

SUSTAINABLE CROPPING SYSTEMS FOR THE NORTHERN GREAT PLAINS – ENERGETIC  
AND ECONOMIC CONSIDERATIONS

by

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A dissertation submitted in partial fulfillment  
of the requirements for the degree

of

Doctor of Philosophy

in

Ecology and Environmental Sciences

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## DEDICATION

This dissertation is dedicated to my sons Ian and Eric. Their lives will surely be impacted by the inevitable transition out of the fossil fuel era. It is my hope that clear analytical thinking will guide the difficult decisions that will have to be made about the use of fossil energy during their lives. This is my contribution to that effort to date. I hope to do more.

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## TABLE OF CONTENTS

1. INTRODUCTION .....	XIII
Energy Analysis and Agriculture .....	1
Energy Terminology .....	6
Contemporary Approaches to Energy and Agriculture .....	10
Changes in Soil Fertility .....	13
Agricultural Sustainability on the Northern Great Plains .....	17
Historical Perspectives on Sustainability .....	17
A Systems Approach to Sustainability .....	21
Legume Green Manure Cover Crops – Partial Intensification .....	24
Research Objectives .....	26
References .....	28
2. ENERGETIC AND ECONOMIC ANALYSES OF DIVERSIFICATION AND INTENSIFICATION OF FALLOW-BASED CROPPING SYSTEMS.....	37
Introduction.....	37
Materials and Methods .....	41
Site Description .....	41
Experimental Design and Management .....	42
Economic Analysis .....	46
Energy Analysis.....	48
Statistical Analysis .....	50
Results and Discussion.....	51
Inputs to Crop Production .....	51
Mixed Model Statistical Results .....	53
Transition to No-Till Fallow: Rotation 1 vs. 2 .....	53
Intensification of Fallow with Continuous Wheat: Rotation 2 vs. 3 .....	56
Diversification - Replacing Spring Wheat with Spring Pea: Rotation 3 vs. 4 .....	58
Replacing Spring Pea with Winter Pea: Rotation 4 vs. 5 .....	60
Harvest of Pea Biomass as Forage: Rotation 5 vs. 6.....	61
Change to Spring Wheat in Year 2: Rotations 6 vs. 7 .....	64
Organic Production of WP <sub>f</sub> -WW: Rotation 7 vs. 8.....	65
Pea Green Manure for Organic Spring Wheat: Rotation 8.....	66
Accounting for Changes in Soil Fertility.....	67
Scenario Analysis Using Price Ratios .....	68
Conclusions.....	70
Comparison of Energy Intensity to U.S. National Average.....	70
Machine Operations and Fuel Consumption.....	71

## TABLE OF CONTENTS- CONTINUED

Nitrogen Fertilizer .....	71
Marginal Energy Intensity and System Energy Intensity .....	72
Comparison of Tilled and No-Till systems .....	73
Organic Crop Production Systems .....	74
Recommendations .....	74
Acknowledgements .....	76
Tables and Figures .....	77
References .....	86
3. PULSE CROPS IMPROVE ENERGY INTENSITY AND PRODUCTIVITY OF CEREAL PRODUCTION IN MONTANA, USA .....	93
Contribution of Authors and Co-Authors .....	93
Manuscript Information Page .....	94
Abstract .....	95
Introduction .....	95
Description of study area .....	100
Methodology .....	102
Crop Energy Budgets .....	102
Statistical analysis .....	106
Results and Discussion .....	107
Comparative Analysis of Pulses and Cereals (Year 1) .....	107
Rotational Effect of Pulses on Wheat .....	111
Analysis of the 2-Year Systems .....	115
Conclusions .....	116
Acknowledgements .....	117
Tables and Figures .....	118
References .....	123
4. TILLAGE OF GREEN MANURE AFFECTS DRYLAND SPRING WHEAT PRODUCTION: ECONOMIC AND ENERGETIC ANALYSES. ....	129
Introduction .....	129
Materials and Methods .....	133
Site Description .....	133
Crop Management .....	134
Economic Analysis .....	140
Energy Analysis .....	141
Statistical Analysis .....	143
Results and Discussion .....	144

## TABLE OF CONTENTS- CONTINUED

Legume Green Manure Growth .....	144
Weed Competition .....	145
LGM C:N Ratio and Total N Content.....	145
Soil Water .....	146
Soil NO <sub>3</sub> -N.....	149
Wheat Yield & Quality .....	150
Costs of LGM Management.....	155
Cropping System Economics .....	156
Cropping System Energetics.....	156
Economic and Energetic Costs of LGM N .....	160
Conclusions.....	162
Acknowledgements .....	163
Tables and Figures .....	164
References .....	170
5. EFFECT OF GROWTH TIMING OF ANNUAL LEGUME GREEN MANURE COVER CROPS ON SOIL WATER USE, BIOMASS PRODUCTION, AND SUBSEQUENT WHEAT PRODUCTION.....	177
Introduction.....	177
Materials and Methods .....	179
Site Description .....	179
Crop Management .....	180
Statistical Analysis .....	185
Results and Discussion.....	186
Legume green manure growth and water use.....	186
Soil Water .....	188
Soil Nitrate-N.....	190
Wheat Yield and Quality.....	191
Conclusions.....	192
Acknowledgements .....	193
Tables and Figures .....	194
References .....	200

TABLE OF CONTENTS- CONTINUED

6. EPILOGUE.....	203
Personal Reflection.....	203
A New Paradigm For Agriculture and Energy. ....	206
Analyzing the Use of Energy in Agriculture .....	208
Green Manure Cover Crops.....	210
References.....	212

## LIST OF TABLES

Table	Page
2.1 Monthly total precipitation and mean temperature for 2005 and 2006 crop year (Sept.-Aug).....	77
2.2 Crop sequences of the eight rotation treatments, and explanation of the stepwise changes. ....	77
2.3 Summary of split-plot N fertilization strategies. ....	78
2.4 Tillage operations and herbicide applications. ....	79
2.5 Economic and energetic costs of inputs on areal basis. ....	80
2.6 Crop yield and grain protein content 2005 and 2006.....	81
2.7 Economic profit for 2005, 2006, and combined 2005-2006 cropping system. ....	82
2.8 Energy Intensity (EI) and Net Energy Yield (NEY).....	82
3.1 Energy coefficients for manufacture, operation, and maintenance of farm equipment. ....	121
3.2 Embodied energy coefficient for selected inputs.....	122
4.1 Precipitation and Temperature .....	164
4.2. Dates and descriptions of field operations.....	164
4.3. Prices and energy coefficient for inputs and outputs. ....	165
4.4 LGM and weed biomass treatment means and post-hoc multiple comparison results .....	165
4.5. Soil water and NO <sub>3</sub> -N Treatment means .....	166
4.6. Mixed model fixed effect F values and main effect means for wheat yield components, quality, and economic and energetic metrics.....	167
4.7 Economic and Energetic costs of Fallow and LGM treatments .....	167
4.8 Economic and energetic costs of LGM N. ....	168
5.1 Growing season monthly precipitation and mean monthly temperatures, 2008-2011, Amsterdam MT.....	194
5.2 Dates and details of field operations.....	194

## LIST OF TABLES - CONTINUED

Table	Page
5.3 Legume green manure shoot biomass ( $\text{Mg ha}^{-1}$ ) and biomass N ( $\text{kg N ha}^{-1}$ ). .....	195
5.4 Mean values by year of soil water and nitrate N, 0-90 cm depth, for fallow plots, and marginal values (i.e. difference from fallow) for all other treatments. F, I, and P indicate Flower, Intermediate, and Pod termination times.....	196
5.5 Mixed model values of the <i>F</i> -ratio, <i>P</i> -values, and least squares means for marginal soil water and nitrate N for model with year as fixed effect only for treatments present in all years.....	197
5.6 Mixed model <i>F</i> -ratios for effect of LGM of Wheat yield components.....	198
5.7 Means of wheat yield components at N fertilizer level of $50 \text{ kg N ha}^{-1}$ .....	199

## LIST OF FIGURES

Figure	Page
1.1 Average Montana wheat yield 1919-2010 .....	27
2.1 Categorized energy inputs ( $\text{GJ ha}^{-1}$ ) for each crop rotation. TF: tilled fallow, CF: chemical fallow, SW: spring wheat, SP: spring pea, WP: winter pea, WPf: winter pea forage, GM: green manure. WW: winter wheat. N-Hi, N-1/2, and N-Lo refer to N fertilization strategies. ....	83
2.2 Categorized input costs ( $\text{\$ ha}^{-1}$ ). TF: tilled fallow, CF: chemical fallow, SW: spring wheat, SP: spring pea, WP: winter pea, WPf: winter pea forage, GM: green manure. WW: winter wheat. N-Hi, N-1/2, and N-Lo refer to N fertilization strategies .....	84
2.3 Price ratio of Urea-N to US#1 hard red winter wheat. Bars indicate annual range in price ratio for protein range from $110 \text{ g kg}^{-1}$ to $130 \text{ g kg}^{-1}$ . Data from USDA NASS.....	85
3.1 Location of surveyed farms and major pulse-producing counties in Montana. ....	118
3.2 Embodied energy ( $\text{GJ ha}^{-1}$ ) for crop production inputs... ..	119
3.3 Energy Intensity ( $\text{MJ kg}^{-1}$ ) of Year 1 pea, lentil, and wheat, and Year 2 wheat following those Year 1 crops. ....	120
3.4 Net Energy Yield (NEY) of Year 1 pea, lentil, and wheat, and Year 2 wheat following each of those Year 1 crops.....	121
4.1 Species (S) x Nitrogen (N) interactions at levels of tillage for wheat yield components, economic, and energetic metrics for Pea (SP), and Lentil (SL) green manure and Fallow (F) control treatments.....	169

## ABSTRACT

Reliance on non-renewable resources is among the fundamental challenges to agricultural sustainability. Quantification of inputs in units of embodied fossil energy offers insight into sustainable use of these resources. Metrics of intensity, efficiency of non-renewable energy inputs to agriculture have been proposed for optimization in search of sustainability in the face of energy scarcity. Such analyses have found controversial results however, and further theoretical understanding is necessary. The research presented here focuses on approaches to sustainability targeting the semiarid northern Great Plains of North America. The 4 million ha of cropland fallowed in this region every year represent both a challenge to sustainability and an opportunity to address that challenge. Long identified as unsustainable when accomplished by tillage and without fertilizer input, the summerfallow – wheat crop production system is also energy-efficient by definitions that do not account for changes in soil fertility. It is shown here that accounting for lost soil N as an energy input to crop production partially resolves this paradox, but no strategy for energetic valuation of systems that build soil quality is apparent. Alternatives to summerfallow considered here include pulse crops (e.g. pea and lentil ) grown for grain, forage, or as cover crops. In research conducted on farms already growing pulses, the largest effect on cropping system energy productivity was due to increased wheat yield rather than a reduction of inputs. In plot-scale research addressing a wider variety of production practices, neither system-level energy intensity nor productivity provided more insight into energy price exposure than basic economic analyses. Legume green manure (LGM) cover crops increased wheat grain yield and protein, especially when incorporated with tillage, but did not improve cropping system energy intensity. It was found by a novel approach, however, that the energy cost of the short-term N equivalance of LGM cover cropping was less than that of fertilizer N, while the economic cost was greater. Pulse crops were found to have potential for improving the sustainability of cropping systems in the northern Great Plains, both harvested for grain where that is feasible and used as cover crops where water is more limiting.

## 1. INTRODUCTION

### Energy Analysis and Agriculture

“For every calory [*sic*] obtained from food in the U.S.A. we put a little more than a calory of fossil fuel into the production of the food”

-F. Daniels, 1956, *citing a survey conducted by V. Stoikov. from Black (1971).*

“Energy intensity and energy output/input ratio are integrative indicators of the environmental effects of crop production, which can be used to formulate recommendations for fertilization, which are optimum as far as the environment is concerned”

-Hülsbergen *et al.* (2001).

“Unfortunately there is no suitable measure to evaluate the efficiency of these energy subsidies, a fact that has not stopped such efforts... Critics of modern agriculture see such ratios as perfect proof of the dubious nature of subsidized farming, but the ratios are inappropriate and should be avoided”

-Smil (2008, p. 303)

Analysis of the use of fossil energy in farm production has a controversial history going back nearly to the beginning of widespread mechanization of farm field operations (Black, 1971; Leach, 1975). The field of study was predated and inspired by anthropological analyses of the metabolic energy used by primitive cultures in food procurement (Pimentel and Pimentel, 2008, Ch.6). Concern about the reliance of modern agriculture on non-renewable resources gained prominence with the energy shock of the early 1970's (Pimentel et al., 1973), spawning detailed energy budgets of a wide variety of crops and cropping systems, as cataloged by Pimentel and Pimentel (2008, Ch. 8-12).

In a review of the methodology underlying those studies, Jones (1989) concluded that energy analysis had “failed to live up to the expectations of early proponents”, noting persistent confusion on issues of methodology and interpretation, little impact of energy analyses on agriculture policy, and a trend of “primarily taxonomic studies giving details of energy analyses of yet further systems”. Jones (1989) presented the three most pressing questions for agricultural energy analysis as:

1. What can we measure?
2. How do we measure it?
3. What does it mean?

Some potential answers to these questions were debated in a heated exchange among economists earlier. Webb and Pearce (1975) argued that the critical issues in economics of fossil energy use were equitable intertemporal and intergenerational rationing of finite resources, and optimized substitution of labor-intensive and energy-intensive technologies. Analyses based on energy content of products were found to offer no additional insight beyond basic economic analysis, and were even deemed to obscure some issues. A fundamental difficulty facing energy analysis was claimed to be the lack of a common energetic unit to value labor and capital. The assumption of homogeneity of different energy sources was also criticized. Market price was deemed to be a better indicator of the value of scarce resources. Energy analysis was concluded to be a “technique in search of a function”, “of no use beyond that which is currently served by some other technique”, and potentially harmful due to the potential to mislead policy makers and lay people (*Ibid*).

Common (1976) countered that Webb and Pearce (1975) had fundamentally misunderstood the aims of energy analysis, and mistakenly attributed claims of normative value to the results. An important function for energy analysis claimed by Common (1976) was the prediction of the effect of changes in fuel prices, and particularly a fuel tax, on non-energy commodity prices.

Details of the ensuing debate in the pages of the journal *Energy Policy* (Webb and Pearce, 1977; Common 1977, Chapman, 1977) are beyond the scope of the application to agriculture. Counter claims of miscomprehension and misrepresentation were debated with examples including copper mining and nuclear power plant construction. A single point of agreement does seem to have emerged: energy analysis is a descriptive technique, *not by itself sufficient for project evaluation or resource allocation optimization*. Webb and Pearce (1975) seem to have been initially motivated to criticism of energy analysis by implied claims of normative value and resulting perception of undue status of energy analysis in political circles. A source of disagreement between economists and proponents of energetic theories of value is the long history in the field of economics of the conceptual distinction between positive and normative conclusions (Weston, 1994), while energy studies have often been implicitly more prescriptive (Webb and Pearce, 1975).

Edwards (1976) added insightful commentary on two assumptions claimed to be implicit to the advocacy of energy valuation for resource allocation. The first is that relative market prices for different food products and for farm production inputs are

inadequate at reflecting relative values and costs to society. The second implied assumption is that the energy 'value' of those products more closely reflects their true social value. Edwards concluded that energy analysis was of little help in resolving the related issues of misallocation of resources attributed to externalities.

Jones (1989) sided with Webb and Pearce (1975) regarding limitations of energy analysis due to omission of labor, capital, and time, and noted additional complications in the application of energy analysis to agriculture with regards to scarcity of land. With specific regards to agricultural application of energy analysis, Jones (1989) noted the potential for confusion regarding the primary energy conversion process (solar to chemical energy via photosynthesis), and the role of fossil energy in mediating that process. The efficiency of the photosynthetic energy conversion process was noted to be quite low (<1%), with variability in response to environmental conditions having nothing to do with the fossil energy used to facilitate the agricultural exploitation of the photosynthetic process. The ultimate conclusions of Jones (1989) were that energy analysis does have some utility, largely as a supplement to economic analysis, for:

1. Identification of particularly energy intensive categories of inputs for prioritization of efficiency optimization.
2. Identifying tradeoff opportunities between energy and other inputs.
3. Identifying energy-related constraints to economic optimization.

Additionally, Jones (1989) suggested that energy analysis of agriculture would be most useful where economic analysis was weakest, for consideration of externalities and inter-temporal preference *over the long term, and at the national level, rather than*

*as a guide to specific day-to-day decisions* (emphasis mine). General comparisons were deemed preferable to specific system analyses, with “parsimonious methodology” supporting “simple, broad-brushed” comparisons most likely to be useful (*Ibid*).

In the more than two decades since Jones’ call for a more coherent framework for interpretation of agricultural energy analysis, little additional theoretical work has been published. The publication of energy budgets of myriad crops and cropping systems has continued (Carlsson-Kanyama et al., 2003), however, garnering popular attention again with recent volatility in energy and commodity markets (Gasparatos et al., 2011). The conceptual appeal of energy efficiency and related ratio-based metrics like carbon footprints (Czarnecki, 2011) appears to be so compelling that further research to improve methodology and clarify appropriate interpretation is necessary.

The research presented in this dissertation was conceived, conducted and interpreted under an evolving appreciation of the difficulty of drawing conclusions from the results. While Jones (1989) might have classified the work presented here as tired taxonomic studies reporting details of yet additional systems it has become a series of studies, perhaps excessive in detail, illustrating some of the insights and pitfalls of energetic analysis as a complement to economic analysis of cropping systems. The overarching goal of the following chapters is to further examine where energetic analysis offers unique insight into agricultural sustainability, with a focus on the cropping systems of the semi-arid northern Great Plains of N. America.

### Energy Terminology

There is a lack of standardized terminology for the various ratios and differences that have been computed from energy inputs and outputs of cropping systems (Liska and Cassman, 2008; Pelletier et al., 2011). In the interest of resolving confusion over terminology, a review is provided here.

Inputs to crop production typically considered in agricultural energy analysis include fuel, machinery, fertilizer, pesticide, and seed. These inputs are accounted for in terms of embodied energy, or the energy used in their manufacture. Published estimates exist for most typical farm inputs, but are not always consistent, warranting caution in comparison of results of different studies. In some cases, different system boundaries or other fundamental assumptions underlie differences in estimated embodied energy content (Baum et al., 2009). In other cases, technological change has resulted in changes to embodied energy over time. Uhlin (1999) reported that the energy required to manufacture 1 kg of ammonia nitrogen (N) (a precursor to urea and other fertilizer products) decreased from 152 MJ in 1956 to 40 MJ in 1993. The theoretical limit of efficiency for the methane steam conversion process responsible for the majority of ammonia production is  $23 \text{ MJ kg}^{-1}$  (Mudahar and Hignett, 1987), so further improvements will be more challenging as the limit is approached. Values for the energy embodied in N fertilizer cited in recent research range from  $32 \text{ MJ kg}^{-1}$  (Rathke and Diepenbrock, 2006), to as much as  $91 \text{ MJ kg}^{-1}$  (Zentner et al, 1989). Smil (2008) noted that older fertilizer plants remain in operation, and Shapouri et al. (2004)

estimated a 2001 global average of  $57 \text{ MJ kg}^{-1} \text{ N}$ , which is used here. There is also uncertainty about the energy embodied in manufacture of herbicides, particularly glyphosate, which is addressed in more detail in chapters 2 and 3 of this dissertation.

When harvested crop material is considered as an output of the system being analyzed it sometimes represented in terms of its energy content, i.e. the energy released when it is burned or metabolized. Values have been cited using higher heating value from bomb calorimeter combustion (Li et al., 2002), or based on efficiency of human metabolism (Zentner et al. 1998), ruminant metabolism (Hoeppner et al. 2006; Gelfand et al. 2010), or biofuel conversion technologies (Gelfand et al. 2010).

The ratio of harvested crop energy content to the energy embodied in the crop production inputs ( $\text{energy}_{\text{out}}/\text{energy}_{\text{in}}$ ) has been reported under the name *energy return on energy invested* (EROEI, or EROI) (Hammerschlag, 2006), but also as *energy efficiency* (Pimentel et al., 1983; Hoeppner et al. 2006, Gelfand et al. 2010), and *net energy ratio* (Liska and Cassman, 2008); this is the measure reported in the exhaustive summaries by Pimentel and Pimentel (2008). While this energy ratio may be a useful concept for comparison of biofuel production systems, where the output product is valued for its energy content, several researchers have noted that it invites inappropriate comparison of food crops valued for properties other than energy (Fluck, 1979; Jones, 1989; Smil 2008).

Fluck (1979) proposed an improved measure, which he termed *energy productivity*, as the quantity of product per unit of input energy ( $\text{kg MJ}^{-1}$ ), to be used for

comparison of systems resulting in the “same product, at the same place, at the same time”. This measure has been reported extensively in the recent research under various other names including: *energy efficiency* (Khakbazan et al., 2009; Zentner et al., 2011) and *weight/energy ratio*, (Cruse et al., 2010). Others have reported the reciprocal of Fluck’s *energy productivity*, in units of  $\text{MJ kg}^{-1}$  or  $\text{GJ Mg}^{-1}$ . This measurement has been called *energy intensity* (Hülsbergen et al., 2002), *energy consumption* (Gomiero et al., 2008), or simply stated as the amount of fossil energy required to produce a quantity of some product [e.g. 1 kg of wheat (*Triticum aestivum* L.) in Piringer and Steinberg (2006)]. A low value of energy intensity corresponds to a high value of energy efficiency. Energy intensity can be converted to energy efficiency by simply taking the reciprocal and multiplying by the energy coefficient of choice for the crop material and utilization process being considered.

Efficiency is a powerfully intuitive concept, understood as a ratio of outputs to inputs, greater efficiency generally being desirable. In the typical engineering interpretation of energy conversion processes, efficiency is always less than 1; efficiency representing the fraction of energy input to a system converted to useful work or heat. Energy ‘efficiency’ of agriculture, when reported as the ratio of crop output energy to fossil input energy is frequently found to be much greater than 1, indicating that the efficiency being measured is not conceptually the same as the traditional interpretation. Indeed, the true energy conversion process in agriculture is photosynthesis, driven by solar energy. To consider the proportion of the resulting photosynthetic yield to the

external energy supplied to agricultural exploitation of the process is not consistent with the traditional interpretation of efficiency.

There is also a common “systematic misperception” of efficiency (Larrick and Soll, 2008) when comparing the quantity of energy consumed (inputs, in the denominator) by systems of differing efficiencies to achieve the same outcome (outputs, in the numerator). This misperception results from the nonlinearity of the reciprocal transformation. Because of the confusion resulting from inconsistent historical use of the term ‘efficiency’, and the more intuitive interpretation of differences among systems when ‘efficiency’ is expressed as a ratio with energy input in the numerator (e.g.  $\text{MJ kg}^{-1}$ ), this metric is used here under the name *Energy Intensity* (EI). A smaller EI number indicates less energy is used to produce a quantity of output. This metric has been reported in many studies (albeit sometimes with a different name) including: Hlsbergen et al, 2001; Bailey et al., 2003; Piringer and Steinberg, 2006; Dieke et al., 2008; Guzmn and Alonso, 2008; Liu et al. 2010; and Aluvione et al. 2011. Another advantage of the concept of EI expressed in  $\text{MJ kg}^{-1}$  is that it is conceptually similar to, and in the same units as, embodied energy (Bullard and Herendeen, 1975), which is familiar across disciplinary boundaries.

Net energy yield (NEY), the difference between the energy value of the crop produced and the energy embodied in the inputs used in producing the crop ( $\text{Energy}_{\text{out}} - \text{Energy}_{\text{in}}$ ) has also been cited frequently. Net energy yield (NEY) has been proposed as the standard measure of energy productivity of biofuel production systems (Liska and

Cassman, 2008). Even in the context of biofuel production, NEY has been criticized on the basis that the different forms of energy accounted for as inputs and outputs of the system are not substitutable and have different uses and values (Shapouri et al., 2004). Nevertheless, net energy yield or gain is frequently reported in energy analyses of cropping systems producing food and feed as well (Hülsbergen et al., 2002; Gelfand et al. 2010).

#### Contemporary Approaches to Energy and Agriculture

Nearly half of the fossil energy used in wheat production in the U.S. is for the production of N fertilizer (Piringer and Steinberg, 2006). In the northern Great Plains, published estimates for this proportion are as high as 71% (Zentner et al. 2004a) due to otherwise relatively low inputs, and moderate to aggressive N fertilization in the pursuit of high protein wheat. Many evaluations of energy use in different cropping systems have shown organic and low-input systems to be more energy efficient in a wide variety of system and environmental contexts (Berardi, 1978; Craumer, 1979; Pimentel et al. 1983; Hoepfner et al. 2006; Khakbazan et al., 2009; Macrae et al., 2010; Cruse et al., 2010; Zentner et al., 2011), where efficiency is typically expressed as a ratio of the energy content of the harvested crop to the energy embodied in crop production inputs. In contrast, Gelfand et al. (2010) found conventional, fertilized, no-till crop production to be more energy-efficient than organic production of corn (*Zea mays* L.)-soybean(*Glycine max* L. Merr.)-wheat rotations in the upper Midwest. Hülsbergen et al.

(2001; 2002), and Rathke and Diepenbrock (2006) also found that a moderate quantity of N fertilizer optimized energy efficiency of winter wheat and canola (*Brassica napus* L.) in intensive production systems central Germany. That there has more typically been found an inverse relationship between crop productivity and cropping system energy efficiency has prompted some researchers to declare these measures useful only in a tradeoff perspective (Hülsbergen et al., 2001; Gomiero et al. 2008), where optimization of that tradeoff remains elusive. Green (1976) claimed “Low agricultural productivity is energy efficient, high agricultural productivity is energy demanding.” There has been little investigative research into the properties of the few systems where increased inputs have been shown to result in increased cropping system energy efficiency.

Zentner et al. (1989) reviewed reports that energy efficiency of Canadian grain production was declining over time due to increased inputs, and conflicting reports that rising yields were offsetting the increased inputs resulting in relatively constant system energy efficiency. Zentner noted spatial trends on the Canadian Prairies where farms in dry areas had lower inputs and were more efficient, as well as reports that inclusion of oilseeds or forages reduced energy efficiency. In their own long-term plot studies, Zentner et al. (1984b; 1989) found the most energy-efficient cropping systems at one location to be those with the highest frequency of summerfallow, lowest diversity (wheat only), and lowest level of N fertilizer. Zentner et al. (2001) explicitly identified a major driving force for this paradox as lack of accounting for the energy removed from the soil in the form of N mineralized from soil organic matter.

Sensitivity analyses were presented in Zentner and Campbell (1988) for the effect of wheat and N fertilizer prices on net economic returns in the same crop rotations considered in Zentner et al. (1984a; 1984b; 1989; and 2001). Either lower fertilizer prices or higher wheat prices made the more intensive crop rotations more profitable than fallow-wheat. Zentner et al. (1989) concluded that the greater EI of the extended crop rotations threatened the economic viability of those rotations under a scenario of increased energy costs deemed likely to occur in the future. No-till management was recognized as a possible energy conserving practice, but the cost of herbicide at the time made adoption economically unfavorable.

In hindsight, neither the energetic nor economic obstacles to cropping system diversification, no-till adoption, and intensification cited by Zentner et al. (1988; 1989) were predictive of the recent changes in Canadian prairie agriculture. The price of glyphosate, the foundational herbicide for no-till crop production, declined substantially after expiration of patent protection (Woodburn, 2000). Adoption of no-till crop production, along with diversification to include pulse and oilseed crops, has since radically changed crop production practices on the Canadian Prairies (Tanaka et al., 2010).

Zentner et al. (2001) presented another update to energy and economic analyses of the same crop rotation study analyzed in Zentner et al. (1984a, 1984b, 1988, and 1989), this time considering a new crop rotation, wheat – lentil (*Lens culinaris* Medickus) that was added in 1979. The crop rotations considered were fallow-wheat (F-W), fallow-

wheat-wheat (F-W-W), wheat-lentil (W-L), and continuous wheat (W-W). The W-L rotation had 24% reduced energy input compared to W-W, with most of the difference due to reduced N fertilizer use. There was no difference in wheat yield between the W-W and W-L rotations, but lentil yielded less than wheat, resulting in reduced NEY for W-L, and only a 5% reduction in system EI for W-L compared to W-W. Both F-W-W and F-W had lower energy intensity than either continuously cropped rotation. Economic analyses, including sensitivity to wheat and lentil prices found that the W-L rotation was more profitable than W-W when the price of lentil exceeded \$350 Mg<sup>-1</sup> if the price of wheat was \$184 Mg<sup>-1</sup>. There was little difference in net revenue among W-W, F-W, and F-W-W, but the rotations including fallow had lower year-to-year variability in net returns.

#### Changes in Soil Fertility

Zentner et al. (2001) also reported several soil quality measurements, including soil organic carbon (SOC), after 30 yr of crop rotation treatments. Cropping systems that appeared to have the greatest energy efficiency (e.g. wheat-fallow) were found to have less SOC content after 30 yr relative to continuously cropped systems. Typical energy balance methodology has an ambiguous system boundary with regards to the soil organic N pool and mineral N pool. Although this anomaly has been noted (Zentner et al. 2001), there have been no published attempts or proposed strategies to account for changes in soil nutrient status or other soil properties in agricultural energy budgets.

One simple approach would be to consider N added to or removed from the soil organic N pool as either an output or an input to the system subject to the energetic analysis. The difference in SOC noted in Zentner et al. (2001) was approximately 4 Mg ha<sup>-1</sup> of SOC between the continuously cropped systems (W-W and W-L) and those having any frequency of fallow (F-W and F-W-W). An approximation of the concomitant soil organic N change may be made by assuming a soil C:N ratio of 8:1, indicating a total loss of approximately 500 kg N ha<sup>-1</sup> in the fallow systems relative to the continuously cropped systems over 30 yr. This corresponds to an average of about 17 kg N ha<sup>-1</sup> yr<sup>-1</sup> of organic soil N removed from the soil and input to the fallow treatments available N pool by mineralization, but not accounted for in the energy budget. If the system boundary is assumed to lie between organic and mineral forms of soil N, mineralization and uptake or loss of SON can be considered an input to the system. If that N is counted as an input at its fertilizer replacement value [91 MJ kg<sup>-1</sup> N assumed by Zentner et al., (1989)], the additional input to the fallow systems would be 1547 MJ ha<sup>-1</sup>. Applying this reasoning to the results shown in Tables 5 and 6 in Zentner et al. (2001) results in an increase in input energy of 67% for the F-W system and 43% for the F-W-W systems respectively, and results in a re-ordering of the energy efficiency ( $\text{Energy}_{\text{out}}/\text{Energy}_{\text{in}}$ ) rankings of the systems so that the fallow-based systems are less energy-efficient than the continuously cropped system (no statistics were reported in the original analysis).

Although unlikely in this specific scenario, it might be assumed that the status quo (e.g. fallow-based) system was at equilibrium with regards to soil N. In this scenario,

the difference in total soil N observed at the end of the study period would be attributed to an *increase* in soil N under the alternative cropping scenario relative to the steady-state equilibrium of the fallow-based systems. If this increase in soil organic N is counted as an output of the system, again at the energy cost of N fertilizer, this would correspond to an increase in output of  $1547 \text{ MJ ha}^{-1} \text{ yr}^{-1}$ . This is at most a 6% increase in system output, in the case of the W-L rotation compared to W-F. Proportionally, this is a much smaller increase in system output than the increased inputs when the change in SON was considered a loss of SON and an input of mineral N to the system. The resulting change in system energy efficiency ( $\text{Energy}_{\text{out}}/\text{Energy}_{\text{in}}$ ; as reported by Zentner et al., 2001) is small, and does not result in a change in rank of the system energy efficiencies.

Accounting for either removal or addition to the soil organic matter pool presents a difficulty for interpretation of agricultural energy analysis. Without accounting for such changes, cropping systems that are mining the soil of nutrients may appear energy efficient, while systems that maintain or restore soil fertility may either appear less energy intensive or may be indistinguishable from systems that are losing N to the external environment. Accounting for soil organic N losses as inputs to be included in ratio-based system energy intensity metrics appeared to clarify the issue somewhat, however accounting for increases in soil organic N as outputs of the system did not yield a proportional change in energy intensity metrics. Changes in soil C and N pools are also notoriously difficult to quantify (Campbell et al., 2000), and experimental designs common in agronomic research have low statistical power for detecting even

large changes in these highly variable pools (Kravchenko and Robertson, 2010). It is therefore unlikely that most short-term cropping system research designed for measurement of agronomic variables will be able to detect differences in SOC.

The capacity for different cropping systems to impact the long-term trajectory of soil organic matter content is of interest from multiple perspectives. From a global climate change perspective, cropland soils represent a potential carbon sink, potentially ameliorating increasing atmospheric CO<sub>2</sub> concentrations (Robertson et al., 2000), although both the size of this potential sink and the wisdom of thinking about it as such have been questioned (Deluca and Zabinski, 2011). Even from a strictly agronomic perspective, soil carbon management presents a challenge, as organic matter presents much of its biological benefit from decomposition. There is value, certainly, in maintaining or even increasing both the quantity of organic matter in storage and the rate of cycling, but this presents something of a management dilemma (Janzen, 2006). Management factors that have been shown to increase soil C storage in the northern Great Plains include cropping system intensification, reduction of tillage, adequate fertilization, application of organic soil amendments, conversion to perennial vegetation (Janzen et al., 1998), and inclusion of legumes (Campbell et al., 2000)

## Agricultural Sustainability on the Northern Great Plains

### Historical Perspectives on Sustainability

A practice once common to crop production across the semiarid northern Great Plains was wheat grown following a 14- or 21-month fallow period for winter- and spring-wheat, respectively (Ford and Krall, 1979; Larney et al., 1994a). Summerfallow is intended primarily to accumulate soil water, thereby reducing the risk of crop failure associated with unreliable growing season precipitation. Additional short-term benefits may include control of some weeds (Austenson et al., 1970), and mineralization of soil organic N into plant available forms (Cochran et al., 2006; Tanaka et al., 2010), important considerations before the advent of modern herbicides and fertilizer. The practice of summerfallow has long been identified, however, as a major challenge to sustainability of NGP agriculture (Janzen, 2001). Summerfallow, especially when accomplished by tillage, has been implicated in reduction of soil quality (Larney et al., 1994a), wind erosion (Larney et al., 1994b), organic matter depletion (Janzen et al., 1998), the development of saline seeps in areas downslope from fallowed land (Halvorson and Black, 1974; Black et al., 1981), and loss of nitrate to leaching (Campbell et al. 2006, Jones and Olson-Rutz, 2011), resulting in groundwater contamination, especially where soil water holding capacity is limited (Bauder et al., 1993).

The development of agriculture in the NGP was unique in that scientists arrived with the first settlers and documented the effects of agriculture on the prairie soils, as chronicled by Janzen (2001). Janzen cites compelling first-person accounts from as early

as 1885 documenting the destructive effect of tilled summerfallow on soil quality and declaring in stark terms the lack of ‘permanence’ of the fallow-crop system.

“That there must be a change in the system of cropping is admitted by all up-to-date farmers, for the growing of wheat alone and summerfallowing every third year, is too favourable to the introduction of weeds, the exhaustion of the soil fibre, and the depletion of fertility.”

- *Angus McKay (1914), Superintendent, Indian Head Experimental Farm, SK, from Janzen (2001).*

Proclamations on sustainability from the 19<sup>th</sup>-century are powerful today, partly because of the quaint and compelling language used. It is clear that the problems addressed here are not new; the fundamental issues have been understood for more than a century, and fallow is rapidly disappearing in most parts of the semiarid NGP (Tanaka et al. 2010). However, the largest cropping region in Montana (MLRA 52) has proven resistant to reduction of fallow.

The issue of permanence, or sustainability, may be addressed from multiple perspectives. Perhaps the most fundamental is maintenance of the productivity of the system over time (Monteith, 1990). From the late 19<sup>th</sup>-Century perspective, this would necessarily have focused on maintenance of the conditions necessary for natural cycling of sufficient N to maintain crop yields. Smil (2001, ch.3) provides interesting historical context to the observations of soil scientists during the latter half of the 19<sup>th</sup> century. During the course of that 50-yr period the role of N in plant nutrition and crop productivity was first firmly established, and the microbiological nature of leguminous N fixation was first confirmed. Global trade in guano mined in S. America flourished, and

then fell into decline as the resource was depleted within a few decades. A similar fate was predicted for sodium nitrate deposits in S. America then being utilized for fertilizer.

One of the obstacles, then, to ‘permanence’, as understood by early critics of summerfallow, was addressed by a disruptive technological advance: synthetic N fertilizer. For more than 50 yr following McKay’s proclamation quoted above, the areal extent of summerfallow in the northern Great Plains increased steadily, peaking in 1971 at over 16 M ha, or 4-fold greater than its extent in 1914 (Tanaka et al., 2010). During that time Montana wheat yields increased steadily (NASS, 2012; Figure 1.1).

Concerns about sustainability persisted, however, shifting focus to the threat of soil erosion, made into a national crisis by the perfect storm of expanded grain production, drought, and economic depression in the 1930’s. In 1935, the Soil Conservation Service was established by public law 74-46, in recognition that “the wastage of soil and moisture resources on farm, grazing, and forest lands . . . is a menace to the national welfare” (NRCS 2011). Early conservation efforts focused on conversion of the most erosion-prone lands back to perennial grazing land, development of conservation tillage techniques to maintain crop residue on the soil surface, and strip cropping in 10 to 20-rod (50 - 100 m) strips perpendicular to prevailing west winds.(Tanaka et al., 2010). Saline seeps also emerged as a sustainability issue with the increase in fallow area. At the height of the prevalence of summerfallow, approximately 800,000 ha of land in the NGP was affected by salinity (Miller et al., 1981).

Since 1971, the extent of summerfallow across the NGP has declined steadily to about the extent present in 1914 when Angus McKay proclaimed the practice to be clearly unsustainable (Tanaka et al., 2010). Major driving forces in the decline in summerfallow have included no-till and conservation tillage production practices (Lafond et al., 1992), associated soil water conservation (Peterson, et al., 1996), and diversification of crop rotations with pulses and oilseeds (Miller et al., 2002

Summerfallow now persists as a regular practice only in the driest areas of the NGP. In MLRA 52, the largest cropland region in the state of Montana, known as the Golden Triangle, summerfallow accounted for 0.8 Mha , or 43%, of cropland in 2010 (NASS, 2012). Pulse crops are potentially adapted to some of the drier cropped areas of the NGP where summerfallow is still common, and are poised to play a role in additional cropping system intensification in this region. Miller et al. (2002) identified research needs for this to proceed, including further refinement of management practices and better characterization of the rotational benefits of pulses on subsequent cereal crops. Recent volatility in fuel and fertilizer prices have resulted in an increase in producer interest in understanding how these rotational benefits and associated potential N fertilizer offsets impact a farm's exposure to energy price volatility. This question motivates a more sophisticated approach to sustainability, a systems approach, where interactions among crops are considered in a systems context (Ikerd, 1993).

### A Systems Approach to Sustainability

“Sustainability is a direction rather than a destination, like a star that guides the ships at sea but remains forever beyond the horizon.”  
 -Ikerd (2008; p 95)

Sustainable agriculture is also codified in U.S. federal law (U.S. Code Title 7, Section 3101) as:

“an integrated system of plant and animal production practices having a site-specific application that will over the long-term:

- Satisfy human food and fiber needs.
- Enhance environmental quality and the natural resource base upon which the agriculture economy depends.
- Make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls.
- Sustain the economic viability of farm operations.
- Enhance the quality of life for farmers and society as a whole.”

Under this definition, sustainability is not a simple binary status declaration (e.g. sustainable vs. not sustainable), but rather involves tradeoffs among multiple social, environmental, and economic objectives. A focus of the research presented in this dissertation is the 3<sup>rd</sup> bullet point in the above definition: *efficient use of nonrenewable resources*, particularly fossil energy. The need to evaluate tradeoffs with other objectives should be noted. How best to balance multiple objectives is inherently subjective, requiring value-based judgments on how to weight the various objectives. If an alternative cropping system makes more efficient use of fossil energy, and meets other sustainability objectives, a clear win-win situation exists and energy analysis will

have found a way to reduce energy use. Where a more resource-efficient system fails to meet other sustainability objectives the interpretation of that observation is more complex. It has been suggested that cropping system energy efficiency offers insight into economic viability under scenarios of increased energy price (Cruse et al., 2010), but this claim has not been evaluated with economic analysis of likely scenarios of energy and non-energy commodity prices.

Some researchers have called for an approach to agricultural sustainability focused on reduction of inputs or elimination of all synthetic inputs (e.g. certified organic), with much ensuing debate on the question of whether such an approach can meet global human needs for food and fiber (Badgley et al., 2007; Cassman, 2007; Hendrix, 2007). Others have suggested that increasing demand for food and limited opportunity for expanding the agricultural land base means that the chief goals of agricultural science should be “ecological intensification” (Cassman, 1999; Tilman et al., 2002), or finding ways to continue to increase crop yields while simultaneously addressing environmental impact and accounting for the value of ecosystem services. Drinkwater and Snapp (2007) called for a “rethinking of the management paradigm” with regards to soil fertility management, towards systems more reliant on biologically mediated processes for nutrient supply.

A form of circular reasoning has been noted when agricultural sustainability is defined in terms of specific practices, themselves forming the basis for the definition of sustainability (Hansen, 1996). Hansen (1996) claimed that a “distorted caricature” of

conventional agriculture results in a tendency to overlook or reject approaches that may enhance sustainability. With particular regards to ecological intensification of dryland wheat production in “unfavorable” production environments, Cassman (1999) called for tempered expectations for ongoing increases in crop yield. The focus in these regions, Cassman said, should be on maintaining or improving soil quality, possibly by means of livestock integration and crop diversification. The effect of reduced tillage and residue management systems on water infiltration, runoff, evaporation, and ultimately crop water use efficiency was noted as a critical component of a systems approach to sustainability in this environment.

Crews and Peoples (2004) reviewed the “bifurcation of perspectives” on the role of N fertilizer use in sustainable agriculture. They concluded that while legume-based agriculture had “marginally greater ecological integrity” than fertilizer-based systems, the differences have largely been overstated, especially when fertilizer is managed with best practices. The single largest sustainability issue identified by Crews and Peoples (2004) for fertilizer N use was the non-renewable energy associated with its manufacture. A big-picture perspective on the energy required for N fertilizer production and the energetic consequences of strategies to partially offset N fertilizer use with crop rotation and legume green manure cover crops is the major focus of the following chapters of this dissertation.

Legume Green Manure Cover  
Crops – Partial Intensification

Under the driest conditions found in the NGP, cropping of wheat in rotation with oilseeds and pulses grown to maturity can result in reduced wheat yield the subsequent year compared to fallow, due to depletion of soil water (Brandt, 1996; Miller and Holmes, 2005). However, when shallow-rooted annual legumes such as pea (*Pisum sativum* L.) and lentil are harvested early as forage or terminated early as legume green manure (LGM) cover crops, the reduced water use relative to crops grown to maturity can benefit the subsequent wheat crop (Miller et al. 2006), especially where residue management can be optimized for soil water conservation (Pikul et al., 1997; Unger and Vigil, 1998).

Legume green manures have been investigated for potential substitution for fallow in the NGP since the arrival of the first European homesteaders (Janzen, 2001), and benefits to the practice were generally elusive to early researchers (Brown, 1964). A review by Army and Hide (1959) of comparisons of LGM and fallow at three locations in Montana over 110 site-years of unreplicated trials between 1909 and 1951 found nearly universal negative effects of green manures on wheat yield and no effect on wheat protein or soil organic matter. Interestingly, however, the authors noted that these conclusions “would probably be altered if a management practice can be devised which materially increases the proportion of the rainfall that is used for plant growth or otherwise favorably influences the water balance of the crop.”

Advances in cropland management and wheat breeding since Army and Hide's (1959) review have had exactly the effects alluded to in their conclusion. Precipitation use efficiency in fallow-wheat systems doubled between the 1930's and 1970's, largely through reduced- and no-till management (Peterson et al. 1996). The mechanisms of improved PUE from reduced-tillage systems are numerous and diverse, including increased infiltration, reduced wind speed and temperature at the soil surface, and improved weed control. Further, modern semi-dwarf wheat cultivars are more water efficiency than standard-height cultivars of the 1950's (Schillinger et al. 2008).

A review by Haas and Evans. (1957) of studies conducted at experiment stations throughout the Great Plains established on unplowed prairie soils in the early 20<sup>th</sup> century, indicated an average loss of 42% of organic carbon and 36% of total nitrogen initially present in the first 37 years of cropping. Loss of soil N was greater under fallow-crop production than continuous cropping. The greater loss of N was not entirely accounted for by N removal in increased crop yield under the crop-fallow system, indicating a role of erosion and other loss mechanisms in soil C and N depletion. Neither rye (*Secale cereal* L.) nor LGM, in most cases once in a 4-year rotation, reduced losses of soil organic matter in the studies reviewed by Haas. The rapid decline in soil organic matter initially observed in newly converted prairie cropland has likely abated as a new equilibrium level is approached (Janzen et al., 1998). With the recent improvements in cropping system water use efficiency and the current reduced level of indigenous soil fertility, LGM cover crops are being investigated again.

In contemporary long-term studies, LGM have been shown to improve several soil quality parameters (Biederbeck et al., 1998; Allen et al., 2011) and allow reduction in fertilizer inputs (Zentner et al., 2004b; Allen et al., 2011). Replacing fallow with LGM requires careful management of the balance between soil water use and LGM growth and concomitant N fixation (Sims and Slinkard, 1991; Townley-Smith et al., 1993; Miller et al., 2002, 2006, 2011; Zentner et al., 2004b), as research at some locations continues to demonstrate reduced yields of wheat following LGM (Zentner et al., 1996; Brandt, 1998; Vigil and Nielsen, 1998; Nielsen et al., 2005). Early termination of LGM has been shown in several studies to be a key practice for the requisite conservation of soil water (Aase et al., 1996; Zentner et al., 2004b; Allen et al., 2011).

Further research is needed to investigate the role of LGM species, tillage, and termination timing on the water use, N contribution, and short-term economics of LGM cover cropping. A major goal of LGM cover cropping is to offset N fertilizer use, and a major sustainability issue with N fertilizer is its energy intensity (Crews and Peoples, 2004) and price volatility.

### Research Objectives

The following chapters investigate several approaches to cropping system intensification and diversification in energetic and economic perspectives. Chapter 2 compares economic and energetic analyses of a series of cropping systems representing a spectrum of approaches to cropping systems intensification in a plot-scale study.

Chapter 3 presents results of a survey of pulse-producing farmers in Montana. Chapters 4 and 5 examine LGM cover cropping in energetic and economic context.

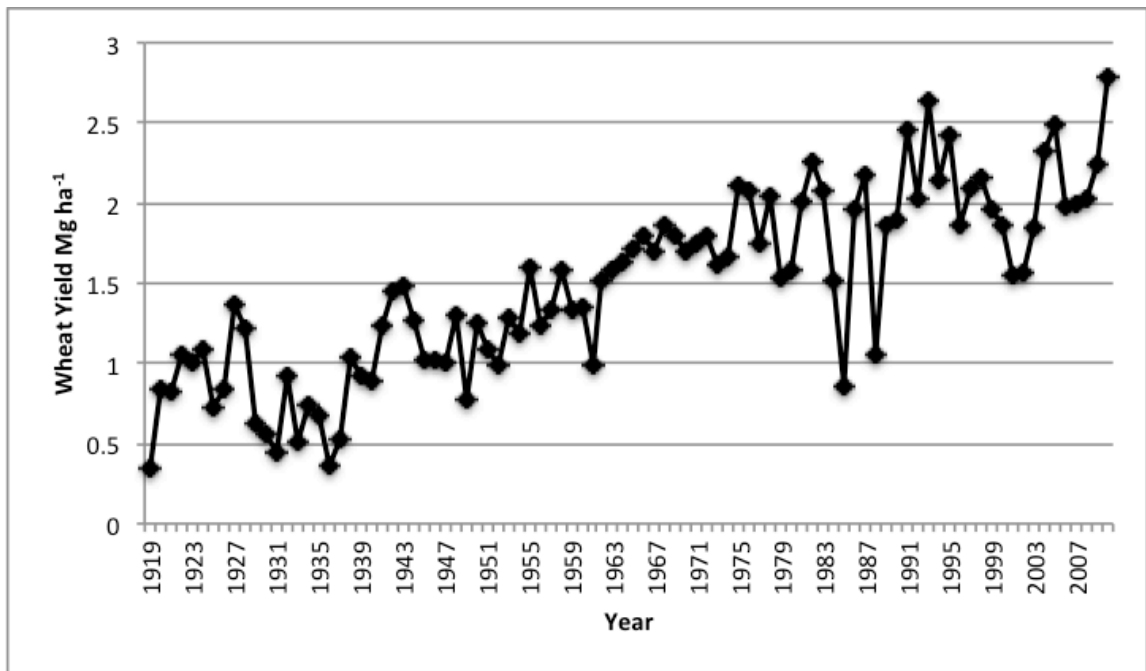


Figure 1.1 Average Montana wheat yield 1919-2010. Data from NASS 2012.

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## 2. ENERGETIC AND ECONOMIC ANALYSES OF DIVERSIFICATION AND INTENSIFICATION OF FALLOW-BASED CROPPING SYSTEMS

### Introduction

Recent volatility in energy-related commodity markets (e.g. fuel, fertilizer, crops) has prompted increased interest in understanding the reliance of agriculture on fossil energy inputs. Crop growth is fundamentally an energy conversion process, with plants converting solar energy to useful forms of stored chemical energy (e.g. cellulose, starch, fat, protein). In agricultural systems, additional energy is added to the system in the form of crop production inputs like tractors, fuel, fertilizer, seeds, and pesticides. All of these inputs can be accounted for in terms of their embodied energy, i.e. the amount of energy expended in their manufacture and delivery. Agricultural energy analysis has focused on the quantities of output and input energy as defined above, as well as the differences and ratios between them.

The difference between crop output energy and crop production input energy per unit area of land has been termed Net Energy Yield (NEY), and has been proposed as an indicator of productivity useful for determination of the petroleum substitution potential of biofuel production systems (Liska and Cassman, 2008). Net energy yield has also been reported extensively in analyses of non-biofuel cropping systems. Net energy yield is reported here in units of  $\text{GJ ha}^{-1}$  and referred to generally as energy productivity.

A variety of ratios among input energy and harvested crop mass or crop energy content have been reported in other research under the name of energy efficiency, resulting in some confusion regarding the desirability of a larger or smaller number. Here, energy intensity (EI) is reported as the ratio of input energy to harvested crop mass ( $\text{MJ kg}^{-1}$ ), a smaller number indicating less energy required to produce 1 kg of crop. This metric has been reported extensively under different names (Hülsbergen et al, 2001; Bailey et al., 2003; Piringer and Steinberg, 2006; Deike et al., 2008; Guzmán and Alonso, 2008; Liu et al. 2010; and Aluvione et al. 2011). For comparison, other energy ratios reported in the literature can readily be computed from EI by taking the reciprocal and/or multiplying by a chosen crop energy coefficient. Energy intensity as reported here is preferred because it keeps crop material in units of mass (Fluck, 1979), and because it has energy inputs in the numerator for ease of appropriate comparison of energy use among systems (Larrick and Soll, 2008).

Energy intensity and productivity of crop production have sometimes been presented as general indicators of sustainability (Pervanchon et al., 2002; Moreno et al., 2011), but more frequently as partial indicators to be considered in light of other measures (Schahczenski, 1984; Dalgaard et al, 2001; Aluvione et al., 2011). It has been suggested that less energy-intensive cropping systems may provide an adaptation to a scenario where energy prices increase without proportional increase in crop prices (Cruse et al., 2010). Several studies have found optimization of energy intensity and productivity to be mutually exclusive (Zentner et al., 1989; Gomiero et al., 2008; Liska

and Cassman, 2008). Green (1976) claimed “Low agricultural productivity is energy efficient, high agricultural productivity is energy demanding.” Many comparative studies of low-input and conventional systems have found low-input systems to be less energy intensive (Berardi, 1978; Pimentel et al., 1983; Dalgaard et al., 2001; Hoepfner et al., 2006; Alonso and Guzmán, 2008; Cruse et al., 2010; Gündoğmus 2010; Macrae et al., 2010; Aluvione et al., 2011; Zentner et al., 2011).

A few studies have combined energy analysis with economic enterprise analysis or sensitivity analysis of economic profit to crop or input prices. Cruse et al. (2010) performed parallel energetic and economic analysis of a conventional 2-yr corn (*Zea mays* L.), - soybean (*Glycine max* L.) rotation with low-input 3-, and 4-yr rotations of corn, soybean, small grain/red clover (*Trifolium pratense* L.) and alfalfa (*Medicago sativa* L.) in Iowa, substituting manure for N fertilizer in the low input systems. They found similar corn and soybean yield and economic returns for the 2- and 4-yr systems, and reduced EI for the 4-yr system. They concluded that the diverse, low-input, 4-yr crop rotation would be favorable if energy prices rose without concomitant increase in crop prices. Zentner et al. (1984a, 1984b, 1988, 1989, 2001) presented economic and energetic analyses for a long-term crop rotation study in southwestern Saskatchewan, including fallow-wheat (*Triticum aestivum* L.), fallow-wheat-wheat, continuous wheat, all with and without N fertilizer, and lentil (*Lens culinaris* Medik.)-wheat. The early economic analyses found the most profitable rotation to be the fallow-wheat-wheat (i.e. medium cropping intensity) with the full recommended rates of N and P fertilizer. The

energetic analysis, in contrast, found the least energy intensive system to be the unfertilized fallow-wheat systems. The greater energy intensity of the more crop-intensive rotations was noted as a possible impediment to adoption of continuous cropping in the early analyses. The apparent low energy intensity of the unfertilized fallow-wheat cropping system was also noted to depend upon unsustainable continued depletion of soil organic N. For the lentil-wheat rotation presented in Zentner et al. (2001), there was little difference between the wheat-lentil and continuous wheat systems in terms of wheat yield or system energy intensity.

The primary objective of this research was to explore the relationship between energetic and economic analyses of cropping systems differing in crop intensity (presence of fallow), diversity, yield potential due to crop growth timing (e.g. winter vs spring crops), and N fertilizer level. A simple approach to analysis of economic sensitivity to crop and fertilizer prices is also presented for purposes of comparison of the same approach to optimization of NEY. Finally, the potential for inclusion of changes to soil fertility status to energy metrics of cropping systems is considered. Jones (1989) stated that the three most important questions for agricultural energy analysis were “what can we measure”, “how do we measure it”, and “what do the results mean”? The ultimate objective of this research is to determine under which circumstances, and for what types of comparisons, energetic analyses provide complementary information to traditional economic and agronomic approaches to evaluating sustainability of cropping systems.

## Materials and Methods

The research reported here consists of energy and economic analyses of a crop rotation experiment that was begun in 2003. The results presented are from a single rotation cycle, from the years 2005-2006, representing the 2<sup>nd</sup> complete cycle of this 2-yr rotation. Results from 2003-2004 were omitted to allow for cumulative effects of the crop rotations to accrue. Due to the lack of replication over time or location, the scope of inference with regards to the agronomic responses is limited.

### Site Description

The crop rotation field experiment is located at the Montana State University (MSU) A.H. Post Agronomy Research Farm 10 km west of Bozeman, MT (45° 40' 20" N 111° 09' 3" W; 1,455 m above sea level). Prior to the initiation of the experiment, the site was used for production of grasspea (*Lathyrus sativus* L.) in 2001 and spring wheat in 2002. The soil is classified as Amsterdam silt loam (fine-silty, mixed, superactive, frigid Typic Haplustolls). This loess-derived soil is well drained, deep, and free of rocks, with average pH of 7.2, and 9.0 g kg<sup>-1</sup> organic carbon in the surface 10 cm (Dusenbury et al., 2008).

At this location, 45% of total annual precipitation normally falls between April and June. Growing season duration is typically limited by the onset of terminal drought in July, rather than frost, so early crop planting and growth are critical. Winter annual crops are especially well adapted to this location due to the synchrony of crop growth

with a cool, humid spring climate. Shallow-rooted pulse crops are particularly dependent upon growing season precipitation. Total crop-year precipitation (Sept – Aug) was 45 mm below average in 2005 and 14 mm above average in 2006, with May rainfall below average in 2005 (Table 2.1), creating conditions for below-average yields of spring-planted crops in 2005. Mean monthly air temperatures were above average in both years.

#### Experimental Design and Management

The experiment was a split-plot design with main plots arranged in four randomized complete blocks. Main plots were 7.6 x 21.3 m and consisted of eight different 2-yr crop rotations. The crop rotations were conceived as a quasi-hierarchical sequence of cropping system intensity and diversity, designed specifically for comparison between consecutive treatments (i.e. 1 vs. 2, 2 vs. 3, 3 vs 4, etc.). A single phase of each rotation was present each year. All eight crop rotations had wheat as the Year 2 crop, while Year 1 treatments included tilled and chemical (no-till) summerfallow, spring wheat, spring pea (*Pisum sativum* L.), winter pea, winter pea forage, and pea green manure in a certified organic treatment, as shown in Table 2.2. Main plots were split into two or three subplots assigned to different N fertilizer management strategies for wheat. The N fertilizer management strategies for all but the organic system were 50 kg of available N per Mg of expected grain yield, midway between MSU extension recommendations for spring and winter wheat (Jacobsen et al., 2005), and a yield target

of 4 Mg ha<sup>-1</sup>. Available N was calculated as the sum of soil NO<sub>3</sub>-N to depth of 60 cm at planting time, applied fertilizer N, and a pulse credit, which reflects expected N mineralization during the season following the pulse crop. The pulse credit was 20 kg N ha<sup>-1</sup> for pea grown to grain, and 40 kg N ha<sup>-1</sup> for pea harvested as forage. The full recommended N level was termed high (Hi-N), providing 200 kg available N ha<sup>-1</sup> for wheat. The 2<sup>nd</sup> level of the split plot factor targeted half (½ -N) the recommended quantity of available N, or 100 kg N ha<sup>-1</sup>. The 3<sup>rd</sup> level (Lo-N) consisted of no additional N fertilizer beyond the amount from delivery of P, K, and S nutrients by commercial fertilizers (e.g. ammonium phosphate), not exceeding 6 kg N ha<sup>-1</sup>. For the certified organic production system, the levels of the split-plot factor were winter or spring pea tilled in as green manure in 2005. Soil test results immediately prior to planting of 2006 crops, actual amounts of N fertilizer applied in 2005 and 2006, and total available N for 2006 are shown in Table 2.3. Applied N fertilizer rates and resulting available N shown in Table 2.3 were not perfectly accurate (i.e. do not exactly match nominal available N goals) due to logistical considerations and limited resolution of the setting on the metering device used for fertilizer application.

With the exception of rotations 1 and 8, all crops were managed with strictly no-till production practices. Tillage and herbicides were used according to standard practice for seedbed preparation and weed control, as outlined in Table 2.4.

All crops were planted with a plot seeder with one gang of double disk openers for seed from a cone distributor. A second gang of disk openers on the seeder allowed

for mid-row banding of fertilizer from a second box. Row spacing was adjusted from 0.26 m in 2005 and 0.30 m in 2006 to reduce disturbance of standing crop stubble by the seeding operation. Seeding rates were calculated based on seed size and germination rate to provide 200 pure live seeds (PLS)  $\text{m}^{-2}$  for wheat, 100 PLS  $\text{m}^{-2}$  for spring pea, and 80 PLS  $\text{m}^{-2}$  for winter pea. The organic systems had all seeding rates increased by 50%, and had half of the seed delivered through the mid-row banding openers, resulting in  $\frac{1}{2}$  the row spacing distance of non-organic systems for improved weed competition.

Cultivars used in 2005 were 'McNeal' spring wheat (Lanning et al., 1994), 'Arvika' spring pea (Tyller, 1974), and 'Melrose' winter pea (Auld et al. 1978). Cultivars used in 2006 were 'Promontory' winter wheat (Hole et al., 1993) and 'Hank' spring wheat (Westbred LLC, Bozeman, MT). Wheat seed in the non-organic rotations was treated with 121 mg a.i.  $\text{kg seed}^{-1}$  difenoconazole {1-((2-(2-chloro-4-(4-chlorophenoxy)phenyl)-4-methyl-1,3-dioxolan-2-yl)methyl)-1H-1,2,4-triazole} and 9.7 mg a.i.  $\text{kg seed}^{-1}$  mefonoxam {(R,S)-2-[(2,6-dimethylphenyl)-methoxyacetyl-amino]-propionic acid methyl ester}. Pea seed was not treated with fungicide as these cultivars have smooth, dark-pigmented, speckled seed coats conferring resistance to common fungal root pathogens (Muehlbauer and Kraft, 1978).

At planting, commercial granular peat-based pulse inoculant containing *Rhizobium leguminosarum* (bv viceae) was banded with the pea seed at 5  $\text{kg ha}^{-1}$ . To reduce the potential for non-N nutrient limitation to crop growth, P, K, and S fertilizers

were banded with all non-organic seed at planting. In 2005 this consisted of 32 kg ha<sup>-1</sup> of ammonium phosphate and 49 kg ha<sup>-1</sup> potassium sulfate, supplying N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O-S at 4-17-25-9 kg ha<sup>-1</sup>. In 2006 the PKS fertilizer was 56 kg ha<sup>-1</sup> each of ammonium phosphate and potassium sulfate, providing N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O-S of 6-26-25-9 kg ha<sup>-1</sup>. The N in this starter fertilizer is included in the total N fertilizer quantities in Table 2.3. The balance of the N fertilizer was mid-row banded at planting time in the form of urea (46-0-0). All non-organic pea seed was also fertilized with 10 kg N ha<sup>-1</sup> of starter N fertilizer, mid-row banded, in the form of urea.

In 2006, winter wheat management was identical for rotations 1-6 other than quantity of N fertilizer applied at planting. Herbicide and tillage operations used for 2006 wheat production are shown in Table 2.4.

All grain crops were harvested with a plot combine to measure grain yield. Wheat grain protein and moisture content were measured using near infrared reflectance (NIR) with the appropriate standard calibrations for each grain class using an Infratec model 1241 grain analyzer (FOSS, Denmark). Forage crops were cut to a height of 10 cm and fresh biomass was immediately removed from the plots and weighed. A subsample of the fresh biomass was oven dried to determine water content, which was used to convert plot yield to dry matter basis.

### Economic Analysis

Enterprise budgets were used to estimate production costs, gross returns, and net profit. Wheat prices, protein premiums, and discounts were based on expected local cash prices at planting time of each year for #1 Dark Northern Spring Wheat (DNS) or Hard Red Winter Wheat (HRWW), based on futures prices and historic basis in north-central Montana. Base prices were \$136 Mg<sup>-1</sup> (\$3.70 bu<sup>-1</sup>) for HRSW and \$127 Mg<sup>-1</sup> (\$3.46 bu<sup>-1</sup>) for HRWW. Wheat grain prices were further adjusted based on protein content expressed at 120 g kg<sup>-1</sup> grain moisture. For HRSW a protein premium of \$0.877 Mg<sup>-1</sup> wheat was added for each 1 g kg<sup>-1</sup> of grain protein content above the marketing standard of 140 g kg<sup>-1</sup> and a discount of \$1.032 was subtracted for each 1 g kg<sup>-1</sup> of protein below the standard to a price floor of \$123 Mg<sup>-1</sup> (\$3.34 bu<sup>-1</sup>) assuming spring wheat below 125 g kg<sup>-1</sup> protein content could be marketed as ordinary feed wheat. For HRWW a protein premium of \$0.588 Mg<sup>-1</sup> wheat added for each 1 g kg<sup>-1</sup> of grain protein content above the marketing standard of 120 g kg<sup>-1</sup> and a discount of \$0.687 Mg<sup>-1</sup> wheat was subtracted for each 1 g kg<sup>-1</sup> of protein below the standard to a price floor of \$120 (\$3.28 bu<sup>-1</sup>) Mg<sup>-1</sup> assuming winter wheat below 110 g kg<sup>-1</sup> protein content could be marketed as ordinary feed wheat. Grain yield was adjusted to 120 g kg<sup>-1</sup> moisture content basis for purposes of calculating revenue, and to a dry weight basis for energy content, and is reported here on a dry-weight basis.

The pea cultivars used were forage types (Slinkard and Murray, 1979), and most grain produced of these cultivars is sold for use as seed for forage production, cover

cropping, and wildlife food plots. Based on communication with a local seed company with a history of marketing forage pea seed in the USA, a price of 12.5% above the market price for green field pea was assumed. The estimated price for forage pea seed produced in 2005 was \$235 Mg<sup>-1</sup> (\$10.66 cwt<sup>-1</sup>).

Pea forage potentially has similar feed value to alfalfa hay, however harvesting and transportation costs can be substantial, making for a largely local market with variable prices. It was assumed that a grain farmer would not have forage harvesting equipment and would sell the standing crop for a price of \$44 Mg<sup>-1</sup> below the market price for baled alfalfa hay, based on communication with local forage producers. For energetic analysis, use of a swather and a baler, but no further transport of the bales was budgeted.

Wheat seed prices were based on nominal grain prices for each year from USDA reports for central Montana, plus a cleaning cost of \$0.04 kg<sup>-1</sup>, seed treatment cost of \$0.12 kg<sup>-1</sup>, where applicable, and \$0.08 kg<sup>-1</sup> PVP (Plant Variety Protection) royalty fee and handling costs, assuming use of purchased certified seed for wheat cultivars used in 2006. The wheat cultivar used in 2005 was a common variety, so only cleaning and seed treatment costs were considered. Prices for purchased pea seed were 1.8 times the sale price for pea seed, based on communication with a local seed dealer.

Machinery operating costs were estimated for the field operations performed, based on published custom farm operation rates in the neighboring state of North Dakota (Aakre 2005). To better approximate realistic farm scenarios, it was assumed

that the tilled fallow-wheat (TF) system would be seeded with a less-expensive conventional seed drill (Table 2.5). It was also assumed that the TF and chem fallow (CF) would use different sprayers, CF using a larger self-propelled sprayer with lower operating costs that can only be achieved by covering larger area associated with repeated sprayer passes needed for no-till production. Fertilizer and herbicide prices were estimated 2005 prices from USDA National Agricultural Statistics Services (NASS) annual agricultural price reports for the actual years analyzed, and the North Dakota Herbicide Price Compendium (NDSU, 2012) with prices adjusted to 2005 or 2006 levels based on the consumer price index. Economic budgets did not include cost of land ownership or rent, crop insurance, or participation in any government commodity programs. Net revenue was calculated on a plot-wise basis, as production costs subtracted from gross revenues and subjected to statistical analysis as described below. For purposes of categorization of fertilizer costs for economic and energetic analyses, the N supplied in ammonium phosphate (applied primarily for its P content) was categorized as N-fertilizer based on the cost of providing that N in the form of Urea, and that cost was subtracted from the cost of the ammonium phosphate product attributed to the P-K-S fertilizer category.

### Energy Analysis

Energy budgets were compiled using a process analysis (Fluck and Baird, 1980; Jones 1989), with system boundaries at the farm field level. Energy budgets included

embodied energy for the manufacture and operation of farm machinery, and manufacture of fuel and lubricant, fertilizer, and herbicide. Energy coefficients for farm machinery were obtained from Zentner et al. (2004) and Nagy (1999). Energy coefficients for herbicides were obtained from Nagy (1999) and Liska et al. (2009). Energy Intensity (EI), the amount of energy used per kg of crop material produced ( $\text{MJ kg}^{-1}$ ), was calculated for each plot. Net Energy Yield was calculated using an energy value of wheat and pea grain of  $18.7 \text{ MJ kg}^{-1}$ , and pea forage of  $17.8 \text{ MJ kg}^{-1}$  based on bomb calorimeter tests, from Nagy (1999). Energy metrics were computed on a plot-wise basis and subject to statistical analysis as described below.

Fallow based crop rotations have been found to have lower EI than continuously cropped systems in the NGP, and that result has been attributed to unsustainable depletion of soil organic matter (Zentner et al., 1989). This reflects an ambiguity in the system boundary for typical agricultural energy analyses. Plant-available forms of soil N (e.g.  $\text{NO}_3$ ) are clearly inside the system boundary. In the plot experiments, soil  $\text{NO}_3\text{-N}$  was measured annually, and when fertilizer N (which is quickly transformed to  $\text{NO}_3$ ) was added it was accounted for as an input. When soil organic N is mineralized, ultimately to  $\text{NO}_3$ , this has not typically been accounted. It is proposed that the system boundary be clarified to make the distinction between organic soil N being outside the system boundary and mineral forms of N being inside the system boundary, to be accounted for in net terms.

To explore one possible alternative energy metric, EI was recalculated for fallow systems based on estimated annual depletion of soil organic N, considering this as an input to the system, at the energetic cost of replacement with N fertilizer, that has typically been unaccounted for in agricultural energy analyses. This adjustment was based on measurements of total soil N reported by McCauley (2011) for soil samples collected in early April 2008, or after a total of 5 years or 2-½ crop rotation cycles; Three soil samples per subplot were collected to a depth of 60 cm, separated by depth intervals of 0 to 10, 10 to 20, 20 to 30, and 30 to 60-cm, and composited by depth. Bulk density was calculated for each composited sample, and a subsample was analyzed for Total N and C in a combustion analyzer (TruSpec CN, LECO Corp. St. Joseph, MI).

#### Statistical Analysis

Statistical analysis was performed using SAS 9.3 (Statistical Analysis Systems, Cary, NC). PROC MIXED was used with REML estimation to fit mixed models with the Satterthwaite approximation of degrees of freedom. Dependent variables were the crop yield and quality measurements and the economic and energetic metrics calculated on a plotwise basis. Crop rotation, the split plot factor of N fertilizer strategy (Hi-N, ½-N, or Lo-N), and their interaction were modeled as categorical fixed effects. Block and the block\*rotation interaction were random effects. Post-hoc comparisons were made using independent t-tests based on the standard error of differences (SED) provided by the PDIFF option to the LSMEANS statement, and deemed significant if the *P*-value was less

than 0.1. Because separate measurements were not made on subplots when they did not receive different treatments (e.g. fallow and pulses in 2005), years were analyzed separately.

## Results and Discussion

### Inputs to Crop Production

Categorized totals of input energy for each crop are shown in Figure 2.1, and categorized input costs are shown in Figure 2.2. Nitrogen fertilizer was the dominant energy input to wheat, accounting for as much as 79% of the total in the Hi-N treatments. In economic terms, N fertilizer was also a major cost, but only accounted for a maximum of 43% of the total cost of production. This discrepancy between proportion of total costs due to N fertilizer between energy and economic values is because other inputs, namely herbicides and machinery, have greater economic cost relative to their energetic costs (Table 2.5).

Energy coefficients for machine operation cited from Nagy (1999) are dominated by fuel consumption; machine overhead (e.g. energy required to manufacture machinery) is based on energy intensity of the raw materials (e.g. steel, rubber) and the weight of individual machines. Economic overhead costs of machine ownership, including the cost of capital, insurance, and taxes, makes fuel a smaller proportion of estimates of economic cost of machine operation (Lazarus and Selley, 2005).

Herbicides that are applied at low rates (e.g. sulfosulfuron, clodinafop-propargyl), or that have low a.i. concentration (e.g. sethoxydim) have little energy associated with production of their active ingredients, but are relatively expensive economically (Table 2.5). When herbicides are effective at increasing crop yield by reducing weed competition, they are clearly beneficial to both energetic and economic objectives (Green and McCulloch, 1976; Deike et al., 2008). Many herbicides are also used with spray adjuvants that are energy intensive, and these have usually been omitted in other published cropping system energy budgets. Selection of specific herbicide chemistry, application rate, and application timing is complex, especially with selective herbicides applied to growing crops where weed control must be balanced with the potential for crop injury. Choices of adjuvant can also impact herbicide efficacy and the potential for crop injury (Harker, 1992). Herbicides can be tank mixed, with potential for synergism or antagonism of activity, also potentially mediated by selection of adjuvants (Wanamarta et al. 1989). Finally, herbicides differ in their risk to human health and the environment, not only based on their toxicity, but their application rates, potential for movement in the environment, and rate of decay (Margni et al., 2001). None of these issues are considered by energetic analysis alone, and energetic analysis therefore appears to be of limited utility in guiding choice of herbicide formulation, application rate, or adjuvants. A final note on the energy intensity of herbicides is that nearly all of the published energy coefficients for herbicide active ingredients can be traced back to a single paper, Green (1987); who specifically questioned the accuracy of

his estimates for products with then-proprietary manufacturing processes. Several new herbicide active ingredients have been developed since then, so many energy coefficients for herbicides are uncertain.

#### Mixed Model Statistical Results

Mixed model main effects of rotation and N level were significant for all variables analyzed. The interaction of rotation and N level was also significant for many of the variables. Because of the unbalanced split-plot experimental design, main effect means are not comparable for all rotations or N levels. Means and standard errors of differences (SED) within and among crop rotations are therefore presented in the Tables 2.3, 2.6, 2.7, and 2.8. Standard errors of differences may be used to make appropriate post hoc multiple comparisons by computing a Least Significant Difference by multiplying the SED by the appropriate value of the T statistic for the estimated degrees of freedom.

#### Transition to No-Till Fallow:

##### Rotation 1 vs. 2

Rotation 1 consisted of tilled fallow (TF) followed by winter wheat, while Rotation 2 substituted chemical fallow (CF), where fallow was managed using herbicide in a no-till production system. Tilled fallow required five field tillage operations, whereas CF only required four herbicide applications (Table 2.4). Other researchers have also found fewer field passes to be necessary for weed control with use of herbicides, both

in this region (Zentner et al. 2004), and more generally (Green and McCulloch, 1976). While more fuel and machinery resources were used for TF, the cost and energy was offset by the increased use of herbicide in CF. Chemical fallow required more input energy (Figure 2.1), and also cost more in economic terms (Figure 2.2). The energy difference was small, just  $57 \text{ MJ ha}^{-1}$ , or 5%, while the economic difference was  $\$18.74 \text{ ha}^{-1}$ , or 28%. Other research on relative cost of NT and T production practices has been inconclusive. Zentner et al. (2002a) also found greater cost for NT management of fallow than tillage, while others have found little or no difference (Lafond et al., 1993). The range of reasonable alternative tillage and herbicide application practices, as well as variability in the relative prices of herbicide and fuel can account for this uncertainty. Economic analyses based on published custom farming rates or engineering approaches to estimates of machine operation costs typically have not included timeliness costs, the potential cost associated with being unable to complete a field operation within the optimal time window (ASABE, 2006). There are several methods for estimation of such costs based on probabilities of favorable working conditions and duration of optimal time windows for specific operations (Short and Gitu, 1991), but these methods have not typically been adopted in enterprise production budgets. Based on the operating assumptions in Nagy (1999), the largest self-propelled sprayers can cover 4- to 8-fold more ground area per hour than typical primary and secondary tillage implements. Timeliness costs and availability of temporary labor for time-critical operations may

therefore be major factors in adoption of NT production practices where the economic motivation is not otherwise apparent.

There was no difference between TF and CF in 2006 winter wheat (WW) yield or grain protein (Table 2.6), profit for 2006 or the 2005-2006 cycle (Table 2.7), EI, or NEY (Table 2.8). Research on the effect of NT production on crop yield in the NGP has had contradictory results, with a variety of mechanisms describing responses. Decreased wheat yield under NT has been attributed to reduced soil temperature and pathogen activity at a semiarid location in eastern Oregon (Rasmussen et al., 1997), and N immobilization in NT has been demonstrated in Saskatchewan, Canada (Matus et al., 1997). Increased yield in NT production has been demonstrated due to favorable microclimate conditions in NT stubble (Aase and Siddoway, 1980), and soil water conservation (Peterson et al., 1993). In this experiment, plots had already been in their respective management systems for one complete rotational cycle (2-yr) before the period analyzed, so some transient soil responses to changes in tillage system may already have occurred.

Winter wheat yield and protein responded positively to N fertilizer in both CF and TF systems (Table 2.6). The yield increased between the Lo-N and  $\frac{1}{2}$ -N levels ( $P < 0.01$ ), and between the  $\frac{1}{2}$ -N and the Hi-N levels ( $P = 0.09$  for TF and  $P = 0.05$  for CF). In both rotations, grain protein did not increase between Lo-N and  $\frac{1}{2}$ -N, but did between  $\frac{1}{2}$ -N and Hi-N, still falling short of the  $120 \text{ g kg}^{-1}$  market standard for #1 HRWW to avoid a price discount (Table 2.6). Despite the response of both yield and protein to the Hi-N

fertilizer level, increasing N fertilizer beyond the  $\frac{1}{2}$ -N rate did not increase profit (Table 2.7), or NEY (Table 2.8) but did increase energy intensity for both rotations.

#### Intensification of Fallow with Continuous Wheat: Rotation 2 vs. 3

Intensification of the cropping system by introducing spring wheat (SW) in place of fallow in 2005 resulted in increased inputs associated with planting, harvesting, and fertilizing the crop. While energy embodied in herbicide applied to SW was less than in CF, the cost of the SW herbicide was greater (Figure 2.1, Figure 2.2). This discrepancy between energetic and economic cost of herbicides occurred with the selective herbicides tralkoxydim and sulfosulfuron, used only on the SW-WW rotation, compared to glyphosate and 2,4-D used on fallow. On an areal basis, the herbicides used on SW are relatively expensive in economic terms but carry little embodied energy due to low concentration of active ingredients or low product application rates (Table 2.5).

Spring wheat yield in 2005 was maximized at the  $\frac{1}{2}$ -N rate, and declined with addition of N up to the Hi-N level (Table 2.6). Following the Hi-N SW there was 120 kg N ha<sup>-1</sup> residual soil NO<sub>3</sub>-N, compared to just 7 and 8 kg N ha<sup>-1</sup> in the Lo-N and  $\frac{1}{2}$ -N treatments, respectively (Table 2.3), indicating that water, rather than N, was the limiting factor for SW yield in 2005. The 164 g kg<sup>-1</sup> grain protein content for 2005 Hi-N SW also indicates that the Hi-N level was more than sufficient to maximize yield (Engel et al., 1999). Because of this large difference in quantity of residual soil N following 2005

crops, the same amount of fertilizer N was used to achieve the Hi-N and  $\frac{1}{2}$ -N available N goals for 2006 WW (Table 2.3).

Winter wheat yield following SW in the SW-WW system (SW-WW; underline denotes emphasis on the Year-2 crop in context of the rotation) was substantially reduced compared to CF-WW (Table 2.6), especially at the Lo-N level. The  $2.28 \text{ Mg ha}^{-1}$  yield difference between rotation treatments at the Lo-N rate illustrates the potential for fallow to supply N by facilitating mineralization of soil organic N to available forms. This is one of the original motivating factors for the practice of summerfallow (Ford and Krall, 1979), and also a major issue with regards to sustainability. The yield difference between CF-WW and SW-WW could not be entirely made up with additional N fertilizer, indicating that other factors like available soil water or disease limited crop yield in SW-WW as well. Yield of SW-WW did not differ significantly between the  $\frac{1}{2}$ -N and Hi-N treatments, however grain protein increased from  $103$  to  $124 \text{ g kg}^{-1}$  with additional available N (Table 2.6).

2006 SW-WW profit was negative at Lo-N, substantially higher at  $\frac{1}{2}$ -N, and higher yet at Hi-N (Table 2.7). When combining 2005 & 2006 profits, however, the Hi-N treatment was not different than the  $\frac{1}{2}$ -N treatment (Table 2.7). Net profit at the most-profitable N-fertilizer level ( $\frac{1}{2}$ -N) did not differ among the CF-WW system and the SW-WW system (Table 2.7). Research at other locations in the NGP has shown equal or greater profit from continuous cropping even when yields were reduced compared to a fallow-crop scenario (Zentner et al., 2002b; DeVuyst and Halvorson, 2004; Lyon et al.,

2004). Net energy yield at the most favorable N-fertilizer level ( $\frac{1}{2}$ N) for SW-WW was 19% greater than the NEY of CF-WW at the highest-yielding N-fertilizer level (Hi-N) for that system (Table 2.8).

#### Diversification - Replacing Spring Wheat with Spring Pea: Rotation 3 vs. 4

Spring pea (SP) production required more energy in the machinery and herbicide categories than SW (Figure 2.1). The greater machinery and fuel energy expenditure for SP than SW was due to energy associated with harvesting, based on assumptions in Zentner et al. (2004). This is due to operation of a combine harvester at a reduced ground speed because of the propensity of pulses to lodge and shatter, and the need to operate the combine harvester with the cutting head very close to the ground. It should be noted that this effect is likely highly variable, depending upon cultivar and environmental conditions. Due to the smaller amount of N-fertilizer applied, total energy input to SP production were 36% less than for SW at the  $\frac{1}{2}$  -N level, and 64% less than SW at the Hi-N level (Figure 2.1).

Spring pea yield was only 37% of spring wheat yield in 2005, resulting in net profit only  $\frac{1}{10}^{\text{th}}$  that of SW (Table 2.6), and NEY less than  $\frac{1}{2}$  that of SW (Table 2.8). This is not typical of pulse producing areas in NE Montana where Burgess et al. (2012) found greater yield of spring pea than spring wheat in a survey of pulse producers. Energy intensity of SP production was less than that of Hi-N SW, but greater than that of  $\frac{1}{2}$ -N SW (Table 2.8).

Soil  $\text{NO}_3\text{-N}$  at WW planting was  $18 \text{ kg N ha}^{-1}$  greater following SP than SW at the Lo-N and  $\frac{1}{2}$ -N levels ( $P=0.06$ ), but  $20 \text{ kg N ha}^{-1}$  less than following fallow ( $P=0.05$ ) (Table 2.3). This is similar to the findings of Zentner et al. (2001), reporting an average over 18 yr where soil  $\text{NO}_3\text{-N}$  to the same depth following lentil was  $22 \text{ kg N ha}^{-1}$  greater than after wheat, but  $10 \text{ kg N ha}^{-1}$  less than following fallow.

With the addition of the  $20 \text{ kg N ha}^{-1}$  pulse credit, fertilizer N applied to SP-WW was the same as following fallow, or  $39 \text{ kg N ha}^{-1}$  less than following SW at the  $\frac{1}{2}$ -N level (Table 2.3). Due to the large quantity of soil  $\text{NO}_3\text{-N}$  present following the Hi-N SW, fertilizer N for Hi-N SW-WW was  $60 \text{ kg N ha}^{-1}$  less than for Hi-N SP-WW.

Yield of Lo-N SP-WW was  $1.86 \text{ Mg ha}^{-1}$  greater than Lo-N SW-WW ( $P<0.01$ ) (Table 2.6), and both had grain protein  $<100 \text{ g kg}^{-1}$ , causing the wheat to be valued as reduced-price 'Ordinary' grade. At the  $\frac{1}{2}$ -N level, yield of SP-WW was  $1.09 \text{ Mg ha}^{-1}$  greater than SW-WW. Between the  $\frac{1}{2}$ -N and Hi-N levels, SP-WW yield increased an additional  $0.96 \text{ Mg ha}^{-1}$ , whereas in SW-WW yield did not increase between  $\frac{1}{2}$ -N and Hi-N levels. Grain protein also increased to  $115 \text{ g kg}^{-1}$  in the Hi-N SP-WW, resulting in wheat value above the 'ordinary' minimum value. The diminishing of the yield difference between SP-WW and SW-WW going from the Lo-N to the  $\frac{1}{2}$ -N level indicates that much of the  $1.86 \text{ Mg ha}^{-1}$  yield difference at Lo-N was due to residual N effects of the pea crop (Beckie et al., 1997). Because the yield difference between rotations persisted at an N level sufficient to maximize yield in the SW-WW rotation, additional non-N benefit of the pea in rotation is also indicated.

Profit for the 2-yr SP-WW system did not increase between the  $\frac{1}{2}$ -N and Hi-N levels, and did not differ from SW-WW systems (Table 2.7). Net energy yield in the SP-WW rotations increased between the  $\frac{1}{2}$ -N and Hi-N level, and at Hi-N did not differ from the NEY of the SW-WW rotation at  $\frac{1}{2}$  -N or Hi-N (Table 2.8). Energy intensity of SP-WW increased with increasing N fertilizer, and did not differ from EI of SW-WW or CF-WW at the same N levels.

#### Replacing Spring Pea with Winter Pea: Rotation 4 vs. 5

Winter pea required greater input energy (Figure 2.1) and input costs (Figure 2.2) than SP due to an additional application of selective in-crop herbicide (sethoxydim) in the fall of 2005. This was somewhat offset by reduced seeding rate for winter pea due to smaller seed size. There were no differences between SP and WP in soil  $\text{NO}_3\text{-N}$  levels in fall 2005 or in the amounts of fertilizer applied to achieve the target available N levels for 2006 WW (Table 2.3).

Winter pea grain yield in 2005 was 67% greater than SP (Table 2.6), resulting in much greater profit (Table 2.7). Chen et al. (2006) also found greater yield potential for WP, but moreso under conditions typical of the Pacific Northwest Mediterranean climate. Most other research on WP in the northern Great Plains has focused on its potential as a green manure cover crop, and in that context WP has been shown to produce equivalent biomass to SP while maturing earlier and using less soil water (Miller et al., 2011). While SP had a net economic loss in 2005, WP had profits as large as any

other 2005 crop. The effect of WP on subsequent WW yield was similar to that of SP (Table 2.6). There were no differences between WP-WW and SP-WW in grain yield or protein at either level of N fertilizer. Combined 2005-2006 profits for the WP-WW system were greater than any Fallow, SW, or SP rotation at any N-level (Table 2.7). Net profit of the WP-WW system at the Hi-N level was not different than at  $\frac{1}{2}$ -N. Net energy yield of the WP-WW system also did not differ between N-levels and did not differ from the Hi-N SP-WW system. Energy intensity of WP was lower than SP, due to higher yield of WP. Energy intensity of WP-WW did not differ from SP-WW at either N level, but energy intensity of WP-WW at Hi-N was nearly twice that at  $\frac{1}{2}$ -N (Table 2.8).

#### Harvest of Pea Biomass as Forage: Rotation 5 vs. 6

Winter pea produced for forage ( $WP_f$ ) required less energy input than winter pea produced for grain (WP) (Figure 2.1). The major differences in production practices were in harvest machinery, and one less post-emergence herbicide application (Table 2.4) made possible by the earlier harvest of forage and necessitated by label restriction of the herbicide active ingredient bentazon on forage crops. Economic cost of production was further reduced for  $WP_f$ , as shown in Figure 2.2, by the assumption that the crop would be sold standing and the cost of harvest would be reflected in a lower price for the crop. Winter pea forage yield was more than 2-fold greater than winter pea grain yield (Table 2.6), however, profit did not differ between the two (Table 2.7). Energy

intensity of winter pea forage was about  $1/3^{\text{rd}}$  that of winter pea harvested for grain, and NEY was more than 2-fold greater (Table 2.8).

Careful interpretation of EI and NEY measurements is warranted when comparing forage to grain because the two products are distinctly different in value and use. When comparing forage and grain systems, some researchers have assumed a feed conversion ratio for a ruminant animal, typically near 10:1 (Zentner et al., 1989; Schroll, 1994) for comparison to human-metabolism-based energy values for grain. This assumption would dramatically reduce the NEY of the forage system presented here, showing pea grain to be a less energy intensive and more productive source of food for humans than beef produced by feeding pea forage to cattle, consistent with findings of Carlsson-Kanyama et al. (2003). This approach is incomplete, however, ignoring the value of manure, and the possibility that harvested forages might be used only as supplemental feed to cattle produced primarily on pasture land not suitable for cropping.

Cruse et al. (2010) compared a suite of energy indicators among alfalfa forage and various grains on the basis of higher heating values (e.g. similar to those used here) and found ratios involving crop energy content for alfalfa to be preferable to corn grain, though alfalfa yields were lower than corn yields in that study. Cruse et al. (2010) assumed corn grain to have been dried with natural gas, a large energy investment. In the present case, the pea grain crop is primarily grown as seed for production of forage or green manure, and its energy content is therefore of little concern. If winter pea were

being grown for a use where energy released on combustion of the harvested material was an important factor (e.g. fired in a power plant, or converted chemically to biofuel), harvest of the entire plant would result in greater NEY for the system.

There was no difference in fall soil  $\text{NO}_3\text{-N}$  level between WP and  $\text{WP}_f$ , however a  $20 \text{ kg ha}^{-1}$  greater N credit was used in calculating N fertilizer application rates on 2006  $\text{WP}_f\text{-WW}$  (Table 2.2) based on previous research near this location (Miller et al. 2008b). Actual applied rates of N fertilizer on  $\text{WP}_f\text{-WW}$  were 26 and  $24 \text{ kg N ha}^{-1}$  less than following WP for the  $\frac{1}{2}\text{-N}$  and Hi-N treatments respectively. Energy inputs to  $\text{WP}_f\text{-WW}$  were less than  $\text{WP-WW}$ , due entirely to the reduction in N fertilizer (Figure 2.1, Figure 2.2).

Winter wheat yield following  $\text{WP}_f$  was not different than following WP at either  $\frac{1}{2}\text{-N}$  or Hi-N levels (Table 2.6). Winter wheat yield following  $\text{WP}_f$  increased in response to addition of fertilizer to the Hi-N level, whereas this increase did not occur following WP. It is likely this increase in yield response can be attributed to greater residual soil water following  $\text{WP}_f$ , as found by Miller et al. (2006), however depth of moist soil measurements taken to depth of 1.4 m cannot confirm this effect in this study.

Profit for 2006, and the combined 2005-2006 rotation did not differ between  $\text{WP-WW}$  and  $\text{WP}_f\text{-WW}$  at either N fertilizer level, and neither system had different profit at Hi-N than  $\frac{1}{2}\text{-N}$  (Table 2.7). Net energy yield for 2006 WW did not differ among WP and  $\text{WP}_f$  rotations, but NEY was greater for  $\text{WP}_f\text{-WW}$  Hi-N than  $\frac{1}{2}\text{-N}$  (Table 2.8), in contrast to the result for economic profit. This difference between energy and economic

analysis is addressed in a more general context in the conclusion section. Energy intensity was lower for WP<sub>f</sub>-WW than WP-WW (Table 2.8), and was lower for the ½-N than Hi-N level of both rotations.

#### Change to Spring Wheat in Year 2: Rotations 6 vs. 7

Rotation 7 also consisted of winter pea forage in 2005, but had spring wheat instead of winter wheat in 2006. This rotation was implemented to contrast with rotation 8, a certified organic system also using spring wheat. Continuous cropping with winter annuals can lead to problems with winter annual weeds (Derksen et al. 2002), in this case downy brome (*Bromus tectorum* L.), and prickly lettuce (*Lactuca serriola* L.), which necessitated repeated application of selective herbicides in all WP crops. Control of these weeds would be problematic in an organically managed system with continuous winter annuals, so spring wheat was chosen for a 2-yr organic crop rotation. Another motivating factor for choosing spring wheat for the organic rotation was the expectation that N cycling would be insufficient to support the yield potential of winter wheat at this location and that spring wheat would be more likely to produce grain of valuable high protein content.

Winter pea forage production in the conventional WP<sub>f</sub>-SW rotation did not differ in terms of inputs, yield, economic, or energetic measures from WP<sub>f</sub>-WW. Soil NO<sub>3</sub>-N content measured before spring wheat planting in 2006 resulted in 5 and 16 kg N ha<sup>-1</sup> less fertilizer N applied on SW than WW for the ½-N and Hi-N levels respectively (Table

2.3). Spring wheat had greater non-fertilizer inputs, both in economic and energetic terms, due to an additional spray operation for pre-plant application of glyphosate. Overall, energy input for SW was similar to WW (Figure 2.1, Figure 2.2). Yield of  $WP_f\text{-SW}$  was approximately half that of  $WP_f\text{-WW}$ , and SW yield did not respond to additional N fertilizer beyond the  $\frac{1}{2}$ -N level, though grain protein increased from 128 to 152 g kg<sup>-1</sup> (Table 2.6). Profit in 2006  $WP_f\text{-SW}$  was less than half that of  $WP_f\text{-WW}$  (Table 2.7), and did not respond to increased N at the Hi-N level, despite the substantial increase in grain protein. Net energy yield of  $WP_f\text{-SW}$  was less than for  $WP_f\text{-WW}$ , and energy intensity was greater (Table 2.8). Energy intensity of SW production was greater at the Hi-N level than  $\frac{1}{2}$ -N.

Organic Production of  $WP_f\text{-WW}$ :  
Rotation 7 vs. 8

Rotations 7 and 8 had the same crops planted, but rotation 8 was certified organic, using no herbicide or fertilizers, and the pea biomass was tilled into the soil rather than harvested as forage. Other than N fertilizer, inputs to organic crop production were only slightly less than the conventional rotation. The reduction due to lack herbicide and other (P,K,S) fertilizer was counterbalanced by increased fuel and machinery use attributed to the tillage operations for green manure incorporation and seedbed preparation, and increased seeding rates used to improve weed competition ability of the organic crop (Figure 2.1, Figure 2.2).

Spring wheat yield in the organic  $\text{Pea}_m\text{-SW}$  systems was no different than conventional  $\text{WP}_f\text{-SW}$  at either level of N fertilizer (Table 2.6). Including the 75% price premium for organic wheat (Miller et al. 2008a), and the cost of green manure management, profit for the organic  $\text{Pea}_m\text{-SW}$  systems also did not differ from the profit of the  $\text{WP}_f\text{-SW}$  system at the  $\frac{1}{2}$ -N rate (Table 2.7). Net energy yield of the organic  $\text{WP}_m\text{-SW}$  system was substantially less than the conventional  $\text{WP}_f\text{-SW}$  rotation owing to the lack of crop harvest in 2005 (Table 2.8). Energy intensity of the organic  $\text{Pea}_m\text{-SW}$  systems (i.e. including energy for 2005 green manure management) was intermediate between that of  $\frac{1}{2}$ -N and Hi-N  $\text{WP}_f\text{-SW}$ .

#### Pea Green Manure for Organic Spring Wheat: Rotation 8

The split-plot factor in rotation 8 was spring pea vs. winter pea green manure in 2005. Input energy and costs shown in Figure 2.1 and Figure 2.2 are for winter pea green manure. Spring pea green manure had greater input energy and cost due to the higher seeding rate necessitated by larger seed size of spring pea, and necessary tillage before planting of spring green manure (Table 2.4), also shown as negative profit for 2005 in Table 2.7 and negative 2005 NEY in Table 2.8.

Spring and winter pea green manures were terminated on the same day, Jul 8 2005, at which point the WP green manure biomass was  $4.2 \text{ Mg ha}^{-1}$  and SP green manure biomass was  $3.0 \text{ Mg ha}^{-1}$ . Spring pea biomass had a greater N concentration, however, resulting in identical values of  $78 \text{ kg N ha}^{-1}$  in aboveground green manure

biomass for winter and spring pea. Subsequent SW yield and protein did not differ. Despite the greater inputs associated with spring pea seed and pre-seeding tillage, organic SP<sub>m</sub>-WW and WP<sub>m</sub>-WW did not differ in profit (Table 2.7), NEY or EI (Table 2.8).

#### Accounting for Changes in Soil Fertility

McCauley (2011) found no effect of fertilizer N level on total soil N or C measured on this study in April 2008. There was an overall effect of crop rotation on total soil N in the top 30 cm of soil. There were few differences among the continuously cropped rotations, but an *a priori* contrast used to test the difference between rotations including fallow (e.g. rotations 1 & 2) and continuously cropped rotations (e.g. rotations 3-8) found 333 kg N ha<sup>-1</sup> more in the continuously cropped rotations than the fallow rotations ( $P < 0.001$ ). Total N quantities in the 0-30 cm depth interval were 4198 kg N ha<sup>-1</sup> for the fallow rotations, and 4531 kg N ha<sup>-1</sup> for the continuously cropped rotations. This amounts to change of 67 kg N ha<sup>-1</sup> yr<sup>-1</sup> over 5 years. Zentner et al. (2001) also found decreased SOC in fallow rotations compared to continuously cropped, equivalent to a decline of 16 kg ha<sup>-1</sup> yr<sup>-1</sup> in total soil N assuming a soil C:N ratio of 8:1 over 30 years. Intensive cropping and reduced tillage in Central N. Dakota also resulted in increases in SOC, particulate organic matter, potentially mineralizable N, microbial biomass, and aggregate stability relative to tilled crop fallow (Liebig et al., 2004)

Without baseline total soil N measurements at the beginning of this study, there is no way to determine if the observed difference in total soil N represents a reduction

in soil N in the fallow systems or a gain in the continuously cropped systems. The scenario considered here is that the continuously cropped systems are at steady-state equilibrium and that the difference represents a decline in total soil N in the fallow systems. As an upper bound on the energy value of this lost soil N, it is considered to have to be replaced or offset at some time in the future at the energetic cost of fertilizer N. Assuming the addition of  $67 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ , or  $134 \text{ kg N ha}^{-1}$  for each 2-yr crop cycle, an increase in input energy of  $7.6 \text{ GJ ha}^{-1}$  substantially increases the EI of the fallow systems, as shown in (Table 2.8), and would decrease NEY of the 2-yr system as well (not shown, but may be calculated by subtracting  $7.6 \text{ GJ ha}^{-1}$  from the 2005-2006 NEY values in Table 2.8).

#### Scenario Analysis Using Price Ratios

Sensitivity of profit to fluctuations of wheat and fertilizer prices over time may be evaluated by comparing the slope of the wheat yield response to N fertilizer to the price ratio of urea-N to wheat shown in Figure 2.3. For example, in the TF-WW rotation, the WW yield at Hi-N level was  $500 \text{ kg ha}^{-1}$  greater than at  $\frac{1}{2}$ -N (Table 2.6), while the difference in quantity of fertilizer N applied was  $99 \text{ kg N ha}^{-1}$ . The slope of the resulting marginal yield increase was therefore  $5.1 \text{ kg wheat kg N}^{-1}$ . There was no other difference in management of these systems. In 2006, the price ratio of urea-N to winter wheat was approximately 6, with little effect of grain protein (Figure 2.3). TF-WW 2006 profit at Hi-N was less than at  $\frac{1}{2}$ -N (Table 2.7). As shown in Figure 2.3, however, in

several other years in recent history the price ratio has been below 5.1, indicating that the yield response to N fertilizer observed in 2006 would have resulted in increased net revenue given the wheat and fertilizer prices those years.

As another example, consider the winter wheat yield response between the Lo-N and  $\frac{1}{2}$ -N levels of the SW-WW rotation. In this case, WW yield increased from 1.36 Mg ha<sup>-1</sup> to 3.26 Mg ha<sup>-1</sup> (Table 2.6) with application of 90 kg N ha<sup>-1</sup> as fertilizer (Table 2.3). The resulting yield response slope is 21 kg wheat kg N<sup>-1</sup>, or about 3 times greater than the largest N:wheat price ratio observed since 1993, as shown in Figure 2.3. While the EI differences between the N-levels of the SW-WW suggest generally that the Lo-N fertilizer rate would become economically favorable with an increase in the N:wheat price ratio, a simple economic analysis can show exactly how much fertilizer prices would have to rise relative to wheat prices for fertilization to the  $\frac{1}{2}$ -N level in this scenario to become unprofitable.

A similar line of reasoning as shown above regarding price ratios and slope of yield response to N fertilizer may be applied to NEY. Net Energy Yield is analogous to net economic return, except the unit of measure of both input and output is MJ (energy) rather than dollars. A general case may be made, then, that NEY is maximized when the slope of the yield response approaches the energy ratio of N:wheat. Consider again, as an example supporting that generalization, the same example of TF-WW, where addition of 99 kg N ha<sup>-1</sup> in 2006 resulted in a yield increase of 500 kg wheat ha<sup>-1</sup>, or a slope of 5.1 kg wheat kg N<sup>-1</sup>, resulting in increased profit in some years, but not 2006.

The ratio of the energy content of urea-N ( $56.7 \text{ MJ kg}^{-1}$ ) to wheat ( $18.7 \text{ MJ kg}^{-1}$ ) is 3.0. Therefore, NEY should have increased between the  $\frac{1}{2}$ -N and Hi-N levels. Although the increase in NEY shown in (Table 2.8) is not statistically significant, the upward trend for NEY (compared to the downward trend for net economic return given 2006 prices) between  $\frac{1}{2}$ -N and Hi-N TF-WW illustrates the important result: that choosing N fertilizer application rate to maximize NEY will typically result in *greater* N fertilizer application rate than would maximize profit.

### Conclusions

#### Comparison of Energy Intensity to U.S. National Average

Energy intensity of all crops, in all crop rotations, and all levels of N fertilizer considered here (Table 2.8) was less than the  $3.9 \text{ MJ kg}^{-1}$  estimated as the U.S. national average energy intensity for wheat production by Piringer and Steinberg (2006), with the sole exception of Hi-N SW in 2005, where wheat yield declined with added fertilizer N beyond the  $\frac{1}{2}$ -N rate. In a survey of actual on-farm wheat production practices, Burgess et al. (2012) found energy intensity of wheat production by Montana farmers ranged from  $2.7 \text{ MJ kg}^{-1}$  for wheat after pulses to  $3.9 \text{ MJ kg}^{-1}$  for wheat after wheat. Energy intensity of Montana wheat production is concluded to be generally less than or equal to the national average, consistent with the regional analysis in Piringer and Steinberg (2006), where grain drying, irrigation, and lime application in other regions contributed to the energy intensity of wheat production.

### Machine Operations and Fuel Consumption

Typical crop production practices in Montana generally leave little room for reduction in fuel and machinery use, short of a radical paradigm shift to human or animal power. Winter wheat production in 2006 was accomplished with just 3 field passes, one each of a seeder, sprayer, and combine harvester. Spring crops grown in continuous cropping systems by farmers surveyed by Burgess et al. (2012) were uniformly grown with four field machinery passes, including two sprayer passes. The crops surveyed here that required additional machinery passes (e.g. repeated spray operations on WP) were among the most profitable, most productive, and least energy intensive systems analyzed. Additional field operations that are necessary to ensure large yields therefore appear not to have a detrimental effect on economic or energetic indicators. Substantial improvements to the fuel efficiency of farm machinery occurred in the U.S. in the 1970's and 1980's due to adoption of diesel power and the adoption of larger equipment on larger farms (Uri and Day, 1992). Further technological advances may be feasible, but specific operating conditions and efficiencies of farm machinery are beyond the scope of this paper. Extension information on tractor operation strategies for improved fuel efficiency is readily available (Lane, 2006).

### Nitrogen Fertilizer

Nitrogen fertilizer was the largest category of input energy for fertilized wheat production, accounting for up to 79% of inputs at the Hi-N level. This proportion is

greater than the 47% reported by Piringner and Stienberg (2006) for the U.S. average, or 66-71% reported by Zentner et al. (2004) for the Canadian Prairies. Neither EI nor NEY of the whole system, however, yielded useful specific information for rational optimization of N fertilizer levels. Energy intensity calculated without adjustment for total soil N change always increased with addition of N fertilizer. This was true even where the yield response to N was economically profitable, and shown to remain profitable up to a tripling of the largest recently observed N:wheat price ratio. Scenario analysis with price and energy ratios showed that NEY is maximized at greater N fertilizer levels than economically optimum. More sophisticated economic modeling tools for optimization of N fertilizer application under different price scenarios, specifically including grain protein response, are already available (Jones and Griffith, 2009), and are recommended.

#### Marginal Energy Intensity and System Energy Intensity

Energy intensity decreased slightly between the Lo-N and ½-N levels of TF-WW and CF-WW under the assumption of 7.6 GJ ha<sup>-1</sup> energy cost associated with mineralization of soil organic N in those systems (Table 2.8). There are few other published reports of cropping system EI decreasing with increased N fertilizer (Hülsbergen, et al., 2002; Rathke and Diepenbrock, 2006). Further investigation of this effect provides insight into the nature and utility of the EI ratio and all ratio-based indicators of cropping system energy use for input optimization. Whether an added

input (e.g. additional fertilizer) will increase or decrease system EI depends on whether the marginal EI of the yield response to the input is greater than or less than the total EI of the unfertilized system.

Consider the case of TF-WW, where WW yield increased by  $1.06 \text{ Mg ha}^{-1}$  with the addition of  $51 \text{ kg N ha}^{-1}$  from the Lo-N to the  $\frac{1}{2}$ -N level. The marginal energy intensity of this increase may be computed from the energy content of the added fertilizer ( $51 \text{ kg N} \times 56.7 \text{ MJ kg}^{-1} = 2892 \text{ MJ}$ ). Dividing this by the wheat yield increase of  $1060 \text{ kg ha}^{-1}$  results in a marginal energy intensity for the increased yield due to the added fertilizer of  $2.73 \text{ MJ kg}^{-1}$  wheat. This is greater than the EI of the Lo-N TW-WW system (Table 2.8), so addition of the fertilizer resulted in greater EI for the  $\frac{1}{2}$ -N level. For the adjusted EI, however, assuming a  $7.6 \text{ GJ ha}^{-1}$  energy input from the soil organic N pool, the EI of the Lo-N TF-WW system was  $3.19 \text{ MJ kg}^{-1}$  (Table 2.8). In this case, the marginal EI of the yield increase due to the added fertilizer ( $2.73 \text{ MJ kg}^{-1}$ ) was less than the EI of unfertilized system EI ( $3.19 \text{ MJ kg}^{-1}$ ), so system EI at  $\frac{1}{2}$ -N was less than at Lo-N. This same result would occur from any other comparable increase in fixed energy inputs to the system resulting from a change in crop production practices, system boundaries, or energy coefficients.

#### Comparison of Tilled and No-Till systems

No economic or energetic differences among T and NT systems were evident in the short term of the research reported here. There are compelling environmental and

agronomic benefits to no-till production (Triplett and Dick, 2010), especially in the semiarid NGP (Tanaka et al., 2010), that constitute externalities to both the economic and energetic analyses presented here. The societal costs and benefits of NT crop production need to be assessed based on appropriately weighted consideration of the myriad environmental, human health, and economic consequences.

### Organic Crop Production Systems

Organic crop production including LGM cover crops may represent a sustainable and economically viable alternative cropping system for the NGP (Miller et al. 2008a). The certified organic crop production systems considered here had far less NEY than any other production system. EI intensity of the organic crop production systems was also greater than many of the moderately fertilized conventional systems, and intermediate between the ½-N and Hi-N levels of the NT system with similar crop rotation (Table 2.8). Despite these findings, the organic systems had similar profit to the contrasting NT system where pea biomass was removed as forage and N fertility for the wheat was supplied with fertilizer, and maintained total soil N levels as well as continuously cropped NT systems (McCauley, 2011).

### Recommendations

Ratio-based energy metrics of agriculture have been criticized as “meaningless and misleading” (Fluck, 1979); and Smil (2008) lamented the lack of any suitable metric for comparison of energy efficiency of cropping systems. Jones (1989) noted that

“Energy analysis of agricultural systems has failed to live up to the expectations of its early proponents” and “Many of the key issues in energy analysis... remain unresolved, and the technique appears to have lost its way in a plethora of detail and sometimes almost metaphysical discussion of methodological issues.” Jones’ ultimate conclusions were that energy analysis was most useful as a “descriptive technique, supplemental to economic analysis” and best served by a parsimonious approach to methodology.

The reality of this characterization is evident here, where energy analysis provided little additional insight into sustainability or energy price sensitivity beyond economic and agronomic analyses, and multiple shortcomings of energy analysis as a general indicator of sustainability were noted. The notion of energy intensity or efficiency is so powerfully intuitive and deeply entrenched, however, that it seems likely to continue to attract interest and be used for generalized comparisons. The following caveats are therefore recommended for comparison of energy intensity and efficiency among agricultural systems.

- Comparisons should be made among systems already optimized by economic analyses regarding input levels and meeting acceptable standards of sustainability by other measures.
- Comparisons should be limited to systems at steady-state equilibrium with regards to soil organic matter content. Where that is not possible, changes in soil fertility status must be considered. Energy analysis is not well-suited for accounting for increases in soil organic matter.

- Comparisons of EI among crops with different end uses should be interpreted with caution. Energy Intensity is not an intrinsic property of a cropping system, but a product of interaction with the environment as well, so comparison of dramatically different systems or climates may not be meaningful.
- There may be potential for energy analysis of opportunities for input substitution to displace N fertilizer, not on the effect on whole-system energy intensity, but on the marginal energy intensity of alternative practices which offset fertilizer use.

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Tables and Figures

Table 2.1 Monthly total precipitation and mean temperature for 2005 and 2006 crop year (Sept.-Aug)

	Total precipitation			Mean temperature		
	LTA	2005	2006	LTA	2005	2006
	----- mm -----			----- °C -----		
Sept.	32	42	27	13.4	13.0	14.3
Oct.	35	41	66	7.2	8.0	9.2
Nov.	23	5	48	0.1	1.3	1.0
Dec.	14	4	14	-5.1	-1.1	-5.6
Jan.	14	5	17	-4.1	-4.8	-0.1
Feb.	14	7	1	-2.5	-0.2	-3.4
Mar.	26	25	14	1.9	3.1	1.3
Apr.	45	58	76	6.3	6.9	7.7
May	71	29	44	10.9	9.8	11.5
June	71	77	87	14.7	12.7	15.3
July	36	27	13	19.0	20.2	21.6
Aug.	31	44	18	18.4	18.6	18.8
Year	411	366	425	6.7	7.3	7.6

† LTA, Long-term average: 1981-2010 from official weather station adjacent to field site.

Table 2.2 Crop sequences of the eight rotation treatments, and explanation of the stepwise changes.

Rotation	2005	2006	Changes from previous level
1. TF-WW	Tilled Fallow	Winter Wheat	Baseline Scenario
2. CF-WW	Chem Fallow	Winter Wheat	Change tilled fallow to chem-fallow
3. SW-WW	Spring Wheat	Winter Wheat	Replace fallow with spring wheat
4. SP-WW	Spring Pea: grain	Winter Wheat	Replace spring wheat with spring pea
5. WP-WW	Winter Pea: grain	Winter Wheat	Replace spring pea with winter pea
6. WP <sub>F</sub> -WW	Winter Pea: Forage	Winter Wheat	Harvest winter pea as forage
7. WP <sub>F</sub> -SW	Winter Pea: Forage	Spring Wheat	Change winter wheat to spring wheat
8. P <sub>m</sub> -SW (ORG)	Pea Green Manure	Spring Wheat	Till in pea as green manure, system is certified organic.

Table 2.3 Summary of split-plot N fertilization strategies.

Rotation	N Strategy	2005	2006	2006	2006	2006
		Fertilizer N	Soil NO <sub>3</sub> N	Fertilizer N	Pulse Credit	Available N†
		-----kg N ha <sup>-1</sup> -----				
1. TF-WW	L-N	0	46	6	0	52
	½-N	0	46	57	0	103
	H-N	0	49	156	0	205
2. CF-WW	L-N	0	55	6	0	61
	½-N	0	55	57	0	112
	H-N	0	55	156	0	211
3. SW-WW	L-N	4	7	6	0	13
	½-N	75	8	96	0	104
	H-N	160	120	96	0	216
4. SP-WW	L-N	15	26	6	0	32
	½-N	15	27	57	20	104
	H-N	15	29	156	20	205
5. WP-WW	½-N	15	30	57	20	107
	H-N	15	35	156	20	211
	½-N	15	37	31	40	108
6. WP <sub>F</sub> -WW	H-N	15	36	132	40	208
	½-N	15	40	26	40	104
	H-N	15	52	116	40	208
8. Pea <sub>m</sub> -SW (ORG)	Winter Pea GM	0	-	0	na	na
	Spring Pea GM	0	-	0	na	na
	SEDa‡		6.5(34)			
	SEDb§		9.6(32)			

† Available N is the sum of soil NO<sub>3</sub> N, Fertilizer N, and the pulse credit.

‡ SEDa: Standard Error of the Difference among N strategies within a crop rotation.

§ SEDb: Standard Error of the Difference among rotations.

Table 2.4 Tillage operations and herbicide applications.

Rotation	Tillage operations and herbicide applications
<b>2005</b>	
1. Tilled Fallow	1x heavy harrow, 1x disk, 2x chisel plow, 1x field cultivator†
2. Chem Fallow	3x glyphosate ‡ (0.63 kg ae ha <sup>-1</sup> ) + AMS § (1.7 kg ha <sup>-1</sup> ) 1x glyphosate ‡ (0.63 kg ae ha <sup>-1</sup> ), + AMS § (1.7 kg ha <sup>-1</sup> ), + 2,4-d amine ¶ (0.53 kg ae ha <sup>-1</sup> )
3. Spring Wheat	PRE1#: glyphosate ‡ (0.63 kg ae ha <sup>-1</sup> ) PRE2#: sulfosulfuron †† (0.04 kg ai ha <sup>-1</sup> ) + NIS ‡‡ (0.47 l ha <sup>-1</sup> ) POST3§§: tralkoxydim ¶¶ (0.16 kg ai ha <sup>-1</sup> ) + NIS (0.47 l ha <sup>-1</sup> )
4. Spring Pea	PRE: glyphosate ‡ (0.63 kg ae ha <sup>-1</sup> ) POST: bentazon †† (1.1 kg ai ha <sup>-1</sup> ) + sethoxydim ††† (0.2 kg ai ha <sup>-1</sup> ) + AMS (1.7 kg ha <sup>-1</sup> ) + MSO‡‡‡ (1.2 l ha <sup>-1</sup> )
5. Winter Pea	PRE: none POST1: sethoxydim (0.22 kg ai ha <sup>-1</sup> ) + COC (2.4 l ha <sup>-1</sup> ) + AMS (1.7 kg ha <sup>-1</sup> ) POST2: sethoxydim (0.22 kg ai ha <sup>-1</sup> ) + COC (2.4 l ha <sup>-1</sup> ) + AMS (1.7 kg ha <sup>-1</sup> ) POST3: bentazon (1.14 kg ai ha <sup>-1</sup> ) + sethoxydim (0.22 kg ai ha <sup>-1</sup> ) + AMS (1.7 kg ha <sup>-1</sup> ) + MSO (1.2 l ha <sup>-1</sup> )
6,7. Winter Pea Forage	PRE: none POST1: sethoxydim (0.22 kg ai ha <sup>-1</sup> ), COC (2.4 l ha <sup>-1</sup> ), AMS (1.7 kg ha <sup>-1</sup> ) POST2: sethoxydim (0.22 kg ai ha <sup>-1</sup> ), COC (2.4 l ha <sup>-1</sup> ), AMS (1.7 kg ha <sup>-1</sup> ) post-harvest: glyphosate (0.63 kg ae ha <sup>-1</sup> ), AMS (1.7 kg ha <sup>-1</sup> ), 2,4-d amine (0.42 kg ae ha <sup>-1</sup> )
8. Org. Winter Pea GM	Pre-Seed: none green manure incorporation & weed control: heavy disk + light disk + chisel plow
8. Org. Spring Pea GM	Pre-Seed: Chisel Plow, field cultivator green manure incorporation & weed control: heavy disk + light disk + chisel plow
<b>2006</b>	
1-6. Winter Wheat	PRE: none POST: clodinafop propargyl ‡ (0.06 kg ai ha), COC (0.70 l ha <sup>-1</sup> ), 2,4-d amine (0.42 kg ae ha <sup>-1</sup> )
7. Spring Wheat	PRE: glyphosate ‡ (0.63 kg ae ha <sup>-1</sup> ) + AMS § (1.7 kg ha <sup>-1</sup> ) POST: clodinafop propargyl (0.06 kg ai ha), COC (0.70 l ha <sup>-1</sup> ), 2,4-d amine (0.42 kg ae ha <sup>-1</sup> )
8. Org. Spring Wheat	pre-seed: field cultivator †

† field cultivator with trailing baskets (Triple K, Kongskilde, Hodgdon, IL).

‡ glyphosate: glyphosate N-(phosphonomethyl) as potassium salt

§ AMS: spray grade ammonium mono-sulfate

¶ 2,4-d amine : (2,4-Dichlorophenoxyacetic acid) as Dimethylamine salt

# PRE: applied pre-emergence

†† sulfosulfuron: (1-(4,6-dimethoxyypyrimidin-2-yl)-3-(2-ethylsulfonylimidazo[1,2-a]pyridin-3-ylsulfonyl)urea)

‡‡ NIS: non-ionic surfactant: alkylphenol ethoxylate, alcohol ethoxylate and tall oil fatty acid

§§ POST: applied post-emergence

¶¶ tralkoxydim: (2-Cyclohexen-1-one, 2-[1-(ethoxyimino)propyl]-3-hydroxy-5-(2,4,6-trimethylphenyl)-(9CI))

### bentazon: (3-{1-methyl-2,1,3-benzothiadiazin-4(3H)-one 2,2-dioxide) as sodium salt

††† sethoxydim: 2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one

‡‡‡ MSO: methylated seed oil (proprietary commercial blend)

§§§ COC: crop oil concentrate (proprietary commercial blend)

¶¶¶ clodinafop propargyl: Propanoic acid, 2-[4-[(5-chloro-3-fluoro-2-pyridinyl)oxy]phenoxy]-,2-propynyl ester, (2R)-

Table 2.5 Economic and energetic costs of inputs on areal basis.

Product	Active Ingredient Concentration	Embodied Energy	Product Use Rate †	Product Price ‡	Energy Cost	Economic Cost
		MJ kg <sup>-1</sup> ai			MJ ha <sup>-1</sup>	\$ ha <sup>-1</sup>
<b>Herbicides &amp; Adjuvants</b>						
2,4-d amine	457 g l <sup>-1</sup>	98	1.2 l ha <sup>-1</sup>	\$3.88 l <sup>-1</sup>	52	\$4.51
AMS	100%	14	1.7 kg ha <sup>-1</sup>	\$0.64 kg <sup>-1</sup>	25	\$1.10
bentazon	601 g l <sup>-1</sup>	493	1.9 l ha <sup>-1</sup>	\$25.50 l <sup>-1</sup>	562	\$31.42
clodinafop-propargyl	241 g l <sup>-1</sup>	298	0.23 l ha <sup>-1</sup>	\$170.00 l <sup>-1</sup>	17	\$39.52
COC	100%	201	2.4 l ha <sup>-1</sup>	\$3.74 l <sup>-1</sup>	466	\$8.69
glyphosate	540 g l <sup>-1</sup>	356	1.2 l ha <sup>-1</sup>	\$10.02 l <sup>-1</sup>	225	\$8.93
MISO	100%	201	2.3 l ha <sup>-1</sup>	4.76 l <sup>-1</sup>	466	\$11.07
NIS	100%	201	0.5 l ha <sup>-1</sup>	\$5.44 l <sup>-1</sup>	93	\$2.53
Sethoxydim	180 g l <sup>-1</sup>	308	1.8 l ha <sup>-1</sup>	\$21.76 l <sup>-1</sup>	97	\$31.06
Sulfosulfuron	75%	366	0.046 kg ha <sup>-1</sup>	\$630.00 kg <sup>-1</sup>	13	\$29.34
Tralkoxydim	205 g l <sup>-1</sup>	314	0.5 l ha <sup>-1</sup>	\$57.80 l <sup>-1</sup>	64	\$29.39
<b>Seed</b>						
Wheat: certified, treated		7.2	81 kg ha <sup>-1</sup>	\$0.38 kg <sup>-1</sup>	583	\$30.78
Winter Pea: purchased		3.2	187 kg ha <sup>-1</sup>	\$0.39 kg <sup>-1</sup>	598	\$72.94
Spring pea: purchased		3.2	82 kg ha <sup>-1</sup>	\$0.39 kg <sup>-1</sup>	262	\$31.98
<b>Fertilizer (N-P-K-S) §</b>						
Urea (N)	46-0-0	56.7	339 kg ha <sup>-1</sup>	\$405 Mg <sup>-1</sup>	8841	\$137.30
Ammon. Phosphate (P)	11-52-0	9.5	56 kg ha <sup>-1</sup>	\$419 Mg <sup>-1</sup>	277	\$23.46
Potassium Sulfate (K)	0-0-50-17	9.9	56 kg ha <sup>-1</sup>	\$242 Mg <sup>-1</sup>	228	\$13.55
<b>Machine Operation</b>						
Conventional seed drill					350	\$19.64
Zero-till air seeder					408	\$26.31
Sprayer, SP					69	\$10.05
Sprayer, pulled					89	\$11.29
Chisel plow					296	\$14.80
Tandem disk					431	\$15.54
Heavy harrow					163	\$10.35
Field cultivator					189	\$12.72
Combine- pea					831	\$49.25
Combine- wheat					350	\$40.19

† Typical values shown for comparison. Actual application rates varied.

‡ 2005 prices shown, 2006 prices differed. Prices shown are for applied product.

§ Fertilizer nutrient concentrations are for % N, P<sub>2</sub>O<sub>5</sub>, K<sub>2</sub>O, and S. Prices are shown for applied fertilizer products. Energy coefficients are shown only for the primary nutrient supplied by each fertilizer product. Energy embodied in secondary nutrients supplied by fertilizer products (e.g. N in ammonium phosphate) was categorized by proportion of nutrient content.

Table 2.6 Crop yield and grain protein content 2005 and 2006.

Rotation	N Strategy	2005		2006	
		Crop Yield <sup>†</sup>	Protein	Crop Yield	Protein
		Mg ha <sup>-1</sup>	g kg <sup>-1</sup>	Mg ha <sup>-1</sup>	g kg <sup>-1</sup>
TF-WW	Lo-N	0	0	3.20	96
	½-N	0	0	4.26	99
	Hi-N	0	0	4.76	117
CF-WW	Lo-N	0	0	3.64	98
	½-N	0	0	4.64	98
	Hi-N	0	0	5.22	115
SW-WW	Lo-N	2.01	101	1.36	96
	½-N	2.91	128	3.26	103
	Hi-N	2.54	164	3.52	124
SP-WW	Lo-N	-	-	3.22	92
	½-N	-	-	4.35	91
	Hi-N	1.08	229	5.31	115
WP-WW	½-N	-	-	4.49	100
	Hi-N	1.80	251	4.76	118
WP <sub>r</sub> -WW	½-N	-	-	4.47	94
	Hi-N	5.20	133	5.26	112
WP <sub>r</sub> -SW	½-N	-	-	2.48	128
	Hi-N	5.36	154	2.45	152
Pea <sub>m</sub> -SW (ORG)	Winter Pea GM	-	-	1.96	135
	Spring Pea GM	-	-	2.17	132
	SEDa(df) ‡	0.10(6)	7.3(5)	0.30(37)	3.5(37)
	SEDb(df) §	0.39(12)	14.5(12)	0.35(45)	6.0(33)

<sup>†</sup> Values of zero, and duplicates of single observations where split plot treatments were not applied are not included in statistical analysis of 2005 yield and protein.

<sup>‡</sup> SEDa: Standard Error of the Difference among N strategies within a crop rotation.

<sup>§</sup> SEDb: Standard Error of the Difference among rotations.

SED may be used for appropriate multiple comparison testing by multiplying by the appropriate value of the T-statistic, e.g. ~1.7 for a 2-tailed test at P=0.10 with df>20

Table 2.7 Net revenue for 2005, 2006, and combined 2005-2006 cropping system.

Rotation	N Strategy	2005 Net Revenue†	2006 Net Revenue	2005-2006 Net Revenue
1. TF-WW	Lo-N	-\$66.	\$250	\$184
	½-N		\$350	\$284
	Hi-N		\$340	\$274
2. CF-WW	Lo-N	-\$85	\$301	\$216
	½-N		\$390	\$305
	Hi-N		\$394	\$309
3. SW-WW	Lo-N	\$51	-\$7	\$43
	½-N	\$123	\$169	\$292
	Hi-N	\$79	\$234	\$312
4. SP-WW	Lo-N		\$245	\$239
	½-N		\$350	\$344
	Hi-N	-\$6	\$406	\$400
5. WP-WW	½-N		\$369	\$514
	Hi-N	\$145	\$338	\$483
6. WP <sub>F</sub> -WW	½-N		\$390	\$505
	Hi-N	\$115	\$410	\$525
7. WP <sub>F</sub> -SW	½-N		\$134	\$260
	Hi-N	\$126	\$79	\$205
8. Pea <sub>m</sub> -SW (ORG)	Winter Pea GM	-\$118	\$426	\$308
	Spring Pea GM	-\$175	\$473	\$297
	SEDa‡ (df)	15(6)	38(37)	39(36)
	SEDb§ (df)	39(12)	49(42)	62(33)

- † net losses in 2005 incurred for fallow and green manure management were not included in the statistical analysis
- ‡ Standard Error of the Difference among N strategies within a crop rotation
- § Standard Error of the Difference among rotations
- SED may be used for appropriate multiple comparison testing by multiplying by the appropriate value of the T-statistic, e.g. ~1.7 for a 2-tailed test at  $P=0.10$  with  $df>20$

Table 2.8 Energy Intensity (EI) and Net Energy Yield (NEY)

Rotation	N Strategy	EI05	NEY05	EI06	Adj. EI ‡	NEY06	NEY05-06
		MJ kg <sup>-1</sup>	GJ ha <sup>-1</sup>	MJ kg <sup>-1</sup>	MJ kg <sup>-1</sup>	GJ ha <sup>-1</sup>	GJ ha <sup>-1</sup>
1. TF-WW	Lo-N	-	-	1.04†	3.19	65.1	63.8
	½-N	-	-	1.36†	2.95	84.7	83.4
	Hi-N	-	-1.3	2.35†	3.81	89.5	88.3
2. CF-WW	Lo-N	-	-	0.86†	2.84	74.3	73.3
	½-N	-	-	1.21†	2.73	92.5	91.5
	Hi-N	-	-1.3	2.03†	3.37	99.2	98.2
3. SW-WW	Lo-N	1.18	40.1	1.66		26.2	66.7
	½-N	2.04	55.2	2.10		61.3	116.9
	Hi-N	4.01	42.5	1.96		66.8	109.7
4. SP-WW	Lo-N	-	-	0.69		65.5	84.5
	½-N	-	-	1.08		86.5	105.5
	Hi-N	3.54	18.7	1.83		101.1	120.1
5. WP-WW	½-N	-	-	1.05		89.4	123.4
	Hi-N	2.48	33.3	2.04		89.5	123.4
6. WP <sub>F</sub> -WW	½-N	-	-	0.76		90.5	179.4
	Hi-N	0.84	88.2	1.62		101.4	190.3
7. WP <sub>F</sub> -SW	½-N	-	-	1.44		48.5	140.3
	Hi-N	0.82	91.2	3.41		42.7	134.6
8. Pea <sub>m</sub> -SW (ORG)	Winter Pea GM	-	-2.7	2.26†		39.2	36.4
	Spring Pea GM	-	-3.6	2.41†		43.6	40.0
	SEDa(df)	0.10(4)	2.2(6)	0.18(36)		6.1(37)	6.3(35)
	SEDb(df)	0.18(13)	7.2(12)	0.24(41)		7.5(45)	9.6(34)

† 2006 Energy intensity for rotations including fallow or green manure include the energy input from 2005.

‡ Adjusted energy intensity for fallow rotations includes average total soil N change as an input to the system.

• SED may be used for appropriate multiple comparison testing by multiplying by the appropriate value of the T-statistic, e.g. ~1.7 for a 2-tailed test at  $P=0.10$  with  $df>20$

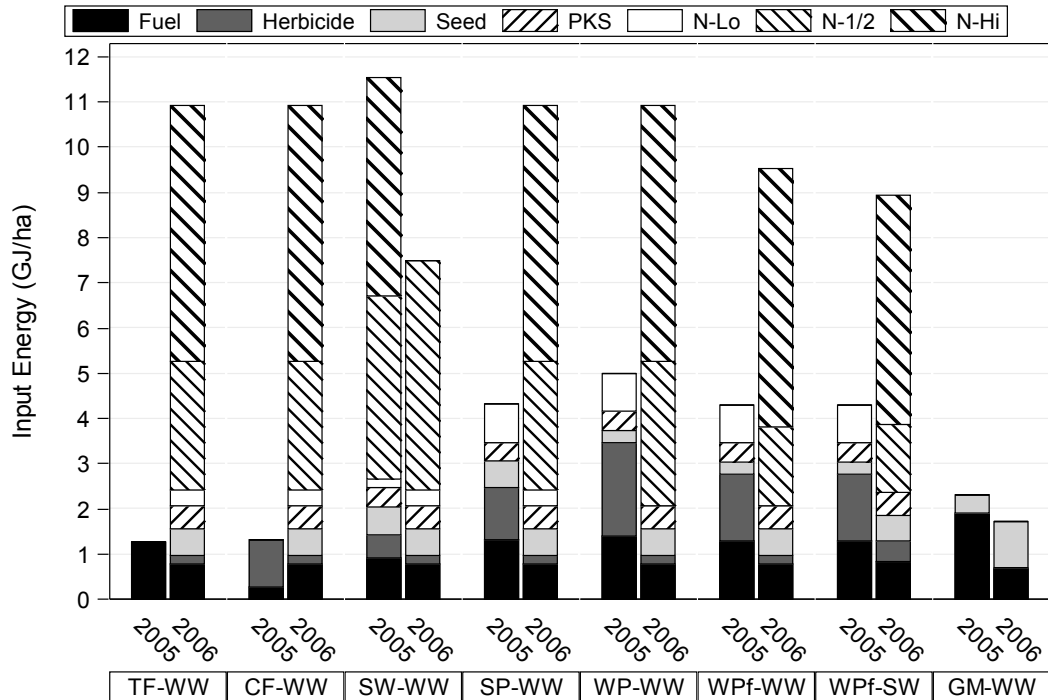


Figure 2.1 Categorized energy inputs ( $\text{GJ ha}^{-1}$ ) for each crop rotation. TF: tilled fallow, CF: chemical fallow, SW: spring wheat, SP: spring pea, WP: winter pea, WPf: winter pea forage, GM: green manure. WW: winter wheat. N-Hi, N-1/2, and N-Lo refer to N fertilization strategies. Note: SW-WW received the same N fertilizer for both N input levels in 2006 due to high soil N carryover in the Hi system from 2005.

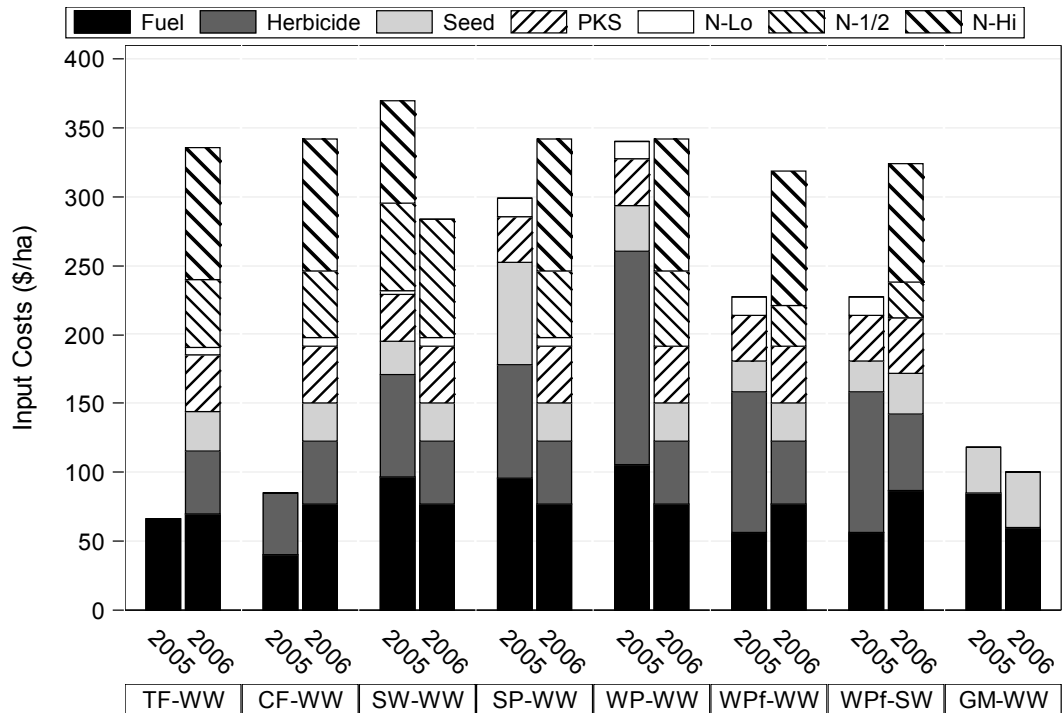


Figure 2.2 Categorized input costs ( $\$ \text{ ha}^{-1}$ ). TF: tilled fallow, CF: chemical fallow, SW: spring wheat, SP: spring pea, WP: winter pea, WPf: winter pea forage, GM: green manure. WW: winter wheat. N-Hi, N-1/2, and N-Lo refer to N fertilization strategies. Note: SW-WW received the same N fertilizer for both N input levels in 2006 due to high soil N carryover in the Hi system from 2005.

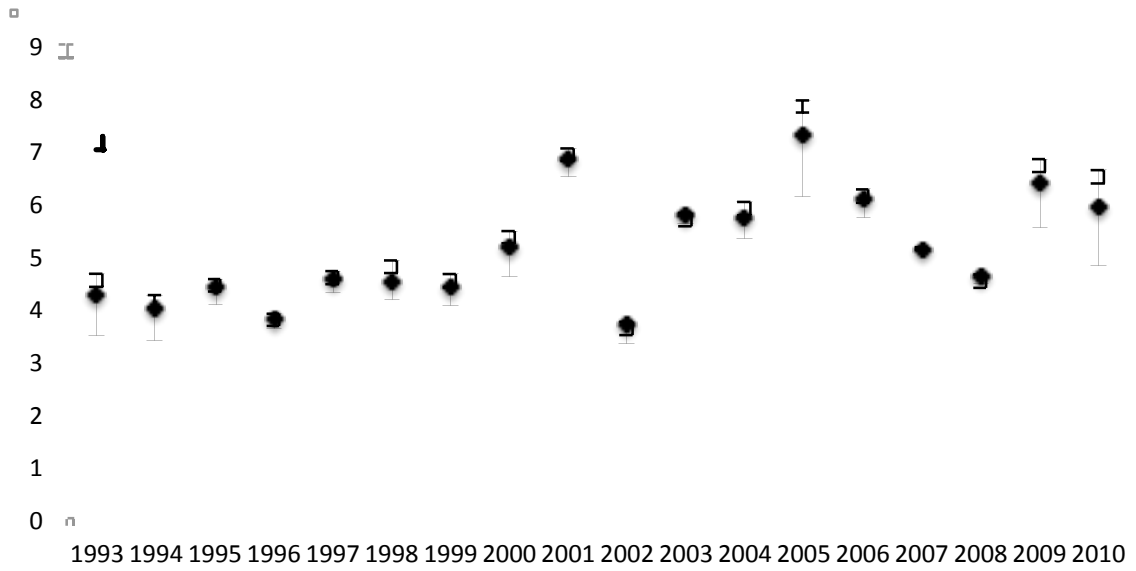


Figure 2.3 Price ratio of Urea-N to US#1 hard red winter wheat. Bars indicate annual range in price ratio for protein range from 110 g kg<sup>-1</sup> to 130 g kg<sup>-1</sup>. Data from NASS 2012.

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3. PULSE CROPS IMPROVE ENERGY INTENSITY AND PRODUCTIVITY OF CEREAL  
PRODUCTION IN MONTANA, USA

Contribution of Authors and Co-Authors

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### Abstract

Energy consumption, intensity, and productivity are indicators of agricultural sustainability in the face of fossil energy scarcity and price volatility. In this study, budgets of energy embodied in crop production inputs were compiled for fourteen paired pulse (annual grain legume)-wheat and wheat-wheat crop sequences using data collected from Montana farmers. We report two energy performance metrics: Net Energy Yield (NEY), the energy content of harvested crop minus energy required to produce it) and Energy Intensity (EI), the ratio of input energy to mass of crop harvested. Nitrogen fertilizer accounted for 58% of the energy used in wheat production, and its absence largely accounted for the 53% reduction in energy inputs to pulses relative to wheat. Energy Intensity of pulses was lower than for wheat, and pulse crops also resulted in reduced energy intensity and increased NEY for subsequent wheat crop compared to wheat grown following wheat. The largest component of the improved energy performance of wheat following pulses was increased yield rather than decreased inputs.

### Introduction

Analysis of the fossil energy used for food production is of interest to consumers, farmers, and policy makers. Increasingly, consumers are concerned with the environmental footprint of their food choices. In response, major food manufacturers and retailers are developing systems to report standardized measures of energy use and

greenhouse gas emissions for individual food products (Sustainability Consortium, 2011). Farmers are concerned primarily with the economic costs associated with farm inputs, but understanding the relative magnitude of energy embodied in those inputs can help with decision making in light of energy price uncertainty. Scientists are responding with renewed initiatives to better understand and explain the role of energy in food production (Anon, 2010). While individual crops may vary in their energy intensity and productivity at any given location, crop choice also impacts energetics of entire cropping systems through rotational effects.

Total direct and indirect non-renewable energy embodied in (i.e. used in manufacture and delivery of) crop production inputs is useful for identifying inputs that are particularly large proportions of the total (Piringer and Steinberg, 2006) and may illuminate opportunities for energy-saving substitution of inputs. Net energy yield (NEY) is the difference between energy content of harvested crop material and energy input for crop production, as described above, per unit area of land ( $\text{GJ ha}^{-1}$ ). Net Energy Yield was proposed by Liska and Cassman (2008) as a standard metric for energy productivity of biofuel production systems, and has been reported (under various other names) by many researchers (Zentner et al., 1998; Hülsbergen et al., 2002; Zentner et al., 2004; and Rathke and Diepenbrock, 2006). Here we use the term *productivity* to refer to NEY in a generic sense. Energy Intensity (EI) is the ratio of input energy to the quantity of harvested crop material ( $\text{MJ kg}^{-1}$ ), a smaller number indicating less energy used to produce a quantity of material. Energy Intensity, and its reciprocal, sometimes multiplied

by a crop energy coefficient, have all been reported as *efficiency*, leading to confusion about whether a smaller or larger number is preferable. In this paper, the term 'energy efficiency' will be used in the common general sense (greater efficiency being desirable) to indicate a larger ratio of outputs:inputs where such a ratio was originally reported in other research, regardless of the units originally used. Our own results will focus on EI as a ratio-based measure of cropping system energy performance, lower intensity being preferable. These measures are essentially equivalent, but putting the input energy in the numerator is more appropriate for comparison of energy use among systems (Larrick and Soll, 2008), and keeping the denominator in units of mass also aids appropriate interpretation (Fluck, 1979, Jones 1989). Energy Intensity expressed in MJ kg<sup>-1</sup> is also similar to the concept of embodied energy used in other disciplines (Bullard and Herendeen, 1975).

In agricultural systems, energy efficiency and productivity have often been found mutually exclusive. Green (1976) claimed "Low agricultural productivity is energy efficient, high agricultural productivity is energy demanding." Many studies have found reduced energy inputs result in reduced EI for low-input systems (Berardi, 1978; Pimentel et al., 1983; Dalgaard et al., 2001; Hoepfner et al., 2006; Alonso and Guzmán, 2008; Cruse et al., 2010; Gündoğmus 2010; Macrae et al., 2010; Aluvione et al., 2011; Zentner et al., 2011). Reduced NEY for low-input systems is also a common finding, as indicated by the review of 78 different crops by Alonso and Guzmán (2010). A few studies have found contrasting or ambiguous results regarding EI of low-input systems,

especially when low-input systems had lower yields and under assumptions of large energy costs for animal manure (Liu et al, 2010), or when otherwise low-input systems included energy-intensive tillage of cover crops (Gelfand et al., 2010). Gomiero et al. (2008), in reviewing comparisons among low-input and conventional systems, noted the apparent inverse relationship between NEY and energy efficiency as a trade-off to be balanced in light of other concerns including land and labor productivity. Liska and Cassman (2008) also noted that the most energy-efficient biofuel production systems (e.g. soy biodiesel) are not as productive, in terms of NEY, as others like corn or ethanol, and propose NEY as the preferred indication of biofuel system productivity where replacement of petroleum fuel is the main goal.

Cereal grains and legumes have been found to be among the least energy intensive food products (Carlsson-Kanyama et al., 2003). Because N fertilizer accounts for half or more of the energy input to wheat production (Piringer and Steinberg, 2006), and because N-fixing legumes require little or no N fertilizer, legumes would be expected to require less energy to produce. Given similar yields, this would result in reduced energy intensity as well. Khakbazan et al. (2009) found lower energy intensity for pea than wheat in a comparison based on field experiments in the subhumid Canadian Prairies. Pimentel and Pimentel (2008; pp. 107-116) also cite higher energy input for wheat production in the U.S. than for dry bean, but similar energy intensity for both. Data for Pimentel's (2008) examples, however, come from different sources and may be based on different assumptions regarding production practices. This highlights a

particular challenge in interpretation of energetic analyses of agriculture addressed specifically by Fluck (1979), who concluded that energy ratios are most useful for comparison of alternative ways of growing “the same product, at the same place, at the same time”.

Research has also focused on the effect of cropping systems, particularly crop sequence, on cropping system energy performance (Cruse et al., 2010; Zentner et al. 2011). Analysis of whole systems captures synergisms and complex interactions (Ikerd, 2003). For example, crops grown in diverse rotations may have greater yield, but also reduced need for inputs like pesticides. Outside of specially restricted systems (e.g. certified organic) where whole classes of inputs are categorically prohibited, there is difficulty in deciding when and to what extent crop diversity enables or justifies reduction in inputs. This is illustrated at a very basic level by the difficulty in arriving at research-based recommendations for reduction of N fertilizer following pulse crops in the northern Great Plains (Walley et al. 2007). Where experimental treatments combine increased diversity with reduced inputs, it can be difficult to tease apart the contributions of the different yield potentials of individual crops, the input reductions, and genuine synergistic effects on unmeasured variables manifest in difference in actual crop yield.

In this study, we focus on the effect of introducing pulses as a rotation crop for wheat in an environmental context where this has not historically been the norm. We specifically compare paired wheat-wheat (W-W) and pulse-wheat (P-W) crop sequences

from the same farm and same years. These paired fields allow comparison of wheat and pulse crops grown under similar conditions in Year 1, and comparison of wheat following wheat (W-**W**) vs. wheat following a pulse crop (P-**W**) in Year 2 (boldfaced italics denoting a focus on the Year 2 crop in context of the previous crop). In this study, experienced farmers chose fertilizer and other input rates and the data presented here was collected post hoc. The observational units were entire farm fields of at least 30 ha. The objective of this study was to compare energy intensity and productivity among these systems to provide valuable practical insight into the differences in energetic performance between pulses and cereals and the systemic contribution of pulses to cereal crops in rotation.

#### Description of Study Area

This study surveys crop production in the northern portion of the State of Montana, in USDA-NRCS Major Land Resource Areas (MLRAs) 46, 52, and 53a (NRCS, 2006). The results should be broadly applicable to cropland in Agroecoregions 1, 9, and 12 as defined by Padbury et al. (2002), representing 14.1 million ha in the states of Montana, N. Dakota, and S. Dakota, and the provinces of Alberta and Saskatchewan (Canada). This region has a semiarid continental climate with cold winters and warm summers with variable winds and highly variable precipitation. There is a notable rainy season coincident with the early growing season, typically followed by terminal summer drought beginning in late June or early July. Mean annual precipitation ranges from

~300-400mm, with annual evapotranspiration of ~550-600mm, and mean annual temperature of ~4.5-7.1 °C (Padbury et al., 2002)

In this region, wheat (*Triticum* spp.) is the dominant crop and was historically grown in rotation with a full season summerfallow accomplished with repeated tillage (Ford and Krall, 1979; Padbury et al., 2002). The practice of summerfallow has long been identified as a major obstacle to sustainability due to detrimental effects on soil quality, among other issues (Janzen, 2001). Throughout the broader Great Plains region, conservation tillage and no-till production have contributed importantly to the diversification and intensification (i.e. reduction of fallow frequency) of agricultural systems (Tanaka et al., 2010). No-till crop production practices are an important element of sustainability in the northern Great Plains (Lafond, et al., 1992; Zentner et al., 2001), directly addressing issues like soil erosion (Larney et al., 1994a,b), conservation of soil organic matter (Peterson et al., 1998), and water-use-efficiency (Peterson et al., 1996).

Although no-till and conservation tillage production practices are dominant in Montana (Watts et al., 2009), lack of suitable rotation crops for cereals has hindered cropping system intensification until recently. Wheat or barley occupied 58% of Montana cropland (i.e. excluding perennial forages and grazing land) in 2010, with summerfallow practiced on 34% (NASS 2010). Oilseeds (e.g. canola [*Brassica* spp.] and flax), which have contributed substantially to diversification of cropping systems in regions to the north and east, are not widely grown in Montana (NASS 2010). However,

pulses especially dry pea and lentil (*Lens culinaris* Medik.) are well adapted in Montana (Miller et al., 2002). Production of pulses has increased steadily in recent years to over 200,000 ha in 2010, representing over 5% of the cropland in the state (NASS, 2010).

Wheat grown in this region is marketed based on protein content, which is desired primarily for reasons of physical properties related to bread and noodle quality (Bruckner et al., 2001). A substantial price premium for high-protein grain encourages farmers to apply N-fertilizer beyond the yield-maximizing level (Engel et al., 1999; Baker et al. 2004). Further, uncertainty regarding stochastic variables such as rainfall may motivate some farmers to manage N fertilizer for risk management objectives as well total profit (Bullock and Bullock, 1994). Depending on individual aversion to risk, some producers may accept lower profits in exchange for reduced variability (a motivation for summerfallow), or may fertilize for optimistic yield goals to ensure high protein in a high rainfall year. One objective of this study was to capture variability resulting from the various real-world strategies for N-fertilizer management in the face of volatile prices.

## Methodology

### Crop Energy Budgets

Energy budgets of crop production were compiled for 14 paired pulse-wheat and wheat-wheat crop sequences using data collected from farmers in Montana.

Approximate locations of the surveyed farms are shown in Figure 3.1. Survey locations were chosen to reflect the spatial patterns of pulse production in Montana, with a focus

on the four NE-Montana counties that together made up 64% of the state's 2010 pulse production area, and where diversification with pulse crops has occurred simultaneously with a substantial decline in summerfallow (Tanaka et al., 2010). Sites were located between 47° and 49° N latitude and at elevations of 589 to 1163 m.

Survey participants were identified by recommendations from Montana State University Extension faculty or by referrals from other farmers participating in the study. We specifically sought out farmers with at least ten years of experience growing pulse crops. Participants were asked for details of field operations, inputs, and crop yields for two fields: one each with a wheat-wheat and a pulse-wheat crop sequence in the same two years, on the same farm, and under similar management. All data reported are from years between 2004 and 2010. Reported pulse crops included various cultivars of spring-planted green and yellow field pea and lentil. Wheat included locally adapted cultivars of hard-red and hard-white spring and winter wheat (*Triticum aestivum* L.) and durum wheat (*Triticum durum* L.). Precipitation data were acquired from the nearest Western Regional Climate Center ([www.wrcc.dri.edu](http://www.wrcc.dri.edu)) weather station to each farm with complete records for the reported years for computation of long-term average precipitation for comparison to the reported years.

Energy budgets were constructed using process analysis methodology (Fluck and Baird, 1980) accounting for energy used for manufacture and operation of farm machinery, fuel, lubricants, fertilizer, and pesticides; using the field operations and inputs reported by the farmer participants for each specific field. Survey methodology

included a printed form asking for details of crop production, as well as a follow-up interview to confirm details of crop production practices.

Energy coefficients for farm machinery were obtained from published literature. The primary source of these coefficients was Zentner et al. (2004), but for implements not listed therein, we used coefficients from Nagy (1999). Both sources include energy for fuel and lubrication as well as energy to manufacture machinery, amortized over its useful life, focusing on large farm-scale equipment in use on the regionally adjacent Canadian Prairies. Energy coefficients for farm machinery are summarized in Table 3.1.

We focused on farm inputs and field operations that might be different for different crops: field preparation, seeding, spraying and harvesting. We did not attempt to account for energy for farm use of pickup trucks, heating of farm buildings or homestead energy use, as these would occur regardless of crop type and rotation. We did not account for the energy value of human labor or solar energy incident on farm fields. These are common approaches in agricultural energy analysis, as the metabolic energy of human labor is negligible compared to fossil energy used in modern mechanized farming operations while solar energy is orders of magnitude greater (Zentner et al., 2004).

Embodied energy coefficients for seed, fertilizer, and selected herbicides are shown in Table 3.2. Participants reported use of 49 different specific herbicide formulations, spray adjuvants, fertilizers, and seed types, with various combinations and concentrations of active ingredients. Most published estimates of energy coefficients for

herbicides are derived from Green (1987). We utilized estimates published in Zentner et al. (2004), which are based on Green's work but include adjustments for energy used for formulation, packaging, distribution, and transportation. Green expressed a high degree of confidence in his methods for determining energy coefficients for chemicals that were in common usage at the time (e.g. phenoxy herbicides), but for chemicals under patent protection, or with then-proprietary manufacturing methods (e.g. glyphosate) he expressed far less confidence. The cost (and likely embodied energy) of producing glyphosate, in particular, has declined substantially over the years since its introduction (Woodburn, 2000). Therefore, for glyphosate and any other products not included in Zentner et al. (2004), an energy coefficient for herbicides was adopted from Liska et al. (2009).

The energy embodied in ammonia synthesis and N fertilizer production has declined steadily over the past century; however, fertilizer-manufacturing facilities using old technology remain in operation (Smil, 2008). We used an energy coefficient for nitrogen adopted from Shapouri et al. (2004), and note that this value agrees with the recent global average estimated by Smil (2008).

The energy values for seed shown in Table 3.2 represent energy embodied in producing the seed as an input to the crop production system. This includes production of the seed on a farm, plus cleaning, storage, packaging, and transportation (Nagy, 1999).

Only one participant reported use of fungicide, and it was applied once to wheat in a tank mix with herbicide, so there was no additional machine energy associated with its application. The energy embodied in this fungicide was not included in the analysis as it was considered negligible and was applied uniformly to wheat grown in both crop rotation treatments. No participants reported use of insecticides. We did not attempt to account for energy embodied in seed treatment products or legume *Rhizobium* inoculant because there are no embodied energy estimates published for some formulations of these products, and usage amounts are small (i.e.  $< 5 \text{ kg ha}^{-1}$  for inoculant and  $< 50 \text{ g a.i. ha}^{-1}$  for seed treatment).

Energy inputs per ha were summed for each field-year and categorized as: fuel & machinery, herbicide, seed, N-fertilizer, and other fertilizer. Energy Intensity, in units of  $\text{MJ kg}^{-1}$  was computed for each field by dividing the input energy (MJ) by the crop yield (kg). For purposes of computing NEY, an energy coefficient for harvested wheat and pulse grain outputs of  $18.7 \text{ MJ kg}^{-1}$  was utilized from Zentner et al. (2004) based on bomb calorimeter combustion. Net energy yield was calculated by subtracting the input energy for crop production from the energy content of the harvest crop.

### Statistical Analysis

Mean values of categorized energy inputs, crop yield, and energy metrics were calculated for each Year 1 crop, and Year 2 wheat in each crop sequence. Data from Year 1 crops, paired by farm and year, were used for comparative analysis of pulses and

wheat. The rotational effect of pulses on wheat was analyzed with data from Year 2 of the 2-yr crop sequences, comparing (W-**W**) to (P-**W**), also utilizing paired comparisons from the same farm and year. A 2-tailed paired t-test was used to determine if there were significant differences between treatments. Each pair of observations came from the same farm and the same year. The paired t-test tests the null hypothesis that the difference between paired observations is zero while ignoring variation among farms and years (Ch. 9 in Zar, 1999). The paired t-test was also used to determine if Year 1 and Year 2 precipitation differed from long-term averages. In the case of energy input data associated with fertilizer application rates, the assumption of normal distribution of the differences was not met, and the assumption of symmetry required for the Wilcoxon paired sample test was also not met. For this variable, we used the 'sign test' adaptation of the binomial test, which is recommended as a paired comparison test wherever with Wilcoxon paired sample test would otherwise be appropriate but the assumption of symmetry is not met (Zar, 1999). Differences were considered significant at *P*-values less than 0.1.

### Results and Discussion

#### Comparative Analysis of Pulses and Cereals (Year 1)

As shown in Figure 3.2, pulses had 53% lower total energy input than wheat ( $P < 0.01$ ), a finding similar to that of Zentner et al. (2004). The largest energy input to wheat, and the largest difference between wheat and pulse crops, was N fertilizer. The

average N application rate on wheat in Year 1 was  $56 \text{ kg N ha}^{-1}$ , accounting for 58% of total energy inputs to wheat production. This is a larger proportion than the national U.S. average of 47% of total input energy for wheat production attributable to N fertilizer (Piringer and Steinberg, 2006). The average N fertilizer application rate of  $0.027 \text{ kg N kg}^{-1}$  wheat was only slightly higher than the national average of  $0.026 \text{ kg N kg}^{-1}$  wheat reported by Piringer and Steinberg (2006), so the increased proportion of energy attributed to N fertilizer was likely due to lower inputs in other categories compared to the national average. In particular, grain drying, liming, and tillage are noted in Piringer and Steinberg (2006) and are more common in other wheat producing areas than in Montana. Zentner et al. (2004) found N fertilizer to account for 66-71% of total energy inputs to wheat production on the subhumid Canadian Prairies.

Pulse crops had 52% higher energy input attributed to machinery & fuel (Figure 3.2,  $P < 0.01$ ). This was due to more energy use for harvesting and land rolling, but offset somewhat by reduced machinery use for fertilizer application. Published estimates of energy consumed by combine harvesters are highly variable. The coefficients for harvesters shown in Table 3.1, from Zentner et al. (2004), indicate a >2-fold higher energy expenditure for harvesting pulses compared to wheat. This higher energy requirement for harvesting pulses is consistent with the experience of several of the farmers surveyed, and is associated with lower harvester ground speed necessitated by the propensity of pulses to lodge and shatter. It should be recognized that there is a large amount of variability in harvester ground speed as a function of local conditions.

Land rollers are commonly used after planting pulse crops to level the soil surface and push rocks down into the soil to facilitate operation of a combine harvester with the cutting head very close to the ground (Olson et al., 2004).

Energy inputs for non-N (e.g. P, K, S) fertilizer were higher for wheat (Figure 3.2,  $P=0.02$ ); in only two of the 14 comparisons was any fertilizer applied to pulse crops. While this practice may have been driven by logistical considerations, as pulses do require these nutrients, it should be noted that the overall contribution of non-N fertilizers to the energy budget was only 3% of the total energy inputs for Year 1 wheat. There was no difference between pulses and wheat in energy inputs attributed to herbicide or seed. Although pulse seed is assumed to be less energy intensive to produce than wheat (Table 3.1), more pea seed is required because the seeds are larger (Gan et al., 2003) and recommended seeding rates for lentil are for higher plant density than for pea (Baird et al., 2009).

An oft-cited potential benefit of cropping system diversification is potential for improved weed control or reduced expenditure on weed control practices due to competitive interactions among crops and weeds and more varied weed control opportunities in more diverse systems (Westerman et al., 2005). In this study, we found no significant difference in energy attributed to herbicide use among treatments in Years 1 or Year 2. Pre-emergence use of glyphosate was universal for both pulse and wheat crops, typically at or below the minimum recommended rate, and with great attention paid to use of adjuvants and tank mixes with various other herbicides to

maximize efficacy and minimize cost. A single application of a selective in-crop or residual pre-emergence herbicide was also universal. There were a large variety of different formulations and active ingredients utilized, with different products used for pulses and cereals; however, there was very little variability among farms in total energy expenditure associated with herbicide use (data not shown). Only one participant indicated use of any tillage tool: a one-time use of a heavy tine harrow for incorporation of herbicide. No farmer used different weed control strategies for P-*W* than for W-*W*. This observation is likely in contrast to broader regional patterns of herbicide use on non-pulse-producing farms, where use of herbicides with residual activity incompatible with the growth of dicot crops is common (Donald and Prato, 1990). The farmers surveyed in this project had all been growing pulse crops extensively on their farms for many years and so may have already adapted to the alternative weed control strategies made possible by a more diverse crop rotation.

Because lentil has smaller yield potential than pea (Miller et al., 2002), we analyzed Year 1 energy metrics separately for pea and lentil. Mean pea yield was 2.62 Mg ha<sup>-1</sup>, 0.6 MG ha<sup>-1</sup> greater than the mean Year 1 wheat yield of 2.02 Mg ha<sup>-1</sup> ( $P=0.03$ ). Pea had a lower EI (Figure 3.3), and greater NEY (Figure 3.4) than wheat ( $P<0.01$  on both comparisons), attributable to both the reduced input energy and higher grain yield for pea compared to wheat.

Three of the 14 pulse-wheat sequences had lentil as the Year 1 pulse crop. Mean lentil yield was 1.34 Mg ha<sup>-1</sup>, considerably lower than that of the paired wheat crop yield

of  $2.22 \text{ Mg ha}^{-1}$  ( $P=0.07$ ). Energy intensity of lentil did not differ from wheat (Figure 3.3,  $P=0.41$ ), nor did NEY (Figure 3.4,  $P=0.11$ ). Year 1 results for lentil should be interpreted with caution due to the small sample size ( $n=3$ ).

Average Year 1 growing season precipitation was 16 mm (5%) more than the long-term averages ( $P=0.1$ ). Ten of the 14 sites had above average precipitation in Year 1, with values ranging from 46 mm above average to 43 mm below. This small, and only marginally significant, difference might represent a slight advantage to pulses compared to long-term expectations because pulses are more reliant on growing season precipitation due to their shallower root systems than wheat (Miller et al., 2003a).

#### Rotational Effect of Pulses on Wheat

Although lentil has lower yield potential than pea (Miller et al., 2003a), the expected rotational effect on a subsequent cereal crop is similar (Miller et al., 2003b, 2006). In this study, there was a positive rotational benefit of pulses on subsequent wheat yield in every paired comparison to wheat following wheat. We analyzed pea and lentil together for the overall effect of pulses on subsequent wheat crop management, yield, and energy indices. Overall, there was no difference between (W-**W**) and (P-**W**) in energy inputs attributed to machinery & fuel, herbicide, seed, or non-N fertilizer (Figure 3.2).

In seven of the 14 paired comparisons, farmers reduced N-fertilizer for (P-**W**) compared to (W-**W**). The average reduction was  $7 \text{ kg N ha}^{-1}$  (Figure 3.2,  $P=0.02$ ), with a

standard deviation of  $11 \text{ kg N ha}^{-1}$  and individual values ranging from 0 to  $39 \text{ kg N ha}^{-1}$ . Only three farmers reduced N fertilizer by more than  $10 \text{ kg N ha}^{-1}$ , resulting in a highly skewed distribution. Some producers anecdotally reasoned that they expected higher yields for (P-**W**) than (W-**W**) due to non-N related factors and wanted to ensure adequate N fertility for production of high grain protein. The average reduction in N-fertilizer resulted in 6.6% lower total input energy for the P-**W** compared to W-**W** (Figure 3.2). Few of the survey participants utilized soil tests to determine N-fertilizer rates for both of the specific fields surveyed in this study. Farmers were more likely to rely on historical records of fertilizer use, crop yield, and grain protein along with selective soil testing. Many farmers utilized GIS systems with real time monitoring of crop yield on combine harvesters to map grain yield, and one producer additionally mapped grain protein to inform variable-rate fertilizer application. The average N-fertilizer reduction of  $7 \text{ kg ha}^{-1}$  on P-**W** relative to W-**W** observed here is identical to that reported by Zentner et al. (2004) for zero-till treatments in a fully-phased, replicated plot study in an environment on the Canadian Prairies with similar yield potential for cereals, where N-fertilizer was applied in response to spring soil nitrate tests.

Research on the impact of pulses on the N fertility needs of subsequent cereal crops in the semiarid northern Great Plains is on going and thus far inconclusive (Walley et al., 2007). Research in the early years of adoption of pulse crops in this region lead to recommendations of N 'credits' proportional to pulse crop grain yield (Beckie and Brandt, 1997). Subsequent research found that pulses provide a positive N contribution

to the soil only to the extent that N fixation exceeds N removed in harvested crop material (van Kessel and Hartley, 2000). Further, this N contribution is highly spatially variable at short distances (Walley et al., 2001), and may mineralize into plant available forms slowly over the course of several years (Beckie et al., 1997), depending on weather conditions. Further complicating interpretation of research in this field is the fact that N uptake in cereal grain can be affected by factors related to crop diversification other than available soil N, also in a spatially-variable manner. For example, reduced incidence of root and leaf diseases, attributable to crop rotation can increase crop growth and hence N demand (Stevenson and van Kessel, 1996).

On average, precipitation in Year 2 was 24 mm (7%) less than long term average ( $P=0.05$ ). Nine of the 14 sites had below-average precipitation in Year 2, with individual values ranging from 74 mm above average to 80 mm below. The 24 mm mean departure from normal is 30% of the standard deviation of annual rainfall for these sites, so does not represent an unusual departure from normal conditions. If the effect of pulse crops on wheat yield is driven by soil water conservation due to shallow rooting systems of pulses, dry conditions in Year 2 might exaggerate that effect compared to long-term expectations. On the other hand, if the effect of pulse crops on wheat yield was due to increased N availability from pulse crop residue, dry conditions might have limited mineralization of N (Cassman and Munns, 1980), contributing to an underestimate of the rotational benefit. Both water conservation and N contribution

effects of pulses on wheat yields have been observed in plot studies in Montana (Miller et al. 2006).

In every paired comparison, P-**W** yielded more than W-**W**. The mean yield of W-**W** was 1.68 Mg ha<sup>-1</sup>, compared to 2.15 Mg ha<sup>-1</sup> for P-**W**, an increase of 0.47 Mg ha<sup>-1</sup> ( $P < 0.01$ ) or 28%. This yield increase due to crop sequence was larger than the difference of 0.12 Mg ha<sup>-1</sup> found by Zentner et al. (2004) for zero-till treatments and the differences ranging from 0.10 to 0.41 Mg ha<sup>-1</sup> found by Miller et al. (2006) at three sites in Montana in a study which included treatments where pea was harvested early for forage and at maturity for grain. The large yield increase observed for P-**W** relative to W-**W** can likely be attributed to a variety of factors including increased soil N, increased residual soil water following shallow rooted pulse crops, and reduced pathogen pressure (Kirkegaard et al., 2008). Not all of the survey participants were able to provide grain protein or test weight data that would help isolate these effects.

This substantial yield increase contributed to reduced EI (Figure 3) and increased NEY (Figure 3.4) for wheat grown following a pulse crop ( $P < 0.01$  for both comparisons). Energy intensity for W-**W** was 3.9 MJ kg<sup>-1</sup>, the same as the national average for wheat estimated by Piringger and Steinberg (2006). Energy intensity for P-**W** was reduced by 31% to 2.7 MJ kg<sup>-1</sup>. Net energy yield (NEY) of wheat was 25.1 GJ ha<sup>-1</sup> for W-**W** and 34.6 GJ ha<sup>-1</sup> for P-**W**, a 38% increase. The portion of the increase in Year 2 wheat NEY attributable to the increase in wheat grain yield was more than 40-fold higher than the decrease in input energy attributed to reduced N fertilizer on wheat in Year 2, and about

3-fold greater than the magnitude of the reduced energy input to the pulse crop in Year 1.

#### Analysis of the 2-Year Systems

Whole system grain yield and NEY are simply the sums of those measures from the years. Combined grain yield for the W-W system was  $3.70 \text{ Mg ha}^{-1}$ , while grain yield for the P-W system was  $4.43 \text{ Mg ha}^{-1}$ , a 20% increase. The difference in NEY was even greater, owing to reduced inputs to the P-W system. Net Energy Yield for the W-W system was  $58.1 \text{ GJ ha}^{-1}$  while it was  $75.6 \text{ GJ ha}^{-1}$  for the P-W system, a 30% increase. The increase in the net energy yield can be partitioned into four effects: 52% from increased wheat yield in the P-W system, 29% due to pulses yielding more than cereals in Year 1, 17% from reduced energy input on pulses in Year 1, and only 2% due to reduced inputs on Year 2 wheat. Energy intensity of the W-W system was  $3.1 \text{ MJ kg}^{-1}$  compared to  $1.8 \text{ MJ kg}^{-1}$  for the P-W system. Another energetic analysis of a conventional 2-yr pulse-wheat crop rotation in this region (Khakbazan et al., 2009) found generally lower 2-yr system NEY values ranging from 31 to  $56 \text{ GJ ha}^{-1}$  as well as lower energy intensities of 1.2- $1.7 \text{ MJ kg}^{-1}$ . The Khakbazan et al. (2009) study was conducted at a site where high levels of available soil N resulted in little response to additional fertilizer N, so high energy productivity and low intensity was the result of moderate yields at low fertilizer rates.

### Conclusions

Pulses grown under typical farm conditions in this region not only have low EI, but also contribute to reduced EI of subsequent wheat and do so while increasing system NEY. This is a unique result in that many studies on low-input systems in other environmental contexts achieve lower EI at the expense of reduced NEY, presenting an unresolved optimization problem (Gomeiero et al, 2008). The largest factor impacting NEY in this study was crop yield, both for pulses and the following wheat crop, followed by the reduction in N fertilizer for pulse crops. A better understanding of the contribution of pulse crops to the energy budgets of traditionally wheat-based cropping systems may provide motivation for more sustainable food purchasing and crop production decisions. While adoption of a simple 2-yr rotation of annual crops is not proposed as a solution to all of the sustainability challenges facing crop production in the semiarid northern Great Plains, increased production of pulses has the potential for substantial contribution to more sustainable crop production in this region. This research shows that there may be an even stronger case for this contribution under scenarios of scarcity or increased prices for energy-intensive inputs.

Although pea, wheat, and lentil have similar amounts of energy when burned, they are used for different purposes where energy content is not the most important quality. Wheat and lentil grown in this region have high-value specialty food markets and are unlikely to be utilized for biofuel production. Our finding that pea had a higher NEY than wheat, while lentil did not, is therefore likely of little consequence to the lentil

producer. Lentil prices are higher than for pea, likely reflecting the lower yield potential (and hence higher cost of production), and some non-energy value as a food product, perhaps palatability. Pea, however, is grown both for food and utilized as feed grain (Miller et al., 2002). Further substantial adoption of pea in this region may be accompanied by increased pea utilization as a feed grain and warrant further research including utilization of animal manure on cropland. None of the farms surveyed in this project used animal manure on cropland.

Pea also contains starch theoretically suitable for use in an integrated livestock-biofuel production system capable of capturing the protein value for animal feed (Nichols et al., 2005). Ethical considerations of utilizing food-producing-land for biofuel production aside, the very low EI and moderately high NEY of pea, and the positive contribution of pea to the EI and yield of food-grade wheat observed in this study may be relevant to such an application. Though a thorough energetic analysis of such a system is beyond the scope of this paper, any such attempt should consider the rotational effect on subsequent wheat and the potential scale of pulse crop adoption on land currently fallowed every-other-year on the semiarid northern Great Plains.

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Tables and Figures

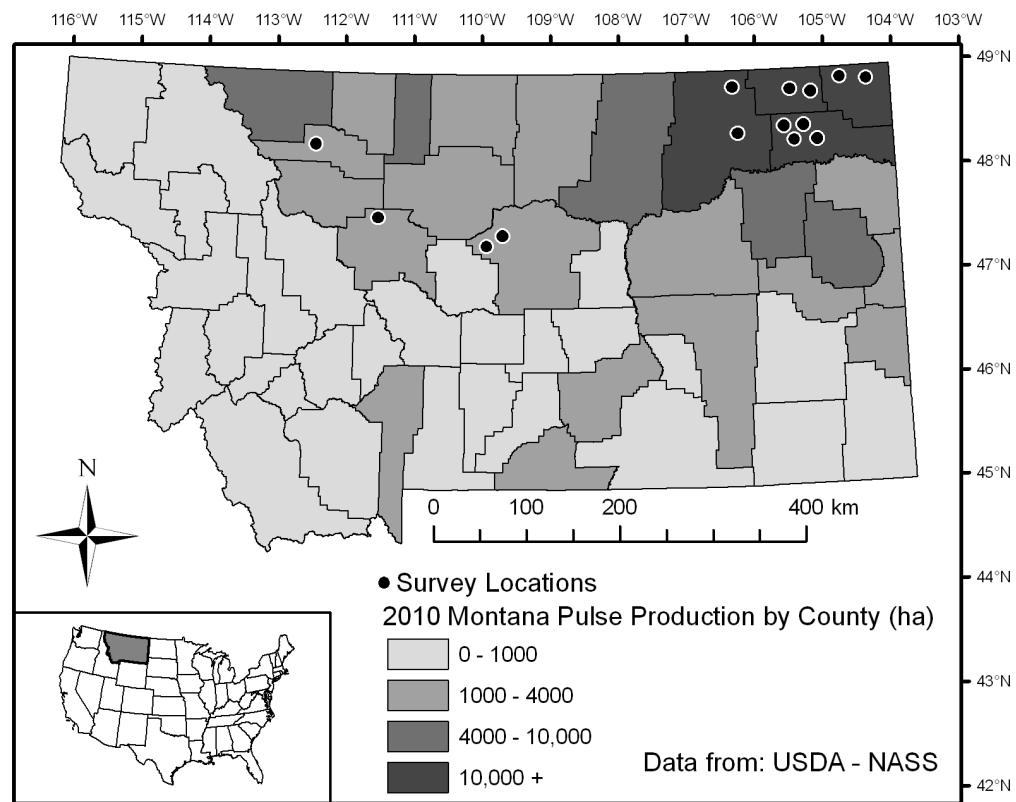


Figure 3.1 Location of surveyed farms and major pulse-producing counties in Montana.

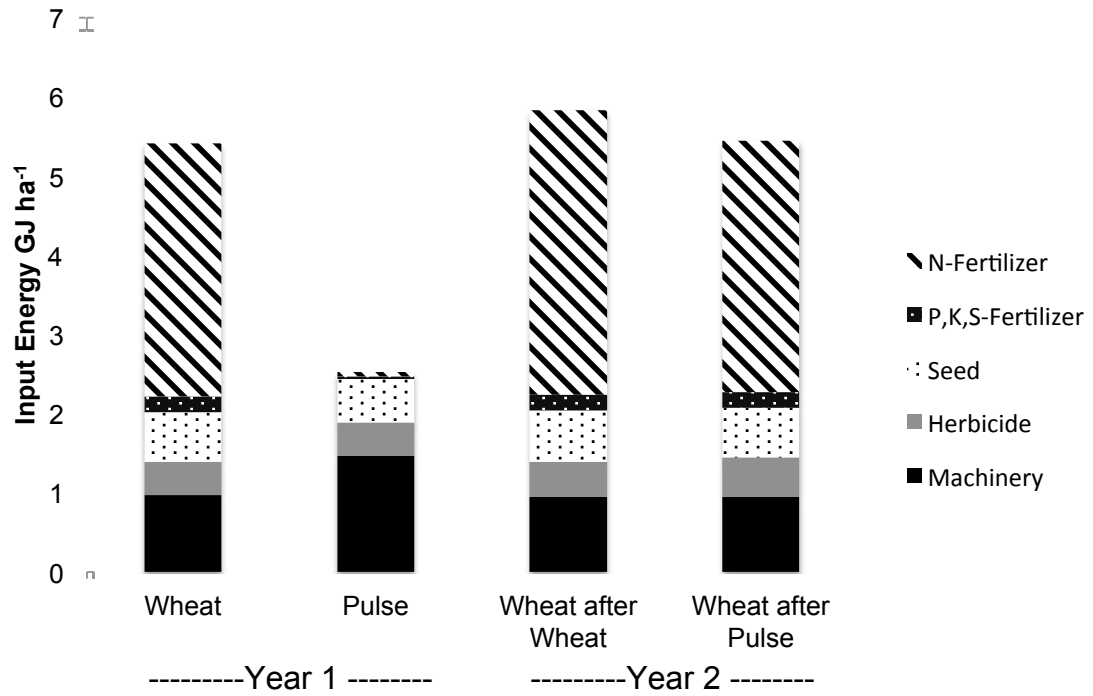


Figure 3.2 Embodied energy (GJ ha<sup>-1</sup>) for crop production inputs. Comparisons are valid only within each year. *P*-values for differences among crops and specific categories are in the text.

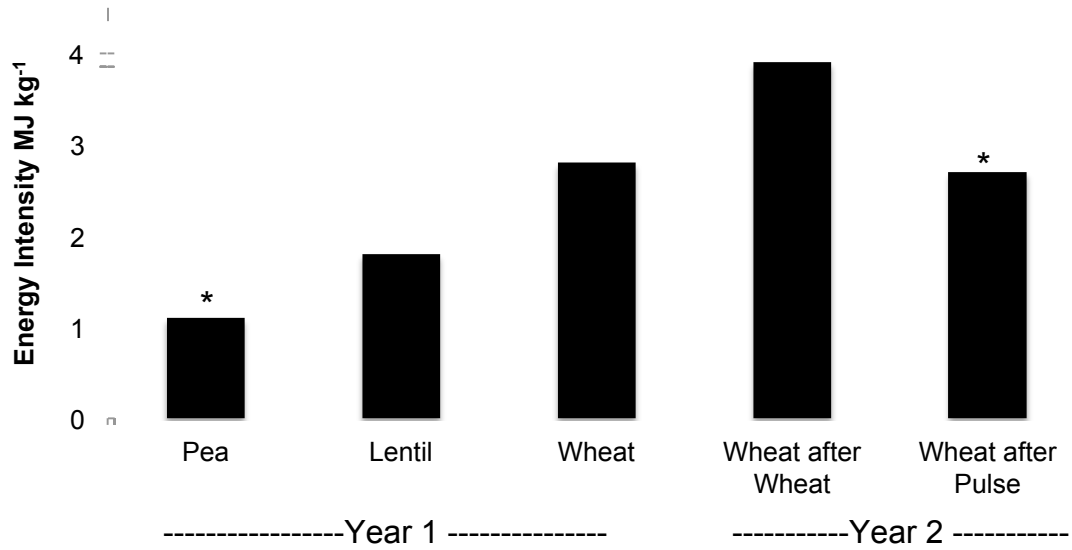


Figure 3.3 Energy Intensity (MJ kg<sup>-1</sup>) of Year 1 pea, lentil, and wheat, and Year 2 wheat following those Year 1 crops. Comparisons are valid only within each year, and for Year 1 only between wheat and each individual pulse crop. \* indicates significant difference from wheat in Year 1 or wheat following wheat in Year 2.

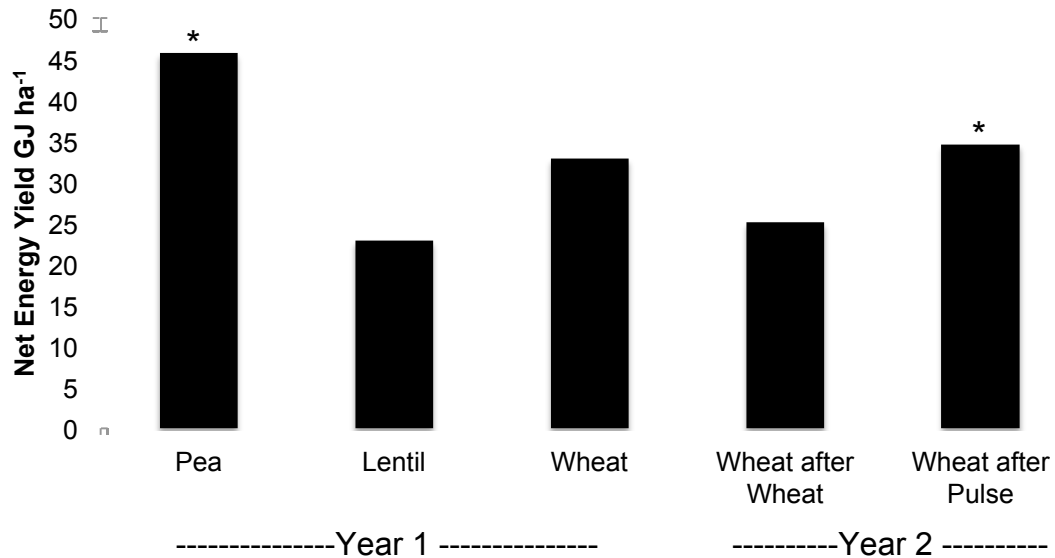


Figure 3.4 Net Energy Yield (NEY) of Year 1 pea, lentil, and wheat, and Year 2 wheat following each of those Year 1 crops. Comparisons are valid only within each year, and for Year 1 between wheat and each individual pulse crop. \* indicates significant difference from wheat in Year 1 or wheat after wheat in Year 2.

Table 3.1 Energy coefficients for manufacture, operation, and maintenance of farm equipment as compiled by Zentner et al. (2004) and Nagy (1999).

Equipment	MJ ha <sup>-1</sup>
Air seeder, 15m, 25cm row spacing	408
Harvester, Class 7, 9 m rigid header + on-farm transport (wheat)	350
Harvester, Class 7, 7 m flex header + on-farm transport (pulses)	831
Sprayer, 250 hp, 27 m boom	63
Land roller, 12 m, 120 hp tractor	161
Heavy Harrow, 24 m	111
Granular Applicator, 16 m	91

Table 3.2 Embodied energy coefficient for selected inputs.

Product	Embodied Energy (MJ kg <sup>-1</sup> )
Glyphosate (acid equivalent)	356.0
2,4-D amine (active ingredient)	98.0
Quizalofop (active ingredient)	384.7
N-fertilizer (per kg N)	56.7
P-fertilizer (per kg P <sub>2</sub> O <sub>5</sub> )	9.5
Wheat Seed	7.2
Pulse Seed	3.2

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#### 4. TILLAGE OF GREEN MANURE AFFECTS DRYLAND SPRING WHEAT PRODUCTION: ECONOMIC AND ENERGETIC ANALYSES.

##### Introduction

Legume green manure (LGM) cover cropping, a common practice for building soil quality and maintaining N cycling in organic crop production, is being considered as a replacement for summerfallow by conventional producers of wheat (*Triticum aestivum* L.) in Montana. Summerfallow, or fallowing cropland for an entire growing season to accumulate water, was once common throughout the northern Great Plains (Cochran et al., 2006; Tanaka et al., 2010), but has declined region-wide with crop diversification largely enabled by improved water use efficiency associated with No-Till (NT) production practices (Aase and Siddoway, 1980; Peterson et al., 1996, Hatfield et al., 2001). Summerfallow has long been identified as a major sustainability challenge due to detrimental effects on soil quality (Larney et al., 1994), but persists as a common practice in north-central Montana, occupying 43% of the 0.8 M ha of cropland in the counties corresponding to Major Land Resource Area 52 (FSA 2010).

Legume green manures have been a subject of research in the northern Great Plains for over 100 years (Janzen, 2001), and short-term benefits from the practice have historically been elusive (Army and Hide, 1959; Brown, 1964) due to soil water depletion relative to summerfallow. Army and Hide (1959) concluded that LGM cover crops were detrimental to wheat yield, but that this conclusion could be altered with development

of management practices to increase efficiency of soil water storage. Some contemporary research has continued to show crop yield decreases in response to LGM cover crops compared to summerfallow (Zentner et al., 1996; Brandt, 1999; Vigil and Nielsen, 1998; Nielsen and Vigil., 2005), motivating further research into the delicate balance between water use and LGM growth. Early planting and early termination of shallow-rooted annual legumes, notably pea (*Pisum sativum* L.) and lentil (*Lens culinaris* Medik.), have emerged as strategies for LGM cover cropping with minimal net soil water utilization (Biederbeck and Bouman, 1994; Aase et al., 1996, Zentner et al., 2004a; Allen et al. 2011; Miller et al., 2011). While pea has been shown to produce more biomass, fix more N, and compete better with weeds, lentil has found favor on the Canadian prairies due to reduced seeding cost and ease of management (Biederbeck et al., 1993; Townley-Smith et al., 1993). Increased lentil prices in recent years may have reduced the cost advantage, but increased production of grain lentil in Montana may also result in increased availability of non-food-grade lentil usable for green manure seed at reduced prices.

Cumulative long-term benefits of LGM have been demonstrated in northern semi-arid areas, and have typically been detected after repeated crop cycles with legumes (Biederbeck et al., 1998; Zentner et al. 2004a; Allen et al. 2011). In NE Montana, Pikul et al. (1997) found an increase in soil potentially mineralizable N after two 2-yr cycles of lentil LGM, but lower yield of unfertilized spring wheat following lentil LGM compared to wheat fertilized with 34 kg N ha<sup>-1</sup> following fallow, despite no net soil

water depletion by LGM in that study. Field research specifically addressing the effect of tillage of LGM on wheat yield in the semiarid northern Great Plains is limited. Pikul et al. (1997) found greater wheat yield following tilled lentil LGM than lentil LGM terminated with herbicide in 1 of 4 yr. Miller et al. (2006) found a positive effect of early-terminated pea on subsequent wheat yield at a N-limited site in Montana, regardless of whether the aboveground biomass was removed as forage, suggesting that belowground processes drove the response. In southern Alberta, Canada, Blackshaw et al. (2010), found that mowed sweet clover (*Melilotus officinalis* L.) green manure with residue left on the surface resulted in similar wheat yield to sweet clover green manure incorporated with tillage. Foster (1989) found no difference among tillage implements of varying intensity on short-term N cycling from sweet clover green manure in Saskatchewan, Canada. Importantly, pulses may fix more N when grown in NT conditions (Matus et al., 1997; van Kessel and Hartley, 2000), so NT management may provide opportunity for improved performance of LGM cover crops. The short-term economics of LGM cover cropping remain of critical interest to producers, and little research has been done on relative management costs and short-term rotational effects of NT and tillage-based management.

Renewed popular interest in LGM cover cropping is being driven in part by concern over recent volatility in fertilizer, energy, and crop commodity prices. Analysis of the fossil energy budgets of cropping systems have been suggested to offer insight into economic exposure to energy price volatility (Cruse et al., 2010), and optimization

of fertilizer application rates (Hülsbergen et al., 2001). Other researchers, however, have advised caution in interpretation of energy analyses of cropping systems (Jones, 1989) and even called the results potentially misleading (Smil, 2008). Gomiero et al. (2008) called for development of energy indicators that would internalize hidden costs, but noted that such indicators are not well developed and that existing energy analysis techniques were most useful in a tradeoff perspective with other indicators of sustainability. Many studies have found low-input or organic cropping systems to generally be less energy intensive (Berardi, 1978; Craumer, 1979; Pimentel et al. 1983; Hoepfner et al., 2006; Khakbazan et al., 2009; Macrae et al., 2010; Cruse et al., 2010; Zentner et al., 2011), but there have been few evaluations of the energy costs of biologically fixed N supplied via LGM cover crops as partial substitution for N fertilizer in the context of conventionally managed NT crop production. This is a particularly relevant question for wheat grown in this region, as price premiums for grain protein often encourage producers to apply N fertilizer in excess of yield maximizing levels (Engel et al., 1999, Selles and Zentner, 2001; Baker et al., 2004), and no-till production is dominant (Watts et al., 2009). Evaluation of substitution opportunities for energy intensive inputs such as N fertilizer is one particular area where Jones (1989) saw potential for energy analysis to contribute to understanding of agricultural sustainability, but there has been little additional development of research methodology towards this end. Wu et al. (2011) found N from LGM cover crops to generally be more energy intensive than fertilizer N, however the assumptions about

energy consumption associated with LGM management in that study were far different than the typical energy costs of LGM seed production and tillage management used in the semiarid NGP.

The primary objective of this study was to investigate the interaction of tillage with pea and lentil LGM, on soil water and N cycling, compared to bare fallow, as manifest in yield and protein content of fertilized spring wheat grown the following year. The second objective was to evaluate the short-term economic value of pea and lentil LGM in place of fallow to partially offset N fertilizer use. Finally, the effects of these alternative management strategies on cropping system energy budgets were investigated, seeking to gain insight into the utility of energy analysis as a predictor of sustainability and an optimization tool for crop production input decisions in the face of uncertainty about fossil energy supplies and prices. This is a unique opportunity to examine the interactions and relative magnitudes of the effects of these management alternatives on energy performance of crop production.

## Materials and Methods

### Site Description

Experiments were conducted between 2007 and 2010 on a farm 6 km west of the community of Amsterdam-Churchill in Gallatin County, Montana (45° 45' N 111° 24' W; 1,433 m above sea level). Three separate 2-yr crop sequences studies were conducted within 1.5 km of one-another on Brocko (coarse-silty, mixed superactive,

frigid Aridic Calcustepts) and Amsterdam (fine-silty, mixed, superactive, frigid Typic Haplustolls) soils. These loess-derived soils are very deep, well drained, and free of rocks. In the top 15 cm, soil pH ranged from 6.6 to 8.2 and soil organic matter averaged 24 g kg<sup>-1</sup>. Previous studies at this location have found cereal grain yield to be responsive to N fertilizer (Miller et al., 2006). Each study site had been used for commercial production of grain in a summerfallow – cereal rotation in a minimum tillage system with a chisel plough used approximately once every three years.

Mean annual precipitation (1981-2010) at the nearest meteorological station at Gallatin Field Airport, 19 km away, was 356 mm. Notably, over 1/3 of the annual precipitation normally falls during the months of May and June, but terminal summer drought beginning in July is typical. Precipitation, measured on site, and monthly mean temperatures from the Gallatin Field Airport meteorological station are shown in Table 4.1

### Crop Management

Legume green manures were established in spring of 2007, 2008, and 2009 in standing stubble of barley (*Hordeum vulgare* L.) or wheat grown the previous year. Legume green manure treatments consisted of pea (c.v. Arvika), lentil (c.v. Richlea), a non-nodulating (NN) mutant pea (c.v. Sparkle; Kneen et al. 1994), non-nodulating pea fertilized with N (NN+), and summerfallow. Summerfallow was a control treatment corresponding to common practice for wheat production in the region. Because the rate

of mineralization of soil organic matter is a function of soil water content (Cassman and Munns, 1980), the NN treatments were included as alternative control treatments with plant growth, concomitant soil water uptake, but no N-fixation. Nitrogen fertilizer for the NN+ LGM treatment was applied in the form of urea, mid-row banded at planting, at a rate of 100 kg ha<sup>-1</sup> N in 2007 (inadvertently high) and 60 kg ha<sup>-1</sup> N in 2008 and 2009 to approximately match expected N fixation by the LGM's. In 2008, NN mutant pea seed was not available in sufficient quantity; so non-inoculated common fenugreek (*Trigonella foenum-graecum* L.) was substituted for the initial planting. When the fenugreek failed to grow vigorously, NN and NN+ plots were sprayed with glyphosate to control weeds, primarily downy brome (*Bromus tectorum* L.). Subsequently common buckwheat (*Fagopyrum esculentum* Moench) was planted and then terminated at bloom to fulfill the planned role of the non-nodulating control.

Tillage treatments were till (T), no-till (NT), till—no-till (T-NT), and no-till—till (NT-T), where till and no-till refer to methods of initial termination of the green manure followed by the primary method of subsequent weed control during the remainder of the fallow season. The five LGM and four tillage treatments were arranged in a full-factorial (n=20) randomized complete block design with four replicate blocks. Plot size was 7.6 by 7.6 m with 9-m alleys between blocks.

Legume green manure plots were planted using a no-till plot seeder with double-disk openers. Row spacing was 0.26 m in 2007 and 2009, and 0.30 m in 2008. Seeding rate was calculated based on seed size and germination rate to provide 100 pure live

seeds (PLS)  $\text{m}^{-2}$  for pea and 130 PLS  $\text{m}^{-2}$  for lentil. Pea and lentil seed were treated with 3.5 g a.i.  $\text{kg seed}^{-1}$  mefenoxam {(R)-2-[(2,6-dimethylphenyl)-methoxyacetyl-amino]-propionic acid methyl ester}, and 2.5 g a.i.  $\text{kg seed}^{-1}$  fludioxonil {[4-(2,2-difluoro-1,3-benzodioxol-4-yl)-1H-pyrrole-3-carbonitrile]}. At planting, commercial granular peat-based pulse inoculant containing *Rhizobium leguminosarum* (bv viceae) was banded with the seed at 5  $\text{kg ha}^{-1}$ . To eliminate the potential for non-N nutrient limitation to LGM growth, all LGM treatments were fertilized with 56  $\text{kg ha}^{-1}$  each of mono-ammonium phosphate (11-52-0) and potassium sulfate (0-0-50-17), banded with the seed, providing total N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O-S additions of 6-27-28-9  $\text{kg ha}^{-1}$ . All LGM plots were sprayed with 0.63  $\text{kg ha}^{-1}$  ae glyphosate (N-(phosphonomethyl) glycine) prior to emergence of LGM's. In 2008 and 2009, LGM plots were sprayed as needed with lambda-cyhalothrin 1[1 $\alpha$ (S\*),3 $\alpha$ (Z)]-( $\pm$ )-cyano-(3-phenoxyphenyl)methyl-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2dimethylcyclopropanecarboxylate at 0.02  $\text{kg a.i. ha}^{-1}$  to control pea leaf weevil (*Sitona lineatus* L.) and grasshopper (primarily *Melanoplus* spp.). Dates and other details of crop management are summarized in Table 4.2.

All LGM were terminated when 50% of the pea plants had at least one open flower, corresponding to BBCH 61 (Lancashire et al. 1991). NT and NT-T treatments were terminated by application of 0.84  $\text{kg ha}^{-1}$  glyphosate acid equivalent (ae), in the form of potassium salt, in 190  $\text{L ha}^{-1}$  water solution. Ammonium sulfate was added to all spray water at 34  $\text{g L}^{-1}$  to counteract potential effects of water hardness on herbicide efficacy. Till and T-NT treatments were terminated by tillage 3 d after the herbicide application to

the herbicide-terminated treatments. This delay was scheduled to allow similar growth (i.e. water use) in all treatments during the initial phase of action of the herbicide. Immediately prior to tillage termination, samples of aboveground biomass were collected from two locations in each plot, each consisting of 2 row-meters of LGM and any weeds from the corresponding inter-row spaces. Biomass was separated into weed and LGM components when weeds were visually estimated to exceed 5% of LGM biomass. Weed and LGM biomass samples were oven-dried at 50° C for 96 h, weighed, then ground and analyzed for total N and C content in a combustion analyzer (LECO Corporation, St. Joseph, MO). After LGM termination, plots were tilled or sprayed with herbicide as needed to control weeds, consistent with the nominal tillage treatment, as shown in Table 4.2. The NT-T and T treatments were tilled twice after the initial LGM termination and also received the pre and post-emergence herbicide treatments associated with wheat production in Year 2.

Tillage termination (T) and first tillage of NT-T pea was done with a heavy-duty double disk with notched disks. Tillage termination (T) and first tillage of NT-T lentil was with a chisel plow without soil inversion, lentil therefore having lower management cost but also less thorough soil incorporation. Subsequent tillage during the fallow year, including all tillage of fallow plots, was done with the chisel plow. In spring of 2009 and 2010, all plots that had been tilled at any time during the LGM/fallow year (eg. T, NT-T, & T-NT) were tilled again with a field cultivator with trailing rolling baskets (Triple K, Kongskilde, Hodgdon, IL) to establish a consistent seedbed for wheat.

Soil samples were taken from fallow plots in the spring near LGM planting time for site characterization, and then from all plots (including fallow) at LGM termination, later that fall. A third soil sampling was done the following spring after the 2008 and 2009 LGM, (i.e. immediately prior to spring wheat planting). Spring soil sampling was not performed in 2007 because the plots had been planted to winter wheat, which was terminated due to weed infestation and replanted to spring wheat. Soil cores were 30.3 mm in diameter and were extracted from a depth of 0.9 m using a truck-mounted hydraulic soil probe. At each sampling date, two cores were taken from each plot, split into 0.3-m depth increments, and the soil from the two cores composited in the field into plastic-lined paper bags. Soil samples were stored in coolers for transportation from the field to the laboratory to minimize effects of disturbance on microbial activity. Soil samples were weighed, then the bags were opened and dried in an oven at 50° C for 4 d. After drying, the soil samples were weighed again to determine gravimetric water content and bulk density. Dry soil samples were crushed (Dynacrush Soil Crusher , Custom Laboratory Equipment, Orange City, FL) and passed through a 2-mm sieve. A subsample of crushed soil was treated with 1-M KCl to extract NO<sub>3</sub>-N (Bundy and Meisinger 1994), and the extract was analyzed with a flow injection analyzer (Lachat instruments Inc., Loveland CO). Soil bulk density was averaged by depth for each sampling date for conversion of NO<sub>3</sub>-N concentration by weight to soil N content.

In Year-2, hard red spring wheat (HRSW, c.v. Choteau) was planted in strip (i.e. split-block) subplots across all Year-1 main plots at four N fertilizer application rates.

Nitrogen fertilizer was supplied as urea, mid-row banded at seeding to supply 0, 50, 100, and 150 kg ha<sup>-1</sup> in 2008 and 0, 25, 50, and 100 kg ha<sup>-1</sup> in 2009 and 2010. Wheat was also fertilized with 56 kg ha<sup>-1</sup> each of mono-ammonium phosphate (11-52-0) and potassium sulfate (0-0-50-17), banded with the seed, providing total N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O-S additions of 6-29-26-9 kg ha<sup>-1</sup>. Wheat seeding rate was 67 kg ha<sup>-1</sup> of commercial certified seed in 2008, and in 2009 and 2010 was calculated based on seed size and germination rate to achieve 250 pure live seeds m<sup>-2</sup>. Wheat seed was treated with 121 mg a.i kg seed<sup>-1</sup> difenoconazole {1-((2-(2-chloro-4-(4-chlorophenoxy)phenyl)-4-methyl-1,3-dioxolan-2-yl)methyl)-1H-1,2,4-triazole} and 9.7 mg a.i. kg seed<sup>-1</sup> mefenoxam {(R,S)-2-[(2,6-dimethylphenyl)-methoxyacetyl-amino]-propionic acid methyl ester}, both fungicides, in 2008-2010, and additionally with 101 mg a.i. kg seed<sup>-1</sup> thiamethoxam {3-[(2-Chloro-1,3-thiazol-5-yl)methyl]-5-methyl-N-nitro-1,3,5-oxadiazinan-4-imine}, a systemic neonicotinoid insecticide, in 2010. All plots were sprayed with glyphosate prior to wheat emergence, and post-emergence herbicide and insecticide as shown in Table 4.2.

Biomass samples of 1-meter-row of wheat were harvested after anthesis (Zadoks 70; Zadoks et al. 1974) to determine plant N uptake by time of anthesis, and the number of wheat tillers was counted at that time. In 2008, feeding on wheat seedlings by larvae of pale western cutworm (*Agrotis orthogonia* Morrison) and army cutworm (*Euxoa auxiliaris* Grote) caused moderate and spatially-variable damage, so mature wheat was harvested by hand from 1-meter-row, in the interior of each subplot, at a location that was judged visually to have had minimal cutworm impact to the sample row and

adjacent rows. Wheat samples from 2008 were threshed in a stationary threshing machine. In 2009 and 2010, edge rows and ends were mowed from each subplot, resulting in subplots of approximately 1.3 by 6 m, and wheat grain was harvested with a plot combine. Grain samples were passed through a screen, and cleaned with an air-blast seed cleaner to remove debris. Clean grain samples were then weighed, and grain density was determined using a standard grain density cup and conical filling hopper. A subsample of grain was placed in a seed counting machine and 250 kernels were weighed to determine average kernel weight. Grain protein and moisture content were analyzed using near infrared reflectance (NIR) with the standard calibration for HRSW using an Infratec model 1241 grain analyzer (FOSS, Denmark). The grain moisture content was used to adjust yield, grain density, and seed weight data to 12% moisture content. Grain N content was calculated from NIR protein values converted to dry weight basis using a conversion factor of 5.7 as the ratio of protein to N (Jones 1941). Total grain N was then calculated using grain yield expressed as a dry weight. Number of kernels per spike was calculated based on moisture-corrected sub-plot yield, tiller density, and average harvested seed weight.

### Economic Analysis

Enterprise budgets were used to estimate costs and returns for each 2-year cycle in real 2010 U.S. Dollars. Wheat prices, protein premiums, and discounts were an average of 2008-2010 expected local cash prices at planting time of each year for #1

Dark Northern Spring Wheat (DNS), based on futures prices and historic basis in North-Central Montana. Wheat prices were calculated based on protein content, expressed at 12% grain moisture, and extrapolated with a linear function using the discount between 130 g kg<sup>-1</sup> and 140 g kg<sup>-1</sup> grain protein DNS for protein values below 140 g kg<sup>-1</sup> and the premium between 140 and 150 g kg<sup>-1</sup> protein for protein above 140 g kg<sup>-1</sup>, with a threshold at 125 g kg<sup>-1</sup> protein below which grain was priced as ordinary feed wheat.

Operating costs for machinery were estimated for the field operations performed in the plot experiments, based on published custom farm operation rates in the neighboring state of North Dakota (Aakre 2011). Fertilizer and herbicide prices were from USDA National Agricultural Statistics Services (NASS) annual agricultural price reports. For pea and lentil seed, which are not traded on futures markets, price information for LGM seed was based on bin-run grain at local market rates. Economic budgets did not include cost of land, crop insurance, or participation in any government commodity programs. Prices used for economic analysis are shown in Table 4.3. Net revenue was calculated on a plot-wise basis and analyzed as described below, omitting the NN and NN+ treatments.

### Energy Analysis

Cropping system energy budgets were compiled using process analysis (Fluck and Baird, 1980; Jones 1989), with system boundaries at the farm field level. Energy budgets accounted for energy used for manufacture and operation of farm machinery,

and manufacture of fuel and lubricant, fertilizer, and herbicide. Energy coefficients for farm machinery were obtained from Zentner (2004b) and Nagy (1999) as shown in Table 4.3.

Energy coefficients for herbicides were obtained from Nagy (1999) and Liska et al. (2007). *Energy Intensity* (EI, MJ kg<sup>-1</sup>) was calculated as an indicator of energy use per kg of grain produced. *Net Energy Yield* (NEY = Energy<sub>out</sub> – Energy<sub>in</sub>, GJ ha<sup>-1</sup>), was calculated using an energy value of wheat of 18.7 MJ kg<sup>-1</sup> based on bomb calorimeter tests from Nagy (1999). Energy metrics were computed on a plot-wise basis and subject to statistical analysis as described below, omitting the NN and NN+ treatments.

Because grain N has economic value whether it occurs as increased yield or protein, total grain N was used as an integrated measure of yield and protein for further analysis of the economic and energetic value of LGM-derived N. Total grain N was calculated by multiplying grain yield by grain N content converted from protein content based on a conversion factor of Nitrogen fertilizer equivalence of each LGM-Tillage treatment was calculated as the amount of N fertilizer required on wheat following fallow to match the grain N removal of unfertilized wheat following each LGM for each tillage treatment, following the technique of Mahler and Auld (1989). The difference in management cost and input energy between each LGM-Tillage treatment and NT fallow was then used to calculate the economic and energetic cost of LGM N relative to the baseline practice of NT fallow and the energy savings of substituting LGM N for fertilizer N at a quantity equal to the N fertilizer equivalence of each LGM treatment.

### Statistical Analysis

Statistical analysis was performed using SAS 9.3 (Statistical Analysis Systems, Cary, NC). For measurements taken at the level of Year-1 main plots (e.g. LGM biomass, soil measurements), PROC MIXED was used with REML estimation to fit mixed models with block as a random effect, and year, tillage, and LGM as fixed effects. Post-hoc multiple comparison tests were made using T-tests based on the standard error of differences using the PDIFF option to the LSMEANS statement of PROC MIXED in SAS.

For measurements taken at the level of Year-2 sub plots (e.g. wheat yield components and quality, and economic and energetic metrics), the PROC MIXED procedure was used with REML estimation to fit mixed models with *block*, *block\*nrate*, *block\*LGM*, and *block\*tillage* as random effects and *block* nested within *year* as recommended for a split block (a.k.a strip-split plot) design by Littell et al. (2006). N fertilizer level (*nrate*) was modeled directly as an independent regression variable, and included as a separate class variable for inclusion in the interaction with the block random effect. A quadratic term was included in the model for *nrate* and interactions between fixed effects and *nrate* where those effects were significant, following Ch.4 of Littell et al. (2006). The 4-way interaction (Y x S x T x N) was not significant for any yield component and was removed from the model. Although treatment-by-year interactions were sometimes significant, they generally did not involve changes in rank among treatments, so analysis was combined for all years with year as a fixed effect.

Spatial autocorrelation was apparent in some wheat yield component and quality data in 2009 and 2010. Residuals from the independent errors models were used to construct semivariograms, which were analyzed visually to estimate spatial covariance parameters. The REPEATED option to PROC MIXED was then used to specify spherical spatial covariance structures with nugget effects for all response variables, using the BY option to specify independent covariance structure for each year. Differences between “-2 \* log likelihood” statistics, were evaluated with Chi-squared tests to determine preferred models for each response variable.

## Results and Discussion

### Legume Green Manure Growth

Pea and lentil differed markedly from one another in their growth, but were remarkably consistent among years (Table 4.4). Mean LGM biomass over all three years was 2.8 Mg ha<sup>-1</sup> for pea and 1.2 Mg ha<sup>-1</sup> for lentil, lentil biomass production being 43% that of pea. These values are smaller, especially for lentil than those found by Biederbeck et al. (1993) of 3.0 Mg ha<sup>-1</sup> for pea and 1.7 Mg ha<sup>-1</sup> for lentil terminated at full bloom. Canadian researchers who have found lentil to be a favored green manure crop have also generally found lentil to produce a larger fraction of the amount of biomass produced by pea: 56% by Biederbeck et al. (1993), 65% by Townley-Smith et al. (1993), and 76% by Biederbeck and Bouman (1994). In all of these studies lentil and

comparison LGM species were terminated on the same date, corresponding to ‘full bloom’, or several days later than the “first bloom” date used here.

### Weed Competition

The most abundant weed species at this site was downy brome, an annual grass with winter or spring germination. In 2007, weed biomass was 11% of total biomass in the lentil plots and 2.5% of the total biomass in the pea treatments. Downy brome growth was clearly stimulated by N fertilizer addition to the NN+ plots, where weed biomass was 19% of the total. In 2008, weed biomass was 17% of lentil biomass and 5% of pea biomass. In both 2007 and 2008, downy brome began anthesis before the pea and lentil LGM. In practice, a producer would likely either terminate the LGM earlier, to prevent seed production by weeds, or would control the weeds in the LGM crop. In 2009, downy brome was controlled with a selective herbicide and weed biomass was not measured.

### LGM C:N Ratio and Total N Content

Biomass C:N ratio for pea and lentil LGM combined with the weeds present in those treatments did not differ from each other within any year (Table 4.4), consistent with the findings of Townley-Smith (1993), but in contrast to Biederbeck et al. (1996), who found lentil LGM biomass to have greater N content than field pea. Pea C:N ratio was smaller in 2007 than in 2008 or 2009 (Table 4.4). Differences in biomass quantity resulted in >2-fold greater total biomass N in pea than lentil. The C:N ratio for NN pea

was consistently and substantially greater than for the N-fixing LGM. The C:N ratio of fertilized non-nodulating (NN+) pea did not differ among years, and was slightly greater than for the N-fixing LGM's (Table 4.4).

### Soil Water

There were differences among years and LGM treatments in the amount of soil water utilized during LGM growth relative to the fallow control. Pea utilized approximately twice the quantity of soil water as lentil during LGM growth (e.g. the difference between soil water under LGM and fallow, at termination; Table 4.5). In 2007 and 2009, the amount of soil water utilized by NN pea did not differ from lentil; however, NN+ pea used less water than pea. Non-nodulating pea was therefore a reasonable alternative control for comparison to lentil, but the NN+ treatment did not result in a good control comparison for N-fixing pea with regards to soil water use.

Pea and lentil both used water preferentially from the top 60 cm of soil, with 85% and 83%, respectively, of total soil water depletion from 0-90 cm occurring in the 0-60 cm depth interval (data not shown). Similar soil water use patterns by depth were found by Miller et al. (2003), and Biederbeck and Bouman (1994).

The rate of evaporation of soil water varies as a function of the amount of water present in the soil, soil-atmosphere energy exchange, and by the rate of upward movement of water through the soil profile. Growth of LGM, and the quantity and management of resulting surface residue can affect all of these factors by use of water

by the LGM, surface cover provided by LGM residue, and disruption of soil capillary by tillage.(Hatfield et al. 2001).

After termination, LGM and tillage treatments continued to affect the amount of water lost to evaporation and gained from infiltration and snowcatch. Between LGM termination in late June and soil sampling in Sept., soil water was lost to evaporation in 2007 and 2008, and gained from precipitation in 2009. There was a narrowing of the differences in soil water between LGM and Fallow during this time in all years (Table 4.5). In Fall 2009, there was no significant difference in soil water between lentil and fallow treatments. This is consistent with the findings of Pikul et al. (1997) that when lentil LGM was terminated early (first bloom), the water-conserving effects of the residue in preventing evaporation from the soil surface were equivalent to the water used for growth of the LGM, resulting in no difference in residual soil water between fallow and lentil LGM.

For the 2008 and 2009 LGM treatments, an additional soil sampling was done the following spring, immediately prior to spring wheat planting, on the dates shown in Table 4.2. Between the fall soil sampling time and the next spring, further narrowing of the differences in soil water between LGM's and fallow occurred (Table 4.5), consistent with previous observations by Miller et al. (2006).

No till stubble management has been shown to conserve soil water by a number of mechanisms, including reduced evaporation, increased infiltration, and increased snow catch (Peterson et al. 1996), but this effect has not always been consistently

observed (Lafond et al., 1992; Townley-Smith et al., 1993). Here, there were no differences among tillage treatments in soil water measured in the fall in 2007 or 2008, but in 2009, NT-T had more soil water than T or T-NT. This finding is consistent with NT management conserving soil water when soil is wet and water loss is limited by atmospheric energy exchange, but tillage reducing soil water loss under drier soil conditions where rate of water movement is limited by unsaturated flow (Hatfield et al. 2001).

Pre-planned orthogonal contrasts were used to test for differences in soil water the following spring for NT vs. all treatments receiving any amount of tillage. For the 2008 LGM year, soil water the following spring was 25 mm greater in NT than in treatments that had received any tillage ( $P < 0.001$ ). This contrast was not significant ( $P = 0.23$ ) in 2009. The effect of tillage on soil water accumulated after the 2008 LGM year was likely driven by stubble snowcatch during an unusually large snow event accompanied by strong wind during the spring of 2009, and may not represent typical conditions. Stubble management for snow catch is a proven tactic in this region (Aase and Siddoway, 1980; Ries and Power, 1981), but the magnitude of the effect varies from year to year. Campbell et al. (1992) observed as much as a 48-mm increase in soil water accumulation from snow catch in tall wheat stubble strips, but an average increase of just 13 mm over 10 yr.

### Soil NO<sub>3</sub>-N

Soil NO<sub>3</sub>-N at LGM termination did not differ among fallow, pea, lentil, and NN treatments in 2007 or 2008, but in 2009 pea and lentil had 21 and 12 kg ha<sup>-1</sup> less soil NO<sub>3</sub>-N respectively than fallow (Table 4.5). Pikul et al. (1997) also found reduced soil NO<sub>3</sub>-N following lentil LGM compared to fallow. There was 29 kg ha<sup>-1</sup> more soil NO<sub>3</sub>-N in the NN+ treatment at LGM termination in 2007 than in fallow plots, due to excess application of N fertilizer at seeding. In 2008 and 2009, when the NN+ treatment received the planned addition of 60 kg ha<sup>-1</sup> N fertilizer, soil N at termination in the NN+ control did not differ from fallow, pea, or lentil. At the fall soil sampling time there continued to be no differences in soil NO<sub>3</sub>-N among fallow and LGM treatments, nor generally among tillage treatments (Table 4.5). This is consistent with other research in northern semiarid regions showing no difference in soil mineral N between LGM and fallow (Biederbeck et al. 1996). Miller and Holmes (2005) found similar results in a study near this same location in Amsterdam, MT, but found reduced soil N following pea, relative to chemical fallow, regardless of termination timing or presence pea biomass, at other locations in MT. Legume green manures reduce soil N by preferentially utilizing available mineral sources of soil N before initiating symbiotic N fixation (Van Kessel and Hartley, 2000) and also by reducing soil water potential and hence mineralization of existing soil organic matter (Cassman and Munns 1980). After termination, however, LGM material is expected to increase soil N as organic N in the LGM plant tissue is

mineralized (Bremer and van Kessel, 1992), and by stimulating the mineralization of existing labile soil organic matter (Fontaine et al., 2003).

At the spring soil sampling following 2008 LGM (i.e. spring 2009) there were 10 and 12 kg ha<sup>-1</sup> more soil N in the lentil and pea treatments respectively than following fallow (Table 4.5). Following the 2009 LGM (i.e. spring 2010) there was no difference in soil NO<sub>3</sub>-N among pea, lentil, and fallow (Table 4.5). Miller and Holmes (2005) also found greater overwinter N mineralization following pea than fallow at two out of three site-years in Montana. Here, there were no effects of tillage on spring soil N either year. Spring soil N in the NN control was less than in the pea and lentil LGM, but not different from fallow. Soil NO<sub>3</sub>-N in the NN+ control was greater than pea and lentil the spring following the 2008 LGM (Table 4.5).

Use of NN+ and NN pea as controls was deemed only partially successful in creating conditions of soil water use and N uptake similar to lentil and pea, with and without N addition. Further analysis of these controls was limited to qualitative confirmation of the role of N in driving wheat yield component responses to LGM.

### Wheat Yield & Quality

Wheat grown the year following Fallow and LGM treatments exhibited a positive linear and quadratic decay response to N fertilizer, as well as response to LGM species (S), tillage (T), and year (Y), and 2- and 3-way interactions among S, T, and N fertilizer level (Table 4.6). Mixed model fixed effect *F*-ratios, *P*-values, and least squares

estimated means for simple main effects at an intermediate N-fertilizer value of 50 kg ha<sup>-1</sup> are shown in Table 4.6. Graphical representations of species x nitrogen (S x N) interactions, at each level of tillage, for each of the wheat yield components are shown in Figure 4.1. Where S x N and T x N interaction affected wheat growth at low levels of N fertilizer with diminishing response at greater N levels, the interpretation is that the LGM or Tillage treatment supplied N to the wheat crop (Beckie and Brandt, 1997). Analysis of these interactions on the sequentially formed yield components of wheat provides additional insight into the timing of the release of N, as well as timing of onset of water stress in the wheat crop.

When considering the role of tillage in stimulating the release of LGM N, the effect of tillage on fallow must be considered. The significance of the SxT and SxTxN interactions indicates generally that tillage impacted N cycling differently for the different LGM treatments. Furthermore, at 0N fertilizer there was not a significant difference in wheat yield, protein, or grain N uptake between NT and T Fallow, while there were differences between these tillage treatments when either lentil or pea LGM were present (data not shown). This indicates that effect of tillage in stimulating release on LGM N was not confounded significantly by an overall effect of tillage on release of N from native soil organic matter.

For the tillage treatments that involved tillage termination of the LGM (e.g. T and T-NT), wheat yield following pea and lentil LGM were greater than following fallow at low levels of N fertilizer, with the effect diminishing at greater N rates (Figure 4.1).

For the NT-T tillage treatment, only pea LGM differed from fallow in subsequent wheat yield. Note that NT-T Pea LGM was ultimately incorporated with a heavy disk (after chemical desiccation), breaking up and incorporating the LGM plant material in to the soil, while the NT-T Lentil LGM was managed with a non-inverting chisel plow which uprooted the plants but did not bury them or push them down into the soil. Wheat grain yield following the NN control was intermediate between the fallow control and the N-fixing LGM's, not differing significantly from either at 50 kg ha<sup>-1</sup> N (Table 4.6).

Analysis of the sequential yield components of wheat provides additional insight into timing of the release of N and onset of water stress relative to the growth stages of wheat (Kiesselbach and Sprague, 1926), indicating the effect of tillage on the timing of mineralization of LGM N. This is important because synchronizing N availability with crop demand is an important aspect of minimizing the environmental effect of supplying large quantities of N to crops (Crews and Peoples, 2005). Although there were not consistent effects of LGM species or tillage treatments on soil N measured before wheat planting, LGM affected wheat yield components in a manner consistent with LGM increasing N supplied to the wheat crop, pea providing more N than lentil, and tillage accelerating the release of that N.

Wheat tiller density (tillers m<sup>-2</sup>) responded positively to N fertilizer (Figure 4.1), as expected. For all of the tillage treatments that involved any amount of tillage, pea LGM also increased tiller density relative to fallow, with the effect diminishing at greater N rates, indicating that tillage played a role in stimulating early mineralization of pea

LGM N. Lentil LGM affected tillers  $m^{-2}$  similarly to pea, though to a smaller magnitude (Table 4.6). Wheat tiller density was also increased by the NN+ control treatment, but not the NN control (Table 4.6), confirming the role of N from the N-fixing LGM's in stimulating wheat tiller production.

The number of kernels per spike was derived from tiller counts, seed weight, and grain yield. The calculated values of kernels per spike therefore incorporate variance from all three sources. Year was, by far, the largest source of variance in number of kernels per spike, and any treatment effects were confounded by crossover interactions with year. Interactions of Year with S and N (Table 4.6) on number of kernels per spike are likely indicative of differences in timing of onset of water stress during anthesis in some treatments and years. Although treatment-by-year interactions for this variable involved crossovers (not shown), these changes were generally consistent with N-fixing LGM, more intense tillage providing more N but stimulating earlier onset of water stress, and water being the limiting factor for kernel formation in 2008 and 2010. This result is indicated by decreased kernel counts for tilled LGM treatments where increasing N fertilizer also resulted in decreased kernel counts those years (Figure 4.1).

Seed weight declined with additional N fertilizer (Figure 4.1), indicating water was universally the limiting factor for this yield component, and illustrating the effect of previously formed yield components on the onset of water stress. Although Y x T and Y x N interactions were significant, they did not involve changes in rank of the treatments or crossovers. There was no effect of tillage on seed weight (Table 4.6). There was an

overall effect of LGM species on seed weight (Table 4.6), but the only difference was between Pea LGM and NN, confirming the role of N supplied by the N-fixing Pea LGM in reducing seed weight relative to the NN control which also used some soil water but did not show evidence of increasing N supply to the wheat crop.

Grain protein responded positively to N fertilizer (Figure 4.1), and Pea LGM also increased grain protein for all tillage treatments relative to fallow, while lentil LGM did not. The average increase in grain protein due to pea LGM relative to fallow was  $8 \text{ g kg}^{-1}$  at  $50 \text{ kg N ha}^{-1}$  fertilizer (Table 4.6), and was consistent across all levels of N fertilizer (Figure 4.1). It is unknown whether the relationship between fertilizer N and grain protein was truly different for the different LGM treatments. The technique illustrated by Beckie et al. (1997) for determining the proportion of a rotational effect due to N cannot be applied here because the maximum fertilizer rates applied were insufficient to maximize grain protein. Other research has found inconsistent effects of LGM on grain protein. Allen et al. (2011) found sporadic effects of lentil LGM on wheat protein, with decreased protein in early years of the study. Neither Tanaka et al. (1997), nor Brandt (1999) found any effect of LGM on wheat grain protein, and Pikul et al. (1997) found reduced grain protein in wheat following lentil LGM compared to fallow.

There was no effect of tillage, nor S x T interaction on grain protein. Grain protein was reduced by the NN control treatment, and increased by the NN+ control, suggesting that the effect of LGM was due to increased N supply rather than water limitation and yield dilution (Terman et al., 1969). Notably, the effect of pea LGM on

grain protein was significant even under NT management (Figure 4.1), suggesting that N supply from NT Pea LGM was delayed relative to the tilled treatments. This is consistent with the results of Lupwayi et al. (2006), who found faster initial release of residue N with tillage, but no difference in total N released between NT and T treatments after 13 months.

Total grain N integrates grain yield and protein, and responded positively to N fertilizer, LGM, and tillage (Figure 4.1). With any termination type, Pea LGM increased total grain N relative to fallow at all but the highest N fertilizer levels (Figure 4.1). Lentil LGM increased total grain N uptake only with tillage termination, and with differences from fallow not always significant with the T-NT treatment (Figure 4.1). Total grain N was used to calculate N fertilizer equivalence of the LGM treatments used in the marginal economic and energetic analyses that follow.

#### Costs of LGM Management

The differences in management costs among tillage strategies were small in economic terms (no more than \$8 ha<sup>-1</sup>), compared to the cost of LGM seed and seeding of \$17.78 ha<sup>-1</sup> for lentil seed, \$32.90 ha<sup>-1</sup> for pea seed, and \$38.24 ha<sup>-1</sup> for operation of seeding equipment (Table 4.7). Because of the greater rate of herbicide used for LGM termination than fallow maintenance, and the different tillage implements used for pea and lentil, the lowest-cost management strategy for fallow and pea was NT, while the lowest cost strategy for lentil was T-NT. Actual costs of various field operations will vary

with a farm's equipment availability and may not be reflected by custom rates for the implements chosen here. Pea LGM increased Year-1 operating costs by about twofold in both economic and energetic terms compared to fallow, while Lentil LGM cost about 10% less than Pea LGM.

### Cropping System Economics

Economic profit increased with additional N fertilizer, and the greatest profit was achieved at the greatest N fertilizer rate and NT Fallow (Figure 4.1). At the intermediate N fertilizer level of  $50 \text{ kg N ha}^{-1}$ , tillage resulted in greater profit than NT, and fallow resulted in greater profit than lentil LGM, while profit from pea LGM did not differ from fallow (Table 4.6). Without tillage termination (e.g NT, NT-T) lentil LGM consistently resulted in reduced profit compared to fallow, but with tillage, profit of lentil LGM did not differ from fallow (Figure 4.1). Under NT and NT-T management, pea LGM matched the profit of fallow at 0 N fertilizer, but did not increase as rapidly with increasing N fertilization, such that at the highest fertilizer rates, fallow was more profitable than pea LGM.

### Cropping System Energetics

The cropping system with lowest EI was unfertilized tilled fallow. Energy intensity ranged from  $1.2 \text{ MJ kg}^{-1}$  for unfertilized wheat grown on tilled fallow to  $3.1 \text{ MJ kg}^{-1}$  for wheat grown with  $100 \text{ kg ha}^{-1}$  of fertilizer N following NT pea LGM. Expressed as (out/in) energy efficiency ratios for comparison to studies that use this metric, assuming

a grain energy content of  $18.7 \text{ MJ kg}^{-1}$ , these intensities are equivalent to (out/in) ratios of 15.7 and 6.0 respectively.

Overall, tillage decreased EI slightly (Table 4.6), but the magnitude of the change was small compared to the difference in energy intensity among years or N fertilizer rates. Zentner et al. (2004b) also found only small differences among tillage systems in cropping system energy efficiency. It is noteworthy that the most energy intensive systems in this study ( $3.1 \text{ MJ kg}^{-1}$  wheat), resulting from the highest applied levels of N fertilizer, regardless of LGM or tillage treatment, still had lower EI than the national average of  $\sim 3.9 \text{ MJ kg}^{-1}$  found by Piringner and Steinberg. (2006) using generally similar system boundaries.

The case of declining energy efficiency (i.e. increasing EI) with increased inputs has been attributed to “growing dependency on inorganic, non-renewable resources” (Moreno et al., 2011). Hülsbergen et al. (2002), and Rathke and Diepenbrock (2006) working in a subhumid region in central Germany, are the only published research showing a concave-up curve describing EI as a function of N fertilizer, with energy intensity minimized at an intermediate level of N fertilizer. Hülsbergen’s study described crop yields of over  $7 \text{ Mg ha}^{-1}$  with no fertilizer in some years, and fertilized yields in excess of  $10 \text{ Mg ha}^{-1}$  with a maximum of  $150 \text{ kg N ha}^{-1}$  fertilizer applied. Also, management was generally far more intensive than the present study, including considerably more energy expended on repeated tillage, fungicide application, and grain transport (e.g. an expanded system boundary compared to the present study).

In a more comparable semiarid environment in southern Saskatchewan, Canada, Zentner et al. (1984, 1989, 2001) also found unfertilized fallow-wheat crop rotations to be the most energy-efficient compared to various continuous cropping scenarios using similar energy analysis methodology. These results should be interpreted as a cautionary note regarding the utility of energy ratios of cropping systems rather than as a meaningful comparison of the systems analyzed here. The cropping system identified here as least energy intensive has been known for over a century to be patently unsustainable due to depletion of soil organic matter (Janzen, 2001). No attempt was made in this short-term study to account for soil organic matter change, but an analysis in Chapter 1 of this dissertation of data presented in Zentner et al. (2001) showed that accounting for soil organic N depletion as a fertilizer input to fallow-based cropping systems resulted in a re-ordering of the cropping system energy efficiency ranks presented in that study. There does not appear to be, however, any meaningful way for energy ratios of whole cropping systems to assign value to systems that increase soil organic matter, a stated goal of green manure cover cropping (Biederbeck et al., 1996, Campbell et al., 2007). The response of cropping system EI to N fertilizer was analyzed in chapter 2 of this dissertation and shown to decrease in response to additional fertilizer only when the *marginal* EI of crop yield response to added N is less than the baseline system EI. Because whole system EI is a function of somewhat arbitrary system boundaries, system EI was shown not to be useful for optimization of N fertilizer levels especially in otherwise low-input systems. Consider that wheat with protein content of

130 g kg<sup>-1</sup> is approximately 2.3% N. If that N is supplied by synthetic fertilizer with an EI of 56.7 MJ kg<sup>-1</sup> (the value assumed for urea here), even assuming an unrealistic 100% uptake efficiency, the marginal energetic cost of additional wheat resulting from fertilization is 1.3 MJ kg<sup>-1</sup>. Since the energy intensity of the unfertilized fallow-wheat system analyzed here was 1.2 MJ kg<sup>-1</sup> wheat, there is no possibility of N fertilizer improving the system energy intensity, with any physically possible yield response to N fertilizer. These results confirm that ratio-based measures of energy intensity of efficiency are unsuitable for optimization of input levels.

Cropping system net energy yield (NEY, MJ ha<sup>-1</sup>) was affected by Year (Y), LGM species (S), tillage (T), and N fertilizer level (N), as well as N x S and N x T interactions, and interactions with Year (Table 4.6, Figure 4.1). At the intermediate N fertilizer level of 50 kg N ha<sup>-1</sup>, there were no differences among LGM and fallow treatments in NEY, but tillage systems did differ in their NEY.

Cropping system NEY response to LGM species and tillage interactions with N fertilizer generally resembled those of grain yield (Figure 4.1), but differed importantly from net profit. Unfertilized tilled pea and lentil LGM and NT-T pea LGM matched the NEY of the most heavily fertilized NT-fallow system. In the economic analysis, however, heavily fertilized NT-Fallow resulted in greater profit than the unfertilized wheat following any LGM (Figure 4.1). This discrepancy between energetic analysis of NEY and economic analysis net profit arises largely because of the lack of energy value to grain

protein (protein has the same energy content as carbohydrate), whereas there are substantial economic incentives for production of high protein grain (Baker et al., 2004).

#### Economic and Energetic Costs of LGM N

The design of this study offers a novel opportunity to evaluate the energy cost of supplying N via LGM cover crops, as a separate analysis from energy intensity or productivity of the entire cropping system. The question addressed here is not whether LGM improves the EI of the cropping system as a whole, but what the energy intensity ( $\text{MJ kg}^{-1} \text{ N}$ ) and economic cost ( $\text{\$ kg}^{-1} \text{ N}$ ) of LGM-supplied N are, and how these compare to synthetic fertilizer N. Wu et al. (2011) demonstrated a similar approach, using estimates of energy required for LGM seed, seeding and tillage management as the inputs and estimates of quantity of N fixed by LGM as the outputs. Here, the N fertilizer equivalence, as defined by Mahler and Auld (1989), was computed from grain N responses to N fertilizer and LGM treatments and was used as an estimate of the N equivalence of LGM, as shown in Table 4.8. The energetic and economic costs of LGM management are also computed relative to the baseline scenario of NT fallow, and presented in Table 4.8.

Tilled lentil, and NT-T pea were the least expensive sources of LGM N, but all LGM N was more expensive in economic terms than N in the form of purchased urea (Table 4.8). In contrast, all LGM treatments that had a fertilizer equivalence significantly greater than 0 provided N at lower energetic cost than synthetic N fertilizer (Table 4.8).

The discrepancy between economic and energetic accounting found here is due primarily to differences in system boundaries between the methods for two categories of inputs: LGM seed, and machinery. The economic value of seed reflects the solar energy it contains, the cost of land upon which to grow it, and its value for competing uses (e.g. food or feed). The energy value of seed used here is the same as for any other manufactured input, simply the energy embodied in its production. For farm machinery, fixed capital costs of farm machinery ownership (e.g. interest, insurance, taxes) dominate total cost of machine usage (Eidman et al., 2000; Lazarus and Selley, 2005), and labor costs are included in custom farming rates, while published energy coefficients focus on fuel and lubrication with a relatively small amount of energy embodied in production of raw materials from which the machine is constructed (Nagy, 1999) and no consideration of capital or labor.

Tilled lentil LGM had the lowest energy intensity of N equivalence of the LGM treatments, less than half that of tilled pea LGM (Table 4.8), owing to equal fertilizer equivalence to the pea LGM treatments but lower energetic costs associated with seeding and termination. It should be noted that although tilled lentil LGM had similar fertilizer equivalence to pea LGM by this analysis, pea produced far more biomass and fixed more N (McCauley et al. 2012) so may have superior long term effects on soil fertility. Nitrogen fixation by pea and lentil LGM were estimated by McCauley et al. (2012) for a field study conducted immediately adjacent to the present study, with identical management methodology up to the point of LGM termination for the years

2009 and 2010. Estimated N fixation by spring-planted pea and lentil LGM terminated at first bloom (e.g. the same planting and termination times considered here) were 95 kg N ha<sup>-1</sup> for pea and 30 kg N ha<sup>-1</sup> for lentil.

### Conclusions

Replacing bare fallow with early-terminated pea and lentil LGM resulted in increased grain yield, with tillage termination being necessary to realize a response for lentil and at least one tillage at any time during the fallow year being sufficient for pea. Additionally, pea LGM consistently increased subsequent wheat grain protein relative to fallow by 0.8 percentage points, while lentil did not. Legume green manures alone did not provide sufficient N to maximize wheat yield or increase profits relative to standard practices given 2010 price and protein premium/discount structures. Legume green manures also did not improve cropping system energy intensity, and this metric is further confirmed to be of limited utility in choosing optimum input levels.

Consistent with the opinion of Jones (1989) it is concluded that system energy intensity/efficiency as calculated here and elsewhere are not unique or meaningful stand-alone measures of cropping system efficiency. As Jones noted, the value obtained depends more on the potential of the system to convert solar energy, primarily a function of climate. Indeed, we observed more variation among years than cropping systems in energy intensity.

The short-term N fertilizer equivalence of LGMs was economically more costly than fertilizer N, but energetically less costly. The short term N fertilizer equivalence would result in a net energy savings of up to  $1.7 \text{ GJ ha}^{-1}$  (NT-T Pea, Table 4.8) if fertilizer N was reduced by an equivalent amount. This is a relatively small net energy yield compared to that of biofuel production systems. For example, Liska and Cassman (2008) report gross energy yield of  $21.1 \text{ GJ ha}^{-1}$  for canola biodiesel production in Canada, and Fore et al. (2011) report a NEY of  $11.4 \text{ GJ ha}^{-1}$  for canola biodiesel assuming a  $1.6 \text{ Mg ha}^{-1}$  canola seed yield and taking account of energy value inputs and co-products from a small-scale biodiesel production system. Regions in the northern Great Plains where LGM is proposed as a substitute for summerfallow may not be well suited for oilseed production, so LGM may represent the best opportunity for fossil energy substitution from crop production on land currently fallowed.

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## Tables and Figures

Table 4.1 Precipitation and Temperature, Amsterdam, MT 2007-2010.

	Monthly Precipitation†					Mean Monthly Temperature ††				
	2007	2008	2009	2010	LTA	2007	2008	2009	2010	LTA
	mm					°C				
May	68	65	25	58	63	12.9	10.9	12.7	9.6	12.0
June	46	56	63	86	63	17.3	15.3	15.4	15.7	16.4
July	8	23	56	18	28	24.9	20.9	19.9	19.5	20.7
Aug	30	2	25	57	27	20.5	19.9	19.5	18.9	20.1

† Growing season precipitation was measured on site with a calibrated automated 'tipping-bucket' rain gauge.

†† Monthly mean temperatures, and long term averages (1981-2010) of temperatures and precipitation are from the nearest weather station (Belgrade, MT airport) reported by the Western Regional Climate Center, Desert Research Institute, Reno, NV.

Table 4.2. Dates and descriptions of field operations.

Operation	LGM treatments	Tillage treatments	2007-2008	2008-2009	2009-2010
LGM Seeding	P, L,NN,NN+	all	11 Apr, 2007	4 Apr, 2008	13 Apr, 2008
LGM PRE herbicide	P,L,NN,NN+	all	16 Apr, 2007 †	11 Apr, 2008 †	19 Apr, 2009 †
LGM POST herbicide/insecticide 1 ‡	P,L,NN,NN+	all	none	20 May, 2008 §	15 May, 2009 §
Fallow herbicide 1	fallow	NT, NT-T	16 May, 2007 †	20 May, 2008 †	22 May, 2009 †
Fallow tillage 1	fallow	T, T-NT	17 May, 2007	9 June, 2008	27 May, 2009
LGM POST herbicide/insecticide 2	P,L,NN,NN+	all	none	none	11 June, 2009 ‡, §
LGM termination-herbicide	P,L,NN,NN+	NT, NT-T	15 June, 2007 ¶	29 June, 2008 ¶	28 June, 2009 ¶
LGM termination-tillage	P,L,NN,NN+	T, T-NT	18 June, 2007	1 July, 2008	1 July, 2009
Fallow herbicide summer	Fallow	NT, T-NT	30 June, 2007 †	14 July, 2008 †	14 July, 2009 †
Fallow/LGM tillage summer	all,	T, NT-T	13 July, 2007	20 July, 2008 #	15 July, 2009 #
Fallow/LGM herbicide fall	all	all, see footnotes	none	31 July, 2008 †, ††	5, Nov 2009 †
Fallow/LGM tillage fall	all	T, NT-T	20 Sept., 2007	4 Aug. 2008	24 Sept., 2009
Fallow/LGM tillage next spring	all	T, NT-T, T-NT	none	19 Apr., 2009	8 Apr., 2010
Spring Wheat Seeding	all	all	12 April 2008	21 Apr., 2009	10 Apr., 2010
Wheat pre-emergence herbicide †	all	all	11 April, 2008 †	2 May, 2009 †	16 Apr., 2010 †
Wheat post-emergence herbicide & insecticide			2 June, 2008 ‡‡	20 May, 2009 ‡‡, §	27 May 2010 §§

† Glyphosate N-(phosphonomethyl) glycine 0.42 kg ha<sup>-1</sup> ae as Potassium salt.

‡ Quialofop-P-ethyl {ethyl(R)-2-[4-(6-chloroquinoxalin-2-yloxy)-phenoxy]propionate} at 0.07 kg ha<sup>-1</sup> a.i.

§ Lambda-cyhalothrin 1 [1 $\alpha$ (S\*),3 $\alpha$ (Z)]-(±)-cyano-(3-phenoxyphenyl)methyl-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate at 0.02 kg ha<sup>-1</sup> a.i.

¶ Glyphosate N-(phosphonomethyl) glycine 0.84 kg ha<sup>-1</sup> ae as Potassium salt.

# Only Fallow plots were tilled, no weeds present in LGM

†† only T-NT treatments sprayed, no weeds present in NT plots

‡‡ 2,4-D (2,4-Dichlorophenoxyacetic acid) at 0.33 kg a.i. ha<sup>-1</sup>

§§ fluroxypyr: ((4-amino-3,5-dichloro-6-fluoro-2-pyridinyl)oxy)acetic acid, 1-methylheptyl ester at 0.099 kg ha<sup>-1</sup> ae  
 florasulam: N-(2,6-difluorophenyl)-8-fluoro-5-methoxy (1,2,4)triazolo(1,5-c)pyrimidine-2-sulfonamide 0.003 kg ha<sup>-1</sup> a.i.  
 pyroxsulam: N-(5,7-dimethoxy[1,2,4]triazolo[1,5-a]pyrimidin-2-yl)-2-methoxy-4-(trifluoromethyl)-3-pyridinesulfonamide at 0.015 kg ha<sup>-1</sup> a.i.

Table 4.3. Prices and energy coefficient for inputs and outputs.

	Price	price units	Energy Coefficient(s)	Energy Coefficient Units
Crop †				
Spring wheat 13% protein	\$164 (\$4.48)	\$ Mg <sup>-1</sup> (\$ bu <sup>-1</sup> )	18.7	MJ kg <sup>-1</sup>
Spring wheat 14% protein	\$184 (\$5.03)	\$ Mg <sup>-1</sup> (\$ bu <sup>-1</sup> )	18.7	MJ kg <sup>-1</sup>
Spring wheat 15% protein	\$199 (\$5.42)	\$ Mg <sup>-1</sup> (\$ bu <sup>-1</sup> )	18.7	MJ kg <sup>-1</sup>
Products used as inputs ‡				
Wheat seed	\$220	\$ Mg <sup>-1</sup>	7.2	MJ kg <sup>-1</sup>
Pea seed	\$150	\$ Mg <sup>-1</sup>	3.2	MJ kg <sup>-1</sup>
Lentil seed	\$260	\$ Mg <sup>-1</sup>	3.2	MJ kg <sup>-1</sup>
Urea	\$547	\$ Mg <sup>-1</sup>	56.7	MJ kg <sup>-1</sup> N
ammonium phosphate (11-52-0)	\$580	\$ Mg <sup>-1</sup>	56.7, 9.5	MJ kg <sup>-1</sup> N, MJ kg <sup>-1</sup> P <sub>2</sub> O <sub>5</sub>
Potassium sulfate (0-0-50-17)	\$305	\$ Mg <sup>-1</sup>	9.9, 1.12	MJ kg <sup>-1</sup> K <sub>2</sub> O, MJ kg <sup>-1</sup> S
glyphosate (540 g l <sup>-1</sup> ae)	\$5.29	\$ l <sup>-1</sup>	356	MJ kg <sup>-1</sup> ae
2,4-d amine (457 g l <sup>-1</sup> ae)	\$4.57	\$ l <sup>-1</sup>	98	MJ kg <sup>-1</sup> ae
Custom Machinery Rates				
air seeder	\$38.24	\$ ha <sup>-1</sup>	408	MJ ha <sup>-1</sup>
chisel plow	\$22.45	\$ ha <sup>-1</sup>	265	MJ ha <sup>-1</sup>
combine harvester	\$63.60	\$ ha <sup>-1</sup>	350	MJ ha <sup>-1</sup>
field cultivator	\$18.90	\$ ha <sup>-1</sup>	120	MJ ha <sup>-1</sup>
Heavy disc	\$31.02	\$ ha <sup>-1</sup>	377	MJ ha <sup>-1</sup>
Sprayer	\$13.44	\$ ha <sup>-1</sup>	43	MJ ha <sup>-1</sup>

† Energy coefficient for grain as an output is based on the energy released upon combustion in a bomb calorimeter (Nagy 1999).

‡ Energy coefficient for grain used as an input (seed) is based on the non-renewable energy embodied in production, treatment and handling of the seed (Nagy 1999)

Table 4.4 LGM and weed biomass treatment means and post-hoc multiple comparison results. Treatments within a column with the same letter do not differ ( $P < 0.05$ ).

LGM	LGM biomass	Weed biomass	C:N ratio	Total N
	Mg ha <sup>-1</sup>			kg ha <sup>-1</sup>
	<u>2007</u>			
Pea	2.69ab	0.07c	11.1f	108a
Lentil	1.14de	0.14bc	12.2ef	47cd
No-Nod	1.02c	0.13bc	24.9ab	20ef
No-Nod+N	2.34bc	0.55a	15.0c	83b
	<u>2008</u>			
Pea	2.88a	0.17bc	12.9de	100ab
Lentil	1.24de	0.26b	12.4ef	47c
No-Nod	0.84e	0.05bc	23.3b	15f
No-Nod+N	1.37d	0.08bc	14.5cd	31de
	<u>2009</u>			
Pea	2.85a	0	13.0de	94ab
Lentil	1.16de	0	12.2ef	41cd
No-Nod	1.29c	0	26.4a	19ef
No-Nod+N	1.93c	0	15.0c	48c

Table 4.5. Soil water and NO<sub>3</sub>-N Treatment means.

	Soil Water			NO <sub>3</sub> -N		
	Termination	Fall	Next Spring	Termination	Fall	Next Spring
	mm			kg ha <sup>-1</sup>		
<u>2007</u>						
Species						
Fallow	217a	189a	na	34b	50bc	na
No-Nod	201b	179b	na	20b	44c	na
No-Nod+N	179c	170b	na	63a	74a	na
Lentil	192b	178b	na	22b	52bc	na
Pea	156d	148c	na	19b	57b	na
Tillage						
NoTill	194a	175a	na	32a	65a	na
NT-T	191a	169a	na	32a	52b	na
Till	184a	174a	na	32a	50b	na
T-NT	188a	173a	na	29a	54b	na
<u>2008</u>						
Species						
Fallow	234a	188a	263a	50a	69ab	83c
No-Nod	na	157b	238b	na	60b	74c
No-Nod+N	na	151b	230bc	na	83a	107a
Lentil	177b	151b	236b	43a	75ab	93b
Pea	135c	121c	220c	40a	75ab	95b
Tillage						
NoTill	181a	150a	256a	44a	71ab	86a
NT-T	181a	155a	226b	43a	77ab	93a
Till	185a	154a	230b	41a	65b	96a
T-NT	182a	157a	236b	49a	78a	86a
<u>2009</u>						
Species						
Fallow	190a	206a	225a	53a	63ab	86ab
No-Nod	159b	197ab	210b	40bc	51b	78b
No-Nod+N	154b	193b	212ab	48ab	69a	97a
Lentil	160b	194ab	215ab	41bc	62ab	88ab
Pea	129c	169c	197c	32c	64ab	97a
Tillage						
NoTill	159ab	196ab	215ab	43ab	65a	89a
NT-T	167a	200a	220a	50a	67a	94a
Till	157ab	188bc	209ab	45a	58a	90a
T-NT	150b	183c	204b	34b	57a	84a

Table 4.6. Mixed model fixed effect F values and main effect means for wheat yield components, quality, and economic and energetic metrics.

Effect	Num DF	Tillers	Kernels	Seed Weight	Yield	Protein	grain N	Profit	Energy Intensity	Energy Prod.
		# m <sup>2</sup>	# spike <sup>-1</sup>	mg seed <sup>-1</sup>	Mg ha <sup>-1</sup>	g kg <sup>-1</sup>	kg ha <sup>-1</sup>	\$ ha <sup>-1</sup>	MJ kg <sup>-1</sup>	GJ ha <sup>-1</sup>
Year (Y)	2	19.2***	146.7***	30.0***	9.4***	46.4***	3.1*	4.1*	6.1**	84.7***
LGM Species(S)	4	17.0***	0.6	4.2**	12.6***	47.5***	32.1***	4.9**	5.8**	5.3**
Tillage(T)	3	9.4***	0.8	1.2	11.2***	0.4	8.4***	6.2***	7.5***	10.2***
S x T	12	1.9*	1.3	0.5	2.3**	1.2	1.4	1.8	2.3*	3.9***
N fertilizer (N)	1	139.2***	0.2	79.6***	212.1***	120.0***	230.3***	32.8***	310.3***	19.1***
N <sub>quadratic</sub>	1	27.2***	0.5	4.3*	61.3***	0.1	14.7***	7.6**	2.0	8.9**
N x S	4	6.0***	0.9	1.2	16.4***	5.0***	13.6***	8.7**	8.7**	11.3***
N x T	3	8.4***	1.3	0.5	10.3***	1.3	6.7***	5.2**	5.5**	4.3**
N x S x T	12	1.2	1.2	0.7	2.1*	0.6	1.3	1.9	2.9**	1.6
Y x S	8	0.5	3.4**	0.7	2.9**	6.7***	2.4*	2.2	1.4	1.8
Y x T	6	3.0**	1.9	3.3**	2.6*	3.6**	1.78	0.7	2.2*	3.0*
Y x S x T	24	0.8	1.6*	0.9	1.9**	1.4	1.14	1.0	1.1	3.8***
N x Y	2	3.2*	17.9***	39.3***	45.5***	87.3**	31.91**	20.0**	46.8**	13.3***
N x Y x S	8	0.5	0.8	1.0	3.7***	3.3**	1.9*	1.2	2.3	2.7*
N x Y x T	6	2.1*	0.7	1.2	4.6***	3.6**	1.77	1.2	3.6**	1.7
LS Means at 50 kg ha <sup>-1</sup> N fertilizer										
		# m <sup>-2</sup>	# spike <sup>-1</sup>	mg seed <sup>-1</sup>	Mg ha <sup>-1</sup>	g kg <sup>-1</sup>	kg ha <sup>-1</sup>	\$ ha <sup>-1</sup>	MJ kg <sup>-1</sup>	GJ ha <sup>-1</sup>
year										
2008		342c	32.6a	25.1a	2.71c	148a	70.1b	180b	2.47a	44.5c
2009		415b	24.4c	30.8b	3.05b	135b	72.6b	193b	2.13b	50.9b
2010		441a	26.6b	32.8c	3.77a	121c	81.5a	264a	1.75c	63.8a
Tillage										
No-Till		392b	27.7a	29.8a	3.11b	134a	73.1b	198b	2.19a	51.7b
No-Till – Till		407a	28.0a	29.3a	3.21a	136a	75.9a	211ab	2.12a	53.4ab
Till		403a	28.0a	29.5a	3.23a	135a	76.0a	230a	2.02b	56.7a
Till – No-Till		394b	28.0a	29.6a	3.15ab	135a	74.1ab	210ab	2.14a	50.6b
Legume Green Manure										
Fallow		378b	28.2a	29.6ab	3.06b	132b	70.7c	225a	1.98c	52.3b
No-Nod		387b	28.3a	30.2a	3.15ab	128c	70.9c	NA	NA	NA
No-Nod +N		411a	28.0a	29.4ab	3.27a	140a	79.4a	NA	NA	NA
Lentil		403a	27.8a	29.8ab	3.21a	133b	75.0b	200b	2.11b	53.9a
Pea		416a	27.3a	28.7b	3.17a	140a	77.8a	211ab	2.25a	53.1ab

\*, \*\*, and \*\*\* indicate P-values of 0.05, .01, and 0.001 respectively.

Means followed by the same letter do not differ ( $P < 0.05$ ).

Table 4.7 Economic and Energetic costs of Fallow and LGM treatments

	Machinery	Herbicide	Seed	Total	Machinery	Herbicide	Seed	Total
	\$ ha <sup>-1</sup>				MJ ha <sup>-1</sup>			
Fallow								
NT	\$53.75	\$22.14	\$0.00	<b>\$75.89</b>	172	796	0	<b>968</b>
NTT	\$68.22	\$11.07	\$0.00	<b>\$79.29</b>	471	398	0	<b>869</b>
T	\$73.68	\$5.54	\$0.00	<b>\$79.22</b>	548	199	0	<b>747</b>
TNT	\$68.22	\$11.07	\$0.00	<b>\$79.29</b>	471	398	0	<b>869</b>
Lentil								
NT	\$91.98	\$26.38	\$17.78	<b>\$136.15</b>	580	951	215	<b>1,746</b>
NTT	\$106.46	\$15.31	\$17.78	<b>\$139.55</b>	879	553	215	<b>1,647</b>
T	\$111.92	\$5.54	\$17.78	<b>\$135.23</b>	956	199	215	<b>1,370</b>
TNT	\$106.46	\$11.07	\$17.78	<b>\$135.31</b>	879	398	215	<b>1,492</b>
Pea								
NT	\$91.98	\$26.38	\$32.90	<b>\$151.26</b>	580	951	398	<b>1,929</b>
NTT	\$110.93	\$15.31	\$32.90	<b>\$159.14</b>	991	553	398	<b>1,942</b>
T	\$119.94	\$5.54	\$32.90	<b>\$158.38</b>	1,213	199	398	<b>1,810</b>
TNT	\$110.93	\$11.07	\$32.90	<b>\$154.90</b>	991	398	398	<b>1,787</b>

Table 4.8 Economic and energetic costs of LGM N.

	N fertilizer equivalence †	Cost of LGM management‡	Cost of LGM N§	Energy for LGM Management¶	Energy Intensity of LGM N ¶¶	Energy value of LGM fertilizer substitution #
	kg ha <sup>-1</sup>	\$ ha <sup>-1</sup>	\$ kg <sup>-1</sup> N	MJ ha <sup>-1</sup>	MJ kg <sup>-1</sup> N	MJ ha <sup>-1</sup>
Lentil						
NT	ns	\$60.26	--	778	--	--
NTT	ns	\$63.66	--	679	--	--
T	37ab	\$59.35	\$1.60	402	10.9	1696
TNT	21c	\$59.42	\$2.89	524	25.0	667
Pea						
NT	26c	\$75.37	\$2.89	961	37.0	513
NTT	48a	\$83.25	\$1.73	974	20.3	1747
T	42ab	\$82.49	\$1.96	842	20.0	1539
TNT	36bc	\$79.01	\$2.19	819	22.8	1222
Urea			\$1.17		56.7	

† N fertilizer equivalence is the quantity of fertilizer N required on fallow to match the level of grain N for the respective LGM and tillage treatments at 0N.

‡ Cost of LGM management is the additional cost above the baseline practice of NT fallow.

§ Cost of LGM N is cost of LGM management divide by N fertilizer equivalence

¶ Energy intensity of LGM N is Energy for LGM management divided by N fertilizer equivalence.

# Energy value of LGM fertilizer substitution is the energy required to produce fertilizer N quantity equal to N fertilizer Equivalence minus the Energy expenditure for LGM management.

Entries marked ns denote no significant difference in grain N between the LGM treatment and fallow for that response variable and tillage treatment at 0N fertilizer.

Values of N fertilizer equivalence followed by the same letter do not differ in total grain N uptake.

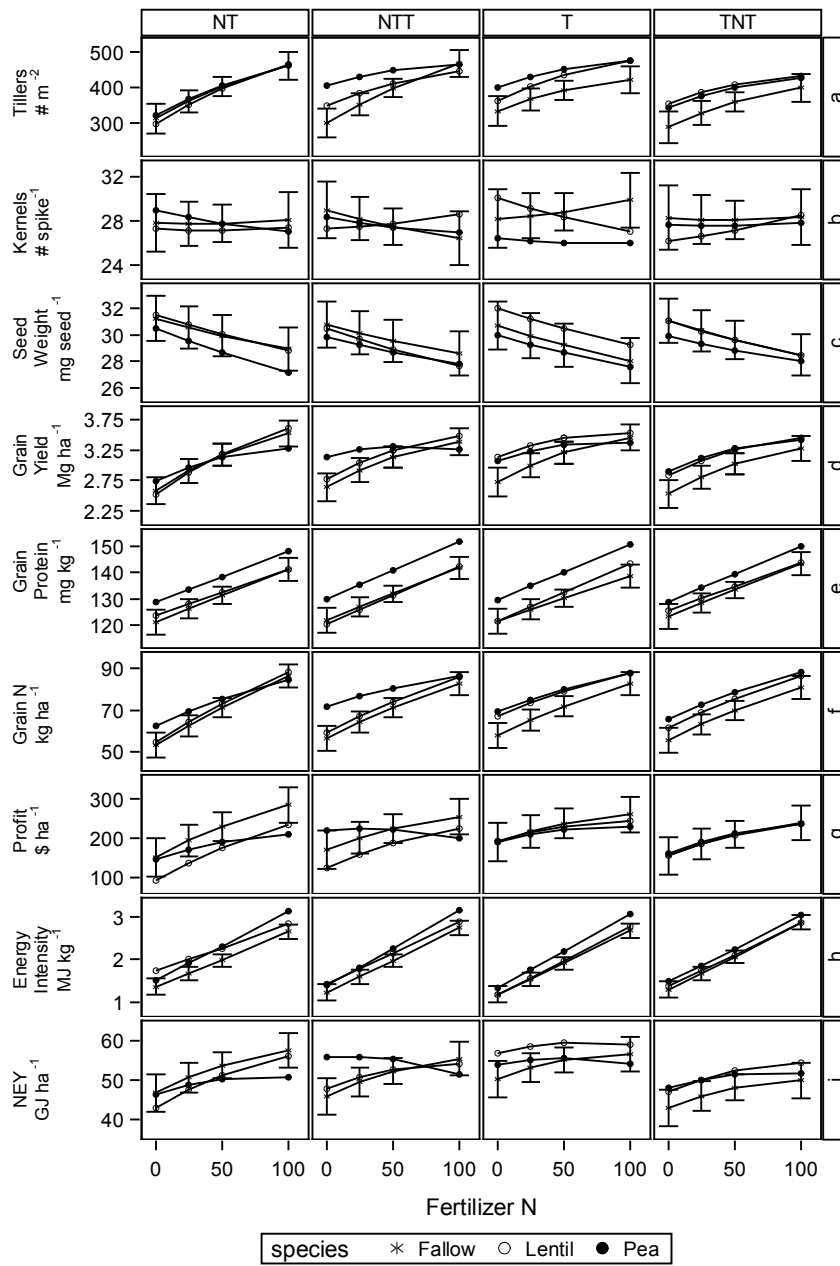


Figure 4.1 Species (S) x Nitrogen (N) interactions at levels of tillage for wheat yield components, economic, and energetic metrics for Pea (SP), and Lentil (SL) green manure and Fallow (F) control treatments. Error bars are shown on the F treatments only and indicate magnitude of a significant ( $\alpha=0.05$ ) difference between Fallow and the Pea LGM treatment at the same level of T and N (e.g. 1.96 X SED pea-fallow).

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5. EFFECT OF GROWTH TIMING OF ANNUAL LEGUME GREEN MANURE COVER CROPS  
ON SOIL WATER USE, BIOMASS PRODUCTION, AND SUBSEQUENT WHEAT  
PRODUCTION.

Introduction

Legume green manure (LGM) cover crops have been proposed as alternatives to summerfallow in the remnant traditional fallow-wheat (*Triticum aestivum* L.) production system of the semi-arid northern Great Plains. No-till management of fallow cropland is dominant in this region (Watts et al., 2009), and has addressed some of the sustainability concerns of tilled fallow management (Liebig et al, 2004). In particular, NT management has improved soil water storage efficiency (Peterson et al., 1996), enabling cropping system intensification and diversification (Cochran et al., 2006). Careful management of soil water storage has long been recognized as a critical element of successful LGM cover cropping in these areas (Army and Hide, 1959). In areas too dry for continuous cropping, LGM may have promise as fallow replacement, especially with NT management contributing to the delicate balance between LGM growth and water use. Early planting and early termination of LGM have been shown to be helpful strategies in this regard (Biederbeck and Bouman, 1994; Aase et al., 1996, Zentner et al., 2004; Allen et al. 2011; Miller et al., 2011). Spring wheat also performs better with earlier planting (Subedi et al., 2007), however, and farmers may be hesitant to sacrifice

cash crop yield to plant cover crops first. Research into the effect of optimal growth period by annual LGM cover crops in this region is therefore needed.

Winter annual legumes have been recognized as potentially superior to spring-planted cultivars for use as LGM due to their capacity to produce more biomass, while reaching key growth stages (e.g. flowering) 14 – 20 d earlier (Auld et al., 1982), in an ideal growth environment at Moscow, ID. Common winter cultivars of pea (*Pisum sativum* L.) and lentil (*Lens culinaris* Medik.) have smaller seed than spring cultivars resulting in a smaller quantity of seed and lower seeding cost to achieve a given plant density (Slinkard and Murray, 1979). Fall seeding also provides logistical flexibility, which may be an important factor for farmer adoption. In central Montana, Miller et al. (2011) found winter pea capable of producing equivalent biomass to spring pea while using less soil water in an organic system. The potential advantages of earlier LGM growth are multi-faceted, involving potential for greater N fixation, less water use, and potentially more time and better conditions for decomposition of the residue. Research into planting date and management of spring legumes indicate that growth earlier in the season may result in legumes fixing a larger proportion of total assimilated N (van Kessel and Hartley, 2000; Horn et al., 1996). Soil water potential can be a limiting factor in soil microbial processes (Cassman and Munns, 1980), so earlier-terminated LGM residue may also have more opportunity to decompose and promote soil organic matter mineralization (Wagger, 1989).

Early spring planting should provide some of the same early-growth advantages as winter pea, relative to later spring planting, but with the potential advantage of an opportunity for weed control in the spring before planting. Further delay in planting should provide even more opportunity for pre-emergence weed control, but may compromise water use efficiency. Planting LGM cover crops in early summer has been promoted by the Natural Resources Conservation Service (NRCS) for soil water uptake in wet years to prevent saline seep formation (NRCS 2011).

The objectives of this project were to assess the effect of growth timing, determined by planting and termination timing, of NT pea and lentil green manure cover crops on LGM biomass production, water use, subsequent soil water conservation, and soil N cycling as ultimately integrated into yield and quality of spring wheat grown the following year.

## Materials and Methods

### Site Description

Experiments were conducted between 2008 and 2011 on a farm 6 km west of the community of Amsterdam-Churchill in Gallatin County, Montana (45° 45' N 111° 24' W; 1,433 m above sea level). Three separate 2-yr crop sequences studies were conducted within 1.5 km of one-another on Brocko (coarse-silty, mixed superactive, frigid Aridic Calciustepts) and Amsterdam (fine-silty, mixed, superactive, frigid Typic Haplustolls) soils. These loess-derived soils are very deep, well drained, and free of

rocks. In the top 15 cm, soil pH ranged from 6.6 to 8.2 and soil organic matter averaged 24 g kg<sup>-1</sup>. Previous studies at this location have found cereal grain yield to be responsive to N input (Miller et al., 2006). The sites had been used for commercial production of cereal grains in a summerfallow – cereal rotation with minimum tillage for at least 3 yr prior to the initiation of research studies.

Mean annual precipitation (1981-2010) at the nearest meteorological station at Gallatin Field Airport, 19 km away, was 356 mm. Notably, 1/3 of the annual precipitation normally falls during the months of May and June, but terminal summer drought in July and August is typical. Precipitation, measured on site, and monthly mean temperatures from the Gallatin Field Airport meteorological station are shown in Table 5.1.

### Crop Management

Legume green manures were grown in 2008, 2009, and 2010 in standing stubble of barley (*Hordeum vulgare* L) or wheat. Planned legume green manure treatments consisted of a factorial combination of planting time, termination time, and LGM species. Targeted planting times were *fall* (Sept 15), *spring* (Mar 21), and *summer* (June 21). Termination times were based on pea phenology: *flower*, when 50% of the plants had one open flower, corresponding to BBCH 60-61 (Lancashire et al. 1991), and *pod*, when 50% of plants had one flat pod, or BBCH 70-71. Species were pea and lentil, with appropriate cultivars chosen for each planting time: winter pea (c.v. Melrose) and lentil (c.v. Toni) for the fall plantings, and spring pea (c.v. Arvika), and lentil (c.v. Richlea)

for the spring and summer plantings. Treatments were arranged in a RCBD design with four replicate blocks and a single summerfallow control plot in each block.

Legume green manure plots were planted using a no-till plot seeder with double-disk openers, with the exception of winter pea and lentil for 2010. 2010 winter pea and lentil were planted with a custom-fabricated plot seeder with single shoot hoe shank openers chosen specifically to create a furrow to catch snow, with the goal of improved winter survival. Plot size was 8 by 12 m with 9-m alleys between blocks. Row spacing was 0.30 m in 2008 and 2010 spring and summer planting, and 0.26 m in 2009 and for the 2010 winter planting. Seeding rate was calculated based on seed size and germination rate to provide 80 pure live seeds (PLS) m<sup>-2</sup> for pea and 120 PLS m<sup>-2</sup> for lentil. Pea and lentil seed were treated with 3.5 g a.i. kg seed<sup>-1</sup> mefenoxam {(R)-2-[(2,6-dimethylphenyl)-methoxyacetyl-amino]-propionic acid methyl ester}, and 2.5 g a.i. kg seed<sup>-1</sup> fludioxonil {[4-(2,2-difluoro-1,3-benzodioxol-4-yl)-1H-pyrrole-3-carbonitrile]}. At planting, commercial granular peat-based pulse inoculant containing *Rhizobium leguminosarum* (bv viceae) was banded with the seed at 5 kg ha<sup>-1</sup>. To eliminate the potential for non-N nutrient limitation to LGM growth, all LGM treatments were fertilized with 50 kg ha<sup>-1</sup> each of mono-ammonium phosphate (11-52-0) and potassium sulfate (0-0-50-17), banded with the seed, providing total N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O-S additions of 6-26-25-9 kg ha<sup>-1</sup>. All LGM plots were sprayed with 0.63 kg ha<sup>-1</sup> ae glyphosate (N-(phosphonomethyl) glycine) prior to emergence. The entire field site was sprayed as needed with Lambda-cyhalothrin 1[1 $\alpha$ (S\*),3 $\alpha$ (Z)]-( $\pm$ )-cyano-(3-phenoxyphenyl)methyl-3-

(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2dimethylcyclopropanecarboxylate, a pyrethroid insecticide, at 0.02 kg a.i. ha<sup>-1</sup> to control pea leaf weevil (*Sitona lineatus* L.) and grasshopper (primarily *Melanoplus* spp.). Dates and other details of crop management are summarized in Table 5.2.

In 2009, winter pea and lentil planted the previous fall failed to establish. Two of the winter-planted plots in each block were replanted at the spring planting time to spring pea and lentil and scheduled for an intermediate termination time 7 d after the flower termination. The remaining two winter-planted plots were replanted on Aug 21, in a late-summer seeding time.

Legume green manures were terminated by application of 0.84 kg ha<sup>-1</sup> glyphosate acid equivalent (ae), in the form of potassium salt, in 190 L ha<sup>-1</sup> water solution. Ammonium sulfate was added to all spray water at 34 g L<sup>-1</sup> to counteract potential effects of water hardness on herbicide efficacy. Summer and late summer planted, pod termination treatments were not chemically terminated but allowed to grow until senescence due to frost or drought. All other LGM treatments were terminated at the dates shown in Table 5.2. Samples of aboveground biomass were collected 3 d after herbicide application from two locations in each plot, each consisting of 2 row-meters of LGM. Biomass samples were oven dried at 50° C for 4 d, weighed, then ground and analyzed for total N and C content in a combustion analyzer (LECO Corporation, St. Joseph, MO). After LGM termination, plots were sprayed with herbicide as needed to control weeds as shown in Table 5.2.

Soil samples were taken from fallow plots in the spring for site characterization, then from LGM and fallow plots at each LGM termination time, and from all plots later that fall, and the following spring before spring wheat planting. Soil cores were 30.3 mm in diameter and were extracted from a depth of 0.9 m using a truck-mounted hydraulic soil probe. At each sampling date, two or four cores were taken from each plot, split into 0.3-m depth increments, and composited in the field into plastic-lined paper bags. Soil samples were stored in coolers for transportation from the field to the laboratory. Soil samples were weighed, then the bags were opened and dried in an oven at 50° C for 4 d. After drying, the soil samples were weighed again to determine gravimetric water content and bulk density. Dry soil samples were crushed (Dynacrush Soil Crusher, Custom Laboratory Equipment, Orange City, FL) and passed through a 2-mm sieve. A subsample of crushed soil was treated with 1-M KCl to extract NO<sub>3</sub>-N (Bundy and Meisinger 1994), and the extract was analyzed with a flow injection analyzer (Lachat instruments Inc., Loveland CO). Soil bulk density was averaged by depth for each sampling date for conversion of NO<sub>3</sub>-N concentration by weight to soil N content in kg ha<sup>-1</sup>.

In Year-2, hard red spring wheat (HRSW) (c.v. Choteau) was planted in strip subplots across all Year-1 main plots at six N fertilizer application rates. Nitrogen fertilizer was supplied as urea, mid-row banded at seeding, at 0, 20, 40, 60, 80, and 100 kg N ha<sup>-1</sup>. Wheat was also fertilized with 56 kg ha<sup>-1</sup> each of mono-ammonium phosphate (11-52-0) and potassium sulfate (0-0-50-17), banded with the seed, providing

total N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O-S additions of 6-29-28-9 kg ha<sup>-1</sup>. Wheat seeding rate was calculated based on seed size and germination rate to achieve 250 pure live seeds m<sup>-2</sup>. Wheat seed was treated with 121 mg a.i kg seed<sup>-1</sup> difenoconazole {1-((2-(2-chloro-4-(4-chlorophenoxy)phenyl)-4-methyl-1,3-dioxolan-2-yl)methyl)-1H-1,2,4-triazole} and 9.7 mg a.i. kg seed<sup>-1</sup> mefenoxam {(R,S)-2-[(2,6-dimethylphenyl)-methoxyacetyl-amino]-propionic acid methyl ester}, both fungicides, in 2009, and additionally with 101 mg a.i. kg seed<sup>-1</sup> thiamethoxam {3-[(2-Chloro-1,3-thiazol-5-yl)methyl]-5-methyl-N-nitro-1,3,5-oxadiazinan-4-imine}, a systemic neonicotinoid insecticide, in 2010 and 2011 to provide cutworm control. All plots were sprayed with glyphosate prior to wheat emergence, and post-emergence herbicide and insecticide as shown in Table 5.2.

Biomass samples of 1-meter-row were harvested after anthesis (Zadoks 70; Zadoks et al. 1974) to determine plant N uptake, and the number of wheat tillers with heads with developed kernels was counted at that time. Edge rows and ends were mowed from each subplot to remove edge effects, resulting in subplots of approximately 1.3 by 6 m, and wheat grain was harvested with a plot combine. Grain samples were passed through a screen, and cleaned with forced air to remove debris. Clean grain samples were then weighed, and grain density was determined using a standard grain density cup and conical filling hopper. A subsample of grain was placed in a seed counting machine and 1000 kernels were weighed to determine average kernel weight. Grain protein and moisture content was analyzed using near infrared reflectance (NIR) with the standard calibration for HRSW using an Infratec model 1241

grain analyzer (FOSS, Denmark). The grain moisture content was used to adjust yield, and seed weight data to 12% moisture content. Grain N content was calculated from NIR protein values converted to dry weight basis using a conversion factor of 5.7 as the ratio of protein to N (Jones, 1941). Total grain N was then calculated using grain yield expressed as a dry weight. Number of kernels per spike was calculated based on moisture-corrected sub-plot yield, tiller count, and average harvested seed weight.

### Statistical Analysis

Statistical analysis was performed using SAS 9.3 (Statistical Analysis Systems, Cary, NC). For measurements taken at the level of Year-1 main plots (e.g. LGM biomass, soil measurements), PROC MIXED was used with REML estimation to fit mixed models with block as a random effect and GM as a fixed effect. Soil water and N values were transformed to marginal values by subtracting the observed value of the fallow plot in each block from all other plots in that block. Years were initially analyzed separately due to different treatments among years. Additional analysis was performed with year included in the model as a fixed effect, with block nested within year, including only those treatments which were present all years (spring & summer planting, flower and pod termination). Post-hoc multiple comparison tests were made using Fishers's protected Least Significant Differences (LSD) computed from the appropriate standard errors of the differences.

For measurements taken at the level of Year-2 sub plots (e.g. wheat yield components and quality), the PROC MIXED procedure was used with REML estimation to fit mixed models with *block*, *block\*nrate*, and *block\*LGM* as random effects and block nested within *year* as recommended for a split block (a.k.a strip-split plot) design by Littell et al. (2006). Nitrogen fertilizer level (*nrate*) was modeled directly as a regression variable, and as a class variable for inclusion in the interaction with the block random effect. A quadratic term was included for *nrate* and interactions between fixed effects and *nrate* where those effects were significant, following Ch.4 of Littell et al. (2006). Although spatial autocorrelation was suggested by examination of residuals from 2009 and 2010, the spatial covariance methods used in Chapter 4 of this dissertation could not be made to converge and are not reported.

## Results and Discussion

### Legume Green Manure Growth and Water Use

Biomass production and N uptake differed among LGM species, planting times, termination times, and years (Table 5.3). In 2008, winter pea and lentil biomass did not differ from the spring-planted pea and lentil respectively at the flower termination time, consistent with Miller et al. 2011. By the 2008 pod termination times, however, both spring pea and spring lentil had accumulated more biomass than their winter counterparts, despite a 3 d longer duration between flower and pod termination for winter than for spring types. This was in sharp contrast to the pattern observed by

Miller et al. (2011), at Big Sandy, MT, where winter pea produced more biomass than spring pea by the pod stage. Chen et al. (2006) also found inconsistent but generally lower yields, and inconsistent survival of winter pea and lentil at this location.

In 2010, winter survival of both pea and lentil was initially adequate, but the plants grew poorly, a situation later determined to likely have been caused by residual activity of the herbicide ingredient pyrosulfotole (5-hydroxy-1,3-dimethyl-1H-pyrazol-4-yl)[2-(methylsulfonyl)-4-(trifluoromethyl)phenyl]methanone) used on the previous year wheat crop. Recurring visual evidence of moderate residual herbicide injury was also noted in the 2010 spring and summer LGM treatments. This consisted of yellowing of LGM plant tissues in stripes across the field site at 16-m intervals, consistent with the overlap of the cooperating farmer's sprayer. Biomass and soil sampling was done outside of these most affected stripes.

While winter pea and lentil hold promise as LGM, winter survival is not reliable in areas where dry fall conditions delay germination and prolonged cool wet springs favor development of disease over plant growth. Further management research and variety development work for winter pulses is therefore warranted to increase the robustness of this brittle system.

Summer-planted pea and lentil emerged rapidly, but were severely impacted by herbivory by grasshoppers, primarily *Melanoplus sanguinipes* Fabricius and *M. bivittatus* Say. Both of these species of grasshopper are polyphagous, eating a wide variety of monocot and dicot plants, including legumes (MacFarlane and Thorsteinson, 1980).

These grasshoppers are migratory, and are attracted to odors associated with actively growing plants (Hopkins and Young 2011). Feeding rates are dependent upon body temperature, and they choose resting habitat structure and location to actively manage radiative and convective heat transfer to maximize time spent feeding (Joern, 1982). These behaviors were manifest in a visually-apparent pattern of feeding where the most severe feeding damage occurred on the edges of summer-planted plots adjacent to already-terminated spring or winter pea plots, indicating that grasshoppers were using the habitat structure of the dead pea residue for a resting area when not feeding on adjacent summer-planted LGM biomass. The biomass yields reported for summer-planted LGM in Table 5.3 do not reflect total biomass production, and it should be noted that herbivory was both locally severe and highly variable within and among plots.

#### Soil Water

Soil water measurements for the 0-90 cm depth interval, at LGM termination, fall, and the following spring are shown in Table 5.4. Soil water is reported as a marginal value relative to the summerfallow control plot in each block. Winter pea and lentil had satisfactory growth only in 2008, and in that year there was an interaction between growth season and termination timing for both pea and lentil effect on marginal soil water. Winter pea and lentil used less water than spring pea and lentil only at the early (flower) termination date. When terminated at pod, winter pea and lentil used as much

soil water as spring pea and lentil. With only 1 year of data, however, the scope of inference of this observation is limited.

Summer pea and lentil grew well all three years, up to the onset of grasshopper herbivory, so comparison of soil water use between these planting dates can be made using the results shown in Table 5.5 modeling year as a fixed effect. Here, the season\*termination interaction was not significant, and summer-planted LGM were found to use 44% more soil water than spring planted as of the fall soil sampling, with the difference persisting to the following spring (Table 5.5). There were species\*termination, species\*termination\*year, and season\*species\*termination, interactions (Table 5.5). Interpretation of multiple interactions is challenging. However, one driver of that effect is apparent in 2008 and 2009, where summer lentil used far less water than summer pea when terminated at flower, but used as much water as pea when left to grow until drought senescence (Table 5.4). Soil water use by LGM was offset in 2010 by August rainfall nearly twice the long term average (Table 5.1).

The intermediate termination timing used only on spring pea and lentil in 2009 resulted in soil water use similar to pod termination, further emphasizing the importance of prompt early termination where soil water conservation is a goal of LGM management. Overall, lentil used less water than pea and early planting and termination were confirmed to be important for managing soil water use by LGM.

### Soil Nitrate-N

Soil nitrate-N measurements are shown in Table 5.4 and Table 5.5. There was no difference in soil nitrate-N at LGM termination between fallow and LGM treatments in 2008 or 2009. By the fall soil sampling time, however, there were large but inconsistent differences in soil nitrate-N among treatments and plots that are best explained by movement of N by grasshoppers from the growing summer-planted LGM plots into some adjacent plots. In both 2008 and 2009, fall soil nitrate N was reduced by 17 to 44 kg N ha<sup>-1</sup> in the summer planted LGM plots relative to fallow, and in 2008 and 2010 there were accumulations of soil nitrate N in spring and winter LGM treatments (Table 5.4). The accumulations of soil nitrate N in spring pea LGM plots terminated at flower are noteworthy because no such accumulation was noted in plots with identical treatment in the adjacent study reported in Ch. 4 of this dissertation (e.g. see Table 4.5). There was also far more within-treatment variability in soil nitrate N in the present study than in the adjacent study that had some of the same spring-planted treatments but did not include summer-planted LGM treatments. In Aug, 2008, 3 d after the first of two insecticide applications over the entire site targeting grasshoppers, an accumulation of grasshopper bodies was noted in dead spring-planted LGM and fallow plots adjacent to still-growing summer-planted LGM plots. Grasshoppers were collected from 1m<sup>2</sup> areas from selected plots, dried and weighed, and a single sample of grasshopper bodies was analyzed for N content. This was not a structured sampling designed to elucidate treatment effects, but rather an unplanned exploratory investigation of the magnitude

of the most extreme effects. Grasshopper body biomass in individual sampling areas ranged from 40 to 150 kg ha<sup>-1</sup>, with N content of 11%. While this quantity of N does not fully explain the quantity of N found in soil tests, it does prompt consideration of the other means by which grasshoppers may have impacted N cycling in this study. It has been suggested that the largest impact of grasshoppers on grassland ecosystem nutrient cycling is increased root respiration and root exudation of grazed plants (Dyer and Bokhari, 1976). Grasshopper frass has also been noted as an important element of the effect of grasshoppers on nutrient cycling in grasslands (Belovsky, 1999; Tanaka and Kasayu, 2011).

#### Wheat Yield and Quality

There were effects of LGM on wheat yield in 2009 and 2010, and LGM\*N interactions in 2009 and 2011, and effects of LGM on grain protein in all three years (Table 5.5). Overall, grain yield responses in this study were not as dramatic as those in Chapter 4 of this dissertation where tillage accelerated N cycling in some treatments. Attempts to account for spatial autocorrelation in the present study were not successful. Interpretation of the effects of NT LGM species and growth timing in this study can be explained by examination of the main effects at the intermediate N fertilizer level of 50 kg N ha<sup>-1</sup> shown in Table 5.7. In 2009, the only LGM treatment to differ from fallow in terms of subsequent wheat yield was winter pea terminated at pod, which resulted in reduced wheat yield. This LGM treatment had a unique combination

of large soil water depletion and small soil N increase relative to fallow (Table 5.4).

While several LGM treatments resulted in increased wheat grain protein, spring pea terminated at flower was the only LGM treatment to result in increased grain N (Table 5.7).

In 2010, wheat grain yield was reduced by spring pea LGM at both intermediate and pod terminations and summer pea pod LGM relative to fallow (Table 5.7). Spring pea terminated at flower did not reduce subsequent wheat grain yield, but did result in increased grain protein. No LGM treatment resulted in increased grain N in 2010, and while both summer-planted pea and lentil resulted in reduced grain N when allowed to grow until natural senescence (pod termination treatment), it cannot be determined how much of this effect was due to soil water depletion vs. the effect of grasshoppers on N cycling.

In 2011, where moderate drought affect wheat during grain formation, seven of the 12 LGM treatments resulted in reduced wheat yield, with no pattern of LGM species or growth timing effect (Table 5.7). While several LGM treatments did increase grain protein, none had a positive effect on total grain N due to decreases in grain yield.

### Conclusions

Research in Ch. 4 of this dissertation found that with early spring planting and early (1<sup>st</sup> flower) termination, both pea and lentil LGM resulted in increased wheat grain N uptake, with some amount of tillage generally necessary to accelerate N cycling from

LGM sufficiently to affect wheat grain yield. In this study, which shared 2 of 3 location-years, the lack of tillage likely accounts for the lack of yield response to LGM for those shared timing treatments (spring planted, 1<sup>st</sup> flower termination). Later planting and termination times generally resulted in increased soil water use, often resulting in decreased wheat yield. Drawing conclusions from the soil N, and hence wheat yield and protein responses to LGM growth timing in this study was severely compromised by the effect of grasshoppers on N cycling across treatment boundaries.

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## Tables and Figures

Table 5.1 Growing season monthly precipitation and mean monthly temperatures, 2008-2011, Amsterdam MT.

	Monthly Precipitation†					Mean Monthly Temperature ††				
	2008	2009	2010	2011	LTA	2008	2009	2010	2011	LTA
	mm					°C				
May	65	25	58	49	63	10.9	12.7	9.6	8.9	12
June	56	63	86	82	63	15.3	15.4	15.7	13.9	16.4
July	23	56	18	22	28	20.9	19.9	19.5	20.0	20.7
Aug.	2	25	57	12	27	19.9	19.5	18.9	19.4	20.1

† Growing season precipitation was measured on site with a tipping bucket rain gauge 2008-2010, and reported from Gallatin field airport for 2011.

†† Monthly mean temperatures, and long term averages (1981-2010) of temperatures and precipitation are from the nearest weather station (Gallatin Field Airport, Belgrade, MT).

Table 5.2 Dates and details of field operations

Operation	LGM	2008-2009	2009-2010	2010-2011
LGM Seeding	Winter	13 Sept, 2007	17 Sept, 2008	16 Sept, 2009
LGM Seeding	Spring	4 Apr, 2008	13 Apr, 2009	24 Mar, 2010
LGM Pre-emergence Herbicide	Spring	11 Apr, 2008†	19 Apr, 2009†	2 Apr, 2010†
LGM herbicide/insecticide 1 #	Winter	na	15 May, 2009§‡	18, May, 2010‡§
Fallow Herbicide/summer	Fallow/summer	20 May, 2008†	22 May, 2009†	18, May, 2010†
LGM herbicide & insecticide #	Spring	na	11 June, 2009§‡	6 June, 2010‡
LGM insecticide #	Winter	na	11 June, 2009§	na
LGM termination	Winter Flower	19 June, 2008¶	na	24 June, 2010¶
LGM Seeding	Summer	20 June, 2008	21 June, 2009	21 June 2010
LGM Pre-emergence herbicide	Summer	21 June, 2008†	na	24 June 2010†
LGM termination	Spring Flower	29 June, 2008¶	28 June, 2009¶	28 June, 2010¶
LGM termination	Spring Int.	na	5 July, 2009¶	na
LGM termination	Winter Pod	7 July, 2008¶	na	11 July, 2010¶
Fallow Herbicide	Fallow	14 July, 2008†	na	29 July, 2010†
LGM termination	Spring Pod	14, July, 2008¶	14 July, 2009¶	11 July, 2010¶
LGM Insecticide 3 ††	All plots	5 Aug, 2008§	10 Aug, 2009§	na
LGM termination	Summer Flower	6 Aug, 2008¶	10 Aug, 2009¶	9 Aug, 2010¶
LGM Insecticide 4 ††	All plots	22 Aug, 2008§	na	na
LGM Seeding	Late Summer	na	na	na
LGM termination	Summer Pod	na	na	25 Aug, 2010¶
Fall Weed Control	All plots	na	5 Nov, 2009†	29 Sept, 2010†
Spring Wheat Seeding	All plots	20 Apr, 2009	10 Apr, 2010	3 May, 2011
Pre-emergence herbicide	All plots	2 May, 2009†	16 Apr, 2010†	2 May, 2011†
Post-emergence herbicide	All plots	21 May, 2009‡‡,§	27 May, 2010§§	25 May, 2011‡‡
Combine Harvest Wheat	All plots	27 Aug, 2009	7 Sep, 2010	25 Aug, 2011

† Glyphosate N-(phosphonomethyl) glycine 0.42 kg ha<sup>-1</sup> ae as Potassium salt.

‡ Quiazalofop-P-ethyl {ethyl(R)-2-[4-(6-chloroquinoxalin-2-yloxy)-phenoxy]propionate} at 0.07 kg ha<sup>-1</sup> a.i.

§ Lambda-cyhalothrin 1 [1 □ (S\*), 3 □ (Z)]-(±)-cyano-(3-phenoxyphenyl)methyl-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate at 0.02 kg ha<sup>-1</sup> a.i.

¶ Glyphosate N-(phosphonomethyl) glycine 0.84 kg ha<sup>-1</sup> ae as Potassium salt.

# insecticide application targeting pea leaf weevil

†† insecticide application targeting grasshoppers

‡‡ 2,4-D (2,4-Dichlorophenoxyacetic acid) at 0.33 kg a.i. ha<sup>-1</sup>

§§ fluroxypyr: ((4-amino-3,5-dichloro-6-fluoro-2-pyridinyl)oxy)acetic acid, 1-methylheptyl ester at 0.099 kg ha<sup>-1</sup> ae

florasulam: N-(2,6-difluorophenyl)-8-fluoro-5-methoxy (1,2,4)triazolo[1,5-c]pyrimidine-2-sulfonamide 0.003 kg ha<sup>-1</sup> a.i.

pyroxusulam: N-(5,7-dimethoxy[1,2,4]triazolo[1,5-a]pyrimidin-2-yl)-2-methoxy-4-(trifluoromethyl)-3-pyridinesulfonamide at 0.015 kg ha<sup>-1</sup> a.i.

Table 5.3 Legume green manure shoot biomass ( $\text{Mg ha}^{-1}$ ) and biomass N ( $\text{kg N ha}^{-1}$ ).

Planting	Termination	Biomass		N	
		Pea ----- Mg ha <sup>-1</sup> -----	Lentil ----- Mg ha <sup>-1</sup> -----	Pea ----- --kg N ha <sup>-1</sup> -----	Lentil ----- --kg N ha <sup>-1</sup> -----
<b>2008</b>					
Winter	Flower	2.94	0.81	95	26
	Pod	3.26	2.38	72	59
Spring	Flower	2.75	1.04	83	36
	Pod	3.84	2.85	86	71
Summer†	Flower	1.44	0.66	49	22
	Pod	1.09	1.03	22	29
	SED (33df)	0.27		7	
<b>2009</b>					
Spring	Flower	2.97	1.55	105	50
	Intermediate	3.74	2.47	98	73
	Pod	4.92	3.71	107	104
Summer†	Flower	2.81	1.51	75	42
	Pod	3.01	4.02	79	107
Late Summer	Pod	na	na	na	na
	SED (27df)	0.35		13	
<b>2010</b>					
Winter‡	Flower	1.02	0.63	na	na
	Pod	2.41	0.56	na	na
Spring	Flower	3.24	1.23	116	45
	Pod	5.04	3.18	147	98
Summer†	Flower	1.84	1.09	47	30
	Pod	2.30	1.66	44	38
	SED (33df)	0.24		6	

†Summer LGM biomass production figures not representative of total growth due to grasshopper herbivory.

‡2010 winter pea and lentil experience severe herbicide injury

Table 5.4 Mean values by year of soil water and nitrate N, 0-90 cm depth, for fallow plots, and marginal values (i.e. difference from fallow) for all other treatments. F, I, and P indicate Flower, Intermediate, and Pod termination times.

Season	Species	Term.	Soil Water			Soil Nitrate		
			Termination	Fall	Next Spring	Termination	Fall	Next Spring
			mm			kg ha <sup>-1</sup> N		
<b>2008</b>								
--	<b>Fallow</b>	--	<b>202</b>	<b>192</b>	<b>264</b>	<b>58</b>	<b>80</b>	<b>90</b>
Winter	Lentil	F	-25*	-12	-9	-6	10	12
Winter	Lentil	P	-91***	-67***	8	-3	-9	-16
Winter	Pea	F	-46***	-46***	-6	-26	52**	44
Winter	Pea	P	-110***	-80***	-47**	4	5	12
Spring	Lentil	F	-44***	-24*	-12	-9	3	16
Spring	Lentil	P	-88***	-66***	-23	-6	-17	14
Spring	Pea	F	-74***	-64***	-34*	4	36*	38
Spring	Pea	P	-102***	-79***	-27	-11	35*	25
Summer	Lentil	F	-48***	-19	-18	-21	-10	2
Summer	Lentil	P	--	-80***	-49**	na	-44**	-1
Summer	Pea	F	-95***	-84***	-28	-31	-21	17
Summer	Pea	P	--	-87***	-23	na	-43	20
		SED	11.2	10.3	16.8	NS (P=0.48)	15.05	NS (P=0.12)
<b>2009</b>								
--	<b>Fallow</b>	--	<b>215</b>	<b>217</b>	<b>224</b>	<b>28</b>	<b>68</b>	<b>76</b>
Spring	Lentil	F	-49***	-24*	-19	-14	-2	-6
Spring	Lentil	I	-58***	-43***	-35**	-8	-7	-6
Spring	Lentil	P	-88***	-51***	-46**	-17	-23**	-20*
Spring	Pea	F	-70***	-40***	-31*	-17	17	26**
Spring	Pea	I	-100***	-75***	-70***	-15.2	-9	-8
Spring	Pea	P	-97***	-71***	-70***	-15.7	-13	-7
Summer	Lentil	F	--	-45***	-17	--	-17	-10
Summer	Lentil	P	--	-92***	-90***	--	-43***	-45***
Summer	Pea	F	--	-71***	-56***	--	-19*	-22*
Summer	Pea	P	--	-85***	-70***	--	-35***	-40***
Late-Sum	Lentil	P	--	-10	-7	--	0	9
Late-Sum	Pea	F	--	-21*	-23	--	-13	-5
		SED	9.1	9.8	13.1	NS	8.9	9.5
<b>2010</b>								
	<b>Fallow</b>			<b>161</b>	<b>205</b>		<b>34</b>	<b>59</b>
Winter	Lentil	F	--	-9	1.3	--	4	0
Winter	Lentil	P	--	-3	-5.1	--	5	-1
Winter	Pea	F	--	-5	-5.2	--	16	26**
Winter	Pea	P	--	-30***	-13.6*	--	15	20*
Spring	Lentil	F	--	-2	4	--	12	2
Spring	Lentil	P	--	-30***	-10	--	12	31**
Spring	Pea	F	--	-8	2	--	47***	37***
Spring	Pea	P	--	-34***	-9	--	35***	45***
Summer	Lentil	F	--	-24***	-14*	--	2	-12
Summer	Lentil	P	--	-41***	-22**	--	-11	-16
Summer	Pea	F	--	-34***	-14*	--	9	-2
Summer	Pea	P	--	-42***	-17**	--	-8	-8
		SED		5.8	6.3	--	10.1	9.2

\*, \*\*, and \*\*\* indicate P-values of 0.05, .01, and 0.001 respectively for differences from fallow.

Table 5.5 Mixed model values of the *F*-ratio, *P*-values, and least squares means for marginal soil water and nitrate N for model with year as fixed effect only for treatments present in all years.

Effect	Soil Water		Soil N	
	Fall	Spring	Fall	Spring
	F-Ratio		F-Ratio	
Year (Y)	40.3**	6.01**	6.19*	25.03**
Season	40.6**	10.82**	107.83**	66.89**
Season*Y	3.4*	0.84	3.91*	4.7*
Species	37.5**	1.98	22.36**	19.76**
Species*Y	7.9**	1.47	0.99	0.55
Season*Species	0.03	2.19	19.93**	4.42*
Season*Species*Y	1.1	0.51	2.73*	1.54
Termination (T)	93.36**	24.66**	32.94**	5.39*
T*Y	1.46	7.37**	1.43	8.53**
Season*T	0.35	0.4	1.28	1.03
Season*T*Y	0.91	0.7	1.03	2.1
Species*T	14.83**	5.9	0.22	0.62
Species*T*Y	4.36**	0.95	1.17	0.24
Season*Species*T	5.21**	4.54**	0.32	3.38*
Season*Species*T*Y	0.72	1.96	0.39	0.21

Effect	Season	Species	Termination	Year	LS Means			
					-----mm-----		-----kg ha <sup>-1</sup> N-----	
Season	spring				-41	-24	12	16
Season	summer				-59	-36	-20	-9
Species		lentil			-41	-28	-12	-4
Species		pea			-58	-33	2	11
Termination			flower		-37	-21	4	7
Termination			pod		-63	-39	-13	0
SED (treatments)					2.3	5.5	3.5	5.9
year				2008	-62	-27	-8	16
year				2009	-60	-54	-18	-15
year				2010	-27	-10	12	10
SED (years)					3.1	8.9	7.9	9.8

\*, \*\*, and \*\*\* indicate *P*-values of 0.05, .01, and 0.001 respectively.

Table 5.6 Mixed model *F*-ratios for effect of LGM of Wheat yield components.

	Tillers # m <sup>-2</sup>	Kernels # spike <sup>-1</sup>	Seed Weight mg seed <sup>-1</sup>	yield Mg ha <sup>-1</sup>	protein mg kg <sup>-1</sup>	Grain N kg ha <sup>-1</sup>
			<b>2009</b>			
LGM	0.64	1.12	0.92	2.37*	5.55***	2.31*
N-Fert (N)	52.46***	0.59	49.26***	82.85***	1.5	18.9***
LGM*N	0.63	0.63	1.29	2.61**	0.9	1.99*
Nquadratic	20.59***	0.07	11.21**	24.52***	2.03	3.7
LGM*Nquad	0.87	0.59	1.25	2.14*	0.53	1.78
			<b>2010</b>			
LGM	1.67	1.22	3.5***	3.12**	2.48**	3.05**
N-Fert (N)	7.25*	1.38	20.98***	1.76	4.57*	4.19
LGM*N	1.42	1.55	1.88*	2.3**	3.93***	1.47
Nquadratic	0.01	2.11	3.45	0.18	9.95**	1.13
LGM*Nquad	1.72	1.53	2.14*	1.51	3.16***	1.52
			<b>2011</b>			
LGM	1.66	0.73	1.4	0.91	8.2***	2.76**
N-Fert (N)	30.81***	0.03	219.7***	7.17*	48.51***	16.23***
LGM*N	0.68	1.67	2.17*	1.46	1.1	1.14
Nquadratic	8.37**	1.36	47.16***	6.62*	1.5	6.18*

Table 5.7 Means of wheat yield components at N fertilizer level of 50 kg N ha<sup>-1</sup>.

LGM			tillers	kernels	seed weight	Yield	protein	grain N
planting	species	termination	# m <sup>-2</sup>	# spike <sup>-1</sup>	mg seed <sup>-1</sup>	Mg ha <sup>-1</sup>	mg kg <sup>-1</sup>	kg ha <sup>-1</sup>
	<b>Fallow</b>		<b>417</b>	<b>25.1</b>	<b>32.1</b>	<b>3.39</b>	<b>129</b>	<b>68</b>
Winter	Lentil	Flower	401	26.4	32.5	3.36	131	68
Winter	Lentil	Pod	385	25.7	33.9**	3.25	138**	69
Winter	Pea	Flower	395	27.6	32.2	3.42	136*	72
Winter	Pea	Pod	357*	25.8	32.2	2.93**	137**	62
Spring	Lentil	Flower	427	25.1	31.9	3.35	133	69
Spring	Lentil	Pod	436	23.4	31.8	3.19	135	67
Spring	Pea	Flower	427	27	32.1	3.57	142***	78**
Spring	Pea	Pod	408	24.8	31.5	3.17	139**	68
Summer	Lentil	Flower	400	27.8	32.5	3.52	130	71
Summer	Lentil	Pod	415	26.4	31.5	3.41	132	70
Summer	Pea	Pod	449	26	31.0*	3.47	137*	74
Summer	Pea	Pod	407	27.9	30.9*	3.45	135	72
		SED	26.6	2	0.53	0.14	2.7	3.6
					<b>2010</b>			
	<b>Fallow</b>		<b>478</b>	<b>26.4</b>	<b>31.8</b>	<b>3.83</b>	<b>116</b>	<b>69</b>
Spring	Lentil	Flower	505	24.8	31.4	3.79	113	66
Spring	Lentil	Int.	475	27.5	30.3	3.87	123	74
Spring	Lentil	Pod	473	25	30.4	3.53	120	66
Spring	Pea	Flower	547	24.9	28.0***	3.6	135***	75
Spring	Pea	Int.	549*	20.7**	28.5***	3.28*	129**	65
Spring	Pea	Pod	587**	19.4**	29.7*	3.34*	128**	66
Summer	Lentil	Flower	457	28.7	31.7	3.99	112	70
Summer	Lentil	Pod	434	25.8	30.8	3.30*	111	57*
Summer	Pea	Flower	533	23	27.8***	3.36*	127**	66
Summer	Pea	Pod	469	22.6	29.4**	3.12**	119	57*
Late Sum.	Lentil	Pod	459	28.6	31.3	3.98	115	71
Late Sum.	Pea	Pod	480	26.3	32.3	3.95	114	70
		SED	36	2.1	0.88	0.22	3.7	5
					<b>2011</b>			
	<b>Fallow</b>		<b>370</b>	<b>20</b>	<b>35.5</b>	<b>2.59</b>	<b>138</b>	<b>55</b>
Winter	Lentil	Flower	365	19.4	31.7**	2.24	137	47*
Winter	Lentil	Pod	370	17.6*	31.8**	2.05**	145	46*
Winter	Pea	Flower	392	19	32.4*	2.38	149**	55
Winter	Pea	Pod	384	19.1	32.5*	2.43	151**	56
Spring	Lentil	Flower	371	18.9	31.2***	2.18*	145	49
Spring	Lentil	Pod	377	18.7	30.0***	2.08*	147*	47*
Spring	Pea	Flower	419*	17.9	28.6***	2.13*	153***	50
Spring	Pea	Pod	394	18.8	31.3**	2.3	157***	56
Summer	Lentil	Flower	335	20.4	31.4**	2.13*	141	46*
Summer	Lentil	Pod	340	20.3	32.0**	2.20*	137	46*
Summer	Pea	Flower	379	18.8	30.9***	2.17*	138	46*
Summer	Pea	Pod	372	19.9	32.5*	2.39	137	51
		SED	20	1.2	1.21	0.19	4	4

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## 6. EPILOGUE

Personal Reflection

My introduction to sustainable agriculture came about 15 years ago with a vision seeded in my mind by Wendell Berry, Gene Logsdon (The Contrary Farmer), Wes Jackson, Jeff Poppen (aka The Barefoot Farmer), Lyn Miller (publisher of the Small Farmer's Journal), and a coffee-table book entitled Fatal Harvest: The Tragedy of Industrial Agriculture. After reading these books I left a career in manufacturing engineering to find that vision.

In northern California I found a vegetable CSA and market garden that generated, through intensive year-round production, gross revenues in excess of \$10,000 per acre, with perhaps the equivalent of one full-time employee equivalent of labor for each acre. One of my first tasks as an intern there was to remove and replace the plastic sheeting on a 30' x 100' hoop-house. On my second load to the dump in a rented dump truck I began to re-examine my commitment to washing, drying, and re-using plastic bags in my kitchen. I'd always questioned the energy tradeoffs of that practice anyhow; did it take more energy to heat the wash water than it did to make the bag? To maximize the utility of that rented dump truck, I put about 400 miles on it over the course of a weekend hauling manure from a goat dairy about 25 miles away. My first date with the woman who is now my wife and the mother of my children was in that dump truck loaded with manure.

I burned more fuel that weekend than I ever would have imagined such an idyllic little farm would require. Over the course of the next few years I came to be a paid employee and ultimately a manager of that farm, and taught courses there through Humboldt State University. I manually unloaded the purchased inputs including gasoline, diesel fuel, peat moss, vermiculite, manure, rock phosphate, cover crop seed etc., and came to wonder just how much that operation differed from 'industrial' farms in terms of the quantity of fossil fuel consumed *per unit of production*.

I am deeply indebted to my mentors at the Arcata Educational Farm, Patrick Oliver & Eddie Tanner, indirectly to their mentors at Live Power Community Farm in Covelo, CA, that served as our model of true sustainability at that time, and to Susan Ornelas, whose vision made our experiences possible. Many of the things I learned from that farm have been invaluable in subsequent farming, home gardening, and cropping systems research fieldwork. Many of life's most important skills and lessons can only be learned by doing, and I am grateful for the opportunities then, and in my doctoral research, to have been able to do so much field work and learn by observation from the outcome. Producing vegetables at that scale and level of intensity is truly an art form, and opportunities for such practice are rare. The tools would mostly be familiar to an experienced home gardener, but the approach is by necessity rather different. Many home gardeners consider theirs a leisure hobby, one that involves hard work for sure, but where one is free to give attention to individual plants, and a hobby for sure. I was

reminded of Aldo Leopold's thoughts on the 'efficiency' of hobby activities and decided to leave my food production activities to a part-time defiance of the contemporary.

"At first blush I am tempted to conclude that a satisfactory hobby must be in large degree useless, inefficient, laborious, or irrelevant...No hobby should either seek or need rational justification. To find reasons why it is useful lowers it at once to the ignominious category of any 'exercise.' A hobby is a defiance of the contemporary. "

— Aldo Leopold, *A Sand County Almanac*

Perhaps the most important lesson I learned at the Arcata Educational Farm was that a major difference between a hobby garden and a farm relates to the amount of time a farmer can realistically afford to spend on any one task, how to prioritize tasks, and the value of labor-saving technology. One day, over a lunch of locally-grown cool season vegetables, artisan bread, cheese, corn chips, hummus, and beer, I came to the realization that most of the substance of the meal came from agricultural production systems far away that I knew little about. I figured that the producers of the inexpensive commodity crops providing the bulk of the calories in that meal must strike an even more important balance between labor and mechanization, and I began to think about the energy efficiency of 'real' farms.

I decided I needed some education about where corn, wheat, barley, and dry edible legumes came from. After nearly a decade on the path, I believe I have arrived at the destination predicted by Mark Twain; Education, he said, is "the path from cocky ignorance to miserable uncertainty". My current philosophical approach to dealing with the misery of uncertainty is to accept that the world is more complex than any one

person can comprehend, Alexander Von Humboldt's attempt to do so and contemporary criticisms of specialization notwithstanding. This is a critical element, I believe, to approaching sustainability of contemporary agriculture. There is a great deal of public demand for simple answers to complex questions. I am further from having answers to those questions than ever, indeed I find myself answering questions with more questions, or with anecdotes that challenge popular assumptions. In this age where strongly worded opinions of any slant, on any topic, are only a finger-click away, I think thought-provoking questions are ultimately more important than answers.

I think this dissertation is of greater breadth than most, yet a part of me believes it might easily have been much broader. In particular, the potential contribution of animals and their manure to crop production in the northern Great Plains is completely ignored here, but is potentially very important. Although this topic is often raised in discussions of sustainable crop production, collaboration between crop and animal scientists is all too rare. In the course of this research I've tried stepping into the shoes of an agronomist, agroecologist, economist, entomologist, soil scientist, and weed scientist. I cannot fill all those roles, but I hope to maintain and improve my ability to communicate with the individuals who can.

#### A New Paradigm For Agriculture and Energy.

The past decade has been marked by the development of newly disruptive linkages between agriculture and fossil energy markets. Biofuel production mandates,

subsidies, and import restrictions in the U.S. and E.U. have reversed a century-long trend of falling real prices for agricultural commodities (Schmidhuber, 2006). As of 2010, seven operational commercial scale ethanol plants in Western Canada produce over 500 million L yr<sup>-1</sup> using wheat as a feedstock (CRFA, 2010), and over 30% of U.S. corn produced is devoted to ethanol production (Martin, 2011).

Since ~2006, increased volatility in energy- and agriculture-related commodity markets (i.e. fossil fuels, crops, fertilizer) have been speculatively (and maybe not entirely correctly) linked to biofuel production mandates (Mueller et al., 2011). This volatility, along with concern about the energy balance of biofuel production systems, has fueled the recent resurgence of interest in fossil energy use in agriculture, predicated largely on the notion that understanding energy relationships will provide insight into the economics of alternative cropping systems under possible scenarios of future increases in energy price without concomitant increases in crop commodity prices (Cruse et al. 2010).

Research by economists on the likelihood of such a scenario is rarely discussed, however, outside of economic circles. An exhaustive review on this topic is beyond the scope of this dissertation; and after trying, I have come to realize I am not qualified to provide such a review. In this field outside my own, I must rely on the conclusions of experts able to communicate in language I can understand. Econometric analyses spanning the decades since the 1940's have indicated changes in energy consumption associated first with mechanization, then with dieselization, but little price elasticity of

demand for direct energy or energy-intensive inputs to U.S. Farms (Lambert and Gong, 2010). My lay summary is that farmers will do what they have to do, the cost will be reflected in the price of their output, and the profitability will be reflected in the price of land. Indeed agricultural commodity prices have risen along side, or even faster than energy commodity prices in recent years, and land prices have risen as well. Baffes (2009) claimed that so long as energy prices remain elevated, non-energy commodity prices are likely to remain elevated as well. Beckman et al. (2011) came to the conclusion that biofuel mandates *strengthen* the linkages between energy and agricultural commodity markets and *reduce* susceptibility of agriculture to energy price volatility. Nazlioglu (2010) found a “persistent causality” between energy prices and crop commodity prices.

### Analyzing the Use of Energy in Agriculture

My introduction to the academic field of energy analysis of agriculture came from Piringer & Steinberg (2006), published in the *Journal of Industrial Ecology*, to which I subscribed at the time as a student member of the *International Society of Industrial Ecology*. The approach in that paper, describing wheat production at the national level in terms exactly analogous to life cycle analysis of industrial processes, was (and is) compellingly interesting. It seemed obvious to take this methodology to individual farms and cropping systems. What has often been missing from recent reports on energy use in agriculture, however, is an appreciation of where this type of analysis has taken us in

the past. Several of the architects of the methodologies currently employed ultimately came to the conclusion that the results do not mean what they first appear to, or must be considered in broader context. Maurice Green, whose estimates of the energy embodied in herbicide manufacture continue to underlie all current work in the field (Green, 1987), concluded in 1976 that:

“As long as any nation indulges in unrestrained private motoring, overheating, overcooling, and overilluminating of its buildings, unrestricted manufacture of a great deal of unnecessary junk, and preparation for war, that nation is getting its priorities dreadfully wrong if it tries to cut down on the comparatively small amount of energy which is used to produce essential food, while it continues to squander energy recklessly elsewhere... the most useful thing we can do with oil is, in fact, to *eat* it.”

Despite debate and warnings on the normative value of such research decades ago, as summarized in the introduction to this dissertation, recent analyses of agricultural use of energy have found a high public profile. I am troubled by the variety of controversial and conflicting “conclusions” being drawn from reviews of analyses lacking standardized methodology or assumptions. Lynch et al. (2011) concluded that “evidence strongly favours organic farming with respect to whole-farm energy use and energy efficiency”, while Wu (2011) (not in specific response to Lynch, but addressing the same topic) claimed “Some scientific papers flawed with wrong assumptions and consequently conveying wrong information... seriously threatens the progress towards the sustainability of agricultural systems.” and that “the higher the claimed efficacy of the proposed ‘system’ or ‘philosophy’, the lower the reliability of the claimant”. While I

am inclined to agree with the latter statement, I am deeply troubled by the implication. Are there really no more efficacious discoveries to be made? With regards to agricultural energy use, perhaps there are not. I have come to agree with Jones (1989), that the most useful pictures here are painted with a broad brush. It is too easy to become bogged down in details that are ultimately not important. The most important element of the big picture is that synthetic N fertilizer is essential for crop production at the level currently practiced (Smil, 2001) and is currently derived from natural gas. I am not convinced that the energy content of natural gas is any better an indicator of its true cost to society than its price. That is not to say that market price reflects the true cost either, but I have come to see no special advantage of energy value in putting the true social cost in practical perspective or addressing the externalities. The energy cost of N fertilizer seems to be most agronomically relevant for consideration of input substitution opportunities also using fossil energy at least remotely substitutable for natural gas (e.g. cover crop management).

#### Green Manure Cover Crops

I continue to be interested in cover cropping, especially where there is opportunity to implement the practice in the fallow period of a wide-spread conventional cropping system, like the summerfallow practiced in the northern Great Plains, or the shoulder seasons of corn-soy-small grain rotations. There remain

opportunities and needs for agronomic research for cover crops that fix N, as well as prevent the loss of N to the external environment.

Despite finding limited immediate short-term benefits to no-till green manure cover crops in the research presented here, I think further research is warranted. While long term agronomic research will be critical, an even more fundamental question that is unanswered is “what happens to the N?” Choice of LGM species, termination timing, and herbicide may all influence immediate pathways of N loss in herbicide-terminated cover crops, and these areas are insufficiently researched. There is also need for improved economic methodology for basic valuation of long-term effects on soil nutrient cycling.

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