter pea	Winter pea	Mowed
Pod	Till	Winter pea	Winter pea	
			Spring pea	
	Crimp-roll, till	Winter pea	Winter pea	
			Spring pea	
	Crimp-roll, no-till	Winter pea	Winter pea	
			Spring pea	

† Additional subtreatments were added 14 and 9-d after termination to bloom crimp-roller and vinegar treatments in attempt to improve efficacy

Table 3.5. Treatment methodology at Bozeman, MT 2005-2006.

Treatment	Green manure	Term. date	Subsequent date	Equipment used
Timing x Method			2005	
Bloom Till	Winter pea	15 June	20 July	Chisel plow†
			12 Sep	Field cultivator‡
Crimp-roll, till	Winter pea	15 June	26 June	Bisected: vinegar
			15 Aug	Crimp-roller
			12 Sep	Field cultivator
Vinegar	Winter pea	15 June	26 June	Bisected: mow
			29 July	Tandem disk
			15 Aug	Tandem disk
			12 Sep	Chisel plow, field cultivator
Pod Till	Winter pea	8 July	29 July	Tandem disk
			12 Sept	Field cultivator
Crimp-roll	Winter pea	8 July	15 Aug	Tandem disk
			12 Sep	Chisel plow, field cultivator
Crimp-roll, no-till	Winter pea	8 July		
Tilled fallow			6 May	Tandem disk
			15 Jun	Tandem disk
			8 July	Tandem disk
			29 July	Tandem disk
			16 Aug	Field cultivator
			12 Sep	Field cultivator
			2006	
Bloom Till	Winter pea	7 June	12 July	Tandem disk
			17 Aug	Chisel plow
			22 Aug	Field cultivator
Till	Spring pea	26 June	17 Aug	Tandem disk
			22 Aug	Field cultivator
Crimp-roll	Winter pea	7 June	14 June	Bisected: vinegar
			12 July	Tandem disk
			17 Aug	Tandem disk
			22 Aug	Field cultivator
Vinegar	Winter pea	7 June	14 June	Bisected: mow
			12 July	Tandem disk
			17 Aug	Chisel plow
			22 Aug	Field cultivator
Pod Till	Winter pea	26 June	17 Aug	Tandem disk
			22 Aug	Field cultivator
Till	Spring pea	12 July	17 Aug	Tandem disk
			22 Aug	Field cultivator
Crimp-roll	Winter pea	26 June	17 Aug	Tandem disk
			22 Aug	Field cultivator
Crimp-roll, No-till	Winter pea	26 June		
Crimp-roll	Spring pea	12 July		
Tilled fallow			11 Apr	Tandem disk
			7 June	Tandem disk
			26 June	Tandem disk
			13 July	Tandem disk
			17 Aug	Chisel plow

† Chisel plow has 360-mm wide shovels
‡ Field cultivator has 170-mm wide shovels
§ 2005 Tandem disk had 380 mm diam. disks
¶ 2006 Tandem disk had 460 mm diam. notched disk

Table 3.6. Means for green manure biomass, weed biomass, and green manure total N content and C:N ratio at Bozeman, MT, 2005-2006.

Green manure and harvest timing		Biomass yield weight	Weed yield weight	Biomass N yield	Biomass C:N ratio
		-------- Mg ha^{-1} --------		kg ha^{-1}	
		---------- 2005 ----------			
Winter pea	Bloom	2.6	0.4	97	14
Winter pea	Pod	4.5	0.5	122	18
LSD†		*0.5*	*NS*	*19*	*2*
		---------- 2006 ----------			
Winter pea	Bloom	2.2	0.0	67	15
Winter pea	Pod	4.6	0.2	132	16
Spring pea‡	Bloom	2.5	0.8	94	16
Spring pea	Pod	4.9	0.7	109	23
LSD		*0.7*	*0.2*	*16*	*2*

† Fisher's Protected LSD ($P < 0.10$) for comparing means within a column.
‡ Spring pea data were collected in 2006 only

Table 3.7. Mean soil NO_3-N in two depth increments and the total 0.6 m soil profile in tilled fallow plots on sequential sampling dates at Bozeman, MT, 2004-2006.

Soil sampling date			0 – 0.3 m	0.3 – 0.6 m	**Total 0.6 m**
2004 -2005			---------- kg NO_3-N ha^{-1} ----------		
19	Oct	2004	19	6	**25**
5	May	2005	31	29	**60**
23	June	2005	32	17	**49**
7	July	2005	32	17	**49**
9	Sep	2005	49	25	**74**
		LSD†	*6*	*6*	***12***
2005 – 2006					
15	Sep	2005	10	12	**22**
26	Apr	2006	10	12	**21**
7	June	2006	10	8	**18**
26	June	2006	14	9	**22**
12	July	2006	17	9	**26**
29	Aug	2006	14	11	**25**
		LSD†	*3*	*4*	***6***

† Protected least significant difference within a column according to Fisher's Protected LSD ($P < 0.10$).

Table 3.8. Treatment means for marginal† soil NO_3-N content at crop termination in a green manure study at Bozeman, MT, 2005-2006.

Green manure treatment		soil depth increment		
		0 – 0.3 m	0.3 – 0.6 m	**Total 0.6 m**
		kg NO_3-N ha^{-1}		
Winter pea		2005		
Bloom	Roll, till	-18	-6	**-24**
Bloom	till	-13	-4	**-17**
Bloom	vinegar	-16	-7	**-23**
Pod	roll, till	-22	-8	**-30**
Pod	roll no-till	-22	-10	**-32**
Pod	till	-16	-10	**-26**
LSD		*NS*	*NS*	***NS***
Winter pea		2006		
Bloom	roll, till	-6	-4	**-9**
Bloom	till	-5	-2	**-7**
Bloom	vinegar, till	-6	-4	**-9**
Pod	roll, till	-6	-4	**-10**
Pod	roll no-till	-1	-4	**-5**
Pod	till	-6	-5	**-11**
Spring pea				
Bloom	till	-7	-3	**-10**
Pod	roll, no-till	-11	-5	**-16**
Pod	till	-12	-6	**-18**
LSD		*3*	*1*	***4***

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.

Table 3.9. Treatment means for marginal† soil NO_3-N content at the end of the green fallow period‡ in a green manure study at Bozeman, MT, 2005-2006.

Green manure treatment		soil depth increment		
		0 – 0.3 m	0.3 – 0.6 m	**0 – 0.6 m**
		kg NO_3-N ha^{-1}		
Winter pea		2005		
Bloom	roll, till §	-9	-8	**-17**
Bloom	till	15	-5	**10**
Bloom	vinegar, till§	-9	-12	**-21**
Pod	roll, till	4	-9	**-5**
Pod	roll no-till	22	-8	**14**
Pod	till	-9	-6	**-14**
LSD¶		*NS*	*NS*	***NS***
Winter pea		2006		
Bloom	roll, till	0	-4	**-4**
Bloom	roll, vinegar	0	-4	**-4**
Bloom	till	8	-1	**7**
Bloom	vinegar, till	-3	-4	**-7**
Bloom	vinegar, mow, till	-4	-2	**-6**
Pod	roll, till	4	-1	**3**
Pod	roll no-till	-1	-5	**-6**
Pod	till	4	-1	**3**
Spring pea				
Bloom	till	2	1	**2**
Pod	roll, no-till	-5	-6	**-11**
Pod	till	-4	-5	**-9**
LSD¶		*4*	*2*	***5***

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control
‡ The end of the green fallow period coincides with winter wheat seeding after one green manure cycle (22 Aug, 2005, 27 Sep 2006)
§ Plots may be further influenced by additional subtreatments because soil samples were taken from the center of plots
¶ Fisher's Protected LSD ($P < 0.10$) for comparing means within a column

Table 3.10. Treatment means for potentially mineralizable nitrogen (PMN) and Olsen P at the end of the green fallow period† in a green manure study at Bozeman, MT, 2005-2006.

Green manure treatment		0 - 0.15 m soil depth	
		---- mg N kg^{-1} dry soil ---	---- mg P kg^{-1} dry soil ---
Winter pea		2005	
Bloom	roll	4	13
Bloom	till	6	11
Bloom	vinegar	13	11
Pod	roll no till	6	9
Pod	roll	13	11
Pod	till	10	10
Fallow		6	13
LSD‡		*NS*	*3*
Spring pea		2006	
Bloom	till	14	18
Pod	roll, no-till	9	16
Pod	till	4	17
Winter pea			
Bloom	roll, till	16	17
Bloom	roll, vinegar, till	6	15
Bloom	till	1	14
Bloom	vinegar, till	9	14
Bloom	vinegar, mow, till	3	15
Pod	roll, till	10	16
Pod	roll no till	11	21
Pod	till	16	18
Fallow		7	18
LSD‡		*NS*	*2*

† The end of the green fallow period coincides with winter wheat seeding after one green manure cycle (22 Aug, 2005, 27 Sep 2006)

‡ Fisher's Protected LSD ($P \leq 0.10$) for comparing means within a column.

Table 3.11. Mean soil water content in four depth increments and the total soil profile in tilled fallow plots on sequential sampling dates at Bozeman, MT, 2004-2006.

Soil sampling date			0 – 0.3 m	0.3 – 0.6 m	0.6 – 0.9 m	0.9- 1.2 m	**Total 1.2 m**
			---------- mm soil water ----------				
2004 -2005							
19	Oct	2004	74	33	30	34	**171**
5	May	2005	86	73	58	45	**261**
23	June	2005	82	75	66	55	**278**
7	July	2005	76	71	62	55	**265**
9	Sept	2005	68	63	57	52	**240**
		LSD†	*4*	*3*	*3*	*3*	***8***
2005 – 2006							
15	Sep	2005	47	34	30	31	**142**
26	Apr	2006	102	87	67	53	**309**
7	June	2006‡	--	--	--	--	**--**
26	June	2006	87	82	75	65	**309**
12	July	2006	81	80	69	61	**291**
29	Aug	2006	69	68	62	54	**253**
		LSD†	*5*	*6*	*10*	*8*	***16***

† Protected least significant difference within a column according to Fisher's Protected LSD ($P < 0.10$).
‡ Missing values for 7 June 2006, bloom-winter pea sample date

Table 3.12. Treatment means for marginal† soil water content at crop termination in a green manure study at Bozeman, MT, 2005-2006.

Green manure treatment		soil depth increment				
		0 – 0.3 m	0.3 – 0.6 m	0.6 – 0.9 m	0.9 – 1.2 m	**0 – 1.2 m**
		mm of soil water				
Winter pea				2005		
Bloom	roll, till	-27	-30	-23	-13	**-93**
Bloom	till	-14	-26	-22	-11	**-73**
Bloom	vinegar, till	-18	-27	-19	-11	**-75**
Pod	roll no till	-24	-23	-28	-17	**-92**
Pod	roll, till	-31	-42	-26	-15	**-113**
Pod	till	-30	-35	-25	-17	**-107**
LSD‡		*NS*	*NS*	*3*	*3*	***14***
Winter pea				2006 §		
Pod	roll, till	-23	-32	-30	-16	**-100**
Pod	roll no till	-26	-34	-33	-19	**-112**
Pod	till	-25	-14	-33	-19	**-113**
Spring pea						
Bloom	till	-18	-20	-18	-12	**-68**
Pod	roll, no-till	-27	-40	-32	-16	**-114**
Pod	till	-26	-39	-32	-16	**-112**
LSD‡		*4*	*5*	*4*	*NS*	***11***

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.
‡ Fisher's Protected LSD ($P < 0.10$) for comparing means within a column.
§ Missing values for 7 June 2006, bloom-winter pea sample date

Table 3.13. Treatment means for marginal† soil water content at the end of the green fallow period‡ in a green manure study at Bozeman, MT, 2005-2006.

Green manure treatment		soil depth increment				
		0 – 0.3 m	0.3 – 0.6 m	0.6 – 0.9 m	0.9 – 1.2 m	**0 – 1.2 m**
		mm of soil water				
Winter pea		2005				
Bloom	roll, till	-14	-30	-23	-17	**-89**
Bloom	till	-11	-17	-15	-1	**-52**
Bloom	vinegar, till	-17	-23	-18	-12	**-70**
Pod	roll no till	-11	-29	-22	-12	**-74**
Pod	roll, till	-10	-30	-21	-10	**-72**
Pod	till	-16	-27	-20	-10	**-73**
LSD§		*NS*	*4*	*3*	*NS*	***10***
Spring pea		2006				
Bloom	till	-14	-14	-14	-11	**-53**
Pod	roll, no-till	-25	-30	-21	-14	**-89**
Pod	till	-24	-29	-21	-14	**-87**
Winter pea						
Bloom	roll, till	-24	-24	-22	-13	**-80**
Bloom	roll, vinegar, till	-20	-22	-20	-14	**-75**
Bloom	till	-5	-6	-9	-11	**-30**
Bloom	vinegar, till	-18	-23	-17	-12	**-70**
Bloom	vinegar, mow, till	-11	-22	-16	-12	**-61**
Pod	roll, till	-22	-25	-19	-13	**-79**
Pod	roll no-till	-18	-24	-18	-11	**-71**
Pod	till	-19	-18	-14	-11	**-62**
LSD§		*4*	*3*	*3*	*NS*	***8***

†Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.
‡ The end of the green fallow period coincides with winter wheat seeding after one green manure cycle (22 Aug, 2005, 27 Sep 2006)
§Fisher's Protected LSD ($P < 0.10$) for comparing means within a column.

CHAPTER 4

SUMMARY OF FINDINGS AND FUTURE RESEARCH

This study evaluated the efficacy of pea as green manure; and more specifically, measured the effects of pea green manure type, termination timing and method for soil water use and soil N contribution. Winter pea was the superior annual green manure in this study, optimizing the soil water conservation and N fertility goals of organic dryland growers in the NGP. This study confirmed previous regional observations that soil water was conserved when annual green manures are terminated at first bloom. The occurrence of spring precipitation followed by a hot, dry summer characteristic of the NGP highlighted the ability of early-terminated manures such as winter pea to conserve soil water required for subsequent crops. Winter pea terminated at bloom also provided the greatest soil N at the end of the green fallow period relative to other green manures. However, , pod-terminated winter pea may enhance soil N fertility due to greater N fixation over the long-term. Although a N advantage of pod-termination was not illustrated in soil NO_3-N data, greater shoot biomass N may eventually contribute greater soil N to the cropping system

Additionally, this study compared two experimental termination strategies, crimp-rolling and vinegar desiccation, with standard disk-tilling in attempt to reduce tillage in organic systems. The efficacy of crimp-rolling and vinegar desiccation was dependent on pea growth stage. At first bloom, disk-tillage was the only method that effectively terminated pea growth. Vinegar did not effectively kill pea without subsequent mowing,

and due to the additional management and exorbitant cost, we do not recommend using vinegar for green manure termination. When terminating pea at pod, both disk-tillage and crimp-rolling were effective. Crimp-rolling at pod eliminated up to three tillage operations, while maintaining comparable soil water use and subsequent wheat yields to disk-tillage. Although the advantage of reducing tillage operations by crimp-rolling could not be directly measured in a 2-yr cropping sequence, longer-term tillage reduction may reveal multiple soil quality benefits for organic growers.

In light of the findings of this study, there is considerable potential for future research in organic cropping systems. Growing organic markets will demand sustainable management as well as provide new niches for farmers. Future research should be directed at other types of green manure crops and crop mixtures for use in organic systems in various climates. Termination timing should also be investigated more fully, as it will be climate-specific. Further exploration of alternative green manure termination strategies opens up a multitude of applied research opportunities, especially for on-farm experiments. Long-term research will be crucial to improving our understanding of how organic cropping systems function.

Going 'beyond organic' to a more sustainable system of agriculture will require new assessment tools, longer-term studies and a paradigm shift towards farm diversity. The currently-used parameters of maximization of yield and profit may have to shift towards more qualitative goals such as enhancing environmental quality, sustaining 'acceptable' yields, creating locally self-reliant food systems, and enhancing the quality of life for farmers. These goals may be difficult to assess with current scientific methods.

I have personally concluded that the most effective way to augment agricultural sustainability is to start farming myself. If a greater percentage of the population were to be involved in their food system, the achievement of agricultural sustainability, at least locally, becomes possible. This study represents a small piece of the larger puzzle that the scientific community needs to complete in order to move towards a system sustainable agriculture. Overall, the findings of this study have demonstrated the importance of legume green manure management on soil N and water use in organic cropping systems of the NGP.

APPENDICES

APPENDIX A

BIG SANDY ADDITIONAL TABLES AND FIGURES

Figure A.1. Plot map for green manure study at Big Sandy, MT 2004-2005.

101.1	Winter pea	Bloom
101.2	Winter pea	Pod
102.1	Buckwheat	Bloom
102.2	Buckwheat	Pod
103.1	Spring pea	Pod
103.2	Spring pea	Bloom
104	Tilled fallow	As needed
105.1	Mustard	Pod
105.2	Mustard	Bloom

201.1	Spring pea	Bloom
201.2	Spring pea	Pod
202.1	Winter pea	Pod
202.2	Winter pea	Bloom
203.1	Mustard	Bloom
203.2	Mustard	Pod
204.1	Buckwheat	Bloom
204.2	Buckwheat	Pod
205	Tilled fallow	As needed

301	Tilled fallow	As needed
302.1	Buckwheat	Pod
302.2	Buckwheat	Bloom
303.1	Mustard	Pod
303.2	Mustard	Bloom
304.1	Winter pea	Pod
304.2	Winter pea	Bloom
305.1	Spring pea	Bloom
305.2	Spring pea	Pod

401.1	Buckwheat	Bloom
401.2	Buckwheat	Pod
402	Tilled fallow	As needed
403.1	Spring pea	Bloom
403.2	Spring pea	Pod
404.1	Mustard	Pod
404.2	Mustard	Bloom
405.1	Winter pea	Bloom
405.2	Winter pea	Pod

---------- 18 m ----------

Figure A.2. Plot map for green manure study at Big Sandy, MT 2005-2006. 5x30m

101.1	Buckwheat	Pod
101.2	Buckwheat	Bloom
102.1	Mustard	Bloom
102.2	Mustard	Pod
103.1	Winter pea	Bloom
103.2	Winter pea	Pod
104.1	Spring pea	Pod
104.2	Spring pea	Bloom
105	Tilled fallow	As needed
201.1	Mustard	Bloom
201.2	Mustard	Pod
202.1	Winter pea	Bloom
202.2	Winter pea	Pod
203	Tilled fallow	As needed
204.1	Spring pea	Bloom
204.2	Spring pea	Pod
205.1	Buckwheat	Pod
205.2	Buckwheat	Bloom
301.1	Buckwheat	Pod
301.2	Buckwheat	Bloom
302.1	Mustard	Bloom
302.2	Mustard	Pod
303.1	Spring pea	Pod
303.2	Spring pea	Bloom
304	Tilled fallow	As needed
305.1	Winter pea	Pod
305.2	Winter pea	Bloom
401	Tilled fallow	As needed
402.1	Buckwheat	Pod
402.2	Buckwheat	Bloom
403.1	Winter pea	Bloom
403.2	Winter pea	Pod
404.1	Mustard	Pod
404.2	Mustard	Bloom
405.1	Spring pea	Bloom
405.2	Spring pea	Pod

---------- 18 m ----------

Table A.3. Analysis of variance (ANOVA) mean squares for shoot biomass, weed biomass, and total biomass N content and C:N ratio, for green manure study at Big Sandy, MT, 2005-2006.

	2005			2006		
Source	df	Mean squares		df	Mean squares	
	Shoot biomass (Mg ha^{-1}) (x10^3)					
Block (B)	3	964	*	3	53	
Green manure crop (C)	3	10109	**	2	1029	**
Winter vs. spring pea contrast	*1*	*906*	*	*1*	*13*	
Winter vs. spring seeded contrast	*1*	*15166*	**	*1*	*664*	**
Pea vs. non-legume contrast	*1*	*29153*	**	*1*	*1431*	**
B x C (Error A)	9	201	*	6	33	*
Harvest timing (T)	1	1922	**	1	712	**
C x T	3	317	*	2	154	*
Residual error (Error B)	12	58		9	12	
	Weed biomass (Mg ha^{-1}) (x10^3)					
B	3	60		3	269	*
C	3	613	**	2	293	**
Winter vs. spring pea contrast	*1*	*582*	**	*1*	*507*	**
Winter vs. spring seeded contrast	*1*	*732*	**	*1*	*575*	**
Pea vs. non-legume contrast	*1*	*162*	*	*1*	*145*	*
B x C	9	34		6	32	
T	1	133		1	48	
C x T	3	106		2	19	
Residual error	12	49		9	37	
	Shoot + weed biomass N content (kg N ha^{-1})					
B	3	700	*	3	623	
C	3	7310	**	2	8852	**
Winter vs. spring pea contrast	*1*	*26*		*1*	*1372*	*
Winter vs. spring seeded contrast	*1*	*7996*	**	*1*	*9200*	**
Pea vs. non-legume contrast	*1*	*21820*	**	*1*	*15870*	**
B x C	9	241	*	6	304	*
T	1	317	*	1	2654	**
C x T	3	176		2	376	*
Residual error	12	69		9	75	
	C:N ratio of shoot + weed biomass (x10)					
B	3	100		3	169	
C	3	1244	**	2	278	
Winter vs. spring pea contrast	*1*	*135*		*1*	*525*	*
Winter vs. spring seeded contrast	*1*	*71*		*1*	*292*	
Pea vs. non-legume contrast	*1*	*3*		*1*	*43*	
B x C	9	117	*	6	104	**
T	1	765	**	1	1035	**
C x T	3	113		2	39	*
Residual error	12	50		9	11	

*, ** denote significance at $P \leq 0.1$ and $P \leq 0.01$, respectively

Figure A.4 Winter pea removal by tractor tires16 June 2005 at Big Sandy, MT.



Figure A.5 Winter pea caught in rotary tiller 16 June 2005 at Big Sandy, MT.



Table A.6. Analysis of variance (ANOVA) mean squares for soil N in tilled fallow plots sampled on sequential dates in two crop cycles from 9 Sep 2004 to 22 Aug 2005, and 2 Sep 2005 to 22 Sep 2006 at Big Sandy, MT.

	2005			2006		
Source	df	Mean squares		df	Mean squares	
	0 – 0.3 core depth kg NO_3-N ha^{-1}					
Block	3	59		3	11	
Date	5	482	**	5	209	**
Residual error	33	95		31	13	
	0.3 – 0.6 core depth kg NO_3-N ha^{-1}					
Block	3	16		3	4	
Date	5	266	**	5	32	*
Residual error	33	23		31	11	
	Total 0.6 kg NO_3-N ha^{-1}					
Block	3	85		3	26	
Date	5	1363	**	5	351	**
Residual error	33	148		31	31	

*, ** denote significance at $P \leq 0.1$ and $P \leq 0.01$, respectively.

Table A.7. Analysis of variance (ANOVA) mean squares for marginal† soil NO_3-N content at crop termination within two depth increments and the total soil column in a green manure study at Big Sandy, MT, 2005-2006.

Source	2005			2006		
	df	Mean square		df	Mean square	
		0 – 0.3 m soil depth				
Block (B)	3	320	*	3	71	*
Green manure crop (C)	3	214		2	79	*
Winter vs. spring pea contrast	*1*	*321*		*1*	*108*	*
Winter vs. spring seeded contrast	*1*	*106*		*1*	*34*	*
Pea vs. non-legume contrast	*1*	*57*		*1*	*49*	*
Early vs. late terminated contrast	*1*	*584*	*	*1*	*156*	**
B x C (Error A)	9	48		6	4	
Harvest timing (T)	1	290		1	64	*
C x T	3	141		2	12	
Residual error (Error B)	12	105		9	13	
		0.3 – 0.6 m soil depth				
B	3	483	**	3	4	
C	3	41		2	0	
Winter vs. spring pea contrast	*1*	*53*		*1*	*0*	
Winter vs. spring seeded contrast	*1*	*11*		*1*	*0*	
Pea vs. non-legume contrast	*1*	*21*		*1*	*0*	
Early vs. late terminated contrast	*1*	*102*		*1*	*1*	
B x C	9	19		6	1	
T	1	21		1	5	
C x T	3	81		2	58	**
Residual error	12	60		9	3	
		Total 0.6 m soil depth				
B	3	1314	**	3	75	*
C	3	440	*	2	91	*
Winter vs. spring pea contrast	*1*	*635*	*	*1*	*122*	*
Winter vs. spring seeded contrast	*1*	*185*		*1*	*36*	*
Pea vs. non-legume contrast	*1*	*146*		*1*	*60*	*
Early vs. late terminated contrast	*1*	*1173*	**	*1*	*180*	**
B x C	9	73		6	7	
T	1	466	*	1	33	*
C x T	3	341	*	2	123	**
Residual error	12	81		9	14	

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.

*, ** denote significance at $P \leq 0.1$ and $P \leq 0.01$, respectively.

Table A.8. Analysis of variance (ANOVA) mean squares for marginal† soil NO_3-N content at the end of the green fallow period within two depth increments and the total soil column in a green manure study at Big Sandy, MT, 2005-2006.

Source	2005			2006		
	df	Mean square		df	Mean square	
		0 – 0.3 m soil depth				
Block (B)	3	656	**	3	185	
Green manure crop (C)	3	607	**	2	748	*
Winter vs. spring pea contrast	*1*	*983*	**	*1*	*1493*	*
Winter vs. spring seeded contrast	*1*	*1712*	**	*1*	*1175*	*
Pea vs. non-legume contrast	*1*	*747*	**	*1*	*3*	
B x C (Error A)	9	75		6	293	
Harvest timing (T)	1	440	**	1	728	
Early vs. late terminated contrast	1	836	**	1	1066	*
C x T	3	55		2	10	
Residual error (Error B)	12	45		9	220	
		0.3 – 0.6 m soil depth				
B	3	211	**	3	88	**
C	3	8		2	16	
Winter vs. spring pea contrast	*1*	*3*		*1*	*11*	
Winter vs. spring seeded contrast	*1*	*8*		*1*	*0*	
Pea vs. non-legume contrast	*1*	*6*		*1*	*20*	
B x C	9	7		6	16	
T	1	23		1	84	**
Early vs. late terminated contrast	1	16		1	27	*
C x T	3	10		2	3	
Residual error	12	13		9	8	
		Total 0.6 m soil depth				
B	3	1040	**	3	242	
C	3	718	**	2	886	*
Winter vs. spring pea contrast	*1*	*1092*	**	*1*	*1764*	*
Winter vs. spring seeded contrast	*1*	*1947*	**	*1*	*1219*	*
Pea vs. non-legume contrast	*1*	*882*	**	*1*	*8*	
B x C	9	106		6	361	
T	1	662	*	1	1305	*
Early vs. late terminated contrast	1	1080	**	1	1431	*
C x T	3	107		2	23	
Residual error	12	83		9	273	

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.

‡ The end of the green fallow period coincides with winter wheat seeding after one green manure cycle (22 Aug, 2005, 27 Sep 2006)

*, ** denote significance at $P \leq 0.1$ and $P \leq 0.01$, respectively.

Table A.9. Analysis of variance (ANOVA) mean squares for soil water in tilled fallow plots sampled on sequential dates from 9 Sep 2004 to 22 Aug 2005, and 2 Sep 2005 to 22 Sep 2006 at Big Sandy, MT.

	2005			2006		
Source	df	Mean squares		df	Mean squares	
	0 – 0.3 core depth mm soil water (x 10^2)					
Block	3	45		3	86	*
Date	5	1521	**	5	1743	**
Residual error	28	51		19	28	
	0.3 – 0.6 core depth mm soil water (x 10^2)					
Block	3	278	*	3	128	*
Date	5	1232	**	5	1959	**
Residual error	28	107		18	47	
	0.6 – 0.9 core depth mm soil water (x 10^2)					
Block	3	283	*	3	355	*
Date	5	640	**	5	1327	**
Residual error	28	79		19	107	
	0.9 – 1.2 core depth mm soil water (x 10^2)					
Block	3	729	**	3	89	
Date	5	48		5	385	**
Residual error	28	142		19	67	
	Total 1.2 core depth mm soil water (x 10^2)					
Block	3	2800	*	3	1356	*
Date	5	9800	**	5	15672	**
Residual error	28	888		18	270	

*, ** denote significance at $P \leq 0.1$ and $P \leq 0.01$, respectively.

Table A.10. Analysis of variance (ANOVA) mean squares for marginal† soil water content at crop harvest in four depth increments in a green manure study at Big Sandy, MT, 2005-2006.

Source	2005			2006		
	df	Mean square		df	Mean square	
	0 – 0.3 m soil depth(x 10^2)					
Block (B)	3	529	*	3	23	
Green manure crop (C)	3	137		2	374	**
Winter vs. spring pea contrast	*1*	*365*		*1*	*169*	*
Winter vs. spring seeded contrast	*1*	*142*		*1*	*540*	**
Pea vs. non-legume contrast	*1*	*40*		*1*	*574*	
B x C (Error A)	9	275		6	9	
Harvest timing (T)	1	247		1	37	
Early vs. late terminated contrast	1	142		1	0	
C x T	3	14		2	17	
Residual error (Error B)	12	133		8	31	
	0.3 – 0.6 m soil depth (x 10^2)					
B	3	850		3	31	
C	3	773		2	78	
Winter vs. spring pea contrast	*1*	*1961*	*	*1*	*153*	
Winter vs. spring seeded contrast	*1*	*930*		*1*	*133*	
Pea vs. non-legume contrast	*1*	*96*		*1*	*0*	
B x C (Error A)	9	121		6	283	
T	1	952		1	7	
Early vs. late terminated contrast	1	1828	*	1	153	
C x T	3	115		2	311	
Residual error	12	391		8	325	
	0.6 – 0.9 m soil depth(x 10^2)					
B	3	371	*	3	1152	*
C	3	796	**	2	827	*
Winter vs. spring pea contrast	*1*	*1930*	**	*1*	*208*	
Winter vs. spring seeded contrast	*1*	*2301*	**	*1*	*41*	
Pea vs. non-legume contrast	*1*	*439*	*	*1*	*1531*	*
B x C (Error A)	9	149		6	220	
T	1	562	*	1	2341	*
Early vs. late terminated contrast	1	1160	**	1	923	*
C x T	3	70		2	70	
Residual error	10	129		8	252	
	0.9 – 1.2 m soil depth (x 10^2)					
B	3	1502	*	3	600	
C	3	413		2	68	
Winter vs. spring pea contrast	*1*	*808*		*1*	97	
Winter vs. spring seeded contrast	*1*	*1192*	*	*1*	*135*	
Pea vs. non-legume contrast	*1*	*384*		*1*	*136*	
B x C (Error A)	9	398		6	*8*	
T	1	71		1	1222	*
Early vs. late terminated contrast	1	231		1	136	
C x T	3	182		2	129	
Residual error	12	280		8	228	

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.

*, ** denote significance at $P \leq 0.1$ and $P \leq 0.01$, respectively.

Table A.12. Analysis of variance (ANOVA) mean squares for marginal† soil water content at the end of green fallow period‡ in four depth increments in a green manure study at Big Sandy, MT, 2005-2006.

Source	2005			2006		
	df	Mean square		df	Mean square	
	0 – 0.3 m soil depth (x 10^2)					
Block (B)	3	236	**	3	73	**
Green manure crop (C)	3	90	*	2	98	**
Winter vs. spring pea contrast	*1*	*103*	*	*1*	*89*	*
Winter vs. spring seeded contrast	*1*	*3*		*1*	*9*	
Pea vs. non-legume contrast	*1*	*130*	*	*1*	*108*	**
B x C (Error A)	9	23		6	9	
Harvest timing (T)	1	586	**	1	216	**
Early vs. late terminated contrast	1	130	*	1	180	**
C x T	3	41		2	9	
Residual error (Error B)	12	16		8	9	
	0.3 – 0.6 m soil depth (x 10^2)					
B	3	122		3	846	**
C	3	137		2	528	**
Winter vs. spring pea contrast	*1*	*375*	*	*1*	*196*	*
Winter vs. spring seeded contrast	*1*	*196*		*1*	*6*	
Pea vs. non-legume contrast	*1*	*10*		*1*	*859*	**
B x C (Error A)	9	105		6	37	
T	1	115	**	1	1163	**
Early vs. late terminated contrast	1	299	*	1	717	**
C x T	3	15		2	179	**
Residual error	12	69		8	9	
	0.6 – 0.9 m soil depth (x 10^2)					
B	3	57		3	87	*
C	3	294		2	239	**
Winter vs. spring pea contrast	*1*	*691*	*	*1*	*11*	
Winter vs. spring seeded contrast	*1*	*564*		*1*	*63*	*
Pea vs. non-legume contrast	*1*	*16*		*1*	*468*	**
B x C (Error A)	9	174	*	6	23	
T	1	213	*	1	650	**
Early vs. late terminated contrast	1	85		1	187	**
C x T	3	126	*	2	25	
Residual error	12	48		8	17	
	0.9 – 1.2 m soil depth (x 10^2)					
B	3	713	*	3	442	*
C	3	337		2	20	
Winter vs. spring pea contrast	*1*	*827*	*	*1*	*40*	
Winter vs. spring seeded contrast	*1*	*884*	*	*1*	*26*	
Pea vs. non-legume contrast	*1*	*118*		*1*	*1*	
B x C (Error A)	9	237	*	6	41	
T	1	139	*	1	118	
Early vs. late terminated contrast	1	211	**	1	34	
C x T	3	7		2	25	
Residual error	12	19		8	64	

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.

‡ The end of the green fallow period coincides with winter wheat seeding after one green manure cycle (22 Aug, 2005, 27 Sep 2006)

*, ** denote significance at $P \leq 0.1$ and $P \leq 0.01$, respectively.

Table A.12. Summary of ANOVA *P*-values for green manure, cultivar, row spacing, and seeding rate in organically managed winter wheat at Big Sandy, MT, 2006.

Source	Grain yield	Test weight	Seed weight	Grain protein	Grain N yield
	---------- *P*-value ----------				
Green manure	**<0.01**	**0.06**	**<0.01**	**<0.01**	**<0.01**
Cultivar	**0.04**	**<0.01**	**<0.01**	0.79	**0.08**
Row space	0.30	**<0.01**	**<0.01**	**<0.01**	0.60
Seed rate	0.47	0.61	**<0.01**	**<0.01**	**0.02**
GM x C	0.12	0.32	0.46	0.21	**0.05**
GM x RS	0.70	0.26	0.67	0.35	0.59
GM x SR	0.44	0.50	**0.01**	**0.02**	0.12
C x RS	**0.01**	0.83	**0.01**	0.53	**0.01**
C x SR	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**
RS x SR	**<0.01**	**0.01**	**0.04**	**<0.01**	**0.02**
GM x C x RS	0.73	0.33	0.39	0.64	0.42
GM x C x SR	0.30	0.30	**0.06**	1.00	0.37
GM x RS x SR	0.75	0.19	0.39	0.51	0.39
C x RS x SR	**0.01**	0.39	0.14	0.16	**0.01**
GM x C x RS x SR	0.92	0.76	0.43	0.87	0.90

Table A.13. Grain yield of winter wheat following green manure treatments and responding to cultivar and agronomic treatments, Big Sandy, MT, 2006.

Source	Grain yield		Test weight		Seed weight		Grain protein		Grain N yield	
	t ha^{-1}		lb bu^{-1}		mg seed^{-1}		g kg^{-1}		kg ha^{-1}	
Green manure treatments from 2005										
Bloom buckwheat	1.67	d	61.7	b	29.9	bc	82	d	26.6	de
Bloom mustard	1.99	bc	61.9	ab	30.4	ab	83	d	32.1	c
Bloom spring pea	1.81	cd	61.8	b	29.8	bc	87	bd	30.6	cd
Bloom winter pea	2.64	a	62.3	a	31.0	a	90	bc	46.3	a
Pod buckwheat	1.35	e	61.7	b	29.6	c	84	d	22.0	e
Pod mustard	1.63	de	61.8	b	29.8	bc	83	d	26.2	de
Pod spring pea	1.63	de	61.9	ab	29.4	c	93	b	29.7	cd
Pod winter pea	2.15	b	62.1	ab	30.4	ab	101	a	41.6	ab
Tilled fallow	2.47	a	62.1	ab	31.1	a	86	cd	41.3	b

Means accompanied by the same letter in each column section do not differ ($P > 0.10$).

APPENDIX B

BOZEMAN ADDITIONAL TABLES AND FIGURES

Figure B.1. Plot map for green manure study at Bozeman, MT 2004-2005.

101	SC	Bloom	Disk	301	WP	Bloom	Disk
102	TF		Disk	302	WP	Pod	Crimp-roll§
103	WP	Bloom	Crimp-roll, vin† Crimp-roll	303	WP	Pod	Crimp-roll, disk
104	WP	Pod	Crimp-roll§	304	WP	Bloom	Crimp-roll Crimp-roll, vin
105	SC	Pod	Disk	305	TF		Disk
106	WP	Pod	Disk	306	SC	Bloom	Disk
107	WP	Bloom	Vin Vin, mow‡	307	SC	Pod	Disk
108	SC	Bloom	Vin	308	WP	Pod	Disk
109	WP	Bloom	Disk	309	WP	Bloom	Vinegar, mow Vinegar
110	WP	Pod	Crimp-roll, disk	310	SC	Bloom	Vinegar
201	SC	Bloom	Disk	401	WP	Pod	Disk
202	WP	Pod	Crimp-roll, disk	402	SC	Bloom	Disk
203	WP	Bloom	Crimp-roll Crimp-roll, vinegar	403	WP	Pod	Crimp-roll, disk
204	TF		Disk	404	WP	Bloom	Vinegar Vinegar, mow
205	WP	Pod	Disk	405	SC	Bloom	Vinegar
206	WP	Bloom	Disk	406	WP	Bloom	Disk
207	SC	Bloom	Vinegar	407	SC	Pod	Disk
208	WP	Bloom	Vinegar, mow Vinegar	408	WP	Pod	Crimp-roll§
209	WP	Pod	Crimp-roll§	409	WP	Bloom	Crimp-roll, vinegar Crimp-roll
210	SC	Pod	Disk	410	TF		Disk

† Winter pea plots that were crimp-rolled at bloom were bisected so half of the plot received an additional vinegar treatment.
‡ Winter pea plots that were sprayed with vinegar at bloom were bisected so half of the plot received an additional mowing treatment.
§ Of the two winter pea plots that were crimp-rolled at pod, the cleaner plot was chosen to be no-till and winter wheat was directly seeded without tillage

Figure B.2. Plot map for green manure study at Bozeman, MT 2005-2006. Plot width 5-m, length 10-m.

101	WP	Pod	Disk
102	WP	Bloom	Disk
103	SP¶	Pod	Disk
104	WP	Pod	Crimp-roll§
105	TF		Disk
106	SP	Bloom	Disk
107	WP	Pod	Crimp-roll, disk
108	WP	Bloom	Crimp-roll Crimp-roll, vinegar†
109	SP	Pod	Crimp-roll
110	WP	Bloom	Vinegar Vinegar, mow
201	SP	Pod	Disk
202	SP	Pod	Crimp-roll
203	WP	Bloom	Vinegar Vinegar, mow
204	WP	Pod	Crimp-roll§
205	WP	Bloom	Disk
206	WP	Pod	Crimp-roll, disk
207	SP	Bloom	Disk
208	WP	Pod	Disk
209	TF		Disk
210	WP	Bloom	Crimp-roll Crimp-roll, vinegar

301	TF		Disk
302	WP	Pod	Crimp-roll, disk
303	WP	Bloom	Vinegar Vinegar, mow‡
304	SP	Pod	Crimp-roll
305	WP	Pod	Crimp-roll§
306	SP	Bloom	Disk
307	WP	Pod	Disk
308	WP	Bloom	Crimp-roll Crimp-roll, vinegar
309	SP	Pod	Disk
310	WP	Bloom	Disk
401	WP	Pod	Crimp-roll§
402	WP	Bloom	Crimp-roll Crimp-roll, vinegar
403	SP	Bloom	Crimp-roll
404	TF		Disk
405	WP	Pod	Disk
406	WP	Bloom	Disk
407	SP	Pod	Crimp-roll
408	WP	Bloom	Vinegar Vinegar, mow
409	SP	Pod	Disk
410	WP	Pod	Crimp-roll, disk

† Winter pea plots that were crimp-rolled at bloom were bisected so half of the plot received an additional vinegar treatment.
‡ Winter pea plots that were sprayed with vinegar at bloom were bisected so half of the plot received an additional mowing treatment.
§ Of the two winter pea plots that were crimp-rolled at pod, the cleaner plot was chosen to be no-till and winter wheat was directly seeded without tillage.
¶ Spring pea replaced sweet clover plots in 2006.

B.3 The Rodale Institute© and MSU designs for a crimp roller





Table B.4 Analysis of variance (ANOVA) mean squares for shoot biomass, weed biomass, and shoot biomass N content and C:N ratio, for green manure study at Bozeman, MT, 2005-2006.

	2005			2006		
Source	df	Mean squares		df	Mean squares	
	Shoot biomass (Mg ha^{-1}) (x10^{2})					
Block (B)	3	73		3	55	
Treatment (T)	1	2026	**	3	1683	**
Bloom vs. pod contrast	*1*	--		*1*	*4019*	**
Winter vs. spring pea contrast†	*1*	--		*1*	*57*	
Residual error	19	36		27	63	
	Weed biomass (Mg ha^{-1}) (x10^{3})					
B	3	332	**	3	176	*
T	1	86		3	1117	**
Bloom vs. pod contrast	*1*	--		*1*	*10*	
Winter vs. spring pea contrast	*1*	--		*1*	*3013*	**
Residual error	19	39		27	60	
	Shoot + weed biomass N content (kg N ha^{-1})					
B	3	1104	*	3	510	
T	1	3661	**	3	8681	**
Bloom vs. pod contrast	*1*	--		*1*	*11659*	**
Winter vs. spring pea contrast	*1*	--		*1*	*49*	
Residual error	19	*378*		37	702	
	C:N ratio of shoot + weed biomass (x 10)					
B	3	212	**	3	112	*
T	1	1275	**	3	860	**
Bloom vs. pod contrast	*1*	--		*1*	*1156*	**
Winter vs. spring pea contrast	*1*	--		*1*	*937*	**
Residual error	19	24		37	31	

*, ** denote significance at $P < 0.1$ and $P < 0.01$, respectively.

† Spring pea data were collected in 2006 only

Table B.5. Analysis of variance (ANOVA) mean squares for soil NO_3-N in tilled fallow plots sampled on sequential dates in two crop cycles from 19 Oct 2004 to 9 Sep 2005, and 15 Sep 2005 to 29 Aug 2006 at Bozeman, MT.

	2005		2006	
Source	df	Mean squares	df	Mean squares
	0 – 0.3 m depth: kg NO_3-N ha^{-1}			
Block	3	60	3	28 *
Date	4	891 **	5	49 **
Residual error	18	49	19	12
	0.3 – 0.6 m depth: kg NO_3-N ha^{-1}			
Block	3	57	3	45 *
Date	4	749 **	5	19
Residual error	18	46	19	16
	0 – 0.6 m: kg NO_3-N ha^{-1}			
Block	3	115	3	109 *
Date	4	2961 **	5	39
Residual error	18	149	19	30

Table B.6. Analysis of variance (ANOVA) mean squares for marginal† soil NO_3-N content at crop termination within two depth increments and the total soil profile in a green manure study at Bozeman, MT, 2005-2006.

Source	2005			2006		
	df	Mean square		df	Mean square	
	0 – 0.3 m soil depth					
Block	3	186	*	3	94	**
Treatment	5	20		8	43	**
Bloom vs. pod contrast	*1*	*3*		*1*	*19*	
Spring vs. winter pea contrast	--	--		*1*	*214*	**
Residual error	9	68		24	13	
	0.3 – 0.6 m soil depth					
Block	3	324	**	3	17	**
Treatment	5	12		8	6	*
Bloom vs. pod contrast	*1*	*27*		*1*	*27*	**
Spring vs. winter pea contrast				*1*	*8*	*
Residual error	9	16		24	3	
	Total 0.6 m soil depth					
Block	3	940	**	3	131	**
Treatment	5	42		8	66	**
Bloom vs. pod contrast	*1*	*48*		*1*	*90*	*
Spring vs. winter pea contrast				*1*	*304*	**
Residual error	9	118		24	18	

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.

Table B.7. Analysis of variance (ANOVA) mean squares for marginal† soil NO_3-N content at the end of the green fallow period† within two depth increments and the total soil profile in a green manure study at Bozeman MT, 2005-2006.

Source	2005			2006		
	df	Mean square		df	Mean square	
		0 – 0.3 m soil depth				
Block (B)	3	919		3	461	**
Treatment (T)	5	705		10	58	*
Bloom vs. pod contrast	*1*	*267*		*1*	*6*	
Spring vs. winter pea contrast	*1*	--		*1*	*97*	*
Till vs. no-till termination contrast	*1*	*5*		*1*	*104*	*
Residual error	15	477		30	25	
		0.3 – 0.6 m soil depth				
B	3	654	**	3	61	**
T	5	28		10	19	*
Bloom vs. pod contrast	*1*	*4*		*1*	*16*	
Spring vs. winter pea contrast	*1*	--		*1*	*7*	
Till vs. no-till termination contrast	*1*	*91*		*1*	*54*	**
Residual error	15	48		30	7	
		Total 0.6 m soil depth				
B	3	1818	*	3	785	**
T	5	843		10	128	*
Bloom vs. pod contrast	*1*	*338*		*1*	*40*	
Spring vs. winter pea contrast	*1*	--		*1*	*157*	*
Till vs. no-till termination contrast	*1*	*140*		*1*	*308*	*
Residual error	15	730		30	48	

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.
‡ The end of the green fallow period coincides with winter wheat seeding after one green manure cycle (9 Sep, 2005, 29 Aug 2006)
*, ** denote significance at $P < 0.1$ and $P < 0.01$, respectively.

Table B.8. Analysis of variance (ANOVA) mean squares for potentially mineralizable nitrogen (PMN-N) and Olsen P at the end of the green fallow period† in a green manure study at Bozeman, MT, 2005-2006.

Source	2005			2006		
	df	Mean square		df	Mean square	
	0 – 0.15 m soil depth					
MgN kg dry soil^{-1}	Ln (x 10^2)					
Block (B)	3	113		3	20	*
Treatment (T)	6	77		11	158	
Tilled fallow vs. crop contrast	*1*	2		*1*	*116*	
Bloom vs. pod contrast	*1*	145	*	*1*	*31*	
Winter vs. spring pea contrast	--	--		*1*	*12*	
Till vs. no-till termination contrast	*1*	*1*		*1*	*323*	*
Residual error	18	61		33	104	
Mg P kg $^{-1}$						
Block (B)	3	11		3	125	**
Treatment (T)	6	8		11	15	*
Tilled fallow vs. crop contrast	*1*	*22*		*1*	*8*	
Bloom vs. pod contrast	*1*	*7*		*1*	*51*	*
Winter vs. spring pea contrast	--	--		*1*	*12*	
Till vs. no-till termination contrast	*1*	*3*		*1*	*3*	
Residual error	18	14		32	9	

*, ** denote significance at $P \leq 0.1$ and $P \leq 0.01$, respectively.

† The end of the green fallow period coincides with winter wheat seeding after one green manure cycle (9 Sep, 2005, 29 Aug 2006)

Table B.9. Analysis of variance (ANOVA) mean squares for soil water content in tilled fallow plots sampled on sequential dates from 19 Oct 2004 to 09 Sep 2005, and 15 Sep 2005 to 29 Aug 2006 at Bozeman, MT.

	2005			2006†		
Source	df	Mean squares		df	Mean squares	
	0 – 0.3 core depth mm soil water (x 10^3)					
Block	3	129		3	546	*
Date	4	2102	**	4	24912	**
Residual error	20	167		16	123	
	0.3 – 0.6 core depth mm soil water (x 10^3)					
Block	3	489	**	3	71	
Date	4	24974	**	4	28784	**
Residual error	20	87		16	36	
	0.6 – 0.9 core depth mm soil water (x 10^3)					
Block	3	414	**	3	248	
Date	4	16277	**	4	20136	**
Residual error	20	78		16	174	
	0.9 – 1.2 core depth mm soil water (x 10^3)					
Block	3	909	**	3	87	**
Date	4	6319		4	11249	**
Residual error	20	103		16	144	
	Total 1.2 core depth mm soil water (x 10^3)					
Block	3	5684	**	3	2581	**
Date	4	147045	**	4	314198	**
Residual error	20	609		16	414	

† Missing values for 7 June 2006, bloom-winter pea sample date

*, ** denote significance at $P < 0.1$ and $P < 0.01$, respectively.

Table B.10. Analysis of variance (ANOVA) mean squares for marginal† soil water content at crop termination in a green manure study at Bozeman, MT, 2005-2006.

Source	2005			2006‡		
	df	Mean square		df	Mean square	
		0 – 0.3 m soil depth(x 10^3)				
Block	3	759		3	760	*
Treatment	5	1745		5	485	*
Bloom vs. pod contrast	*1*	*4238*	**	*1*	*1995*	**
Winter vs. spring pea contrast	--	--		*1*	*363*	*
Residual error	15	482		13	135	
		0.3 – 0.6 m soil depth (x 10^3)				
Block	3	1209		3	125	
Treatment	5	1957		5	422	*
Bloom vs. pod contrast	*1*	*2809*		*1*	*4014*	
Winter vs. spring pea contrast	--	--		*1*	*3187*	
Residual error	15	1245		14	1994	
		0.6 – 0.9 m soil depth(x 10^3)				
Block	3	751	**	3	338	
Treatment	5	395	**	5	1357	**
Bloom vs. pod contrast	*1*	*1478*	**	*1*	*6496*	**
Winter vs. spring pea contrast	--	--		*1*	*1441*	*
Residual error	15	67		15	190	
		0.9 – 1.2 m soil depth (x 10^3)				
Block	3	237	*	3	308	
Treatment	5	344	*	5	261	
Bloom vs. pod contrast	*1*	*1409*	**	*1*	782	*
Winter vs. spring pea contrast	--	--		*1*	712	*
Residual error	15	80		15	156	
		Total 1.2 m soil column (x10^3)				
Block	3	5522	*	3	6196	**
Treatment	5	10469	**	5	11923	**
Bloom vs. pod contrast	*1*	*33200*	**	*1*	*54823*	**
Winter vs. spring pea contrast	--	--		*1*	*7708*	*
Residual error	15	2015		12	1078	

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.

‡ Missing values for 7 June 2006, bloom-winter pea sample date

*, ** denote significance at $P < 0.1$ and $P < 0.01$, respectively.

Table B.11. Analysis of variance (ANOVA) mean squares for marginal† soil water content at the end of the green fallow period‡ in four depth increments and the total soil column in a green manure study at Bozeman, MT, 2005-2006.

Source	2005			2006		
	df	Mean square		df	Mean square	
	0 – 0.3 m soil depth(x 10^2)					
Block (B)	3	45		3	435	**
Treatment (T)	5	34		10	142	**
Bloom vs. pod contrast	*1*	*19*		*1*	*172*	*
Winter vs. spring pea contrast	--	--		*1*	*395*	**
Tillage vs. non-tillage termination	*1*	*0*		*1*	*118*	*
Residual error	14	29		27	32	
	0.3 – 0.6 m soil depth (x 10^2)					
B	3	279	**	3	45	
T	5	91	**	10	183	**
Bloom vs. pod contrast	*1*	*245*	**	*1*	*132*	*
Winter vs. spring pea contrast	--	--		*1*	*517*	**
Tillage vs. non-tillage termination	*1*	*117*	*	*1*	*497*	**
Residual error	14	16		28	20	
	0.6 – 0.9 m soil depth(x 10^2)					
B	3	78	**	3	14	
T	5	31	*	10	66	**
Bloom vs. pod contrast	*1*	*42*	*	*1*	*40*	*
Winter vs. spring pea contrast	--	--		*1*	*69*	*
Tillage vs. non-tillage termination	*1*	*62*	*	*1*	*210*	**
Residual error	14	9		30	13	
	0.9 – 1.2 m soil depth (x 10^2)					
B	3	14		3	36	**
T	5	18		10	5	
Bloom vs. pod contrast	*1*	*20*		*1*	*3*	
Winter vs. spring pea contrast	--	--		*1*	*0*	
Tillage vs. non-tillage termination	*1*	*37*		*1*	*10*	
Residual error	14	15		29	7	
	Total 1.2 m soil column (x10^2)					
B	3	518	*	3	223	
T	5	388	*	10	1085	**
Bloom vs. pod contrast	*1*	*87*		*1*	*863*	*
Winter vs. spring pea contrast	--			*1*	*2327*	**
Tillage vs. non-tillage termination	*1*	*788*	*	*1*	*2351*	**
Residual error	14	104		24	126	

† Marginal refers to the difference between the green manure treatment and a tilled bare fallow control.

‡ The end of the green fallow period coincides with winter wheat seeding after one green manure cycle (9 Sep, 2005, 29 Aug 2006)

*, ** denote significance at $P < 0.1$ and $P < 0.01$, respectively.