PHOSPHORUS FERTILITY IN NORTHERN GREAT PLAINS DRYLAND ORGANIC CROPPING SYSTEMS

by

Terry Lynn Rick

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

of

Master of Science

in

Land Resources and Environmental Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

January, 2009

APPROVAL

of a thesis submitted by

Terry Lynn Rick

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style, and consistency, and is ready for submission to the Division of Graduate Education.

Dr. Clain A. Jones
(Chair)

Approved for the Department of Land Resources and Environmental Sciences

Dr. Bruce Maxwell

Approved for the Division of Graduate Education

Dr. Carl A. Fox

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Terry Lynn Rick

January, 2009

ACKNOWLEDGEMENTS

First, I would like to extend my utmost gratitude to my committee chair Dr. Clain Jones for offering me this special opportunity and for his guidance, extraordinary patience, and encouragement throughout this challenging endeavor. I would also like to express my appreciation to my co-chair, Dr. Richard Engel, for asking tough questions and motivating me to challenge myself. I would also like to thank my committee member, Dr. Perry Miller, for his wisdom and technical expertise throughout this project. I would also like to thank Dr. Cliff Montagne for igniting my interest in soil science and graduate school. I am eternally indebted to Rosie Wallander for her tireless support, both in the lab and the field. Many thanks go to Jeff Holmes for all his tilling and toiling in the field, but especially for his great fishing stories. A special note of appreciation is due to Bob Quinn, Thad Willis, and the many generous farmers who offered their time and their farms in the pursuit of research. This project was completed only by the hard work of many dedicated assistants, including Derek, Sharon, Evette, Corinne, Malcolm, Sara, Matt, and Elizabeth, as well as, countless others. I'd also like to thank my family and my friends for their enduring support. Lastly, I would like to thank my husband and best friend, Kevin, for his forbearance, unwavering support and friendship throughout our many years together. He and our two beloved fuzzy friends, Woofie and Banjo, sustained me in the long hours of fret and joy.

TABLE OF CONTENTS

1. INTRODUCTION 1

Background 1
Soil Fertility in Organic Cropping Systems in the Northern Great Plains 4
Project Objectives 8
References Cited 9

2. EFFECT OF GREEN MANURE AND ROCK PHOSPHATE ON PHOSPHORUS AVAILABILITY IN THE NORTHERN GREAT PLAINS 14

Introduction 14
Methods and Materials 18
Field Site Description 18
Rock Phosphate Characterization 19
Experimental Design 20
Crop Management 20
Soil Analyses and Phosphorus Fractionation 21
Crop Data Collection and Analyses 22
Statistical Analyses 24
Results and Discussion 24
Pre-experimental Soil Analyses 24
Green Manure Phase 25
Winter Wheat Phase 28
Sequential Phosphorus Fractionation 31
Conclusions 32
References Cited 35

3. PHOSPHORUS AND BIOMASS RESPONSES OF SPRING WHEAT GROWN IN A GREENHOUSE TO GREEN MANURES AND ORGANIC PHOSPHATE FERTILIZERS 50

Introduction 50
Methods and Materials 54
Soil Description and Analysis 54
Phosphorus Sources 55
Experimental Design 55
Green Manure Phase 56
Wheat Phase 57
Statistical Analyses 58
Results and Discussion 59
Phosphorus Grade Analysis 59

TABLE OF CONTENTS – CONTINUED

Green Manure Phase 59
Wheat Phase 63
Conclusions 66
References Cited 69

4. SOIL FERTILITY DIFFERENCES BETWEEN NON-ORGANIC NO-TILLAGE AND ORGANIC CROPPING SYSTEMS IN MONTANA 80

Introduction 80
Methods and Materials 84
Crop Diversification Rotation Study 84
Site Description 84
Experimental Design 85
Soil Sampling and Analyses 86
Comparison of Nutrient Levels on Organic and Non-Organic Farms 88
Study Design 88
Site Description 89
Soil Sampling and Analysis 89
Statistical Analyses 90
Results and Discussion 90
Crop Diversification Rotation Study 91
Organic and Non-organic Soil Fertility Comparison Study 93
Conclusions 96
References Cited 98

5. SUMMARY 118

APPENDICES 123

APPEDNIX A: Statistical Tables Referenced in Chapter 2 124
APPENDIX B: Statistical Tables Referenced in Chapter 3 128

LIST OF TABLES

Table Page

2.1 Monthly precipitation and mean temperature, Big Sandy, MT, 2005-2007 39

2.2 Cultivar, seeding date and seeding rate for Big Sandy, MT 40

2.3 Green manure termination and tillage schedule for Big Sandy, MT 40

2.4 Summary of sequential P fractionation procedure 41

2.5 Mean shoot biomass, P uptake and tissue P concentration of green manure crops, Big Sandy, MT 41

2.6 Mean grain yield, shoot biomass, grain and shoot P uptake, grain and shoot P concentration for winter wheat, Big Sandy, MT 42

3.1 Selected soil properties for soil used in the greenhouse pot study 74

3.2 Fertilizer application rates for greenhouse pot study 74

3.3 Listed grade, ammonium citrate-soluble and total P content for fertilizers in the greenhouse pot study 75

3.4 Mean shoot biomass, P uptake, and tissue P concentration of green manure crops in the greenhouse pot study 76

3.5 Summary of significant effects and interaction for measured dependent variable in the greenhouse pot study 77

3.6 Mean shoot biomass, P uptake, and tissue P concentration of spring wheat in the greenhouse pot study 78

4.1 Monthly precipitation, Arthur H. Post Agronomy Farm, Bozeman, MT 2005-2007 104

4.2 Four year fully phased crop rotations for CDRS cropping systems, Arthur H. Post Agronomy Farm, Bozeman, MT, 2000-2003 104

4.3 Four year dual phased crop rotations for CDRS cropping systems, Arthur H. Post Agronomy Farm, Bozeman, MT, 2004-2007 105

LIST OF TABLES – CONTINUED

Table Page

4.4 Soil characteristics of contrasting cropping systems in Organic and Non-Organic Soil Fertility Comparison Study 106

4.5 Crop management factors for Organic and Non-Organic Soil Fertility Comparison Study.....107

4.6 Mean nutrient concentrations for Organic and No-till cropping systems, CDRS, Arthur H. Post Agronomy Farm, Bozeman, MT, 2007.....108

LIST OF FIGURES

Figures Page

2.1 Mean pre-experimental Olsen P soil concentrations, Big Sandy, MT....43

2.2 Mean shoot biomass of green manure, Big Sandy, MT....44

2.3 Mean P uptake of green manure, Big Sandy, MT....45

2.4 Mean grain yield of winter wheat, Big Sandy, MT....46

2.5 Grain protein of winter wheat, Big Sandy, MT....47

2.6 Mean total P uptake of winter wheat, Big Sandy, MT....48

2.7 Mean Bicarb-P, NaOH-P and HCl-P for Big Sandy, MT....49

3.2 Regression analysis of mean tissue P concentration of buckwheat as a function of applied P in the greenhouse pot study....79

3.3 Regression analysis of mean P uptake of buckwheat as a function of applied P in the greenhouse pot study....79

4.1 Photo of contrasting management systems in the Organic and Non-Organic Soil Fertility Comparison Study, north-central, MT....109

4.2 Map of field site locations for Organic and Non-organic Soil Fertility Comparison Study, north-central, MT....110

4.3 Soil sampling schematic for the Organic and Non-Organic Soil Fertility Comparison Study, north-central, MT....111

4.4 Mean soil inorganic P concentrations from sequential P fractionation, CDRS, Arthur H. Post Agronomy Farm, Bozeman, MT....112

4.5 Mean potentially mineralizable nitrogen concentrations, CDRS, Arthur H. Post Agronomy Farm, Bozeman, MT....113

4.6 Mean nitrate-N concentrations, CDRS, Arthur H. Post Agronomy Farm, Bozeman, MT....114

LIST OF FIGURES – CONTINUED

Figure Page

4.7 Mean soil inorganic P concentrations from sequential P fractionation, Organic and Non-organic Soil Fertility Comparison Study 115

4.8 Mean soil nitrate concentrations for Organic and Non-Organic Soil Fertility Comparison Study 116

4.9 Mean soil potentially mineralizable nitrogen concentrations for Organic and Non-organic Soil Fertility Comparison Study 117

ABSTRACT

Maintaining phosphorus (P) fertility in northern Great Plains (NGP) dryland organic cropping systems is a challenge due to high pH, calcareous soils that limit P bioavailability. Organic P fertilizers, including rock phosphate (RP) and bone meal (BM) are sparingly soluble in higher pH soils. Certain crops species have demonstrated an ability to mobilize sparingly soluble P sources. Objectives of this project were to 1) evaluate the effect of green manure (GM) crops and organic P fertilizers on the P nutrition of subsequent crops, and 2) investigate P fertility differences between organic and non-organic cropping systems.

A two-year cropping sequence was conducted on an organic farm in north-central Montana (mean pH=6.6; Olsen P=16 mg kg^{-1}). Spring pea (*Pisum sativum* L), buckwheat (*Fagopyrum esculentum* L.), yellow mustard (*Sinapis alba* L.) and tilled fallow were fertilized with 0, 3.1 and 7.7 kg P ha^{-1} as RP, grown to flat pod stage and terminated with tillage. Winter wheat (*Triticum aestivum* L.) was grown on these plots in year two. Phosphorus uptake of winter wheat was enhanced ($P>0.05$) by RP following buckwheat only ($P=0.02$) at 7.7 kg P ha^{-1} compared to 0 P. Results indicate buckwheat can enhance P in a subsequent crop.

A greenhouse pot experiment in a low P soil (Olsen P=4 mg kg^{-1}) consisted of four green manures; buckwheat, spring pea, wheat, and a non-crop control fertilized with 7.0 and 17.5 kg available P ha^{-1} as RP, 13.0 and 32.5 kg available P ha^{-1} as BM and 10 and 25 kg available P ha^{-1} as monocalcium phosphate (MCP). Green manures were harvested, dried, analyzed for nutrient content, and returned to pots. Pots were seeded with wheat. Phosphorus uptake in wheat following all crops was enhanced by MCP ($P<0.05$). Phosphorus uptake of wheat following buckwheat was enhanced by all P sources over the control. Buckwheat demonstrates the capacity to increase the availability of organic P fertilizers.

Soil sampling of organic and non-organic no-tillage (NT) cropping systems was conducted in two separate studies to determine differences in P availability between management systems. Soil analysis determined available P tends to be lower in non-fertilized systems.

INTRODUCTION

Background

Worldwide, there are many diverse agricultural systems that share one important characteristic: their continued existence rests upon the fertility of the soil. During the 20th century, much of the world experienced one of the most revolutionary transformations in soil fertility management (Mazoyer and Roudart, 2006). Specifically, biologically-based fertility systems shifted to systems based on fossil fuels. Instead of building soil fertility through the addition of animal manures, cover crops, and crop rotations, soil fertility management morphed into a system dependent on the synthesis of chemical nutrients (Smil, 2001). Development of the Haber-Bosch process (circa. 1913; International Fertilizer Industry Association, 1998) made the production of ammonia nitrogen (NH_3) fertilizer from atmospheric dinitrogen (N_2) gas relatively cheap and accessible (Mortvedt et al., 1999). In addition, advances in mining technology and processing transformed phosphorus (P) bearing ore into highly refined, water soluble phosphates, thus easing widespread P deficiency. Modern fertilizer technology helped double global food production over the past 35 years, but it came with significant increases in chemical-based nitrogen (N) and phosphorus (P) fertilization (Tilman, 1999; Cassman, 1999), and an ever increasing dependence on non-renewable energy. Global demand for food, fiber, and biofuels is expected to expand in response to population projections that predict upwards of 10 billion people by the middle of the 21st century (FAO, 2001; Tilman et al.,

2002). As energy supplies dwindle and production costs rise, it's unknown if soil fertility management based on non-renewable energy is sustainable.

In addition to the large expenditure of non-renewable energy resources utilized in the synthesis of chemical fertilizers, the legacy of adverse environmental impacts caused by their manufacture and use are well documented. Increased production of carbon dioxide from the burning of natural gas in the Haber-Bosch process and efflux of nitrous oxide from agricultural ecosystems contribute to greenhouse gas emissions and global climate change (Cole et al., 1997; Haynes and Sherlock, 1986; Galloway et al., 1995). Nitrate and phosphate fertilizers can contaminate ground and surface waters which contribute to eutrophication of marine and fresh water systems (Goolsby et al., 1999; Powers, 2007). Rock phosphate (RP), a naturally occurring P bearing ore used in the processing of soluble chemical P fertilizers may also contain heavy metals, such as arsenic (As), lead (Pb), and cadmium (Cd), as well as the radioactive elements uranium (U), thorium (Th), and radium (Ra) (Rutherford et al., 1994; Sam and Holm, 1995; Camelo et al., 1997; Lysandrou et al., 2007; Paridaens and Vanmarcke, 2008). These by-products can adversely affect human health and disposal can be costly.

Organic production is often cited as a more ecologically sustainable model for managing soil fertility than conventional management systems. Unlike conventional production systems that focus on chemical fertilization, organic systems operate without the use of chemical fertilizer inputs (IFOAM, 2006; National Organic Program, 2007). Instead, organic production systems emphasize biological-based soil fertility by implementing strategies that create diverse biological communities to enhance natural

biological nutrient cycling in the soil (IFOAM, 2002; Treadwell et al., 2003). Organic production systems attempt to maintain soil fertility by utilizing carbon-based nutrient sources, such as manure, compost, and crop residues (Nelson and Janke, 2007) to cycle soil organic matter (SOM). Soil organic matter has a profound impact on nutrient cycling within the soil (Schoenau and Campbell, 1996;Watson et al., 2002; Stockdale et al., 2002) since it serves as a reservoir for large quantities of soil N and a variety of organic P compounds (Berry et al., 2002; Nelson and Mikkelsen, 2008) that provide nutrition to subsequent crops upon mineralization. Nitrogen (N_2) fixing legume-based systems are also common in organic systems since they provide a relatively low cost on-farm input for N fertilization. It has been suggested that legume-based green manure (GM) systems may improve the N use efficiency of cropping systems due to increased SOM and better synchronization between mineralization of N in crop residues and plant N uptake (Biderbeck et al., 1996; Biderbeck et al., 1998; Cline and Silvernail, 2002; Cherr et al., 2006).

While the sustainability of modern industrial agriculture is in question, so too is the sustainability of organic production. One argument contends that without modern synthetic fertilizers and pesticides, agriculture would fail to meet the growing demand for food (Trewavas, 2002). Some contend that organic crop yields are considerably lower than in conventional systems, particularly when N_2 fixing legumes are the sole input into the system (Smil, 1997; Cassman et al. 2002). Nitrogen fixing legumes may represent a renewable source of N, but they do not provide an income source in the year that they are grown. Furthermore, there is concern that systems dependent solely on biological N

fixation will not match the net contribution of N provided by chemical based systems (Peoples et al., 1995). Unprocessed mineral sources, primarily rock phosphate (RP) and bone meal (BM), are used to enhance soil P fertility in organic systems; however, these materials generally have low solubility and availability, particularly in certain soil conditions (Khasawneh and Doll, 1978). Moreover, as previously suggested, RP ore can contain heavy metals which could contaminate soil and crops.

Soil Fertility in Organic Cropping Systems in the Northern Great Plains

In the agricultural region of North America's northern Great Plains (NGP), both geographic and climatic factors constrain soil fertility management in organic cropping systems. Geographically, the NGP is a vast land area swathed with large-acre grain farms. While the use of animal manure is often a staple in organic farming systems to supply N and P, the cropland in the NGP is often too distant from manure sources to make its use practical or cost effective. Thus, without access to nutrient-rich animal manures, organic producers in the NGP have limited options available to maintain soil fertility.

Climatic factors shape the NGP production environment and create additional challenges for the organic producer. The climate is semiarid (300-450 mm of precipitation annually), rainfall is erratic and unevenly distributed, and drought is common (Padbury et al., 2002; Peterson and Westfall, 2004). In most months, evapotranspiration exceeds precipitation and growing seasons are usually defined by moisture availability with soil water depletion typically terminating plant growth rather than frost (P. Miller, pers. comm.). Climatic conditions favor the growth of cool season,

drought tolerant small-grain cereals, such as wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.), as well as oil seed and pulse crops (Cochran et al., 2006). Climatic factors also strongly influence biogeochemical processes that affect soil fertility. Specifically, the semiarid climate affects SOM levels, soil water content, soil pH, and crop growth and development, all of which affect nutrient availability and represent a major challenge for organic production in the region.

Soil organic matter is the foundation of soil fertility management in organic production systems (Stockdale et al., 2002) since it stores nutrients, improves soil quality, and serves as a substrate for microbes and soil fauna that decompose and mineralize nutrients in the soil. The quantity and quality of SOM is affected by the quantity and quality of organic inputs added to the soil and relative rates of mineralization and/or immobilization. The mineralization and immobilization processes are directly affected by the climatic regime, particularly soil moisture availability and temperature. Specifically, as moisture levels are limited across the semiarid NGP the quantity of SOM and soil organic N (SON) are typically low and may become depleted by cropping if N is not replaced.

Maintaining sufficient levels of SON is a major challenge in NGP organic cropping systems, and is most often achieved through the inclusion of leguminous green manure (GM) crops, most notably yellow sweet clover (*Melilotus officinalis* L.), alfalfa (*Medicago sativa* L.), and annual legumes, such as field pea (*Pisum sativum* L.), lentil (*Lens culinaris* L.), and chickling vetch (*Lathyrus sativus* L.). The use of legumes in a rotation can add significant amounts of N to the soil (Krall and Schuman, 1996; Entz et

al., 2002). While biennial and perennial legumes may contribute the most N via fixation, they generally utilize the most water (Nielsen et al., 2004). In dry years perennial forages often reduce the yield of the subsequent crop even in sub-humid regions (Entz et al., 2002). Annual legume species like pea and lentil may provide a better trade-off between water use and N contribution in semiarid regions (Biederbeck et al., 1993; Zentner et al., 2004), yet long-term benefits in influencing the availability of N, and other nutrients such as P, are relatively unknown.

Phosphorus availability often limits crop growth in the NGP, and is heavily influenced by soil pH (Nelson and Janke, 2007; Nelson and Mikkelsen, 2008). Relatively insoluble Ca-P minerals form in high pH soils, so while total P reserves in the soil may be sufficient for decades of cropping, much of the P in the soil is unavailable to crops. High pH soils are widespread in semiarid regions, like the NGP, where precipitation is less than evapotranspiration and leaching of calcium carbonate ($CaCO_3$) and base cations such as calcium (Ca) and magnesium (Mg) from the soil is minimal (DeLuca et al., 1989; Bauder et al., 1997; Brady and Weil, 2004). Phosphorus is relatively immobile in the soil and is the least available macronutrient in NGP agricultural systems. Thus, P deficiency often limits plant growth and crop yields in the NGP (Campbell et al., 2005), and P bioavailability is of particular concern in organic production systems.

Research on soil P budgets has found significantly lower available P levels under organic management systems (Watson et al., 2002; Berry et al., 2003; Gosling and Shepherd, 2005; Miller et al., 2008) especially in legume-based systems. Studies in the NGP have found a similar decreasing trend in soil P fertility in organic cropping systems

(Entz, et al., 2001; Martin et al., 2007) suggesting that in the absence of fertilization available P levels decline. Some suggest the declining available P levels support the argument that organic systems mine soil P from reserves built during conventional management and the long-term export of P without replacement is unsustainable (Berry et al., 2003; Gosling and Shepherd, 2005). Organic farming is increasing across the NGP (Dimitri and Greene, 2002; Smith et al., 2004; Montana Department of Agriculture, 2008); therefore, it is essential to establish reliable strategies for maintaining soil P fertility within the confines of organic production standards. While legume GM crops can add N to a cropping system, GM crops do not add P to the system, thus organic growers in the NGP need mechanisms to replace P exported by cropping, improve P use efficiency, and maintain optimal productivity of cropping systems.

To ensure productivity and long-term sustainability of organic systems in the NGP a balance of nutrient inputs and exports are needed. One approach for improving soil P fertility in organically managed cropping systems in the NGP is to apply unprocessed organic mineral P fertilizers. However, these products are often less effective in neutral to alkaline soil conditions typical in the NGP. While GM crops do not add P to the system, there is considerable evidence that certain GM species can influence the efficacy of unprocessed phosphate materials via rhizosphere interaction (Haynes, 1992; Zhu et al., 2002), yet none of this research has been conducted in the northern Great Plains. In addition, it's unknown in this region whether organic cropping systems are depleting soil N and P levels compared to non-organic systems.

Objectives of Project

The studies presented in this thesis focus on the ability of GM crops used with, and without, unprocessed organic mineral phosphate fertilizers to enhance crop P nutrition and enhance soil P fertility in NGP organic systems. The first study evaluates the ability of a GM crop to enhance the availability of rock phosphate for a subsequent wheat crop in a field setting. The second study is a companion greenhouse study to the field study that looks at the ability of GM crops fertilized with two organically certified P materials to enhance P nutrition of a subsequent crop when compared with a synthetic P fertilizer. Finally, two studies were conducted to understand how management practices influence nutrient availability in contrasting organic and non-organic cropping systems. Specifically, the goals were to evaluate P management strategies for maintaining soil P fertility in dryland large-acre organic cropping systems in the NGP.

References Cited

Bauder, J.W., M. Shaukat, B.E. Schaff, D.J. Sieler, J.S. Jacobsen, and E.O. Skogley. 1997. Effect of phosphorus soil test level on Sorghum-Sudangrass response to phosphorus fertilizer. Agron. J. 89: 9-16.

Berry, P.M., R. Sylvester-Bradley, L. Phillips, D.J. Hatch, S.P. Cuttle, F.W. Rayns, and P. Gosling. 2002. Is the productivity of organic farms restricted by the supply of available nitrogen? Soil Use Mgt. 18: 248-255.

Berry, P.M., E.A. Stockdale, R. Sylvester-Bradley, L. Phillips, K.A. Smith, E.I. Lord, C.A. Watson, and S. Fortune. 2003. N, P and K budgets for crop rotations on nine organic farms in the UK. Soil Use Mgt. 19: 112-118.

Biederbeck, V.O. , O.T. Bouman, C.A. Campbell, L.D. Bailey, and G.E. Winkleman. 1996. Nitrogen benefits from four green-manure legumes in dryland cropping systems. Can. J. Plant Sci. 76: 307-315.

Biederbeck, V.O., C.A. Campbell, V. Rasiah, R.P. Zentner, and G. Wen. 1998. Soil quality attributes as influenced by annual legumes used as green manure. Soil Biol. Biochem. 30: 1177-1185.

Brady, N.C., and R.R. Weil. 2004. Elements of the Nature and Properties of Soils, 2nd Ed., Pearson Prentice Hall, Upper Saddle River, New Jersey.

Campbell, C.A., R.P. Zentner, F. Selles, P.G. Jefferson, B.G. McConkey, R. Lemke, and B.J. Blomert. 2005. Long-term effect of cropping system and nitrogen and phosphorus fertilizer on production and nitrogen economy of grain crops in a Brown Chernozem. Can. J. Plant Sci. 85: 81-93.

Camelo, L.G.L., S.R. Miguez, and L. Marban.1997. Heavy metals inputs in phosphate fertilizers used in Argentina. Sci. Total Enviro. 204: 245-250.

Cassman, K.G. 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. Proc. Natl. Acad. Sci. USA. 96: 5952-5959.

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

Cline, G.R., and A.F. Silvernail. 2002. Effects of cover crops, nitrogen and tillage on sweet corn. HortTech. 12: 118-125.

Cole, C.V., J. Duxbury, J. Freney, O. Heinemeyer, K. Minami, A. Mosier, K. Paustian, N. Rosenberg, N. Sampson, D. Sauerbeck, and Q. Zhao. 1997. Global estimates of potential mitigation of greenhouse gas emissions by agriculture. Nutr. Cycl. Agroecosyst. 49: 221–228.

Dimitri, C., and C. Greene. 2002. Recent growth patterns in the U.S. organic foods industry. Economics Research Service, USDA. Agriculture Information Bulletin Number 777. Sept,. 2002. www.ers.usda.gov/publications/aib777/aib777.pdf (verified 9 Oct. 2008)

DeLuca, T.H., E.O. Skogley, and R.E. Engel. 1989. Band-applied elemental sulfur to enhance the phytoavailability of phosphorus in alkaline calcareous soils. Biol Fertil Soils. 7: 346-350.

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

Galloway, J.N., W.H. Schlesinger, H. Levy, A. Michaels, and J. Schnoor. 1995. Anthropogenic enhancement – environmental response. Biogeochem. 9: 235-252.

Goolsby, D.A., W.A. Battaglin, G.B. Lawrence, R.S. Artz, B.T. Aulenbach, R.P. Hooper, D.R. Keenley, and G.J. Stensland. 1999. Flux and sources of nutrients in the Mississippi-Atchafalaya River Basin. Topic 3 Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico. NOAA, Washington DC.

Gosling, P., and M. Shepard. 2005. Long-term changes in soil fertility in organic arable farming systems in England, with particular reference to phosphorus and potassium. Agric. Ecosyst. Envrion. 105: 425-432.

Haynes R. J., and R. R. Sherlock. 1986. Gaseous losses of nitrogen. p. 242-302. *In* R. J. Haynes (ed.) Mineral Nitrogen in the Plant-Soil System. Academic Press, Toronto.

Haynes, R.J. 1992. Relative ability of a range of crop species to use phosphate rock and monocalcium phosphate as P sources when grown in soil. J. Sci. Food Agric. 60: 205-211.

FAO. Food and Agriculture Organization of the United Nations. 2005. Global trends in organic agriculture markets and countries' demand for FAO assistance. International Farming Systems Association Roundtable, Rome, Italy. ftp://ftp.www.fao.org/organicag (verified 8 Oct. 2008)

IFOAM. 2006. Basic standards for organic production and processing decided by the IFOAM general assembly in Basel, Switzerland, September 2000. http://www.ifoam.org/standard/index.html (verified 9 Oct. 2008).

International Fertilizer Industry Association. 1998. The Fertilizer Industry, World Food Supplies and the Environment. IFA and UNEP, Paris, France.

Khasawneh, F.E., and E.C. Doll. 1978. The use of phosphate rock for direct application to soils. Adv. Agron. 30: 159-206.

Krall, J.M., and G.E. Schuman. 1996. Integrated dryland crop and livestock production systems on the Great Plains: extent and outlook. J. Prod. Agric. 9: 187-191.

Krupinsky, J..M., D.L. Tanaka, S.D. Merrill, M.A. Liebig, and J.D. Hanson. 2006. Crop sequence effects of 10 crops in the northern Great Plains. Agric. Syst. 88: 227-254.

Lysandrou, M., A. Charalambides, and I. Pashalidis. 2007. Radon emanation from phosphogypsum and related mineral samples in Cyprus. Radiation Measurements. 42: 1583-1585.

Lindsay, W. 1979. Chemical equilibria in soils. Wiley-Interscience Pub. New York, NY.

Martin, R.C., D.H. Lynch, B. Frick, and P. van Straaten. 2007. Perspective: Phosphorus status on Canadian organic farms. J. Sci. Food Agric. 87: 2737-2740.

Mazoyer, M., and L. Roudart. 2006. A history of world agriculture: from the Neolithic age to the current crisis. Monthly Review Press, New York, NY.

Menzel, R.G., 1968. Uranium, radium and thorium content in phosphate rocks and their possible radiation hazard. J.Agr. Food Chem.16: 231-284.

Miller, P.R., D.E. Buschena, C.A. Jones, and J.A. Holmes. 2008. Transition from intensive tillage to no-tillage and organic diversified annual cropping systems. Agron. J. 100: 591-599.

Montana Department of Agriculture. 2008. Organic production in Montana. http://agr.mt.gov/organic/info/02Montana.pdf

Montgomery, D.R. 2007. Soil erosion and agricultural sustainability. Proc. Natl. Acad. Sci. USA. 104: 13268-13272.

Mortvedt, J.J. , L.S. Murphy, and R.H. Follett. 1999. Fertilizer technology and application. Meister Publ. Co., Willoughby, OH.

National Agricultural Library. 2008. Organic production. Beltsville, MD. http://afsic.nal.usda.gov/nal_display/index.php?tax_level=1&info_center=2&tax_subject=296 (verified 12 Oct. 2008)

National Organic Program. 2007. National list of allowed and prohibited substances. Washington, D.C. http://www.ams.usda.gov/NOP/NOP/NOPhome.html (verified 10 Oct. 2008)

Nelson, N.O., and R.R. Janke. 2007. Phosphorus sources and management in organic production systems. Hort. Tech. 17: 442-454.

Nelson, N., and R. Mikkelsen. 2008. Meeting the phosphorus requirement on organic farms. p. 12-14. *In* Better Crops with Plant Food. No. 1. International Plant Nutrition Institute. Norcross, GA.

Paridaens, J., and H. Vanmarcke. 2008. Radiological impact of almost a century of phosphate industry in Flanders, Belgium. Health Physics. 95: 413-424.

Peoples, M.B., D.F. Herridge, and J.K. Ladha. 1995. Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production? Plant Soil. 174: 3-28.

Peterson, G.A. 1996. Cropping systems in the Great Plains. J. Prod. Agric. 9: 179.

Peterson, G.A., and D.G. Westfall. 2004. Managing precipitation use in sustainable dryland agroecosystems. Ann. Appl. Biol. 144: 127-138.

Powers, S. 2007. Nutrient loads to surface water from row crop production. Int. J. Life Cycle Ass.12: 399-407.

Rutherford, P.M., M.J. Dudas, and R.A. Samek. 1994. Environmental impacts of phosphogypsum. Sci. Total Environ. 149: 1-38.

Sam, A.K., and E. Holm. 1995. The natural radioactivity in phosphate deposits from Sudan. Sci. Total Environ. 162: 173-178.

Schoenau, J.J., and C.A. Campbell. 1996. Impact of crop residues on nutrient availability in conservation tillage systems. Can. J. Soil Sci. 76: 621-626.

Smil, V. 1997. Global population and the nitrogen cycle. Sci. Am. 227: 76-81.

Smil, V. 2001. Enriching the earth: Fritz Haber, Carl Bosch, and the transformation of world food production. MIT Press, Cambridge, MA.

Smith, E.G., M.J. Clapperton, and R.E. Blackshaw. 2004. Profitability and risk of organic production systems in the northern Great Plains. Renewable Agric. Food Sys. 19: 152-158.

Stockdale, E.A., M.A. Shepherd, S. Fortune, and S.P. Cuttle. 2002. Soil fertility in organic farming systems – fundamentally different? Soil Use Mgt. 18: 301-308.

Tilman, D. 1999. Global environmental impact of agricultural expansion: the need for sustainable and efficient practices. Proc. Natl. Acad. Sci. USA. 96: 5995-6000.

Tilman, D., K.G. Cassman, P.A. Matson, R. Naylor, and S. Polasky. 2002. Agricultural sustainability and intensive production practices. Nature. 418: 671-677.

Treadwell, D.D., D.E. McKinney, and N.G. Creamer. 2003. From philosophy to science: a brief history of organic horticulture in the United States. Hortscience. 35: 1009-1014.

Trewavas, A. 2002. Malthus foiled again and again. Nature. 418: 668-670.

Watson, C.A., H. Bengtsson, M. Ebbesvik, A.K. Loes, A. Myrbeck, E. Salomon, J. Schroder, and E.A. Stockdale. 2002. A review of farm-scale nutrient budgets for organic farms as a tool for management of soil fertility. Soil Use Mgt. 18: 264-273.

Zhu, Y-G, Y-Q He, S.E. Smith, and F.A. Smith. 2002. Buckwheat (*Fagopyrum esculentum* Moench) has higher capacity to take up P from a Ca-bound source. Plant Soil. 239: 1-8.

CHAPTER 2

EFFECT OF GREEN MANURE AND ROCK PHOSPHATE ON PHOSPHORUS AVAILABILITY IN THE NORTHERN GREAT PLAINS

Introduction

Phosphorus (P) is one of the most important soil nutrients for crop productivity in Northern Great Plains (NGP) dryland organic cropping systems (Campbell et al., 1996; Entz et al., 2001; Fixen and Murrell, 2002; Martin et al., 2007). Low P availability is largely a result of the conversion of residual and applied P into insoluble calcium phosphates in neutral to alkaline soils common in the NGP (Brady and Weil, 2004). Thus, the soil may be high in total P, but deficient in soluble P for plant uptake. Maintaining soil P fertility with the application of soluble synthetic P fertilizers is prohibited in organic production systems (USDA, 2007), and use of animal manure, while an excellent source of P, is impractical in much of the NGP due to long haul distances. Organic producers in the NGP require reliable methods for managing soil P fertility while remaining within the standards of organic production.

One potential approach for enhancing soil P fertility in NGP organic production systems is to utilize rock phosphate (RP), a naturally occurring mineral P source and precursor to highly refined phosphate fertilizers. Early studies by Kasawneh and Doll (1978) on the effectiveness of RP determined the value of RP for enhancing soil P fertility is highly dependent upon soil properties, including soil pH, calcium (Ca) concentration, and soil phosphate ($H_2PO_4^-$, HPO_4^{-2}) levels. Effective dissolution of

calcium-rich RP requires an adequate supply of protons (H^+) and removal of Ca and/or phosphate from the zone of dissolution (Bolan et al., 1997). Soil pH has been recognized as one of the most important factors affecting the availability of P from the dissolution of RP. Specifically, the agronomic effectiveness of RP is higher on acidic soils than neutral to alkaline soils (Ellis et al., 1955; Peaslee et al., 1962; Ensminger et al., 1967; Barnes and Kamprath, 1975). If RP is to be utilized as a material to enhance soil P fertility in the NGP, the soil environment must be modified to optimize RP dissolution, yet viable options for modification are limited.

Crop species exhibit a differential ability to influence dissolution of RP (Hoffland et al., 1989; Haynes, 1992; Rajan et al., 1996). Certain crop species enhance the dissolution of RP by favoring cation uptake over of anion uptake, producing a net efflux of hydrogen (H^+) ions to maintain the charge balance within the plant, thereby reducing rhizosphere pH. Several studies have found buckwheat (*Fagopyrum esculentum* L.) is highly efficient at mobilizing P from RP sources by increasing the Ca uptake rate compared to cereal crops (van Ray and van Diest, 1979; Bekele et al., 1983; Haynes, 1992). In these studies, cereals were notably inefficient at utilizing RP particularly when nitrate (NO_3^-) was applied as the nitrogen (N) source. For example, in a growth chamber experiment, Zhu et al. (2002) determined that total P uptake of buckwheat supplied with RP was 10-fold higher than for wheat (*Triticum aestivum* L.) when NO_3^- was the only N source. Legume species have also demonstrated an ability to effectively utilize RP as a P source by decreasing rhizosphere pH, particularly when plants utilize symbiotically fixed N which results in higher uptake of cations than anions, thereby releasing protons

(Aguilar and van Diest, 1981). In a greenhouse experiment, the legume, *Lupin angustifolius* L., utilized RP equally well as monocalcium phosphate (MCP) when symbiotically fixed N was the exclusive N source (Haynes, 1992). A field study in New Zealand found P uptake in maize (*Zea mays cv.* Elita) was enhanced following lupin (*L. angustifolius* cv. Fest) fertilized with RP indicating improved utilization of RP (McLenaghen et al., 2004).

As the previous studies indicate N source is an integral factor in plant induced rhizosphere acidification because it can influence the cation/anion uptake ratio. Commonly, rhizosphere pH decreases when crop species are supplied with ammonium (NH_4^+), and by contrast, will increase when crops are supplied with NO_3^- (Kirby and Mengel, 1967; Gahoonia et al., 1992). Crop species that assimilate NH_4^+ and legumes that fix atmospheric N typically absorb more cations than anions, thus creating an acidifying effect beneficial to the dissolution of RP (Weil, 2000; Steen Jensen and Hauggaard-Nielsen, 2003).

Certain *Brassicaceae*, or mustard species, exhibit the potential to mobilize P from RP sources without favoring cation uptake. Haynes (1992) demonstrated rape (*Brassica napus* L.) and kale (*Brassica oleracea*) could utilize RP equally to that of monocalcium phosphate (MCP) despite anion uptake exceeding cation uptake resulting in a higher rhizosphere pH. Bekele et al. (1983) concluded the P solubilizing ability of rape resulted from increased crop absorption of Ca, thus lowering soil Ca concentrations enough to induce dissolution of RP. Conversely, Hoffland et al. (1989) determined neither ion uptake nor Ca absorption fully explained the ability of rape to mobilize RP, but suggested

exudation of organic acids may play a role. Chien et al. (2003) found rape utilized low reactivity RP 50% as well as highly soluble triple superphosphate (TSP) in alkaline soils.

Green manure (GM) crops are crops with a valuable suite of attributes grown specifically to improve soil fertility or soil quality when incorporated into the soil. Organic producers in the NGP utilize GM crops, primarily N fixing legume species, to increase soil N fertility for subsequent crops. As the evidence suggests, GM crops capable of mobilizing sparingly soluble RP or utilizing P from less labile soil P fractions may represent a relatively labile source of P for subsequent crops when residues are incorporated into the soil. In addition, GM crops with increased tissue P concentrations may expand the soil organic P pool, supplying inorganic P for subsequent crops via mineralization of decomposing crop residues.

Although there is considerable evidence that certain crop species can enhance the availability of RP and native soil P, many of the studies examining the dissolution capacity of RP and mobilization of less labile soil P by GM crops have been largely restricted to controlled greenhouse environments. Moreover, many of the studies (Bekele et al., 1983; Hoffland et al., 1989; Zhu et al., 2002) have been conducted in sand cultures with low P buffering capacity at uneconomical available P rates (~50 to 100 kg P ha^{-1}). There is scant research on the ability of GM crops to increase the effectiveness of RP or affect the P nutrition of a subsequent crop, particularly in a field setting when using GM crop species adapted to the NGP. Therefore, a field study was conducted to investigate if GM crops fertilized with RP can influence the P nutrition of a subsequent crop.

The objectives of this field study were to: (i) evaluate the effect of RP on GM growth and P uptake, (ii) evaluate the effect of fertilized incorporated GM residues on the P nutrition of a subsequent winter wheat crop, and (iii) determine if RP and GM residues affect labile and non-labile P soil fractions. This chapter describes a field study investigating the effect of three GM crop species [buckwheat, field pea (*Pisum sativum* L.) and yellow mustard (*Sinapis alba* L.)] and RP on the P nutrition of a subsequent winter wheat crop.

Methods and Materials

Field Site Description

A field experiment was conducted from 2005 to 2007 on an organic dryland grain farm in north central Montana approximately 19 km south of Big Sandy, Montana (48˚ 02′ 13.14″ N, 110˚ 01′05.56″ W, elevation 957 m). The field site was on a rolling upland of glacial till with a gentle north-south trending slope. Soil at the site was a well drained Telstad-Joplin loam (fine-loamy, mixed, Aridic Argiboroll) with 43% sand, 38% silt, 19% clay, 16 g kg^{-1} soil organic matter, soil pH between 6.4 to 7.7 with an average 6.6, and $CaCO_3$ between 0 and 0.5%.

Cultivation of this site initially occurred in the early 1900's (circa. 1917) and continues to the present. Synthetic fertilizer and pesticide applications were discontinued in 1985, three years prior to organic certification. During the conventional management period, soil fertility was maintained through the addition of commercial fertilizers, with approximately 20 kg P ha^{-1} applied during the crop year in a crop-fallow system. Soil

fertility following organic certification was limited to inclusion of periodic annual, biennial, and perennial N_2-fixing legumes into crop rotations. Small grain and oil seed crops, along with alfalfa, were harvested as cash crops. Until drought conditions persisted in the 1990's, alfalfa was a key rotational crop harvested as forage in the seeding year then terminated and incorporated as a green manure the following year (R. Quinn, pers. comm.). Fallow periods were infrequent. Field tillage operations were generally performed to prepare the seed bed, terminate GM crops, or to control weeds. Chisel plow, heavy duty tandem disc, and cultivator with spring tine harrow were commonly used in tillage operations.

The site was semiarid with average annual precipitation approximately 356 mm (~60% of the total received from April to July) and a mean annual temperature of 6.5 ˚C, as measured at the nearest Western Regional Climate Center (WRCC) meteorological site in Big Sandy, Montana (19 km from field site and 135 m lower in elevation). During the study, monthly precipitation data was measured differently between years, with 2006 growing season (May-August) data collected on-site using a manual rain gauge, and overwinter precipitation (Sep-Apr) data for 2006 and 2007 and growing season data for 2007 obtained from the WRCC station located at Big Sandy (Table 2.1).

Rock Phosphate Characterization

Pellatized Idaho Springs (USA) RP fertilizer was analyzed for available P with a neutral ammonium citrate extraction at pH 7 (Gliksman, 1994). Total P was determined using a 4:1 ratio of nitric:hydrochloric acid and heat digestion (AOAC, 2008). Available and total P concentrations were 0.9% and 5.7%, respectively.

Experimental Design

The study consisted of a two-year cropping sequence. Three GM crop species, spring pea (cv. *Arvika*), buckwheat (cv. *Mancan*), and yellow mustard (cv. *AC Base*) plus a non-cropped fallow control were established during the first year, or GM phase, of the experiment. Green manure crop main plots (11 x 5.5 m), including the fallow plot were divided into three equal sub-plots (5.5 x 3.6 m) each receiving either 0, 333, or 834 kg ha^{-1} RP fertilizer. Based on the available and total P concentrations of the RP, these equate to 0 (0P), 3.1 (3.1P) and 7.7 (7.7P) kg ha^{-1} available P and 0, 19 and 48 kg ha^{-1} total P, respectively. During year two of the cropping sequence, referred to as the winter wheat phase, winter wheat (*Triticum aestivum* L. cv. *Tiber*) was seeded uniformly across the study area. The experimental design was a randomized complete block design split-plot arrangement with GM crops as main plots and RP fertilizer treatments as sub-plots. All treatments were replicated four times.

.

Crop Management

The field study was established at a site that had previously been seeded to kamut (*Triticum turgidum* L.). Rock phosphate was broadcast-applied by hand on 4 Apr 2006 and incorporated to a depth of 10 cm with tillage using a 4-m wide heavy duty tandem disc prior to seeding the GM crops. Green manure crops were seeded on 13 April 2006 using a 1.8-m wide no-till plot-scale disc seeder with 0.13 m row spacing. Agronomic management specifics for cultivar, seeding date, and rate are summarized in Table 2.2. Buckwheat, compromised by frost damage, was tilled and reseeded into the same plots on

2 June. Green manure crops were terminated at flat pod stage (50% of plants with one full length pod) and incorporated into the soil surface (0-10 cm depth) by tillage using a 4-m wide heavy duty tandem disc. Termination and tillage schedules for GM crops and tilled fallow are summarized in Table 2.3. Following the GM phase, winter wheat was seeded 28 Sept 2006 in 0.15 m rows at a targeted rate of 300 seeds m^{-2} in a direction perpendicular to the row direction of the GM crops.

Soil Analyses and Phosphorus Fractionation

Soil cores were collected 4 Apr 2006 and 26 Apr 2007 at three standardized points within each sub-plot to a 0.15 m depth using a soil push probe (3 cm diameter core). Cores were bulked, oven dried at 50˚C and finely ground to pass a 2-mm sieve. Soil samples collected in 2006 were extracted with 0.5 *M* $NaHCO_3$ at pH 8.5 (Olsen-P) (Olsen et al., 1954; Olsen and Sommers, 1982) to establish relative homogeneity of available P across the study site. Specifically, 25 ml of 0.5 *M* $NaHCO_3$ was added to 1.25 g soil, shaken for 30 min, and filtered through a Whatman 42 glass fiber filter. A 5-ml aliquot of extract was used to determine P concentrations with an ascorbic acid method (Kuo, 1996) and analyzed by spectroscopy (Spectronic 601, Rochester, NY) at 880 nm. To evaluate soil physical and chemical characteristics across the site, composite samples were created by bulking ten randomly selected soils from within each block. Particle size analysis by hydrometer method (Gee and Bauder, 1986), organic matter by loss on ignition (Thomas, 1996), $CaCO_3$ (Loeppert and Suarez, 1996), and soil pH on a 1:1 soil:deionized water slurry (Thomas, 1996) were determined on the bulked samples.

Soil samples collected in Apr 2007 were subjected to a sequential P fractionation

procedure (Table 2.4) based on the methods of Hedley et al. (1982), Yang and Jacobsen (1990) and Yang et al. (2002). All extractions used a solution:soil ratio of 20:1 (25 ml extractant/1.25 g dry soil). First, soil samples were extracted with 0.5 *M* $NaHCO_3$ at pH 8.5 (Bicarb-P) in a 50-ml centrifuge tube, shaken for 30 min, and centrifuged at 10,000 rpm for 30 min. Supernatant was decanted into a 60-ml syringe and filtered through a 0.2-µm sterile nylon syringe filter. Soil residue was then subjected to two subsequent extractions, 0.1 *M* NaOH followed by 1 *M* HCl, each with a 16 h shaking period followed by centrifugation and filtration as detailed above. Phosphorus concentrations in all extracts were determined colorimetrically using the ascorbic acid method (Kuo, 1996). The sequential fractionation procedure identifies labile P fractions adsorbed onto surface soil components and $CaCO_3$ (Bicarb-P), P held strongly by chemisorption to Fe and Al components and held on internal soil surfaces (NaOH-P), and Ca-bound P associated with apatite-type minerals and P occluded within soil matrices (HCl-P). The fractionation procedure identifies P fractions that vary in the extent of their availability to growing plants, ranging from highly labile to recalcitrant (Hedley et al., 1982).

Crop Data Collection and Analyses

Green manure shoot biomass estimates were determined in 2006 by hand clipping plants at the soil surface from two 1 m^2 areas within each main subplot. Mustard, spring pea, and buckwheat harvests occurred on 19 June, 6 July, and 19 July, respectively. Biomass from the two subsamples was weighed in the field. One of the subsamples was returned to the plot, the second was reserved for tissue analysis and moisture content determination. Biomass samples were oven dried at 50˚C for 7 d, weighed and finely

ground to pass a 1-mm mesh using a Wiley mill (Thomas Scientific, Swedesboro, NJ) followed by a Cyclone sample mill (Thomas Scientific, Swedesboro, NJ). Subsamples were extracted using nitric acid-perchloric acid wet digestion and extracts were analyzed for P by inductively coupled plasma (ICP). Shoot biomass and tissue P concentration were multiplied to calculate P uptake of GM crops.

Shoot biomass of the winter wheat was collected by hand clipping 4 crop rows 1-m in length (0.61 m^2) at the soil surface. Biomass was oven dried at 50˚C, weighed, and a representative straw subsample was obtained for use in tissue P analysis to calculate P uptake of the straw. Straw subsamples were chopped in a mill (Kitchen Aid, St. Joseph, MI) then finely ground to pass a l-mm mesh using a Cylcone mill and subsamples submitted for total tissue P analysis, as above. Grain of the biomass was threshed using a Vogel bundle thresher (Bill's Welding, Pullman, WA) and weighed.

Winter wheat grain yield was measured using a plot-scale combine to harvest a swath through the center of each subplot equivalent to approximately 6.3 m^2. Grain samples were dried at 50˚C for 72 h, cleaned and weighed. Grain subsamples were finely ground using a Cyclone mill and further subsampled for tissue P analysis using the same procedure as detailed above. Aboveground P uptake of winter wheat crop was calculated by summing P uptake of straw and grain. Carbon and N content of winter wheat grain was determined on a subsample of dried grain flour using a LECO TruSpec CN combustion analyzer (LECO Corporation, St. Joseph, MO). Grain N concentrations were multiplied by 5.7 to attain protein concentrations (Jones, 1941).

Statistical Analyses

Analysis of variance (ANOVA) was conducted using JMP IN 5.1 statistical software (Sall, et al., 2007). Pre-experimental Olsen P was analyzed using ANOVA to examine the level of P heterogeneity across the field site prior to initiation of treatments. ANOVA was performed to examine differences in treatment means for main plot effects (GM crop and fallow), subplot effects (fertilizer treatments), and their interactions using Fisher's Protected Least Significant Difference (LSD) test (Kuhel, 2000). Differences were considered significant at $P < 0.05$. Block was considered a random effect while crop type (including tilled fallow) and fertilizer treatment were considered fixed effects. When crop effect was significant, mean square error of block x crop interaction was used to calculate LSD to determine significant differences among crop means. Regression analysis was utilized to determine the relationship between 2006 Olsen P values and both biomass production and P uptake of GM crops.

Results and Discussion

Pre-experimental Soil Analyses

Pre-experimental plant-available P (Olsen P) in the surface layer (0-0.15 m) across the study site ranged from 9.8 to 25.2 mg kg^{-1} with an average of 16.0 mg kg^{-1}, which is near the critical value for most Montana crops (Jacobsen et al., 2005). However, a critical value of 24 mg kg^{-1} has been established for winter wheat in Montana (Jackson et al., 1991), suggesting that winter wheat at this site has the potential to be P-responsive. Despite the wide range in Olsen P values, Olsen P concentrations were not different

among prospective crops or P rates with the exception that Olsen P was higher at the 7.7P rate than the 0P control in the soils to be seeded with mustard (Figure 2.1; Appendix Table A.1). High P application rates (20 kg P ha^{-1} annually) during the conventional farming era may account for Olsen P values near the critical range despite 20 y without P fertilization. Olsen P values approaching critical levels suggest GM productivity may not be limited by P availability and yield response to added P may be variable and difficult to quantify, especially at low agronomic rates. However, studies indicate P uptake and crop yield may still be responsive to added P even in NGP soils with Olsen P values above critical levels (Yang and Jacobsen, 1990; Bauder et al., 1997).

Green Manure Phase

Shoot biomass production differed among GM crop species (P <0.001; Appendix Table A.2) with total shoot biomass production higher in spring pea (3.8 Mg ha^{-1}) than either buckwheat (0.7 Mg ha^{-1}) or mustard (0.6 Mg ha^{-1}). Disparity in shoot biomass production among crop species may be a result of weather related factors and depletion of soil N reserves. First, buckwheat, a warm season broadleaf crop, experienced frost damage following an early seeding date (13 Apr), so was tilled and reseeded on 2 June. Late seeding delayed the termination date for buckwheat until 21 July which was one month later than mustard and 12 d later than spring pea. Thus, buckwheat plots were cropped longer than the other GM crops, thereby increasing the potential for soil nutrient depletion, particularly N. Soil NO_3^- levels measured in an adjoining companion study (identical GM plots) over the 2006 GM growing season (Izard, 2007) indicate the field site was severely N limited, thus offering the most likely explanation for the

disproportionate growth and biomass production between leguminous and non-leguminous species. Low soil N levels often limit productivity and crop quality in NGP production systems (Campbell et al., 2005) highlighting the importance of including N fixing leguminous species into NGP cropping systems. Soil water also affects crop growth and productivity. Precipitation in June 2006 during the GM phase was 76 mm, a 13% increase over the LTA, but was followed by a 21% (20 mm) reduction from the LTA in July, thus rainfall was well within a "normal" range. Soil N concentrations, rather than soil moisture levels, most likely reduced shoot biomass production of the buckwheat crop, as well as mustard.

Buckwheat and spring pea shoot biomass production showed no significant response to increasing P rate, whereas mustard biomass production was 51% higher at the 7.7P rate than the control (Figure 2.2) possibly due to differences in pre-experimental Olsen P as described above. Regression analysis determined the relationship between pre-existing Olsen P levels and biomass production response in mustard was significant ($P = 0.02$; $R^2 = 0.41$). Unfortunately, it is unknown whether the difference in biomass production by rate for mustard was due primarily to pre-existing soil P availability, applied P, or a combination of factors. Regardless, these findings strongly suggest that mustard growth was enhanced by increased P levels despite average soil P levels near the critical level. In a glasshouse experiment using a low Olsen P (Olsen P = 6.2 mg kg^{-1}), low pH soil (5.6), Haynes (1992) found biomass yield for two mustard species, rape and kale, was higher when supplied with RP compared to a 0 P control, despite an increase in

anion uptake and resultant increase in soil pH. Thus, these results highlight the potential responsiveness of *Brassicaceae* species to P, even when in sparingly soluble form.

Tissue P concentrations were nearly two fold higher for mustard (0.3%) than either spring pea (0.16%) or buckwheat (0.16%); however tissue P concentrations were not significantly enhanced by the addition of RP for any crop species (Table 2.5; Appendix Table A.3). This is in contrast to studies by Haynes (1992) and Bekele et al. (1983) who found tissue P concentrations of the Brassica specie, rape, were significantly higher following the application of a low solubility RP compared to a 0P control. Tissue P concentrations for buckwheat in the Haynes (1992) study were also enhanced by the application of RP. Buckwheat shoot tissue P concentrations in our study were nearly half that found by Haynes (1992) and were unresponsive to increasing P rate, perhaps due to differences in experimental conditions. Specifically, the soil pH in the study by Haynes was 5.6, one to two units lower than the range seen at the Big Sandy site. At this lower pH, calcium phosphates should be substantially more soluble. In addition, Haynes (1992) utilized North Carolina RP in the study, which is considered one of the most reactive RP products (Khasawneh and Doll, 1978).

Phosphorus uptake differed among crop types ($P < 0.001$; Appendix Table A.4) and followed the pattern of spring pea P uptake (6.1 kg ha^{-1}) greater than mustard (1.8 kg ha^{-1}) greater than buckwheat (1.0 kg ha^{-1}) and was related primarily to the significant differences in the biomass response. Phosphorus uptake of buckwheat and spring pea was unresponsive to increasing P rate whereas mustard P uptake was significantly higher (53%) at the 7.7P level compared to the control (Figure 2.3). Buckwheat and spring pea

showed no P uptake response to increasing P rate suggesting these crops were not limited by P. The absence of a P response in buckwheat to applied P in this study differed from previously observed studies (Haynes, 1992; Zhu et al., 2002; Rick et al., 2007), however these studies were conducted in greenhouse experiments in soils with much lower residual P levels. Mustard P uptake responded to increasing P rate from either pre-existing plant available Olsen P or applied RP. The amount of applied plant available P exceeded P uptake for buckwheat and mustard at all rates, and for spring pea at the 7.7P rate, but not the 3.1P rate. Applied rates of available P in this study were lower than is typical in many research studies making responses to applied rates difficult to quantify, particularly when coupled with pre-existing Olsen P levels at or near critical levels. However, the applied rates do reflect economically viable rates for organic producers and the pre-existing Olsen P levels at this site are similar to the range found in other NGP organic systems (Chapter 4).

Winter Wheat Phase

Winter wheat grain yields differed with respect to previous GM crop (Figure 2.4; Appendix Table A.5). Grain yields of wheat following mustard (2.7 Mg ha $^{-1}$) and tilled fallow (2.6 Mg ha^{-1}) were significantly higher than wheat following buckwheat (2.4 Mg ha^{-1}). Grain yields following spring pea (2.5 Mg ha^{-1}) did not differ from either tilled fallow or buckwheat. Differences in soil moisture prior to seeding the winter wheat crop in Sept 2006 may partially explain the disparity in the grain yield. Soil water contents in the upper 30-cm can affect seedling establishment period and followed the order: fallow = mustard > buckwheat > spring pea (P. Miller, in prep.). Soil moisture contents in the

upper 120-cm may also impact crop growth and yield potential and followed the order: fallow > mustard > buckwheat > spring pea (P. Miller, in prep). Reduction in soil moisture can affect N assimilation due to diminished mass flow of NO_3^-, in addition to directly affecting plant growth. Soil water following spring pea was the lowest at the time of winter wheat sowing, yet grain yields following spring pea were not significantly lower than tilled fallow. In the water limited production environment of the NGP, grain yields are commonly higher following summer fallow, so it is noteworthy in this study that grain yields following two of the three GM crops did not differ significantly from tilled fallow despite higher water utilization and greater P (and N) uptake of the GM crops. Precipitation during the establishment and early growth period of the winter wheat crop (Sept-Oct) was 28% above the LTA, likely decreasing effects of water content differences at seeding.

Grain yields of the winter wheat crop following spring pea, mustard, and tilled fallow did not differ significantly among P rates, with the exception of wheat following buckwheat which was higher at the 7.7P level than the 0P control. When averaged over crop, grain yields responded to increasing P rate which boosted grain yields from 2.4 Mg ha^{-1} (0P) to 2.6 Mg ha^{-1} (7.7P). The absence of a robust yield response to added P may be because soil test P levels were near or above critical levels or that agronomic rates of available P applied were too low to elicit a measurable response. However, the absence of a larger yield response may be related more to severe N limitation at the site which would reduce P response. Grain yields in the 0P control were lower following buckwheat

than after fallow or mustard, yet at the 7.7P rate there were no significant differences among crops.

Grain protein levels of the wheat test crop were low, averaging only 8.7% across all treatments, indicating plant growth at the site was N limited (Figure 2.5). Protein levels were highest following spring pea (9.2%) and mustard (8.9%) and lowest following tilled fallow (8.6%) and buckwheat (8.1%). Grain protein levels below 12.1 % indicate N deficiency in winter wheat (Engel et al., 2006). In the adjoining companion study soil NO_3-N content at the close of the GM stage (27 Sept 2006) was higher in tilled fallow (29 kg ha^{-1} at 0.6 m depth) than in spring pea (22 kg ha^{-1}; Izard, 2007), yet wheat grain protein levels following spring pea were higher than following tilled fallow. Spring pea did take up 66 kg N ha^{-1} (Izard, 2007), which would have the potential to become available to the subsequent wheat crop upon decomposition. Low grain protein levels of wheat following buckwheat suggest the extended duration of the buckwheat crop may have mined soil N reserves, or reduced soil water contents enough to affect N uptake, or both. Higher grain protein levels of wheat following spring pea underscore the benefit of an N-fixing legume GM in organic systems when external inputs are limited. However, all grain protein levels at this site were well below the 12.1% critical level suggesting legume GM alone may not be capable of meeting the N need of grain crops.

Phosphorus tissue concentrations measured in the wheat crop were 10 fold higher in the grain than in the shoot biomass (Table 2.6). Average tissue P concentration of grain and shoot biomass were 0.35% and 0.03%, respectively. Total aboveground P uptake (shoot + grain) of wheat was relatively consistent across crop types with the

exception of buckwheat. Phosphorus uptake in wheat following buckwheat was 15% higher for 7.7P than for 0P (Figure 2.6; Appendix Table A.6). The P uptake difference between these treatments represented 45% of the applied available P. The corresponding increase in P uptake with increased P rate in wheat following buckwheat suggests buckwheat is capable of dissolving the added P in RP. Phosphorus uptake in the wheat following spring pea, mustard, and tilled fallow was not enhanced significantly by RP fertilization. Total P uptake for all treatments exceeded the rates of available P applied in this experiment; therefore the wheat crop accessed existing available soil P reserves to meet crop demand. Rock phosphate adds a greater quantity of total P than available P to the soil, thus total P added was higher than P uptake levels of both GM and winter wheat crops combined; however, the total P fraction of RP is relatively recalcitrant and likely remains insoluble under NGP soil conditions.

Sequential P Fractionation

Inorganic soil P fractions for spring 2007 are presented in Figure 2.7. Mean Bicarb-P concentration was 16.2 mg kg^{-1}. The Bicarb-P fraction did not differ among crops or rate, but crop by rate interaction was significant and was similar to that prior to the initiation of the study (Figure 2.1; Appendix Table A.7). The pre-existing soil test P pattern for mustard observed in the 2006 Olsen analysis was present in the 2007 Bicarb-P results and persisted in the NaOH and HCl inorganic P fractions, as well, making it difficult to determine if P uptake in mustard was responding to soil test P levels or applied P (Appendix Tables A.8, A.9). Despite the addition of RP and growth of a GM crop there was little change between the 2006 Olsen P and 2007 Bicarb-P concentrations.

Addition of RP did not significantly change Bicarb-P values in 2007 (data not shown). Bicarb-P across the study site ranged from 9.7 mg kg^{-1} to 24.1 mg kg^{-1}; hence, available soil P reserves may not be sufficient to meet the needs of the developing winter wheat crop making it necessary to access less labile soil P fractions to meet P demand.

In neutral to alkaline soils, RP is sparingly soluble and does not readily dissolve, thus RP applied in such conditions can remain as a Ca-P mineral relatively inaccessible to plants. It is expected that this recalcitrant form of Ca-P would manifest in the HCl-P fraction, yet there were no significant differences between the 7.7P rate than the 0P control, despite an apparent trend in that direction. As labile P is removed from the soil through the harvesting of crops, less labile fractions can eventually become available based on long term research comparing organic and conventional systems (Gosling and Shepard, 2005).

Conclusions

In a two-yr cropping sequence the combined use of RP with annual GM crops was generally not effective in improving yield or P nutrition of a subsequent winter wheat crop. Grain yields and P uptake in the winter wheat crop following mustard, spring pea, and tilled fallow were not significantly enhanced by the addition of RP. Conversely, in wheat following buckwheat, P uptake increased as P rate increased, indicating buckwheat may modify the rhizosphere and facilitate the dissolution of RP in a neutral to alkaline soil environment. Unfortunately, the absence of a clear response to increasing available P may reflect the low agronomic rates of available P applied in this study or the severe N

limitation of the site. Total phosphate in RP is considerably higher than available P, and total P applied was more than sufficient to meet the P uptake demand of both the GM and winter wheat crops. Phosphorus in the form of RP added to the soil system, while not highly plant available, will increase residual soil P supplies for potential long-term use and may prevent mining of soil P reserves. For broad-acre farms in the NGP that are far from manure sources, RP may represent the only practical strategy for maintaining P fertility in organic cropping systems.

Soil water and N are the most limiting factors to crop productivity in the NGP and results of this study illustrate how important N is to organic production systems. Nitrogen is essential to prevent low grain protein and yield loss. Nitrogen fixing legumes form the foundation of N fertility management in NGP organic cropping systems, therefore it is essential that any decision to replace a N-fixing crop with a non-N-fixing crop have a distinct benefit superseding that of N, otherwise N fertility will decline. Based on the results of this study it is recommended that GM crops be selected on the basis of their ability to increase N fertility through fixation rather than their P solubilizing capability. A brief two-yr field experiment at a single site with relatively high labile soil P levels may not be representative of organic systems. Therefore, additional work on lower P soils is needed to confirm, or refute, the findings of this study.

References Cited

Aguilar S., and A. Van Diest. 1981. Rock phosphate mobilization induced by the alkaline uptake pattern of legumes utilizing symbiotically fixed nitrogen. Plant Soil. 61: 27-42.

AOAC. 2008. Association of Official Analytical Chemists Official Method 978.01: Phosphorous (Total) in Fertilizers. AOAC, International, Gaithersburg, MD.

Barnes, J.S., and E.J. Kamprath. 1975. Availability of North Carolina rock phosphate applied to soils. Tech. Bull. 229: 3-23.

Bauder, J.W., S. Mahmood, B.E. Schaff, D.J. Sieler, J.S. Jacobsen, and E.O. Skogley. 1997. Effect of phosphorus soil test level on sorghum-sudangrass response to phosphorus fertilizer. Agron. J. 89: 9-16.

Bekele, T., B.J. Cino, A.I. Ehlert, A.A. Van Der Maas, and A. Van Diest. 1983. An evaluation of plant-borne factors promoting the solubilization of alkaline rock phosphates. Plant Soil. 75: 361-378.

Bolan, N.S., J. Elliot, P.E.H. Gregg, and S. Weil. Enhanced dissolution of phosphate rocks in the rhizosphere. Biol. Fertil. Soils. 24: 169-174.

Brady, N.C., and R.R. Weil. 2004. Elements of the Nature and Properties of Soils, 2nd Ed., Pearson Prentice Hall, Upper Saddle River, New Jersey.

Bumaya, A.H., and D.V. Naylor. 1988. Phosphorus sorption and extractability in Andic soil incubated with plant residues of variable P content. Plant Soil. 112: 77-81.

Campbell, C.A., G.P. Lafond, J.T. Harapiak, and F. Selles. 1996. Relative cost to soil fertility of long-term crop production without fertilization. Can. J. Plant Sci. 76: 401-406.

Campbell, C.A., R.P. Zentner, F. Selles, P.G. Jefferson, B.G. McConkey, R. Lemke, and B.J. Blomert. 2005. Long-term effect of cropping system and nitrogen and phosphorus fertilizer on production and nitrogen economy of grain crops in a Brown Chernozem. Can. J. Plant Sci. 85: 81-93.

Chien, S.H., G. Carmona, J. Henao, and L.L. Prochnow. 2003. Evaluation of rape response to different sources of rock phosphate in alkaline soil. Comm. Soil Sci. Plant Anal. 34: 1825-1835.

Ellis, R., Jr., M.A. Quader, and E. Truog. 1955. Rock phosphate availability as influenced by soil pH. Soil Sci. Soc. Am. Proc. 19: 484-487.

Engel, R.E., D.S. Long, and G. Carlson. 2006. Grain protein as a post-harvest index of N status for winter wheat in the Northern Great Plains. Can. J. of Plant Sci. 86: 425-431.

Ensminger, L.E., R.W. Pearson, and W.H. Armiger. 1967. Effectiveness of rock phosphate as a source of phosphorus for plants. U.S. Dept. Agric. ARS 41-125. Washington, D.C.

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

Fixen, P.E., and T.S. Murrell. 2002. P and K reserves growing thinner. Fluid J. 10: 1-3.

Gahoonia, T.S., N. Claassen, and A. Jungk. 1992. Mobilization of phosphate in different soils by ryegrass supplied with ammonium or nitrate. Plant Soil.140: 241-248.

Gee, G.W. and J.W. Bauder. 1986. Particle size analysis. p. 383-411. *In* A. Klute (ed.) Methods of Soil Analysis, Part 2, 2nd Ed. Agron. Mongr. No. 9. ASA and SSSA. Madison, WI.

Gliksman, J.E. 1994. Comparison of direct extraction and AOAC official methods for available P_2O_5 in fertilizers: collaborative study. J. AOAC Int. 77: 795-802.

Gosling, P., and M. Shepard. 2005. Long-term changes in soil fertility in organic arable farming systems in England, with particular reference to phosphorus and potassium. Agric. Ecosyst. Environ. 105: 425-432.

Grant, C.A., D.N. Flaten, D.J. Tomasiewicz, and S.C. Sheppard. 2001. The importance of early season phosphorus nutrition. Can. J. Plant Sci. 81: 211-224.

Haynes, R.J. 1992. Relative ability of a range of crop species to use phosphate rock and monocalcium phosphate as P sources when grown in soil. J. Sci. Food Agric. 60: 205-211.

Hedley, M.J., J.W.B. Stewart, and B.S. Chauhan. 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. Soil Sci. Soc. Am. J. 46: 970-976.

Hoffland, E., R. Günter, F. Nelemans, and J.A. Nelemans. 1989. Solubilization of rock phosphate by rape. Plant Soil. 113: 115-160.

Izard, Erica. 2007. Seeking sustainability for organic cropping systems in the Northern Great Plains: legume green manure strategies. Master's Thesis. Montana State University, Bozeman, MT.

Jackson, G.D., G.D. Kushnak, G.R. Carlson, D.M. Wichman, and J.S. Jacobsen. 1991. Correlation of the Olsen phosphorus soil test: winter wheat response. Commun. Soil Sci. Plant Anal. 22: 907-918.

Jacobsen, J., G. Jackson, and C. Jones. 2005. Fertilizer guidelines for Montana crops. Public. #EB 161, Montana State Univ. Ext. Serv., Bozeman, MT.

Jones, D.B. 1941. Factors for converting percentages of nitrogen in foods and feeds into percentages of protein. Circ. 183. USDA, Washington, D.C.

Khasawneh, F.E., and E.C. Doll. 1978. The use of phosphate rock for direct application to soils. Adv. Agron. 30: 159-206.

Kirby, E.A., and K. Mengel. 1967. Ionic balance in different tissues of the tomato plant in relation to nitrate, urea and ammonium nutrition. Plant Physiol. 42: 6-14.

Kuehl, R.O. 2000. Design of Experiments: Statistical Principles of Research Design and Analysis. Duxbury Press, Pacific Grove, CA.

Kuo, S. 1996. Phosphorus. p. 869-915. *In* D.L. Sparks et al., (eds.) Methods of Soil Analysis, Part 3. Chemical Methods. SSSA Book Ser. 5. SSSA and ASA, Madison, WI.

Loeppert, R.H., and D.L. Suarez. 1996. Carbonate and gypsum. p. 437-494. *In* D.L Sparks et al., (eds.) Methods of Soil Analysis. Part 3. Chemical Methods. SSSA Book Ser. 5. SSSA and ASA, Madison, WI.

Martin, R.C., D.H. Lynch, B. Frick and P. van Straaten. 2007. Perspective: Phosphorus status on Canadian organic farms. J. Sci. Food Agric. 87: 2737-2740.

McLenaghen, R.D., P.S. Randhawa, L.M. Condron, and H.J. Di. 2004. Increasing phosphate rock availability using a lupin green manure crop. SuperSoil 2004: 3rd Australian New Zealand Soils Conference. Dec. 5-9. Sidney, Australia.

Nelson, D.W. and L.E. Sommers. 1982. Organic carbon. p. 539-579. *In* A.L. Page (ed.) Methods of Soil Analysis, Part 2, 2nd Ed., Page, A.L., Ed., Agron. Mongr. No. 9. ASA and SSSA, Madison, WI.

Nielsen, D.C., and M.F. Vigil. 2005. Legume green fallow effect on soil water content at wheat planting and wheat yield. Agron. J. 97: 684-689.

Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Circ. No. 939 p. 19. USDA, Washington, D.C.

Olsen, S.R., and L.E. Sommers. 1982. Phosphorus. p. 403-430. *In* A.L. Page (ed.) Methods of Soil Analysis, Part 2, 2nd Ed. Agron. Mongr. No. 9. ASA and SSSA. Madison, WI.

Peaslee, D.E., G.R. Burns, and C.A. Black. 1962. Estimation of the relative value of phosphate rock and superphosphate to plants on different soils. Soil Sci. Soc. Am. Proc. 26: 566-570.

Rajan, S.S.S., J.H. Watkinson, and A.G. Sinclair. 1996. Phosphate rocks for direct application to soils. Adv. Agron. 57: 77-159.

Rick, T.L., C.A. Jones, R.E. Engel, and P.R. Miller. 2007. Ability of a green manure crop to increase availability of organic phosphorus fertilizers. Abstract. ASA-CSSA-SSSA International Annual Meetings, New Orleans, LA. Nov. 4-8.

Sall, J., L.Creighton, and A. Lehman. 2007. JMP Start Statistics: A Guide to Statistics and Data Analysis Using JMP, 4th Ed. Cary, NC: SAS Institute Inc.

Steen Jensen, E., and H. Hauggaard-Nielsen. 2003. How can increased use of biological N_2 fixation in agriculture benefit the environment? Plant and Soil. 252: 177-186.

Thomas G.W. 1996. Soil pH and soil acidity. p. 475-490. *In* Sparks, D.L. et al. (eds.). Methods of Soil Analysis. Part 3. Chemical Methods, SSSA Book Ser. 5. SSSA and ASA, Madison, WI.

USDA. 2007. National Organic Program Regulations and Guidelines. Washington, D.C. http://www.ams.usda.gov/NOP/NOP/NOPhome.htm (verified 18 April, 2008).

van Ray, B., and A. van Diest. 1979. Utilization of phosphate from different sources by six plant species. Plant Soil. 51: 577-589.

Weil, R.R. 2000. Soil and plant influences on crop response to two African phosphate rocks. Agron. J. 92: 1167-1175.

Yadvinder-Singh, Bijay-Singh, and C.S. Khind. 1992. Nutrient transformations in soils amended with green manures. Adv. Soil Sci. 20: 237-309.

Yang, J.E., and J.S. Jacobsen. 1990. Soil inorganic phosphorus fractions and their uptake relationships in calcareous soils. Soil Sci. Soc. Am. J. 54: 1666-1669.

Yang, J.E., C.A. Jones, H.J. Kim, and J.S. Jacobsen. 2002. Soil inorganic phosphorus fractions and Olsen-P in phosphorus-responsive calcareous soils: effects of fertilizer amount and incubation time. Commun. Soil Sci. Plant Anal. 33: 855-871.

Zhu, Y-G., Y-Q. He, S.E. Smith, and F.A. Smith. 2002. Buckwheat (*Fagopyrum esculentum* Moench) has high capacity to take up phosphorus (P) from a calcium (Ca)-bound source. Plant Soil. 239: 1-8.

Table 2.1. Monthly precipitation and mean temperature for the crop-year (Sep-Aug) at Big Sandy, Montana, 2005-2007.

	Monthly Precipitation (mm)			Mean monthly temperature (˚C)		
	2005-06*	2006-07	*LTA*[§]	2005-06	2006-07	*LTA*[§]
Sep†	10	41	36	14.8	14.9	14.3
Oct	23	32	21	9.9	6.5	8.2
Nov	34	9	12	2.9	-1.0	-0.6
Dec	13	6	12	-9.0	-2.5	-6.3
Jan	13	5	13	2.1	-4.2	-8.6
Feb	3	25	10	-2.8	-5.6	-5.5
Mar	8	14	17	0.0	5.7	0.2
Apr	40	71	29	10.0	13.2	7.4
May	53	76	61	13.9	17.8	13.1
Jun	76	70	67	18.6	25.5	17.1
Jul	20	3	44	24.0	20.9	21.5
Aug	33	10	34	21.5	14.8	20.2
Crop Year	326	362	356	8.8	8.8	6.8

†Overwinter precipitation is Sep-Apr.

*2005-2006 growing season (May-Aug) precipitation data collected on study site using a manual rain gauge. All other precipitation data obtained from nearest meteorological station at Big Sandy, MT (19 km from study site) as reported by the Western Regional Climate Center (WRCC), Desert Research Institute, Reno, NV.

[§]Long-term average (LTA) climate data from 1971-2000 (WRCC).

Table 2.2. Cultivar, seeding date, and seeding rate.

Crop	Cultivar	Seeding date	Targeted seed rate
			seed m^{-2}
Winter Pea§	*Melrose*	6 Sept 2005	120
Buckwheat*	*Mancan*	13 Apr 2006	200
Spring Pea§	*Arvika*	13 Apr 2006	120
Yellow Mustard	*AC Base*	13 Apr 2006	200
Winter Wheat	*Tiber*	28 Sept 2006	300

§*Nitragin Soil Implant* granular inoculant (Milwaukee, WI), strain 'C' was used to provide rhizobia for pea.
*Early seeded buckwheat crop failed to establish sufficiently, so was terminated with tillage on June 2 and reseeded on same date.

Table 2.3. Green manure termination and tillage operation schedule, 2006.†§

Crop	Termination Date	Tillage Dates
Buckwheat	21 July	13 Apr
		2 June
		4 Sep
Spring Pea	10 July	13 Apr
		18 July
		4 Sep
Yellow Mustard	20 June	13 Apr
		18 July
		4 Sep
Tilled Fallow*		13 Apr
		10 July
		18 July
		4 Sep

†Tillage and termination operations performed parallel to crop rows, except for tillage perpendicular to crop 4 Sept 2006.
§A 4-m heavy duty tandem disc was used for all tillage and termination operations with additional use of a cultivator with spring tine harrows on 13 Apr and 4 Sept.
*Tilled fallow received additional tillage for weed control.

Table 2.4. Summary of sequential P fractionation methods.

Fraction	Extractant	Procedure
1. $NaHCO_3$-P (Bicarb-P)	0.5 *M* $NaHCO_3$ at pH 8.5	Soil:$NaHCO_3$ ratio (1:20); batch-shaken for 0.5 h; centrifuged*
2. NaOH-P	0.1 *M* NaOH	$NaHCO_3$ residue:NaOH ratio (1:20); batch-shaken 16 h; centrifuged
3. HCl-P	1 *M* HCl	NaOH residue:HCl ratio (1:20); batch-shaken 16 h; centrifuged

*Centrifugation at 10,000 rpm for 30 min.

Table 2.5. Mean shoot biomass, P uptake, and tissue P concentration of green manure crops.†

Crop	P Rate‡	Biomass yield	Biomass P uptake	Tissue P concentration
	kg ha^{-1}	-----Mg ha^{-1}-----	------kg ha^{-1}------	------%------
Buckwheat	0	0.67 bc	1.08 c	0.17 b
	3.1	0.65 bc	1.03 c	0.16 b
	7.7	0.65 bc	1.07 c	0.17 b
Mustard	0	0.39 c	1.11 c	0.29 a
	3.1	0.59 bc	1.80 bc	0.31 a
	7.7	0.80 b	2.44 b	0.31 a
Spring Pea	0	3.65 a	5.71 a	0.16 b
	3.1	3.85 a	6.24 a	0.16 b
	7.7	3.94 a	6.45 a	0.17 b
$LSD_{(0.05)}$		*0.40*	*0.87*	*0.03*

†Mean values within a column section followed by the same letter do not differ according to Fisher's Protected LSD ($P < 0.05$).
‡P rate (citrate soluble at pH 7.0) applied as rock phosphate.

Table 2.6. Mean grain yield, shoot biomass yield, grain P uptake, shoot P uptake, grain P concentration, and shoot P concentration for winter wheat, Big Sandy, Montana, 2007.†

Previous Crop	P Rate‡	Grain yield		Shoot biomass		Grain P uptake		Shoot P uptake	Grain P conc.		Shoot P conc.
	kg ha^{-1}	----------Mg ha^{-1}---------				----------kg ha^{-1}--------			---------%--------		
Buckwheat	0	2.18	c	4.36	bc	7.46	c	1.87	0.340	ab	0.043
	3.1	2.32	bc	4.17	c	8.00	bc	1.90	0.345	ab	0.046
	7.7	2.57	ab	5.21	ab	9.21	a	1.78	0.357	a	0.034
Mustard	0	2.62	ab	5.28	ab	9.25	a	1.74	0.354	ab	0.033
	3.1	2.70	a	5.84	a	9.45	a	1.41	0.350	ab	0.025
	7.7	2.71	a	5.25	ab	9.05	ab	2.01	0.336	b	0.039
Spring Pea	0	2.32	bc	4.77	ab	8.08	bc	2.04	0.350	ab	0.044
	3.1	2.55	ab	5.47	ab	8.71	ab	1.40	0.349	ab	0.025
	7.7	2.49	abc	5.16	ab	8.52	ab	2.25	0.342	ab	0.042
Tilled	0	2.50	ab	4.43	bc	8.76	ab	1.81	0.352	ab	0.044
	3.1	2.45	abc	5.23	ab	8.57	ab	1.92	0.353	ab	0.037
	7.7	2.73	a	5.16	ab	9.25	a	1.60	0.340	ab	0.032
$LSD_{(0.05)}$		*0.32*		*1.12*		*1.06*		*NS**	*0.020*		*NS*

†Mean values within a column followed by the same letter do not differ according to Fisher's Protected LSD ($P < 0.05$).

‡Rate is 0, 3.1 and 7.7 kg available P ha^{-1} (citrate soluble at pH 7.0) applied as rock phosphate (RP).

**NS* denotes not statistically significant.

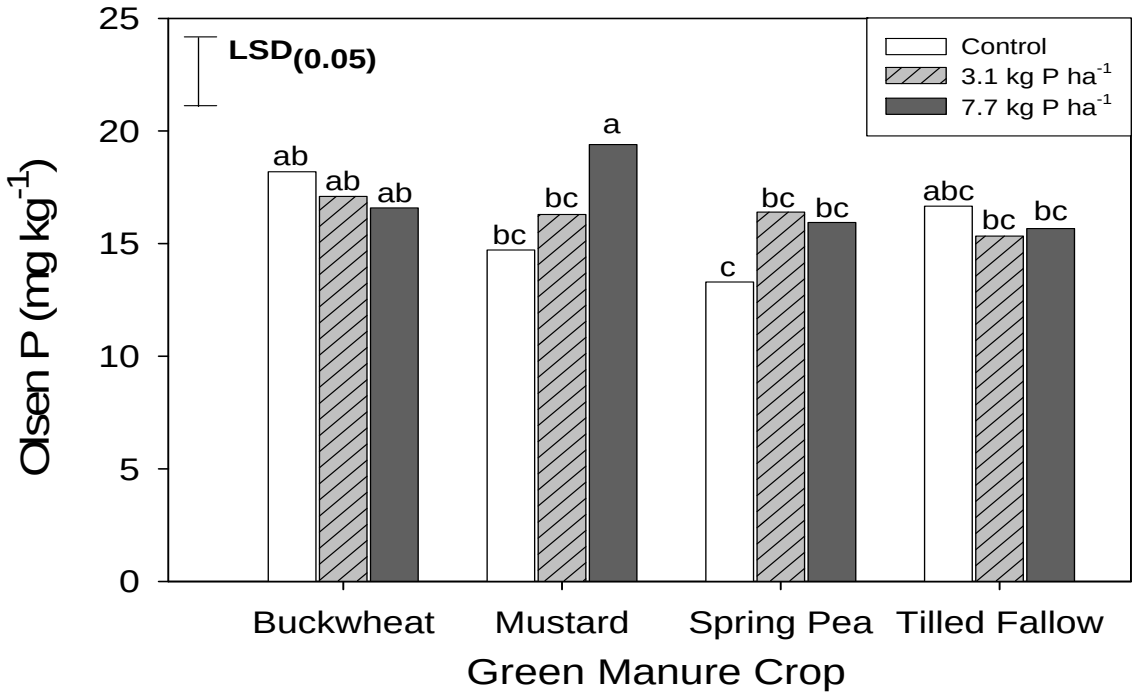

Figure 2.1. Mean pre-experimental Olsen P soil concentrations (mg kg^{-1}) by crop and rate. Prospective fertilizer treatments correspond to 0, 3.1, and 7.7 kg available P ha^{-1} (citrate soluble at pH 7.0) as rock phosphate (RP). Bars with same letter are not significantly different according to Fisher's Protected LSD. $LSD_{(0.05)}$=3.52 mg kg^{-1}.

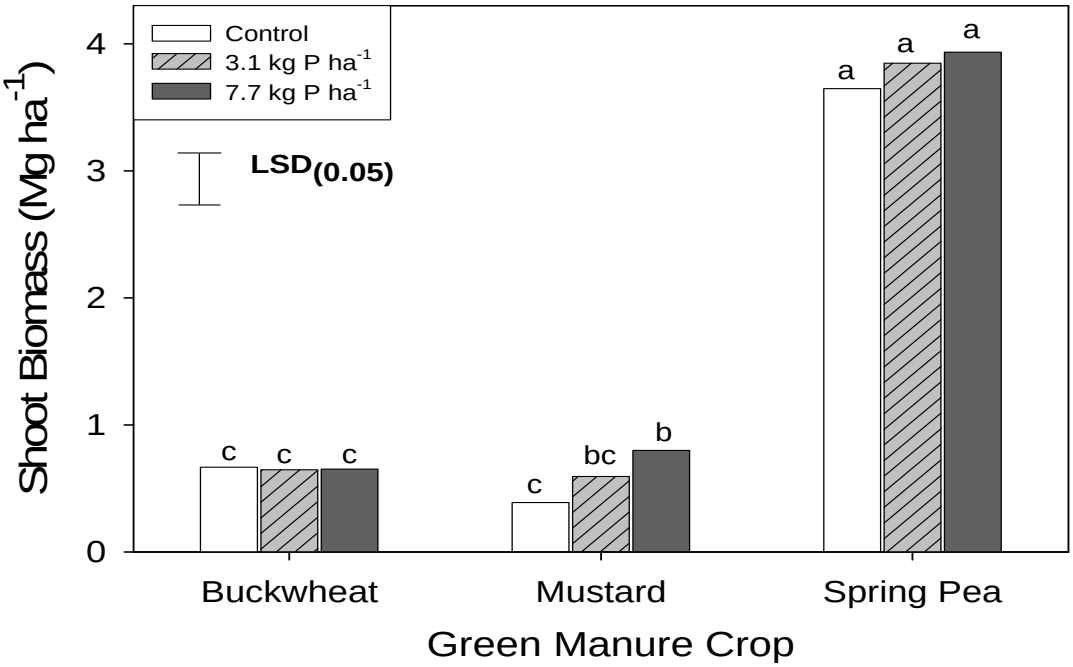

Figure 2.2. Mean shoot biomass yield for three green manure species supplied with 0, 3.1, and 7.7 kg available P ha^{-1} (citrate soluble at pH 7.0) applied as rock phosphate (RP). Bars with same letter are not significantly different according to Fisher's Protected LSD. $LSD_{(0.05)}$=0.39 Mg ha^{-1}.

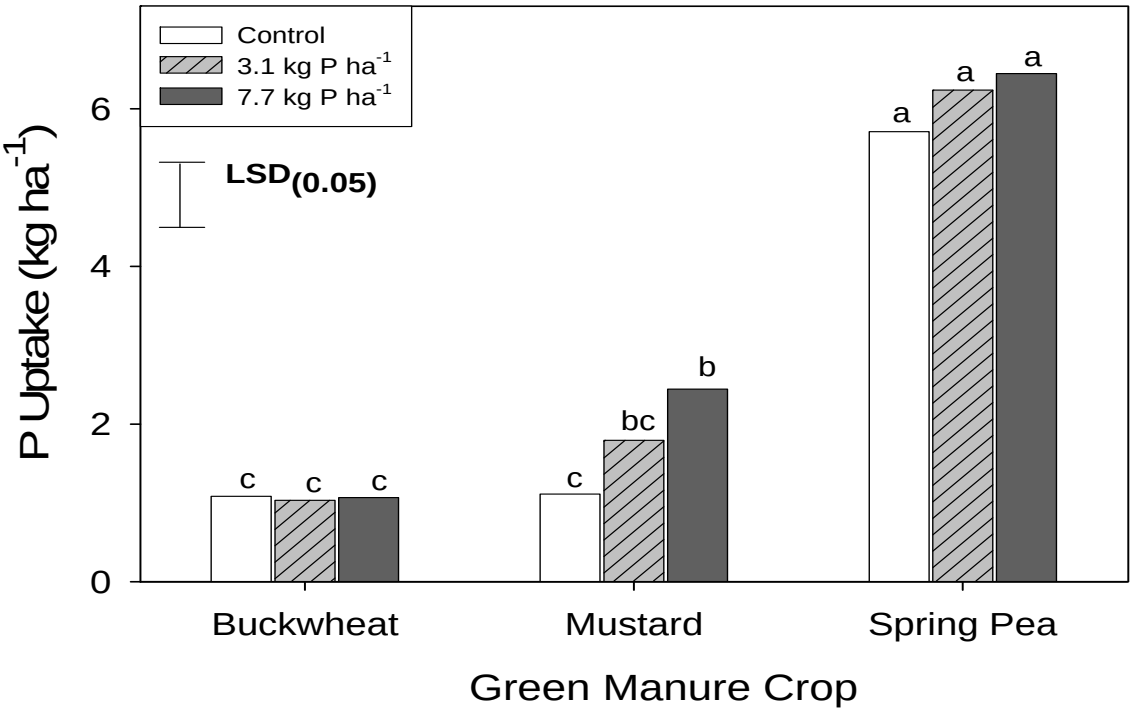

Figure 2.3. Mean P uptake of three green manure species supplied with 0, 3.1, and 7.7 kg available P ha^{-1} (citrate soluble at pH 7.0) applied as rock phosphate (RP). Bars with same letter are not significantly different according to Fisher's Protected LSD. $LSD_{(0.05)}$=0.87 kg ha^{-1}.

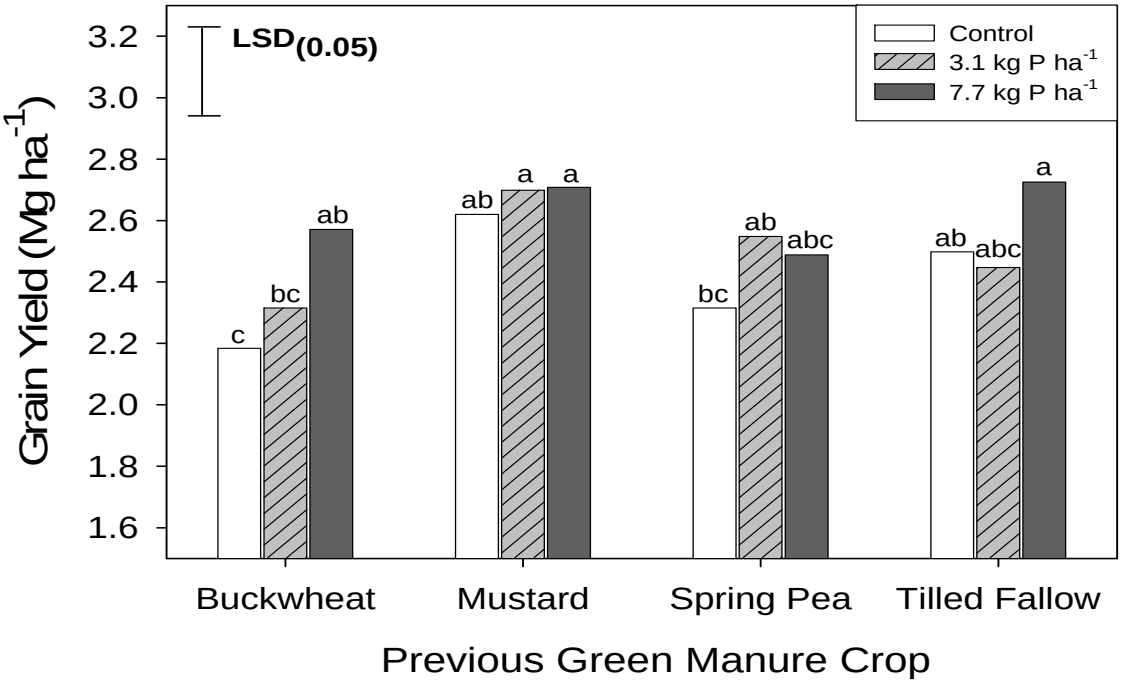

Figure 2.4. Mean grain yield of winter wheat test crop grown following green manure crops treated with 0, 3.1, and 7.7 kg available P ha^{-1} (citrate soluble at pH 7.0) applied as rock phosphate (RP). Bars with same letter are not significantly different according to Fisher's Protected LSD. $LSD_{(0.05)}$ = 0.31 Mg ha^{-1}.

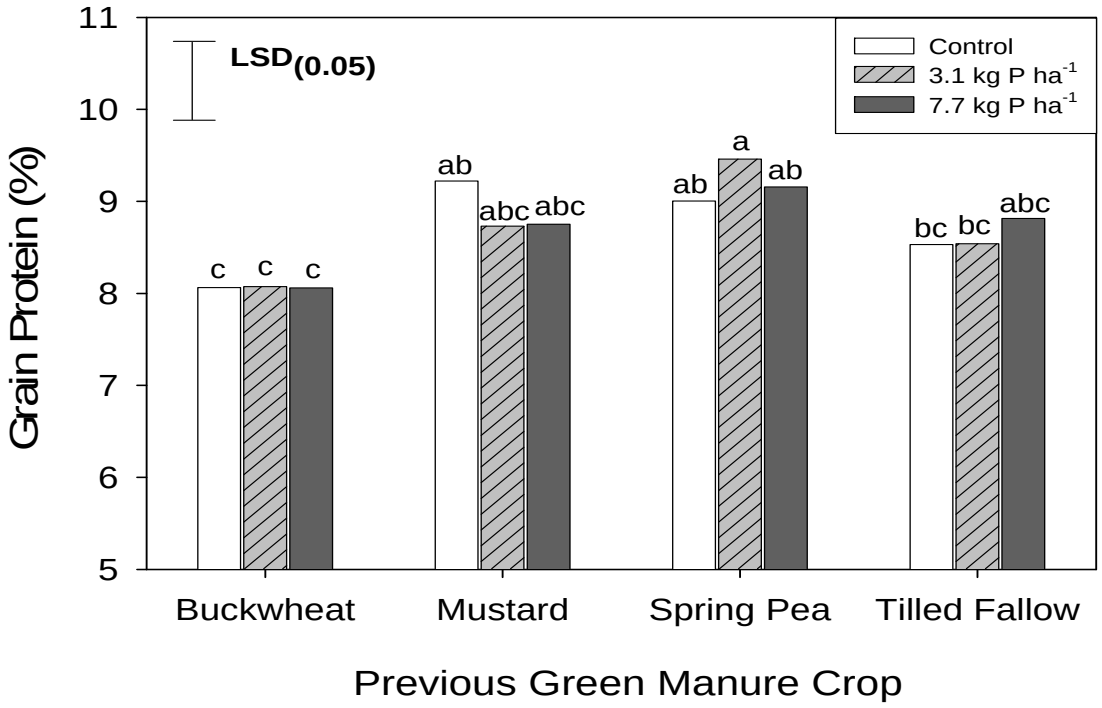

Figure 2.5. Grain protein of winter wheat test crop following green manure crops treated with 0, 3.1, and 7.7 kg available P ha $^{-1}$ (citrate soluble at pH 7.0) applied as rock phosphate (RP). Bars with same letter are not significantly different according to Fisher's Protected LSD. $LSD_{(0.05)}$=0.9%.

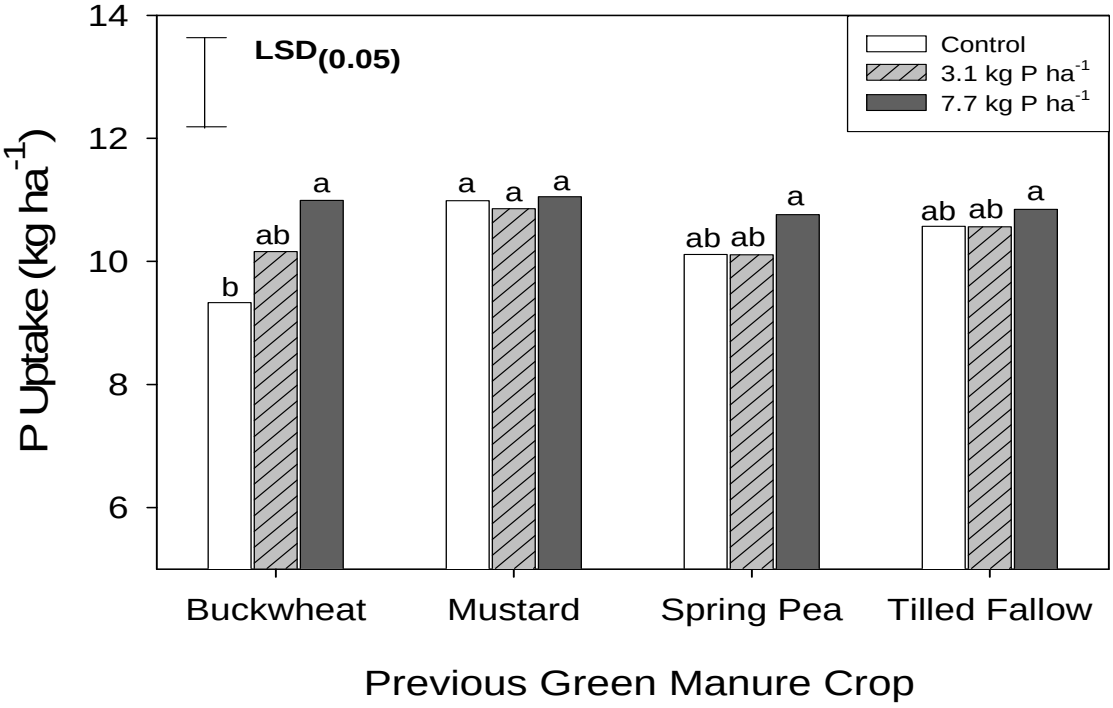

Figure 2.6. Total mean P uptake (grain plus biomass) of winter wheat test crop grown following green manure crops treated with 0, 3.1, and 7.7 kg available P ha^{-1} (citrate soluble at pH 7.0) applied as rock phosphate (RP). Bars with same letter are not significantly different according to Fisher's Protected LSD. $LSD_{(0.05)}$ = 1.4 kg ha^{-1}.

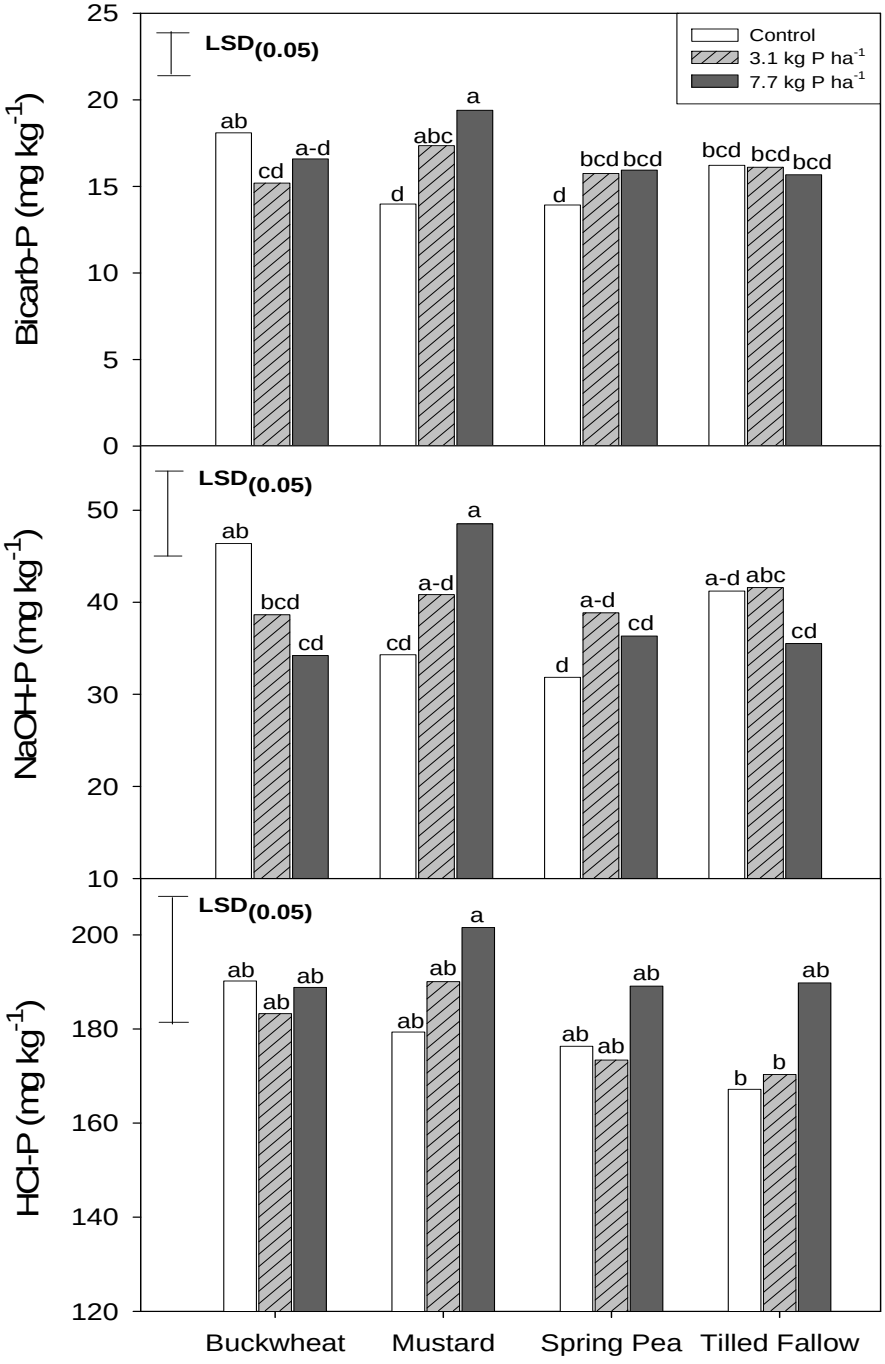

Figure 2.7. Effect of previous green manure crop and fertilization rate [0, 3.1, and 7.7 kg available P ha^{-1} (citrate soluble at pH 7.0) as applied RP] on inorganic soil P fractions (Bicarb-P, NaOH-P, and HCl-P) in Apr 2007. Bars with same letter are not significantly different according to Fisher's Protected LSD. Bicarb-P $LSD_{(0.05)}$=2.8 mg kg^{-1}; NaOH-P $LSD_{(0.05)}$= 9.7 mg kg^{-1}; HCl-P $LSD_{(0.05)}$= 28.9 mg kg^{-1}.

CHAPTER 3

PHOSPHORUS AND BIOMASS RESPONSES OF SPRING WHEAT GROWN IN A GREENHOUSE TO GREEN MANURES AND ORGANIC PHOSPHATE FERTILIZERS

Introduction

Soil phosphorus (P) fertility management in Northern Great Plains (NGP) organic dryland cropping systems is a challenge for producers due to low soil P availability and inadequate mechanisms for replacing P lost or exported during harvest (Fixen and Murrell, 2002; Martin et al., 2007; Nelson and Mikkelsen, 2008). The NGP is dominated by high pH, calcareous soils with a capacity to retain applied and native P, thus limiting P bioavailability (DeLuca et al., 1989; Bauder et al., 1997). Availability of applied P in alkaline soils, even highly soluble P, decreases over time through conversion of P to less soluble forms (Mullins, 1991; Bauder et al., 1997). Low soil P availability is difficult to rectify on organic farms because organic production standards restrict the use of water soluble synthetic P fertilizers, and manure resources are limited in the NGP and contain weed seeds. Organic producers must develop alternative strategies to replenish P lost during harvest and enhance soil P fertility to prevent substantial yield losses. Certified-organic mineral P fertilizers combined with green manure (GM) crops represent a potential approach for increasing soil P fertility on organic farms in the NGP.

Rock phosphate (RP) and bone meal (BM) represent two mineral P sources compatible with organic production standards (National Organic Program, 2007). Rock phosphates are generally ground, unprocessed calcium (Ca) phosphate minerals that

belong to the broad category of apatitic minerals (McClellan and Gremillion, 1980). The composition of RP can differ significantly depending on its geochemical origin and the level of isomorphic substitution which affects the reactivity of the RP in the plant-soil system, and ultimately, agronomic performance (Rajan et al., 1996; van Straaten, 2002). In neutral to high pH soils, calcium-rich RP fertilizers are relatively insoluble often resulting in solution P concentrations too low to provide sufficient P uptake for intensive cropping. (Khasawneh and Doll, 1978; Rajan et al., 1996). Bone meal is raw degreased ground bone containing primarily a calcium phosphate mineral (hydroxyapatite) that is more soluble than RP, but decidedly less soluble than synthetic phosphate fertilizers (Nelson and Mikkelsen, 2008). Bone meal was one of the earliest forms of P fertilizer utilized in agriculture (Leikam and Achron, 2005; Nelson and Mikkelsen, 2008) and in the mid-1800's acidulation of bone meal was initiated to increase its P solubility and plant availability (Stewart et al., 2005; Sanchez, 2007). The dissolution and plant availability of low solubility P sources is dependent on soil characteristics, climate, crop species, and crop management factors.

To enhance availability of sparingly soluble mineral P sources, one proposed approach is to include crop species that are capable of altering the rhizosphere through exudation of organic compounds (Haynes, 1990; Pilbeam et al., 1993; Horst et al., 2001) and/or acidification (Bekele et al., 1983; Haynes 1990; Haynes 1992). Certain plant species are capable of mobilizing P through the exudation of organic acid anions, such as citrate or malate (Dinkelaker and Marschner, 1992; Nuruzzaman et al., 2005). Organic acid anions can influence P nutrition by competing with phosphate groups for both

binding sites in the soil and by forming stable complexes with cations such as aluminum (Al), iron (Fe), and Ca (Hue, 1991; Jones, 1998; Ryan et al., 2001). Gerke et al. (2000) found a close relationship between P solubility and sorption of carboxylates, specifically citrate and oxalate, to the solid phase of the soil. In P-deficient soil conditions, certain legume species, particularly lupin (*Lupinus albus* L.) and chickpea (*Cicer arietinum* L.) have demonstrated the ability to exude large quantities of organic acids into the rhizosphere (Veneklaas et al., 2003).

Plants can affect the dissolution of P sources by modifying the rhizosphere pH through active ion uptake (Aguilar and Van Diest, 1981). Specifically, as plants take up unequal amounts of nutritive anions and cations, plants maintain internal electroneutrality by excreting OH^- or H^+ in quantities stoichiometrically equivalent to the excess in cation or anion uptake (Hedley et al., 1982; Bekele et al., 1983; Haynes, 1990), thereby modifying the rhizosphere pH. For this reason nitrogen (N) source can exert a strong influence on rhizosphere pH. For example, Gahoonina et al. (1992) found rhizosphere pH decreased by 1.6 units when ryegrass (*Lolium perenne*) was supplied with NH_4^+ and increased by 0.6 units when supplied with nitrate (NO_3^-).

Green manure crop species capable of extracting P from sparing soluble mineral P sources may transform P into more labile organic P pools which may be mineralized and released into the soil upon incorporation and mineralization (Stewart and Tiessen, 1987). Since net mineralization will occur only if microbial P demand is less than the quantity of P mineralized, decreasing tissue C:P ratios, or increasing tissue P concentrations, may enhance P release during decomposition. Incorporation of P-enriched residues to P-

deficient soil can further increase soil P availability through the release of organic acids which may enhance dissolution of soil P (Sharpley and Smith, 1989) and decrease P sorption in soils (Singh and Jones, 1976).

As detailed in the previous chapter, a field experiment was conducted in a NGP organic cropping system to evaluate the ability of GM crops fertilized with RP to affect the P nutrition of a subsequent wheat crop. The results of the study were inconclusive perhaps because the field site was marginally P-deficient, was clearly N-limited, and soil water at winter wheat seeding differed among crops, thus interjecting a level of variability into the results making meaningful inference difficult. Buckwheat fertilized with RP appeared to demonstrate an ability to enhance the P uptake of a subsequent wheat crop above an unfertilized control; however, the field trial consisted of a single two year cropping sequence in a highly variable production environment. In an effort to control environmental factors affecting crop growth, a greenhouse study was conducted to compare the effect of fertilizing GM crops with both unprocessed and synthetic phosphate fertilizers on P availability. Specifically, the objectives of this study were to: (i) compare the effect of sparingly soluble organic phosphate fertilizers (RP and BM) and highly soluble monocalcium phosphate (MCP) on GM growth and P uptake, and (ii) evaluate the combined effects of previous GM crop and P fertilizer on the P nutrition and growth of a subsequent wheat crop.

Methods and Materials

Soil Description and Analysis

Soil from a site with low available P (Olsen P = 4 mg kg^{-1}) was collected from the Ap horizon (0-0.15 m depth) of a dryland organic grain farm in north central Montana (48˚04′675″N, 109˚5′701″W, elevation 967 m). The soil was classified as a Telstad loam (fine-loamy, mixed, Aridic Argiboroll) with 19% clay, 32% silt and 49% sand. Tilled from native sod in 1988, the field was managed organically without the use of synthetic commercial P fertilizers or chemical weed control. Soil fertility was managed by incorporation of nitrogen fixing (N_2-fixing) leguminous GM crops and crop residues.

Soil was cleaned of coarse fragments and non-decomposed crop residue, oven dried for 7 d at 46˚C, and mixed extensively (25 min) in a cement mixer and by shovel to produce a homogeneous blend to pass through a 2.0 mm sieve. Multiple subsamples of soil were collected, bulked, and analyzed for physical and chemical parameters including particle size by hydrometer (Gee and Bauder, 1986), Olsen P by ascorbic acid method (Kuo, 1996), organic matter by loss on ignition (Nelson and Sommers, 1996), pH using a 1:1 soil/deionized water slurry (Thomas, 1996), exchangeable potassium (K) by ammonium acetate extraction (Helmke and Sparks, 1996), and NO_3^- by extraction with KCl (Keeney and Nelson, 1982; Table 3.1).

Phosphorus Sources

The P sources used in this study included: 1) pellatized RP from Soda Springs, Idaho (USA), 2) pellatized Phyta-Grow® BM, and 3) reagent grade water soluble

monocalcium phosphate (MCP; Fisher's Scientific, Pittsburgh, PA). Plant available P is the sum of both water-soluble and citrate-soluble P in inorganic mineral fertilizers as determined by neutral ammonium citrate analysis (Gliksman, 1994). Sub-samples of RP and BM were collected and composited for analysis of available P (water + citrate soluble) and total P using a 4:1 ratio of nitric acid:hydrochloric acid and heat digestion (AOAC, 2008).

Experimental Design

The greenhouse pot experiment consisted of four cropping sequences, including buckwheat (*Fagopyrum esculentum* L. cv. *Mancan*)-wheat (*Triticum aestivum* L. cv. Choteau), spring pea (*Pisum sativum* L. cv Arvika) -wheat, wheat (cv. Hank)-wheat, and a non-crop control-wheat. The first portion of the study is referred to as the GM phase, and the second portion as the wheat phase. Within each cropping sequence there were seven P fertilizer treatments, consisting of RP, BM, and MCP applied at two rates equivalent to 10 (low) and 25 kg P ha^{-1} (high) and a non-fertilized (0 P) control. Phosphorus application rates were based on manufacturer listed available P contents of 1.3% and 4.4% available P for RP and BM, respectively. The P fraction of MCP ($Ca(HPO_4)\cdot 2H_2O$) was 18%. Fertilizer rates applied to pots are detailed in Table 3.2.

Pots (15.0 cm diameter x 15.2 cm depth) were lined with thin muslin cloth to prevent soil loss and then filled with 2.2 kg of dried soil. To enhance agronomic effectiveness, RP and BM were finely ground to pass a 0.15-mm sieve (Khasawneh and Doll, 1978; Rajan et al., 1996). All fertilizer materials were applied in a subsurface band (5 cm depth) across the center of the pot. Buckwheat, spring pea, and spring wheat seeds

were germinated in flats and then transplanted to the greenhouse pots at the start of the experiment. Spring pea was not inoculated with rhizobia. Each pot contained four seedlings placed two on each side and 2 cm away from the band. The experimental design was arranged in a randomized complete block design with four replicates (*n*=112). All treatment blocks and pots within each block were rotated on a weekly basis to minimize edge effect and microclimatic influence.

To prevent soil surface crusting and optimize infiltration of irrigation water, the surface soil was carefully scarified. Water applications were delivered via a modified drip system using a perforated plastic 500-ml graduated beaker seated on a circular Scotch-Brite™ pad. The pad was placed on the soil surface in the center of each pot. Each pot was individually irrigated by hand to ensure neither excessive, nor deficient, soil water application impacted crop performance. Soil moisture was maintained near field capacity (0.25-0.33 g H_2O g-soil^{-1}) by weight. Plant growth conditions were controlled using a 16 h photoperiod and thermostatic temperature regulation between 22.2˚C (day) and 18.5˚C (night). To preclude deficiencies other than P, nitrogen (N) and sulfur (S) were added as aqueous solutions with irrigation water at rates of 100 mg N kg^{-1} as ammonium nitrate (NH_4NO_3) and 7.5 mg S kg^{-1} as magnesium sulfate ($MgSO_4$) at the initiation of the study.

Green Manure Phase

The aerial portion of the first three plants achieving anthesis from each pot were harvested by clipping each plant at the soil surface (approximately 40 d after transplanting), and the non-flowering plant was discarded. Shoot biomass was oven dried

at 50˚C for 72 h, weighed, and finely ground to pass a l-mm screen mesh using a grinding mill (Kitchen Aid, St. Joseph, MI). A 0.25 g subsample of crop residue was collected and analyzed for total tissue P by nitric and perchloric acid digestion (John, 1970). The remaining dried crop residue was stored for later incorporation. Phosphorus uptake of GM crops was calculated by multiplying biomass per unit area by tissue P concentration.

Wheat Phase

Soil and roots were removed from each pot and pulverized with a mortar and pestle to pass a 2-mm mesh. To estimate available soil N reserves, a 15 g subsample of soil was obtained from two replicates of each crop treatment from the control and high P levels of each fertilizer. Soil samples were extracted with 1 M KCl using a 10:1 solution:soil ratio (50 ml extractant:5 g dry soil). The extracts were filtered through a Whatman 42 filter and analyzed for NO_3-N (Keeney and Nelson, 1982) using flow injection analysis (Lachat Instruments, Loveland, CO). The pulverized soil was returned to its respective pot and mixed thoroughly with ground crop residue from the previous GM crop prior to watering to approximate field capacity by weight. At 21 d following the incorporation of the crop residue, 12 spring wheat (cv. *Choteau*) seeds were sown directly into each pot in six groups of two. Upon germination, groups were thinned for a total of six plants per pot. The spring pea and buckwheat pots were fertilized with 100 mg N kg^{-1} and spring wheat and fallow pots with 75 mg N kg^{-1} as aqueous NH_4NO_3 to match available N levels between treatments based on soil NO_3-N levels to preclude N limitation in crop performance.

Wheat plants were harvested at anthesis (60 d after sowing) by clipping the plant at the soil surface. Shoot biomass was measured after oven drying the plant material at 50˚C for 72 h. The plant material was then ground to pass a 2-mm mesh using a Wiley mill (Thomas Scientific, Swedesboro, NJ), followed by grinding in a Cyclone sample mill (Thomas Scientific, Swedesboro, NJ) to pass a l-mm screen mesh. Subsamples of the ground biomass were analyzed for total tissue P using the method described in the GM phase. A 100 mg subsample of ground plant tissue was oven dried for 3 h at 70˚C, cooled for 1 h, and analyzed for total carbon (C) and N using a LECO TruSpec CN combustion analyzer (LECO Corporation, St. Joseph, MO). P uptake by the wheat test crop was calculated as above.

Statistical Analyses

Analysis of variance (ANOVA) was conducted to examine treatment differences using JMP IN 5.1 statistical software (Sall et al., 2007). All data sets were tested for uniformity of variance according to the F max tests. F max testing for shoot biomass and P uptake of GM crops identified non-constant variance across crop types, thus ANOVA for each GM crop was conducted separately. ANOVA of shoot biomass and P uptake of the wheat test crop was conducted to examine treatment differences among crop type and fertilizer treatments. Fisher's Protected Least Significant Difference (LSD) test was used to identify crop and P rate differences at $P < 0.05$ (Kuhel, 2000). Available P rates varied among fertilizer sources based on subsequent ammonium citrate analysis. Thus, regression analysis was utilized to determine the relationship between the application rate of available P and both tissue P and P uptake.

Results and Discussion

Phosphorus Grade Analysis

Neutral ammonium citrate analysis determined plant available P levels of RP and BM to be 0.93 and 5.7%, respectively, representing a 30% decrease in available P for RP and a 30% increase for BM from manufacturer values (Table 3.3). Thus, available P rates varied between fertilizer sources with actual applied available P rates for RP and BM adjusted to 7.0 and 17.5 kg P ha^{-1} (RP low, RP high), 13.0 and 32.5 kg P ha^{-1} (BM low, BM high) and MCP unchanged at 10 and 25 kg P ha^{-1} (MCP low, MCP high). Total P applied to pots was 16.5 and 41.3 kg ha^{-1} for BM low and high, respectively, and 43.6 and 108.8 kg ha^{-1} for RP low and high, respectively.

Green Manure Phase

Mean shoot biomass was 5.6, 8.9 and 2.4 g pot^{-1} for buckwheat, spring pea and spring wheat, respectively. Shoot biomass of each crop was not increased by P, except at the MCP high rate (Table 3.4; Appendix Tables B.1, B.2, B.3). Shoot biomass of buckwheat at the BM low rate and MCP high rate were not different despite 48% less citrate-soluble P applied in the BM low treatment. Shoot biomass of spring pea was enhanced by MCP high, but not organic P fertilizer sources, indicating spring pea was responsive to water soluble P but not the less soluble RP and BM sources. Shoot biomass production of spring wheat was minimal as the crop failed to tiller effectively. Tillering in spring wheat was reduced in the control, RP and BM fertilizer treatments compared to both MCP treatments, however tillering was not robust in any treatment (data not shown).

Tillering is decreased by P deficiency (Davidson and Chevalier, 1990; Rodriguez et al., 1999) particularly when deficiency occurs early in the development of the crop (Campbell et al., 2001). Thus, because the initial soil P levels were very low (4 mg P kg^{-1}), it is likely that P deficiency impacted growth early in the development especially in the control and organic fertilizer treatments where soluble P concentrations were likely low compared to the highly soluble MCP treatment (Sample et al., 1980). A reduction in shoot biomass production in wheat may also be due to the inability of wheat to acidify the root zone to enhance P acquisition. Wheat is typically not effective at acidification of the rhizosphere (Bekele et al., 1983) as the crop tends to have a preference for NO_3^- as an N source which may result in a rise in the root zone pH.

Mean P uptake was 10.5, 10.0, and 4.3 mg P pot^{-1} for buckwheat, spring pea, and wheat, respectively (Appendix Tables B.4, B.5, B.6). Phosphorus uptake in buckwheat was higher in the BM high and low and RP high treatments compared to the 0 P control, indicating buckwheat is capable of utilizing sparingly soluble P sources (Table 3.4). Buckwheat tissue P concentrations following BM high were significantly higher than at either MCP rate. Tissue P content (Figure 3.1) and P uptake (Figure 3.2) in buckwheat were positively correlated to the water and citrate-soluble P levels determined by analysis of the fertilizer P sources. Similar relationships were not found for spring pea or spring wheat indicating that water and citrate-soluble P tests provide a good index of plant available P in this soil, but only for buckwheat. Haynes (1992) found tissue P concentrations in buckwheat to be consistently higher (0.28-0.33%) than those found in this study (0.12-0.27%). Soil pH in the Haynes (1992) study was 5.6 which is more

favorable for solubilization of P than at the soil pH of 7.2 in this study. Tissue P concentrations of each crop, including buckwheat, were overall lower than the commonly reported 0.2-0.3% required for net mineralization, but higher than the 0.1% threshold level determined by Bumaya and Naylor (1988). Tissue P concentrations are an important determinant of net P mineralization of soil organic P and are especially important because the organic P pool can comprise from 30-80% of the total P in agricultural soils (McCall et al., 1956) and is a key source of P in organic systems.

In this study, buckwheat demonstrated an ability to enhance the availability of sparingly soluble P sources as effectively as water soluble MCP even when supplied with NH_4NO_3 as the N source. The NH_4^+ in NH_4NO_3 is usually quickly oxidized to NO_3^- in the soil and the pH of the rhizosphere of plants utilizing NO_3^- as an N source will often increase and reduce the solubility of P (Flach et al., 1987; Gahoonia et al., 1992). However, despite this generality buckwheat appears to utilize sparingly soluble P sources even in the presence of NO_3^-. Other workers found buckwheat effective at utilizing RP when NO_3- was supplied as an N source (van Ray and van Diest, 1979; Bekele et al., 1983; Haynes, 1992). In fact, Zhu et al. (2002) demonstrated buckwheat was highly efficient at utilizing RP when NO_3^- was the N source, noting total P uptake was 10-fold higher in buckwheat than spring wheat.

Spring pea was generally unresponsive to P fertilization as P uptake was only enhanced above the control for MCP at the high rate. Unlike buckwheat, there was no significant correlation between applied P rate and P uptake or tissue P concentration of spring pea (data not shown). This suggests spring pea was ineffective at mobilizing less

soluble P sources. In contrast, previous studies have found legume species to be highly effective at dissolution and utilization of less soluble P sources primarily through acidification of the rhizosphere or through release of root exudates (Haynes 1992; Kamh et al., 1999; Horst et al., 2001; McLenaghen et al., 2004). It was determined that cation uptake will usually exceed anion uptake in leguminous plants reliant on symbiotic N-fixation for N nutrition resulting in rhizosphere acidification through a net efflux of protons (Hinsinger et al., 2003). However, when leguminous plants are supplied with NO_3^- as an N source or in situations of high N fertility, uptake of anions will generally exceed uptake of cations and the rhizosphere pH will rise. Biological N-fixation in leguminous species is inhibited by NO_3^- because it decreases nodulation (Bekele et al., 1983; Garcia-Plazaloa et al., 2000). Thus, the ability of legumes to acidify the rhizosphere and mobilize sparingly soluble P sources is highly dependent on the source of N nutrition. Since NH_4NO_3 was used to supply N for spring pea, rather then allowing natural N-fixation, rhizosphere acidification was likely suppressed, thereby decreasing the solubility of both RP and BM.

Phosphorus uptake by wheat was lower than spring pea or buckwheat. Uptake of P in wheat did not differ between MCP treatments and the 0 P control. Phosphorus uptake was lower than the control with the application of RP at the low rate. Zhu et al. (2002) found total P uptake was significantly lower in wheat when RP was combined with NO_3^- as the N source compared to wheat supplied with RP and NH_4^+. It was postulated the shift from NO_3^- to NH_4^+ enhanced the mobilization of RP by decreasing the rhizosphere pH from a net efflux of protons (Zhu et al., 2002). Since wheat appears to have a slight

preference for NO_3^- over NH_4^+ nutrition (Bekele et al., 1983) and because NH_4^+ typically oxidizes to NO_3^- quickly under arable field conditions (Schmidt, 1982), the above results suggest that direct application of either RP or BM to wheat is not effective in enhancing P nutrition.

Levels of available P applied among P sources varied due to the disparity between the reported manufacturer's grade and the citrate-soluble analysis. Reactivity of unprocessed non-conventional phosphate fertilizers, like RP or BM, can be highly variable depending upon the chemistry of source and the particular soil-plant system to which it is applied (Khasawneh and Doll, 1978; Rajan et al., 1996). Ammonium citrate is utilized to determine the level of P bioavailability under neutral pH conditions, but actual P bioavailability can be diminished in soils with higher pH or under a limited moisture regime. The degree of variability of available P found in these unprocessed mineral P fertilizers may impact the relative agronomic effectiveness of P source in the NGP.

Wheat Phase

Previous GM crop and P fertilizer treatments demonstrated statistically significant effects on wheat shoot biomass, P uptake, and tissue P concentrations (Table 3.5; Appendix Tables B.7, B.8, B.9). Shoot biomass of wheat followed the order: non-crop control (7.7 g pot^{-1}) > wheat (7.3 g pot^{-1}) = buckwheat (7.1 g pot^{-1}) = spring pea (6.9 g pot^{-1}). Increased biomass production or grain yield following fallow is common in water-limited production environments that utilize a fallow system to conserve water; however, water availability was not a limiting factor in this study. Therefore, increased biomass production in the non-cropped control was likely caused by increased nutrient availability

due to the absence of plant uptake. Biomass production of wheat following buckwheat was largely unresponsive to P source or P rate, except at the MCP high rate where a small increase in shoot biomass was observed (Table 3.6). Shoot biomass of wheat following spring pea, wheat and the non-crop control was more responsive to MCP. Biomass production of wheat was not enhanced by the addition of the organic P sources, except following spring pea when treated with RP at a low rate.

Phosphorus uptake of wheat was significantly affected by previous crop and followed the order: non-crop control (13.5 mg P pot^{-1}) > wheat (11.8 mg P pot^{-1}) = buckwheat (11.8 mg P pot^{-1}) > spring pea (8.9 mg P pot^{-1}). Phosphorus source significantly affected P uptake. Generally significant responses to P fertilization were observed from MCP and RP sources, while BM increased P uptake of wheat only following buckwheat at the higher P rate (Table 3.6). Since the applied available P in this study was 46% higher in BM than RP, this result is noteworthy. Although there is scant research on the solubility of BM, the primary mineral in BM is a Ca-P mineral described as a "calcium-deficient hydroxyapatitie" which is considered more soluble than calcium-based RP, which is closer to fluorapatite (Dorozhkin, 2007; Nelson and Janke, 2007; Nelson and Mikkelsen, 2008). It's likely that the BM dissolved more quickly than RP, giving it more time to become strongly adsorbed or precipitated as a more insoluble mineral. Another possibility for the difference is that more total P was added with RP to obtain the same amount of available P (Table 3.2). Specifically, 0.8 and 2.8 mg P pot^{-1} were added for BM high and RP high, respectively. Only a small fraction of the

"insoluble" P fraction in RP would need to have become available to significantly increase the actual amount of available P.

Phosphorus uptake of wheat following all GM crops improved when supplied with MCP demonstrating that increased bioavailability of a highly soluble P source can positively influence the P nutrition of a subsequent crop. Averaged over all crops MCP was significantly more effective at increasing P uptake than the organic fertilizers ($P < 0.001$). However, RP was effective at increasing P uptake of the wheat crop in the second phase, but not of wheat in the GM phase suggesting RP can be available to wheat if allowed sufficient time to incubate in the soil. Some studies indicate effective dissolution of RP may take as long as 90 d (Rajan et al., 1996).

Phosphorus uptake in the wheat test crop was not correlated with P uptake in the GM ($P = 0.94$). In the GM phase, spring pea and buckwheat produced significantly more biomass than wheat. The addition of GM residues to the soil requires mineralization prior to P becoming available for the subsequent crop. Crop residues had a short residence (21 d) time after incorporation before sowing the wheat test crop, which may have been insufficient for mineralization. For example, Enwezor (1976) determined net P mineralization occurred only after 12 w in pea residue. In addition to residence time, tissue P concentrations affect the C:P ratio of residues and the rate of organic P mineralization. Tissue P concentrations (Table 3.2) of the spring pea were below the 0.2 to 0.3% threshold for mineralization identified by Yadvinder-Singh et al. (1992), but above the 0.1% threshold level determined by Bumaya and Naylor (1988). The higher C:P ratio for spring pea could slow the mineralization process and contribute to the low P

uptake rates for wheat following spring pea. Crop residue with a narrow C:P ratio typically improves P uptake. Perhaps the short duration for mineralization combined with the low tissue P concentration (and hence high C:P ratio) delayed mineralization and decreased P availability for the wheat test crop following spring pea and buckwheat compared to fallow. In a similar greenhouse study investigating P availability following GM incorporation, Cavagelli and Thien (2003) found that P uptake by a sorghum test crop (*Sorghum bicolor* L. Moench) following incorporation of lupin (*Lupinus albus* L.) was lower than other crops tested, including the non-crop control, despite P uptake by lupin being two to three times greater than the other crops tested. This again suggests that high P uptake by a GM crop may not be advantageous to the subsequent crop as hypothesized. Perhaps, as postulated by Enwezor (1976), P availability from GM crops should be considered as a long term, rather than short term benefit.

Conclusions

Sparingly soluble P fertilizers were not effective at increasing biomass production of GM crops compared to a non-fertilized control. This suggests biomass production was less responsive to low solubility P sources in the P deficient soil conditions. Phosphorus uptake in buckwheat was enhanced equally by high levels of MCP BM, and RP, thus buckwheat appears capable of utilizing low solubility P sources, especially when compared to spring pea or wheat. Thus, buckwheat may represent an alternative crop for organic producers to enhance the mobilization of low solubility P fertilizers; however, its

use would need to be balanced against the potential gain of N from legumes typically used as GM in the NGP.

Previous crop and P fertilizer source affected the growth and P nutrition of the subsequent wheat crop. Biomass production of the wheat crop was increased following GM supplied with a high rate of MCP, but was unresponsive to GM amended with organic fertilizers. Phosphorus uptake of the subsequent wheat crop was the lowest following spring pea possibly reflecting the high quantity of low P residue returned to the pot and the short incubation period for decomposition and mineralization prior to seeding. Compared to controls, wheat P uptake was enhanced following all crops fertilized with RP and MCP. Phosphorus nutrition of wheat following buckwheat was significantly improved by all three sources of P fertilizer. Of the two actual GM crops tested, only buckwheat demonstrated a heightened ability to increase the P nutrition of the following crop when utilizing low soluble P sources. This result is consistent with a companion field study in the previous chapter where only buckwheat demonstrated the ability to increase P uptake in a subsequent wheat crop when supplied with RP. Thus, the combined results indicate the use of buckwheat to mobilize P from sparingly soluble P sources may be promising and warrant further investigation.

Fertilizer applications were made in terms of plant available rates, yet actual total P applied to the soil was greater and could build soil P reserves for future use. Despite differences in the abilities of different crops to utilize sparingly soluble organic P sources, P availability for the next crop was not increased by buckwheat or spring pea compared to the wheat or fallow in this greenhouse study. The results of this study suggest that RP

may have the potential for increasing P nutrition of a subsequent wheat crop in neutral to alkaline pH, low P soils common in the NGP, especially when RP is applied a few months to a year prior to seeding. For organic farmers in the region seeking a method to maintain soil P fertility, RP may represent a viable alternative while remaining within organic production standards.

References Cited

Aguilar, S., Van Diest, A. 1981. Rock phosphate mobilization induced by the alkaline uptake pattern of legumes utilizing symbiotically fixed nitrogen. Plant Soil. 61: 27-42.

AOAC. 2008. Association of Official Analytical Chemists Official Method 978.01: Phosphorous (Total) in Fertilizers. AOAC, International, Gaithersburg, MD.

Bauder, J.W., M. Shaukat, B.E. Schaff, D.J. Sieler, J.S. Jacobsen, and E.O. Skogley. 1997. Effect of phosphorus soil test level on Sorghum-Sudangrass response to phosphorus fertilizer. Agron. J. 89: 9-16.

Bekele, T., B.J. Cino, A.I. Ehlert, A.A. Van Der Maas, and A. Van Diest. 1983. An evaluation of plant-borne factors promoting the solubilization of alkaline rock phosphates. Plant Soil. 75: 361-378.

Bumaya, A.H., and D.V. Naylor. 1988. Phosphorus sorption and extractability in Andic soil incubated with plant residues of variable P content. Plant Soil. 112: 77-81.

Cavagelli, M.A., and S.J. Thien. 2003. Phosphorus bioavailability following incorporation of green manure crops. Soil Sci. Soc. Am. J. 67: 1186-1194.

Davidson, D.J., and P.M. Chevalier. 1990. Pre-anthesis tiller mortality in spring wheat. Crop Sci. 30: 832-836.

DeLuca, T.H., E.O. Skogley, and R.E. Engel. 1989. Band-applied elemental sulfur to enhance the phytoavailability of phosphorus in alkaline calcareous soils. Biol. Fertil. Soils. 7: 346-350.

Dinkelaker, B., and H. Marschner. 1992. *In vivo* demonstration of acid phosphatase activity in the rhizosphere of soil-grown plants. Plant Soil 144: 199-205.

Dorozhkin, S.V. 2007. Calcium orthophosphates. J. Mater. Sci. 42: 1061-1095.

Enwezor, W.O. 1976. The mineralization of nitrogen and phosphorus in organic materials of varying C:N and C:P ratios. Plant Soil. 44: 237-240.

Fixen, P.E., and T.S. Murrell. 2002. P and K reserves growing thinner. Fluid J. 10: 1-3.

Flach, E.N., W. Quak, and A. Van Diest. 1987. A comparison of the rock phosphate-mobilizing capacities of various crop species. Trop. Agric. 64: 347-352.

Gahoonia, T.S., N. Claassen, and J. Albrecht. 1992. Mobilization of phosphate in different soils by ryegrass supplied with ammonium or nitrate. Plant Soil. 140: 241-248.

Garcia-Plazaola, J.I., A. Hernandez, J.M. Becerril, and C. Arrses-Igor. 2000. Long-term effects of nitrate on Lucerne (*Medicago sativa* L.) nitrogen fixation is not influenced by the denitrification status of the microsymbiont. Plant Soil. 216: 139-145.

Gee, G.W. and J.W. Bauder. 1986. Particle size analysis. p. 383-411. *In* A. Klute. (ed), Methods of Soil analysis, Part 2, 2nd ed., Agron. Mongr. 9. ASA and SSSA. Madison, WI.

Gerke, J., B. Lutz, and W. Römer. 2000. The quantitative effect of chemical phosphate mobilization by carboxylate anions on P uptake by a single root. I. The basic concept and determination of soil parameters. J. Plant Nutr. Soil Sci. 163: 207-212.

Gliksman, J.E. 1994. Comparison of direct extraction and AOAC official methods for available P_2O_5 in fertilizers: collaborative study. J. AOAC Int. 77: 795-802.

Grant, C.A., D.N. Flaten, D.J. Tomasiewicz, and S.C. Sheppard. 2001. The importance of early season phosphorus nutrition. Can. J. Plant Sci. 81: 211-224.

Grant, C.A., G.A. Peterson, and C.A. Campbell. 2002. Nutrient considerations for diversified cropping systems in the Northern Great Plains. Agron. J. 94: 186-198.

Haynes, R.J. 1990. Active ion uptake and maintenance of cation-anion balance: a critical examination of their role in regulating rhizosphere pH. Plant Soil. 126: 247-264.

Haynes, R.J. 1992. Relative ability of a range of crop species to use phosphate rock and monocalcium phosphate as P sources when grown in soil. J. Sci. Food Agric. 60: 205-211.

Hedley, M.J., P.H. Nye, and R.E. White. 1982. Plant induced changes in the rhizosphere of rape (*Brassica napus* var. Emerald) seedlings. II. The origin of the pH change. New Phytol. 91: 31-44.

Helmke, P.A., and D.L. Sparks. 1996. Lithium, sodium, potassium, rubidium, and cesium. p. 551-573. *In* D.L. Sparks (ed.) Methods of Soil Analysis. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI.

Hinsinger, P., C. Plassard, C. Tang, and B. Jaillard. 2003. Origins of root-mediated pH changes in the rhizosphere and their responses to environmental constraints: a review. Plant Soil. 248: 43-59.

Horst, W.J., M. Kamh, J.M. Jibrin, and V.O. Chude. 2001. Agronomic measures for increasing P availability to crops. Plant Soil. 237: 211-223.

Hue, N.V. 1991. Effects of organic acids/anions on P sorption and phytoavailability in soils with different mineralogies. Soil Sci. 152: 463–471

John, M.K. 1970. Colorimetric determination of phosphorus in soil and plant materials with ascorbic acid. Soil Sci. 109: 214-220.

Jones, D.L. 1998. Organic acids in the rhizosphere – a critical review. Plant Soil. 113: 161-165.

Kamh, M., W.J. Horst, F. Amer, H. Mostafa, and P. Maier. 1999. Mobilization of soil and fertilizer phosphate by cover crops. Plant Soil. 211: 19-27.

Keeney, D.R. and D.W. Nelson. 1982. Nitrogen-Inorganic forms. p. 643-698. *In* A.L. Page et. al. (eds.) Methods of Soil Analysis. Part 2, 2nd ed., Agron. Mongr. No. 9. ASA and SSSA, Madison, WI.

Khasawneh, F.E., and E.C. Doll. 1978. The use of phosphate rock for direct application to soils. Adv. Agron. 30: 159-206.

Kuo, S. 1996. Phosphorus. p. 869-915. *In* D.L. Sparks et al., (eds.) Methods of Soil Analysis, Part 3. Chemical Methods. SSSA Book Ser. 5. SSSA and ASA, Madison, WI.

Lachat Instruments. 2000. Quick-Chem Method no. 10-107-04-1-B. Nitrate in 2 M KCl soil extracts. Lachat Instruments, Loveland, CO.

Leikam, D.F., and F.P. Achorn. 2005. Phosphate fertilizers: production, characteristics, and technologies. p. 23-50. *In* Sims, J.T., and A.N. Sharpley (eds.) Phosphorus: Agriculture and the Environment. Agron. Mongr. No. 46. ASA, CSSA, and SSSA, Madison, WI.

Martin, R.C., D.H. Lynch, B. Frick and P. van Straaten. 2007. Perspective: Phosphorus status on Canadian organic farms. J. Sci. Food Agric. 87: 2737-2740.

McCall, W.W., J.F. Davis, and K. Lawton. 1956. A study of the effect of mineral phosphates upon the organic phosphorus content of organic soil. Proc. Soil Sci. Am. 20: 81.

McClellan, G.H., and L.R. Gremillion. 1980. Evaluation of phosphatic raw materials. p. 43-80. *In* F.E. Khasawneh et al. (eds.) The Role of Phosphorus in Agriculture. ASA,CSSA, and SSSA, Madison, WI.

Mullins, G.L. 1991. Phosphorus sorption by four soils receiving long-term applications of fertilizer. Commun. Soil Sci. Plant Anal. 22: 667-681.

National Organic Program. 2007. National list of allowed and prohibited substances. Washington, D.C. http://www.ams.usda.gov/NOP/NOP/NOPhome.html (verified 10 Oct. 2008)

Nelson, D.W. and L.E. Sommers. 1982. Organic carbon. p. 539-579. *In* A.L. Page (eds.) Methods of Soil Analysis, Part 2, 2nd Ed., Page, A.L., Ed., Agron. Mongr. No. 9. ASA and SSSA, Madison, WI.

Nelson, N., and R. Mikkelsen. 2008. Meeting the phosphorus requirement on organic farms. p. 12-14. *In* Better Crops with Plant Food. No. 1. International Plant Nutrition Institute. Norcross, GA.

Nelson, N.O., and R.R. Janke. 2007. Phosphorus sources and management in organic production systems. HortTech. 17: 442-454.

Nuruzzaman, M., H. Lambers, M.D.A. Bolland, and E.J. Veneklaas. 2005. Distribution of carboxylates and acid phosphatase and depletion of different phosphorus fractions in the rhizosphere of a cereal and three grain legumes. Plant Soil. 281: 109-120.

Pilbeam, D.J., I. Cakmak, H. Marschner, and E.A. Kirkby. 1993. Effect of withdrawal of phosphorus on nitrate assimilation and PEP carboxylase activity in tomato. Plant Soil. 154: 111-117.

Rajan, S.S.S., J.H. Watkinson, and A.G. Sinclair. 1996. Phosphate rocks for direct application to soils. Adv. Agron. 57: 77-159.

Ryan, P.R., E. Delhaize, and D.L Jones. 2001. Function and mechanism of organic anion exudation from plant roots. Annu. Rev. Plant Physiol. Plant Mol. Biol. 52: 527–560

Rodriguez, D., F.H. Andrade, and J. Goudriaan. 1999. Effects of phosphorus nutrition on tiller emergence in wheat. Plant Soil. 209: 283-295.

Sall, J., L. Creighton, and A. Lehman. 2007. JMP Start Statistics: A Guide to Statistics and Data Analysis Using JMP, 4th Ed. Cary, NC: SAS Institute Inc.

Sample, E.C., R.J. Soper, and G.J. Racz. 1980. Reaction of phosphate fertilizers in soils. p. 263-310. *In* F.E. Khasawneh et al (eds.) The Role of Phosphorus in Agriculture. ASA, CSSA, and SSSA, Madison, WI.

Sanchez, C. 2007. Phosphorus. p.51-86. *In* A.V. Barker, and D.J. Pilbeam (eds.) Handbook of Plant Nutrition. CRC Press. Boca Raton, FL.

Sharpley, A.N., and S.J. Smith. 1989. Mineralization and leaching of phosphorus from soil incubated with surface-applied and incorporated crop residues. J. Environ. Qual. 18: 101-105.

Singh, B.B., and J.P. Jones. 1976. Phosphorus sorption and desorption characteristics of soil as affected by organic residues. Soil Sci. Soc. Am. J. 40: 389-394.

Stewart, J.W.B., and H. Tiessen. 1987. Dynamics of soil organic phosphorus. Biogeochem. 4: 41-60.

Schmidt, E.L. 1982. Nitrification in soil. p. 253-288. *In* S. J. Stevenson (ed.) Nitrogen in Agricultural Soils. Agron. Monogr. 22. ASA, CSSA, and SSSA, Madison, WI.

Thomas G.W. 1996. Soil pH and soil acidity. p. 475-490. *In* D.L. Sparks et al. (eds.). Methods of Soil Analysis. Part 3. Chemical Methods, SSSA Book Ser. 5. SSSA and ASA, Madison, WI.

van Ray, B., and A. van Diest. 1979. Utilization of phosphate from different sources by six plant species. Plant Soil. 51: 577-589.

Yadvinder-Singh, Bijay-Singh, and C.S. Kind. 1992. Nutrient transformations in soils amended with green manures. Adv. Soil Sci. 20: 237-309.

Van Straaten, P. 2006. Farming with rocks and minerals: challenges and opportunities. Anais Da Academia Brasileria De Ciencias. 78: 731-747.

Veneklaas, E.J., J. Stevens, G.R. Cawthray, S. Turner, A.M. Grigg, and H. Lambers. 2003. Chickpea and white lupin rhizosphere carboxylates vary with soil properties and enhance phosphorus uptake. Plant Soil. 248: 187–197.

Zhu, Y-G., Y-Q. He, S.E. Smith, and F.A. Smith. 2002. Buckwheat (*Fagopyrum esculentum* Moench) has high capacity to take up phosphorus (P) from a calcium (Ca)-bound source. Plant Soil. 239: 1-8.

Table 3.1. Selected physical and chemical properties of the soil used in the greenhouse pot experiment. Soil from the Ap horizon (0-0.15 m depth).

Texture	pH	NO_3-N	Olsen P	Exchangeable K	Organic Matter
		---------- mg kg^{-1} ----------			%
Loam	7.2	2.5	4.0	248	2.1

Table 3.2. Fertilizer application rates based on listed label rate.*

P source		Application Rate
		--------g pot^{-1} ------
Bone Meal (BM)	Low	0.336
	High	0.843
Rock Phosphate (RP)	Low	1.122
	High	2.809
Monocalcium phosphate (MCP)	Low	0.081
	High	0.204

*Fertilizer applied to pots was based on supplying 0, 10, and 25 kg ha^{-1} available P using reported P contents of 1.3, 4.4, and 18.% for RP, BM, and MCP, respectively.

Table 3.3. Phosphorus content for fertilizers used in the greenhouse green manure-phosphate study according to fertilizer label (listed rate) and neutral ammonium citrate analysis (citrate-soluble) and the available and total P application rate based on P content.

	P Content		P Application Rate	
P source	Listed Rate	Citrate-soluble	Available P	Total P
	----------% P---------		----------% P----------	
Bone Meal (BM)	4.4	5.7	---	---
BM low	---	---	13.0	16.5
BM high	---	---	32.5	41.3
Rock Phosphate (RP)	1.3	0.93	---	---
RP low	---	---	7.0	43.6
RP high	---	---	17.5	108.8
Monocalcium (MCP)	18.0	18.0	---	---
MCP low	---	---	10	10
MCP high	---	---	25	25

*Fertilizer applied to pots was based on supplying 0, 10 and 25 kg ha^{-1} available P using manufacturers listed rates.

Table 3.4. Mean shoot biomass production, P uptake, and tissue P concentration of green manure crops in the green manure-phosphate greenhouse study.¶

Crop	Phosphorus Treatment	Shoot Biomass Yield		P Uptake		Tissue P Concentration	
	P source§ P rate‡	g pot^{-1}		mg pot^{-1}		%	
Buckwheat	Control	5.18	b	6.14	d	0.120	d
	BM low	6.61	ab	11.72	ab	0.180	bc
	BM high	4.82	b	13.06	ab	0.265	a
	RP low	5.18	b	7.42	cd	0.145	cd
	RP high	5.96	ab	11.02	ab	0.185	bc
	MCP low	5.99	ab	8.96	bc	0.150	cd
	MCP high	7.32	a	14.83	a	0.205	b
LSD$_{(0.05)}$		*1.96*		*4.16*		*0.041*	
Spring Pea	Control	8.58	bc	8.66	c	0.100	b
	BM low	8.42	bc	8.42	c	0.100	b
	BM high	8.44	bc	8.49	c	0.100	b
	RP low	8.17	c	9.26	c	0.115	ab
	RP high	8.33	bc	9.65	c	0.115	ab
	MCP low	9.66	ab	11.61	b	0.120	a
	MCP high	10.66	a	13.94	a	0.130	a
LSD$_{(0.05)}$		*1.46*		*1.76*		*0.015*	
Spring Wheat	Control	2.29	bc	4.38	ab	0.190	ab
	BM low	2.17	c	4.30	ab	0.200	ab
	BM high	1.95	c	3.94	bc	0.205	a
	RP low	1.84	c	2.95	c	0.160	d
	RP high	2.39	abc	4.57	ab	0.190	ab
	MCP low	2.88	ab	4.88	ab	0.170	cd
	MCP high	2.97	a	5.17	a	0.175	bc
LSD$_{(0.05)}$		*0.60*		*1.22*		*0.026*	

¶ Non-constant variance across crop types, therefore ANOVA completed individually per crop. Mean values within a column followed by the same letter do not differ according to Fisher's Protected LSD at $P < 0.05$.
§ Phosphorus sources are bone meal (BM), rock phosphate (RP) and monocalcium phosphate (MCP).

Table 3.5. Summary of significant effects and interactions for previous crop and phosphorus level on each of the measured dependent variables.

Factor	df	Shoot biomass	P uptake	Tissue P Concentration
			P > F	
Previous Crop (C)	3	<0.001	<0.001	<0.001
Phosphorus Level (P)	6	<0.001	<0.001	<0.001
C x P	18	NS*	0.02	0.03

*NS - not significant at *P* = 0.05.

Table 3.6. Mean shoot biomass, P uptake, and tissue P concentration of spring wheat (cv. *Choteau*) crop following green manure crop in green manure-phosphate study, 2006.

Previous GM Crop	Phosphorus Treatment	Shoot Biomass Yield		P Uptake		Tissue P Concentration	
	P source§ P rate‡	g pot^{-1}		mg pot^{-1}		%	
Buckwheat	Control	6.6		9.8		0.148	
	BM low	6.8		11.3		0.165	*
	BM high	7.3		11.9	*	0.163	*
	RP low	7.1		12.3	*	0.173	*
	RP high	7.2		12.7	*	0.175	*
	MCP low	7.1		11.8	*	0.168	*
	MCP high	7.5	*	12.7	*	0.170	*
Spring Pea	Control	6.0		7.4		0.123	
	BM low	6.4		7.8		0.123	
	BM high	6.2		7.3		0.118	
	RP low	7.1	*	9.1	*	0.128	
	RP high	6.7		9.1	*	0.135	
	MCP low	7.4	*	9.6	*	0.130	
	MCP high	8.4	*	12.2	*	0.145	*
Spring Wheat	Control	6.7		10.2		0.153	
	BM low	6.5		9.3		0.143	
	BM high	6.7		10.8		0.160	
	RP low	7.3		12.4	*	0.170	*
	RP high	7.5		11.9	*	0.160	
	MCP low	7.7	*	12.6	*	0.165	
	MCP high	8.4	*	15.6	*	0.185	*
Non-crop Control	Control	7.2		11.3		0.158	
	BM low	6.9		11.5		0.165	
	BM high	7.4		12.6		0.170	
	RP low	7.4		13.7	*	0.185	*
	RP high	7.4		13.0	*	0.178	*
	MCP low	8.1	*	15.4	*	0.190	*
	MCP high	9.2	*	16.7	*	0.183	*
$LSD_{(0.05)}$		*0.8*		*1.6*		*0.010*	

§ Phosphorus sources are bone meal (BM), rock phosphate (RP), and monocalcium phosphate (MCP).

*Starred values are significantly different from the 0 P control within the respective previous crop according to Fisher's Protected LSD using $P = 0.05$.

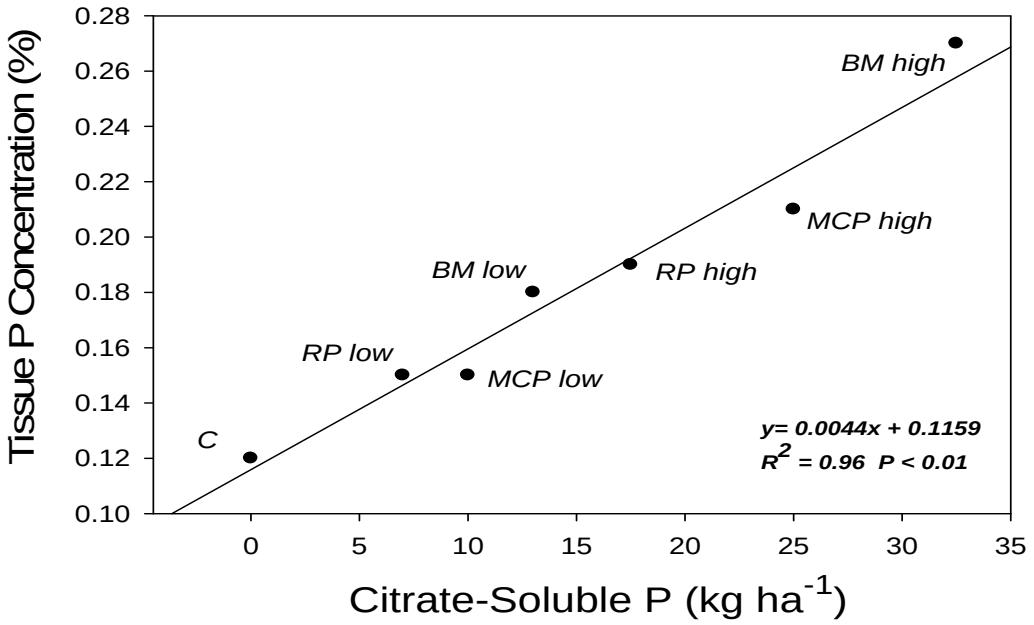

Figure 3.1. Mean tissue P concentration of buckwheat as a function of increasing applied available P. Phosphate sources are 0 P control (C), bone meal (BM), rock phosphate (RP), and monocalcium phosphate (MCP).

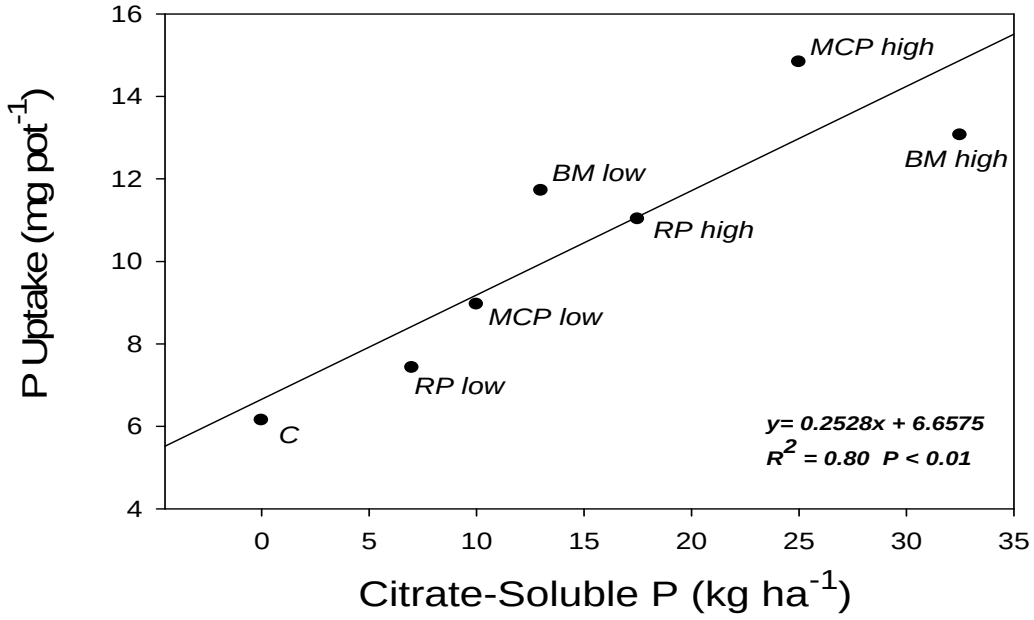

Figure 3.2. Mean P uptake of buckwheat as a function of increasing applied available P. Phosphate sources are 0 P control (C) bone meal (BM), rock phosphate (RP), and monocalcium phosphate (MCP).

CHAPTER 4

SOIL FERTILITY DIFFERENCES BETWEEN NON-ORGANIC NO TILLAGE AND ORGANIC CROPPING SYSTEMS IN MONTANA

Introduction

Dryland cropping systems in the Northern Great Plains (NGP) have traditionally consisted of small grain cereal crops, primarily wheat (*Triticum aestivum* L.), grown in an alternating system of summer fallow-crop (Padbury et al., 2002). Fallow-wheat systems were favored in the semiarid environment to decrease the risk of crop failure by conserving soil moisture and nutrients in one year for the next (Peterson et al., 1996). However, tilled fallow-wheat cropping systems are considered ecologically and economically unsustainable. Conventional tillage is detrimental to fragile semiarid agroecosystems because it leaves soil bare and vulnerable to erosion. Tillage also depletes soil organic matter (SOM) with a deleterious effect on soil fertility (Haas et al., 1957; Monreal and Janzen, 1993; Biederbeck, et al., 1994). Summer fallow increases the risk of saline seep development (Halvorson and Black, 1974) and nutrient leaching, and is notoriously inefficient at storing soil water for crop production (Black et al., 1974; Farahani et al., 1998). Moreover, cereal-based monocultures are highly susceptible to disease and weed infestations which can impact crop productivity. Finally, conventional dryland cropping systems are highly dependent on petroleum-based chemical fertilizers and pesticides which may not be sustainable (Rogner, 2000; Crews and Peoples, 2004). Concerns surrounding the unsustainable nature of conventional fallow-wheat system have

driven the search for sustainable alternatives (Zentner et al., 2001). Organic and no-tillage (NT) cropping systems have emerged as potential alternatives for enhancing the sustainability of dryland cropping systems of the NGP.

Organic cropping systems are purportedly more sustainable than conventional cropping systems because they utilize an ecologically-based production model that reduces the use of non-renewable petroleum-based inputs in favor of biologically based strategies that promote soil biological diversity, enhance natural biological cycles (Drinkwater et al., 1995; Mäder et al., 2002; Oehl et al., 2003), and build SOM to manage soil fertility. While organic systems still use conventional tillage to prepare seedbeds, manage weeds, and incorporate green manure (GM) crops, they attempt to minimize tillage by employing cultural methods, such as diversified cropping rotations, weed-competitive narrow row spacing, and cover crops to interrupt disease and pest cycles.

Conservation tillage methods, specifically NT, minimize soil erosion and enhance the precipitation storage efficiency of the soil by eliminating the need for broad-field conventional tillage operations (Tanaka and Anderson, 1997). No-till systems eliminate soil inverting tillage by drilling seed directly through residues of the previous crop and by using herbicides to manage weeds. A key feature of the NT method is that residues from the previous crop remain relatively intact on the soil surface to form a protective cover that reduces surface wind speeds, slows water runoff, and increases infiltration (Fenster and Peterson, 1979). Crop residues also insulate the soil to cool the surface and reduce evaporative losses incurred during the fallow period (Greb et al., 1967; Bond and Willis, 1969; Peterson and Westfall, 2004). In semiarid environments, greater soil water storage

capacity allows for intensifying crop production and diversification of crop rotations beyond the fallow-wheat system.

Cropping system management can affect the accumulation, depletion, and distribution of nutrients in the soil profile. Differing management strategies can alter the physical, chemical, and biological properties that influence soil fertility, including tillage, fertilization, crop rotation, cropping intensity, and yield potential. Tillage is one of the most influential factors affecting soil fertility, specifically as it relates to the SOM content of the soil. No-till can improve soil quality parameters, such as total soil carbon (C) (Campbell et al., 1996; Sainju et al., 2007), soil nitrogen (N) (Karlen and Doran 1994; Campbell et al., 1996; Blevins et al., 1998), and soil aggregation (Malhi et al, 2008). McConkey et al. (2002) found NT increased total soil N levels in crop residues and in the upper 7.5 cm of the soil. In continuous cropping NT systems, Liebig et al. (2004) found soil organic carbon (SOC) increase by 7.3 Mg ha^{-1}, potentially mineralizable N (PMN) increased by 34 kg ha^{-1}, and aggregate stability increased by 33%, when compared to a fallow-crop conventional till system. An increase in SON can enhance plant available N to crops through mineralization. While NT can positively influence SOM and SON levels, NT is also known to stratify soil nutrients near the soil surface. Accumulation of plant residues on the soil surface combined with a lack of soil mixing tend to sequester surface applied fertilizers in a nutrient-rich layer on the surface of NT systems. For example, a study in the NGP found soil nitrate (NO_3-N) concentrations were higher in the upper 0-5 cm soil layer under NT management than conventional tillage; however stratification did not appear to influence nutrient uptake in a subsequent wheat crop

(Lupwayi et al., 2006). Since P is less mobile in the soil, NT systems may stratify P near the surface away from root systems.

Conventional tillage in organic systems may accelerate the loss of SOM through oxidation; however, organic systems also attempt to build SOM through intensification of cropping and by incorporating diverse crops into rotations, particularly N-fixing legumes with low C:N ratios. Legume-based cropping systems can enhance SOM and soil N fertility (Biederbeck et al., 1996; Biederbeck et al., 2005) and potentially reduce N losses in the system (Drinkwater et al., 1998). Organic and NT systems often intensify and diversify cropping systems which influence the quantity and quality of crop residues returned to the soil. Continuous cropping and increased crop diversification will affect the rate of nutrient cycling and can accelerate the rate of nutrient removal as yields increase (Kolberg et al., 1996; Peterson et al., 1996; Grant et al., 2002). Thus, to remain sustainable, cropping systems must balance nutrient removal and replacement.

There is growing concern that soil P fertility in organic cropping systems may decline over time without adequate mechanisms to replace P removed during crop harvest (Oehl et al., 2002; Gosling and Shepherd, 2005). In the NGP where access to soil amendments like animal manure is limited, researchers are finding P deficiency (Entz et al., 2001; Grant et al., 2005; Martin et al., 2007). Entz et al. (2001) determined available P levels on organic fields in Manitoba were low especially on fields organically farmed over 30 y. Brandt and Ulrich (2001) and Entz (2006) also found depleted levels of available P in organically managed research plots at Scott, SK and Glenlea, MB, respectively.

In recent years, growers in the NGP have increasingly adopted both NT and organic production systems as a means of enhancing the sustainability of crop production in the region (Smith et al., 2004). As organic and NT systems increase it is essential to understand how each management system affects soil fertility for optimal crop performance and profitability while conserving resources. Few studies in the NGP have compared these two systems. Thus, our objective was to compare soil nutrient levels in contrasting organic and NT cropping systems. In order to achieve this, two separate studies were conducted. The first study was conducted in the 8th year of a diversified crop rotation study contrasting diversified organic and NT management strategies. A second study in north central Montana compared soil fertility differences in organic and NT systems.

Methods and Materials

Crop Rotation and Diversification Study

Site Description: A field experiment was established in 2000 at the Montana State University Arthur H. Post Agronomy Farm located 10 km west of Bozeman, MT (45˚ 40′20″ N, 111˚ 09′3″ W, elevation 1463 m) to examine the agronomic, economic, and soil nutrient effects of transitioning from conventional tillage to no-tillage and organic diversified cropping systems. In 2007, a study was conducted to compare soil nutrient levels between organic and no-till cropping systems in the 8th year of the study. Annual precipitation at the dryland site is 421 mm (Table 4.1). The soil at the field site is formed from windblown loess and classified as a well drained Amsterdam silt loam (fine-

silty, mixed, superactive, frigid Typic Haplustolls) with a soil organic matter (SOM) concentration of 25 g kg^{-1} and soil pH of 7.2 to 7.7 in the upper 0-0.15-m depth. Prior to 2000 the study site was intensively tilled and received conventional chemical fertilizer and pesticide applications for several decades.

Experimental Design: The experiment included five annual cropping systems: a NT system emphasizing spring cool-season spring crops (NTS) and a complementary NT winter (NTW) system highlighting crops with a winter habit; a highly diversified NT cropping system (NTD) including two cool and two warm season crops; an organically (Org) managed system without synthetic fertilization or pesticides; and a NT continuous wheat (NTCW) system serving as a control (Table 4.2). From 2000 to 2003, each cropping system, except for CW, was a four-year rotation with two phases dedicated to broadleaf crops and two to cereal crops with all phases (fully phased) present each year. Continuous wheat alternated between spring and winter habit with a single phase present annually. Cropping system phases were randomly assigned to 7.3 x 14.6 m experimental plots. The experimental design was a randomized complete block with four replicates (*n* = 68). Crop management and experimental design are described in more detail by Miller et al. (2008).

Broadleaf and cereal crops grown concurrently in the fully phased design lacked adequate spatial isolation to deter pest infestation. Thus, to mitigate pest problems, the study design was modified for the 2004 crop season from a fully phased design to a dual phase design with alternate year legume-cereal rotations. A high (H) and low (L) input strategy was implemented in each system to compensate for the phase design change

(Table 4.3). The major differences between the H and L input strategy were that the L input regime had ½ the N fertilization, greater seeding rates, and reduced herbicide use. A pesticide-free production system (PFP) was established by converting two of the Org phases into PFP systems, again beginning with the 2004 crop. Pesticide-free production is defined here as a fertilized high input NT system with pesticide use restricted to pre-emergent and post-harvest applications in food crops, the crop rotation matched the Org system. The Org system is a low input tilled system, relies only on biological N fixation for nutrient replacement, and includes two years of winter crops with two years of spring crops for management of weeds.

Soil Sampling and Analysis: Cropping systems sampled for this study were Org, PFP, NTW and NTD. Sampling occurred prior to the seeding of spring crops (19 -30 March 2007) and in between the rows of seeded winter habit crops to avoid sampling seed-placed P. Each plot was sub-divided into four equal quadrants. At the center of each quadrant a core was hand drilled using a 38-mm diameter auger to 0-0.15 m, 0.15-0.30 m, and 0.30-0.60 m depths. Core segments from each respective depth within each plot were composited, then stored in cold, moist storage to maintain field moist conditions. Field-moist samples were hand chopped and mixed thoroughly prior to subsampling 20 g for gravimetric water content. Based on gravimetric water content and bulk densities, a dry weight equivalent field moist composite of the 0-60 cm depth was generated for each plot for ammonium (NH_4^+) and potentially mineralizable nitrogen (PMN) analyses. The remainder of the soil was oven dried at 50˚C and finely ground to pass a 2-mm sieve.

Potentially mineralizable nitrogen was analyzed using a 7 d anaerobic incubation method (Bundy and Meisinger, 1994). Pre-incubation ammonium (NH_4^+) was determined on a field-moist composite sample using a 1 *M* KCl (potassium chloride) extraction in a solution:soil ratio of 5:1 (25 ml extractant:5 g moist soil). Anaerobic incubation consisted of mixing a 5 g (dry weight equivalent) soil sample with 12.5 ml deionized water in a 50 ml centrifuge tube, and then purging the sample of oxygen (O_2) using dinitrogen (N_2) gas. Samples were placed in a water bath for 7 d at 40˚C. After the incubation, 12.5 ml of 2 *M* KCl was added to the centrifuge tube, shaken on a mechanical shaker for 1 h, and filtered through Whatman No. 42 filter. Ammonium concentration of the supernatant was determined using flow injection analysis (Lachat Instruments, Loveland, CO). Potentially mineralizable nitrogen was calculated by subtracting pre-incubation NH_4^+ from NH_4^+ produced during the incubation.

Surface (0-0.15 m) soil samples were analyzed for total Kjeldahl nitrogen (TKN) using a wet acid digest (Stevenson, 1996). Nitrate (NO_3-N) analysis was completed for each collected sample using a 1 *M* KCl extraction with a solution:soil ratio of 10:1 (50 ml extractant:5 g oven dried soil) shaken for 0.5 h, filtered through a Whatman 42 filter and analyzed using cadmium (Cd) flow injection analysis (Willis, 1980; Lachat Instruments, Loveland, CO).

Surface (0-0.15 m) soil samples were subjected to a sequential P fractionation procedure based on the methods of Hedley et al. (1982), Yang and Jacobsen (1990), and Yang et al. (2002) as summarized in Chapter 2 (Table 2.4). Briefly, all extractions used a solution:soil ratio of 20:1 (25 ml extractant/1.25 g oven-dry soil). Bicarbonate extracted

P (Bicarb-P) was extracted with 0.5 *M* $NaHCO_3$ at pH 8.5 in a 50-ml centrifuge tube, shaken for 30 min and centrifuged at 10,000 rpm for 30 min. Supernatant was decanted into a 60-ml syringe and filtered through a 0.2-µm sterile syringe filter. Soil residue was then subjected to two subsequent extractions, 0.1 *M* NaOH followed by 1 *M* HCl, each with a 16 h shaking period followed by centrifugation and filtration as detailed above. Phosphorus concentrations in all extracts were determined colorimetrically using the ascorbic acid method (Kuo, 1996). Sequential fractionation identifies labile P fractions adsorbed onto surface soil constituents and $CaCO_3$ (Bicarb-P), P held strongly by chemisorption to Fe and Al components and held on internal soil surfaces (NaOH-P), and Ca-bound P associated with apatite-type minerals and P occluded within soil matrices (HCl-P). The fractionation procedure identifies P fractions that vary in the extent of their availability to growing plants, ranging from highly labile to recalcitrant (Hedley et al., 1982).

Organic and Non-organic Soil Fertility Comparison Study

Study Design: A field study was conducted in the dryland wheat growing region of north central Montana from 19 May to 28 June 2007 to investigate nutrient availability in contrasting organic (Org) and non-organic (NO) cropping systems. Field site selection criteria included: 1) Org and NO management systems in close proximity across an anthropogenic management boundary (e.g. fenceline or farm lane; Figure 4.1); 2) Org fields with a minimum of seven years in organic production; 3) similar landscape position

and topography on both sides of the management boundary to limit the effect of microclimate and topography on soil properties, specifically soil texture.

Site Description: Three study sites were identified (Figure 4.2) with seven Org and NO paired fields selected for sampling. One site was located 32 km east of Conrad, MT with two Org-NO fields sampled (C1 and C2); one site was 3.5 km west of Big Sandy, MT with a single field sampled (WBS); and a third site was 20 km south of Big Sandy, MT with four fields sampled (SBS1, 2, 3 and 4). Site locations and soil properties are displayed in Table 4.4. Crop management factors for each Org and NO pair are summarized in Table 4.5.

Soil Sampling and Analysis: Sampling occurred 23 May and 19 June for fields C1 and C2, respectively. Fields WBS, SBS1 and SBS2 were sampled 28 June and SBS3 and SBS4 were sampled on 29 June. On each side of the Org-NO management boundary seven paired soils were sampled, except for the SBS4 site where only six paired sites were sampled (Figure 4.3). Distance between sampling sites along the boundary was approximately 100 m with samples collected approximately 10 m inside the crop to avoid an edge effect or buffer strips. At each site, six surface (0-0.15 m depth) cores were collected in a standardized pattern using a 3-cm (diameter) soil probe and bulked. Gravimetric water was measured on a 20 g sample dried at 105˚C. Potentially mineralizable N, NO_3-N, NH_4-N, and sequential P extractions were completed as previously described. To gather base-line physical and chemical properties, 20 g of oven dried soil from each of the seven samples along each Org and NO field were composited.

Each composite was analyzed for soil texture (Gee and Bauder, 1986), SOM by loss on ignition (Thomas, 1996), and soil pH on a 1:1 soil:deionized water slurry (Thomas, 1996).

Statistical Analyses: Analysis of variance (ANOVA) was conducted using SAS JMP IN 5.1 statistical software (Sall, et al., 2007). Significant differences in treatment means were determined using Fisher's Protected Least Significant Difference (LSD) using a *P*- value < 0.05 unless otherwise indicated (Kuhel, 2000). Planned orthogonal contrasts were conducted to compare soil fertility properties between Org and NT cropping systems in the CDRS study. Nutrient comparisons between Org-NO systems were performed separately on individual paired fields Org-NO using ANOVA.

Results and Discussion

Crop Diversification Rotation Study

Mean plant available P (Bicarb-P) concentrations were 23% lower ($P = 0.03$) in the Org system (15.7 mg kg^{-1}) than in the NT systems (20.5 mg kg^{-1}) (Table 4.6). In 2004, plant available P (Olsen P) concentrations (essentially identical procedure to Bicarb-P) were measured after the first four-year crop rotation cycle and averaged 18 and 21 mg kg^{-1} for the Org and NT systems, respectively (Miller et al., 2008). These results suggest a downward trend in the labile soil P fraction in the non-fertilized Org system. Findings in other non-fertilized systems are similar (Gosling and Shepherd, 2005; Welch et al., 2006). For instance, in a long term rotation study evaluating the effect of intensification of cropping and fertilizer management on soil P, McKenzie et al. (1992)

found that without adequate fertilization continuous cropping reduced both soil inorganic and organic P pools. In addition, after 21 y with no external P fertilization, Oehl et al. (2002) found the average input-output budget was -20.9 kg P ha^{-1} yr^{-1} and +3.8 kg P ha^{-1} yr^{-1} for non-fertilized and fertilized conventional systems, respectively. Bicarb-P levels for the organic plots have fallen below the 24 mg kg^{-1} critical value established for winter wheat in Montana (Jackson, 1991), suggesting that winter wheat in organic plots have the potential to be P-responsive, and are slightly below the 16 mg kg^{-1} critical value used for all other crops (Jacobsen et al., 2005).

Soil P fractionation determined soil NaOH-P concentrations were significantly lower in the Org system than the NT system (Figure 4.4) indicating that cropping without adequate fertilization may be mining P from the NaOH-P fraction in the Org plots. Significantly lower levels of NaOH-P were also found by Welch et al. (2006) in non-fertilized organic managed systems compared to fertilized production systems. Moreover, it was determined that management system had a greater impact on soil P levels than did type of cropping rotation (Welch et al., 2006). Phosphorus fractionation determined there were no differences among any of the cropping systems with respect to the more recalcitrant HCl-P fraction (Figure 4.4). Values for the HCl-P fraction at the CDRS site were, in fact, substantially higher than observed in the Big Sandy field study outlined in Chapter 2. This may reflect the long history of high input intensive conventional agriculture practiced at this study site combined with higher pH soils. The high levels of P in less labile fractions may serve as a reservoir for supplying crop production in the short term, but it is unknown how long it will take before P mining of

moderately labile soil fractions will become problematic and affect crop quality and yield.

Concentrations of PMN did not differ ($P = 0.40$) between Org and NT systems. This result is different than that found following the first 4 y rotation cycle in 2004 when PMN was higher in the Org systems (Jones et al., 2005; Miller et al., 2008). A decreasing trend in PMN in the Org system from 2004 to 2008 may reflect the effects of mechanical tillage, climatic factors, or the effect of crop rotation (Rice and Havlin, 1994). Conventional tillage breaks up soil aggregates exposing SOM to oxidation and increases soil to residue contact which can increase microbial activity and enhance mineralization (Six et al., 1999). Franzluebbers (1999) suggested exposure of occluded SOM would stimulate microbial action and temporarily immobilize N. The only significant difference in PMN among cropping systems was that PMN was higher in the NTW-H system than in NTW-L which may reflect increased N fertilization rates and possibly lower C:N ratios in residue and/or soil (Figure 4.5).

Soil NO_3-N (0-0.60 depth) did not significantly differ ($P = 0.20$) between NT and Org systems and there were no significant differences in NO_3-N observed among any of the cropping systems (Figure 4.6). Soil NO_3-N levels were measured prior to N fertilization of non-organic plots and so available N would have been much higher in the NT than Org systems following fertilization. Concentrations of TKN did not differ between Org (0.127%) and NT (0.123%) systems ($P = 0.68$), nor were there any differences among cropping systems. This finding suggests that legume-based N inputs are capable of maintaining total soil N levels equally well as conventionally fertilized

systems. Concentrations of TKN were similar in the Org system between 2004 (0.121%) and 2007 (0.123%).

It is very noteworthy that after 8 y of cropping there were no significant differences in soil N fertility between Org and NT systems despite N fertility in the Org system being managed solely with the inclusion of one N_2 fixing legume green manure and one harvested legume in a 4 y rotation. This is in contrast to the NT systems that receive yield targeted applications of conventional N fertilizer. However, there may be concern that while N fertility indices show no significant differences in N fertility between the Org and NT systems, there may be concern related to grain protein levels. In the first 4 y of this study, grain protein yields were significantly lower in the Org system (Miller et al., 2008). Grain protein yields are an important consideration because farmers receive monetary protein premiums for high protein grain.

Organic and Non-organic Soil Fertility Comparison Study

Five of the seven Org-NO paired sites had identical soil textures and the remaining two had sand, silt, and clay contents that did not vary by more than 8% from its respective pair. Soil nutrient dynamics varied widely between the NO systems due to the variability of multiple crop management factors. Despite a concerted effort to locate complementary NO systems, each NO system varied substantially with respect to fertilization, cropping history, and other crop management factors. For example, fertilization of NO fields at the C1 and C2 sites consisted of targeted fertilizer applications of approximately 80 kg ha^{-1} fertilizer annually (½ urea and ½ 11-52-0 drilled with the seed). This is in contrast with the four NO systems south of Big Sandy where

three (SBS1, SBS2 and SBS3) of the four NO sites received little to no fertilization for the past three years and the fourth site (SBS4), a fallow-barley field, had received no fertilization since 1985. Moreover, there were considerable differences between Org systems, as most fields were cropped to cereals, primarily spring and winter wheat, but one was a recently tilled spring pea (*Pisum sativum* L.) GM, as observed in SBS2. The level of variation among NO and Org cropping systems made direct comparisons of systems untenable, therefore all comparisons were exclusively between each Org-NO pair.

In two of seven fields, mean plant available P (Bicarb-P) was significantly higher in the NO system than in its corresponding unfertilized Org system (Figure 4.7). The Bicarb-P differences between the NO and Org systems at the WBS site was close to the 0.05 probability level ($P = 0.06$), indicating where P fertilization was applied, labile P remains high. In one Org field (SBS2) Bicarb-P was higher than in the NO system. Soil Bicarb-P levels in five of the Org systems were below the critical level of 16 mg P kg^{-1} for most Montana crops (Jacobson et al., 2005) and all but one fell well below the critical level of 24 mg P kg^{-1} for winter wheat (Jackson, 1991). Bicarb-P levels exceeded the 24 mg P kg^{-1} threshold in NO systems that received annual fertilization up to the time of sampling (C1, C2 and WBS) while those not receiving fertilization were either at or below 16 mg P kg^{-1}. Mean NaOH-P was higher in the NO system in two of seven fields and these were the same two fields that had elevated Bicarb-P (C1 and C2). Clay content for fields C1 and C2 ranged between 28.4 and 36.4% compared to 14.4 to 26.4% for the remaining soils. The high clay content may reflect an enhanced P buffering capacity for

these clayey soils. Mean NaOH-P was significantly higher in two Org systems SBS1 and SBS2. Mean HCl-P was higher in the NO system in three of seven fields all of which were fields receiving consistent fertilization. In the unfertilized NO systems there were no significant differences between the NO and Org systems with respect to HCl-P. Results of P fractionation indicate that in Org cropping systems labile and moderately labile P levels appear to have become depleted. Additionally, unfertilized NO systems deplete labile and moderately labile P in the soil. Unfertilized systems, regardless of management designation can see a decline in available P and without replenishment available P may become a limiting nutrient in crop productivity in the future.

Mean soil NO_3-N concentrations were significantly higher in two of seven NO systems (C1 and C2) than in the respective Org system (Figure 4.8). In three of seven Org systems (WBS, SBS2, and SBS3) soil NO_3-N concentrations were higher, with one considerably higher. The higher NO_3-N concentrations in the Org system at SBS2 reflects a recent plow down of a pea GM crop compared to a nearly mature winter wheat crop in the NO system. In C1 and C2 soil NO_3-N concentrations were higher in the fertilized NO systems where both NO and Org systems were planted to a similar stage winter wheat. The Org system in WBS, planted to spring wheat, had significantly higher soil NO_3-N concentrations than the NO system, planted to winter wheat. Soil NO_3-N concentrations were variable between field pairs and systems. This variability reflects the highly dynamic nature of soil NO_3-N with respect to many factors, including timing of sampling, presence or absence of fertilization, timing of fertilization, N uptake by the crop, crop or fallow rotation, and the habit of crop (spring or winter).

Soil PMN concentrations differed in only two of seven (C2 and SBS4) Org-NO pairs (Figure 4.9) with higher PMN concentrations in the Org system. Thus, for the majority of the Org-NO pairs no differences in PMN concentrations were observed. This result is similar to that found in the CDRS experiment previously described where soil PMN concentrations did not differ between fertilized NT and non-fertilized Org systems. The NO system with the lowest PMN value was a fallow-barley system not fertilized since 1985. Since N mineralized from SOM and crop residues can be a major N contribution in agricultural systems, it is notable that five of the seven Org-NO paired systems did not differ with respect to PMN perhaps indicating that legume-based systems can provide sufficient N via the organic pool.

Conclusions

Following eight years of continuous diversified cropping at the CDRS study site soil P analyses indicate the potential for labile soil P levels to wane in unfertilized Org systems and that the addition of legume green manures alone will not adequately maintain soil P levels in Org systems. This finding is significant for large acreage dryland grain producers currently operating without a satisfactory mechanism for inputting P exported during harvest. Soil P fractionation results suggest continued cropping in unfertilized systems may mine more recalcitrant soil P reserves which over time may have an adverse effect on crop quality and productivity.

Soil N analyses from the CDRS study suggest soil N fertility in Org systems is keeping pace with fertilized NT systems. However, low grain protein levels in the Org

system from the first four year rotation cycle suggest legume-based systems alone may not be sufficient to maintain adequate protein levels.

Direct comparisons between Org and NO farming systems in the Organic-NO Cropping System Fertility Study were fraught with difficulty since it is not possible to control for the high level of heterogeneity among the systems. While management practices overlap among systems there are fundamental differences in fertilization levels and cropping history that make the comparison of idealized systems difficult. Soil P analyses do indicate a potential for P deficiency to occur in non-fertilized systems regardless of whether Org or NT. Producers not fertilizing for economic reasons or to meet organic standards may experience a decline in crop quality or yield without adequate fertilization.

References Cited

Biederbeck, V.O., H.H. Janzen, C.A. Campbell, and R.P. Zentner. 1994. Labile soil organic matter as influenced by cropping practices in an arid environment. Soil Biol. Biochem. 26: 1647-1656.

Biederbeck, V.O., W.A. Rice, C. van Kessel, L.D. Bailey, and E.C. Huffman. 1996. Present and potential future nitrogen gains from legumes in major soil zones of the Prairies. p. 441-445. *In* Proceedings of Saskatchewan Soils and Crops. University of Saskatoon.

Biederbeck, V.O., R.P. Zentner, and C.A. Campbell. 2005. Soil microbial populations and activities as influenced by legume green fallow in a semiarid climate. Soil Bio. Biochem. 37: 1775-1784.

Black, A.L., F. H. Siddoway, and P.L. Brown. 1974. Summer fallow in the northern Great Plains (winter wheat). p. 36-50. *In* Summer Fallow in the Western United States. USDA Conserv. Res. Rep. No. 17, U.S. Government Printing Office, Washington, DC.

Blevins, R. L., R. Lal, J.W. Doran, G.W. Langdale, and W.W. Frye. 1998. Conservation tillage for erosion control and soil quality. p.51-68. *In* F.J. Pierce, and W.W. Frye (eds.) Advances in Soil and Water Conservation.. Chelsea Mich.: Ann Arbor Press.

Bond, J.J. and W.O Willis.1969. Soil water evaporation: surface residue rate and placement effects. Soil Sci. Soc. Am. Proc. 33: 445 448.

Brandt, S., and D. Ulrich. 2001. Crop productivity with alternative input use and cropping diversity strategies. *In* A.G. Thomas, and S.A. Brandt (eds.) Scott Alternative Cropping Systems Project Review: the First Six Years. Vol. 9 – Workshop Proc. [CD ROM]. Agric. Agric. Agri-Foods Canada, Saskatoon Res. Ctr., Saskatoon, SK.

Bremner, J.M. 1996. Nitrogen-total. p. 1085-1121. *In* D.L Sparks (ed.) Methods of Soil Analysis. Part 3. Chemical Methods. SSSA Book Series No. 5. ASA and SSSA, Madison, WI.

Bundy L.G., and J.J. Meisinger. 1994. Nitrogen availability indices. p. 951-984. *In* Methods of Soil Science. Part 2: Microbiological and biochemical properties. SSSA Book Series No. 5. ASA and SSSA, Madison, WI.

Campbell, C.A., B.G. McConkey, R.P. Zentner, F. Selles, and D. Curtin. 1996. Long-term effects of tillage and crop rotations on soil organic C and total N in a clay soil in southwestern Saskatchewan. Can. J. Soil Sci. 76: 395-401.

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

Drinkwater, L.E., D.K. Letourneau, F. Workneh, A.H.C. van Bruggen, and C. Shennan. 1995. Fundamental differences between conventional and organic tomato agroecosystems in California. Ecol. Appl. 5: 1098-1112.

Drinkwater, L.E., P. Wagoner, and M. Sarrantonio.1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature. 396: 262-265.

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

Entz, M.H. 2006. Welcome to the Glenlea study – Canada's oldest organic-conventional cropping comparison. [Online] Available at http://www.umanitoba.ca/afs/plant_science/glenlea/glenleasresresults.html (verified 30 Sept. 2008).

Farahani, H.J., G.A. Peterson, and D.G. Westfall. 1998. Dryland cropping intensification: a fundamental solution to efficient use of precipitation. Adv. Agron. 64: 197-223.

Fenster, C.R., and G.A. Peterson. 1979. Effects of no-tillage as compared to conventional tillage in a wheat-fallow system. Research Bull. 289, Agric. Exp. Stn. University of Nebraska, Lincoln.

Franzluebbers, A.J. 1999. Potential C and N mineralization and microbial biomass from intact and increasingly disturbed soils of varying texture. Soil Biol. Biochem. 31: 1083–1090.

Gee, G.W. and J.W. Bauder. 1986. Particle size analysis. p. 383-411. *In* A. Klute (ed.) Methods of Soil Analysis, Part 2, 2nd Ed. Agron. Mongr. No. 9. ASA and SSSA. Madison, WI.

Gosling, P., and M. Shepherd. 2005. Long-term changes in soil fertility in organic arable farming systems in England, with particular reference to phosphorus and potassium. Agr. Ecosyst. Environ. 5: 425-432.

Grant, C.A., G.A. Peterson, and C. A. Campbell. 2002. Nutrient considerations for diversified cropping systems in the Northern Great Plains. Agron. J. 94: 186-198.

Grant, C., S. Bittman, M. Montreal, C. Plenchette, and C. Morel. 2005. Soil and fertilizer phosphorus: effects on plant P supply and mycorrhizal development. Can. J. Plant Sci. 85: 3-14.

Greb, B.W., D.W. Smika, and A.L. Black. 1967. Effect of straw mulch rates on soil water storage during summer fallow in the Great Plains. Soil Sci. Soc. Am. Proc. 31: 556-559.

Haas, H.J., C.E. Evans, and E.F. Miles. 1957. Nitrogen and carbon changes in Great Plains soils as influenced by cropping and soil treatments. Technical Bulletin 1164, USDA, Washington, D.C.

Halvorson, A.D., and A.L. Black. 1974. Saline-seep development in dryland soils of northeastern Montana. J. Soil Water Conserv. 29:7 7-81.

Hedley, M.J., J.W.B. Stewart, and B.S. Chauhan. 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. Soil Sci. Soc. Am. J. 46: 970-976.

Jackson, G.D., G.D. Kushnak, G.R. Carlson, D.M. Wichman, and J.S. Jacobsen. 1991. Correlation of the Olsen phosphorus soil test: winter wheat response. Commun. Soil Sci. Plant Anal. 22: 907-918.

Jacobsen, J., G. Jackson, and C. Jones. 2005. Fertilizer guidelines for Montana crops. Public. #EB 161, Montana State Uni. Ext. Ser., Bozeman, MT.

Jones, C.A., and P.R. Miller. 2005. Soil fertility differences in diversified no-till and organic rotations following a 4 year transition. Western Nutrient Management Conference. Salt Lake City, UT.

Karlen, D. L., and J. W. Doran. 1994. A framework for evaluating physical and chemical indicators of soil quality. *In* J.W. Doran et al. (eds.) Defining Soil Quality for a Sustainable Environment. SSSA Spec. Publ. No. 35. SSSA and ASA. Madison, WI.

Kolberg, R.L., N.R. Kitchen, D.G. Westfall, and G.A. Peterson. 1996. Cropping intensity and nitrogen management impact of dryland no-till rotations in the semi-arid western Great Plains. J. Prod. Agric. 9: 517-522.

Kuehl, R.O. 2000. Design of Experiments: Statistical Principles of Research Design and Analysis. Duxbury Press, Pacific Grove, CA.

Kuo, S. 1996. Phosphorus. p. 869-915. *In* D.L. Sparks et al., (eds.) Methods of Soil Analysis, Part 3. Chemical Methods. SSSA Book Ser. 5. SSSA and ASA, Madison, WI.

Lachat Instruments. 2005. Methods list for automated ion analyzers (flow injection analyses, ion chromatography) Available at www. lachatinstruments.com/applications/Methods list.PDF. (Accessed 9 Feb 2007).

Liebig, M.A., and J.W. Doran. 1999. Impact of organic production practices on soil quality indicators. J. of Environ. Qual. 28: 601-1609.

Lupwayi, N.Z., G.W. Clayton, J.T. O'Donovan, K.N. Harker, T.K. Turkington, and Y.K. Soon. 2006. Soil nutrient stratification and uptake by wheat after seven years of conventional and zero tillage in the Northern grain belt of Canada. Can. J. Soil Sci. 86: 767-778.

Mäder, P., A. Fliebbach, D. Dubois, L. Gunst, P. Fried, and U. Niggli. 2002. Soil fertility and biodiversity in organic farming. Science. 296: 1694–1697.

Malhi, S.S., A.P. Moulin, A.M. Johnston, and H.R. Kutcher. 2008. Short-term and long-term effects of tillage and crop rotation on soil physical properties, organic C and N in a Black Chernozem in northeastern Saskatchewan. Can. J. Soil Sci. 88: 273-282.

Martin, R.C., D.H. Lynch, B. Frick and P. van Straaten. 2007. Perspective: Phosphorus status on Canadian organic farms. J. Sci. Food Agric. 87: 2737-2740.

McKenzie, R.H., J.W.B. Stewart, J.F. Dormaar, and G.B. Schaalje. 1992. Long-term crop rotation and fertilizer effects on phosphorus transformations: I. In a Chernozemic soil. Can. J. Soil Sci. 72: 569-579.

McConkey, B.G., D. Curtin, C.A. Campbell, S.S. Brandt, and F. Selles. 2002. Crop and soil nitrogen status of tilled and no-tillage systems in the semiarid regions of Saskatchewan. Can. J. Soil Sci. 82: 489-498.

Miller, P.R., D.E. Buschena, C.A. Jones, and J.A. Holmes. 2008. Transition from intensive tillage to no-tillage and organic diversified annual cropping systems. Agron. J. 100: 591-599.

Monreal, C.M., and H.H. Janzen. 1993. Soil organic-carbon dynamics after 80 years of cropping a Dark Brown Chernozem. Can. J. Soil Sci. 73: 133-136.

Oehl, F., A. Oberson, H.U. Tagmann, J.M. Besson, D. Dubois, P. Mader, H.R. Roth, and E. Frossard. 2002. Phosphorus budget and phosphorus availability in soils under organic and conventional farming. Nut. Cycl. Agroecosyst. 62: 25-35.

Oehl, F., E. Sieverding, K. Ineichen, P. Mäder, T. Boller, and A.Wiemken. 2003. Impact of land use intensity on the species diversity of arbuscular mycorrhizal fungi in agroecosystemsof central Europe. Appl. Environ. Microbiol. 69: 2816–2824.

Padbury, G., S. Waltman, J. Caprio, G. Coen, S. McGinn, D. Mortensen, G. Nielsen, and R. Sinclair. 2002. Agroecosystems and land resources of the Northern Great Plains. Agron. J. 94: 251-261.

Peterson, G.A., A.J. Schlegel, D.L. Tanaka, and O.R. Jones. 1996. Precipitation use efficiency as affected by cropping and tillage systems. J. Prod. Agric. 9: 180-186.

Peterson, G.A., and D.G. Westfall. 2004. Managing precipitation use in sustainable dryland ecosystems. Ann. Appl. Biol. 144: 127-138.

Rice, C.W., and J.L. Havlin. 1994. Integrating mineralizable nitrogen indices into fertilizer nitrogen recommendations. p. 1–13. *In* J.L. Havlin et al. (eds.) Soil testing: Prospects for Improving Nutrient Recommendation. SSSA Spec. Publ. No. 40. SSSA. Madison, WI.

Rogner, H. 2000. Energy resources. p. 135-171. *In* J. Goldemberg (ed.), World Energy Assessment. United Nations Development Programme, New York.

Sainju U.M., T. Caesar-TonThat, A.W. Lenssen, R.G. Evans, and R. Kolberg. 2007. Long-term tillage and cropping sequence effects on dryland residue and soil carbon fractions. Soil Sci. Soc. Am. J. 71: 1730-1739.

Sall, J., L. Creighton, and A. Lehman. 2007. JMP Start Statistics: A Guide to Statistics and Data Analysis Using JMP, 4th Ed. Cary, NC: SAS Institute Inc.

Six, J., E.T. Elliott, and K. Paustian. 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J. 63: 1350-1358.

Stevenson, F.J. 1996. Nitrogen – organic forms. p.1185-1200. *In* D.L. Sparks et al. (eds.) Methods of Soil Analysis: Part 3. SSSA Book Ser. 5. ASA and SSSA, Madison, WI.

Smith, E.G., M.J. Clapperton, and R.E. Blackshaw. 2004. Profitability and risk of organic production systems in the northern Great Plains. Renewable Agric. Food Sys. 19: 152-158.

Tanaka, D.L., and R.L. Anderson. 1997. Soil water storage and precipitation storage efficiency of conservation tillage. J. Soil Water Conserv. 52: 363-367.

Thomas G.W. 1996. Soil pH and soil acidity. p. 475-490. *In* D.L. Sparks, et al. (eds.). Methods of Soil Analysis. Part 3. Chemical Methods, SSSA Book Ser. 5. SSSA and ASA, Madison, WI.

Welch, C., M. Tenuta, D. Flaten, C. Grant, and M. Entz. 2006. Organic crop management and soil phosphorus. Better Crops. 90: 6-7.

Willis, R.B. 1980. Reduction column for automated determination of nitrate and nitrite in water. Anal. Chem. 52: 1376-1377.

Yang, J.E. and J.S. Jacobsen. 1990. Soil inorganic phosphorus fractions and their uptake relationships in calcareous soils. Soil Sci. Soc. Am. J. 54: 1666-1669.

Yang, J.E., C.A. Jones, H.J. Kim, and J.S. Jacobsen. 2002. Soil inorganic phosphorus fractions and Olsen-P in phosphorus-responsive calcareous soils: effects of fertilizer amount and incubation time. Commun. Soil Sci. Plant Anal. 33: 855-871.

Zentner, R.P., C.A. Campbell, V.O. Biederbeck, P.R. Miller, F. Selles, and M.R. Fernandez. 2001. In search of a sustainable cropping system for the semiarid Canadian Prairies. J. Sustainable Agric. 18: 117-136.

Table 4.1. Mean monthly precipitation for the crop-year (Sep-Aug), Arthur H. Post Agronomy Farm, Bozeman, MT, 2005-2007.

	Monthly Precipitation (mm)			
	LTA‡	2005	2006	2007
Sep-Apr†	215	190	260	235
May	67	28	42	117
June	66	70	80	58
July	38	28	18	3
Aug	35	36	14	14
Crop Year	421	352	414	427

†Overwinter is Sept-Apr; Growing season is May-Aug.
*Climate data obtained form the official National Weather Service site located 100 m from study area at latitude: 45˚ 40' 25" longitude: 111˚ 09' 00" elevation 1436-m.

Table 4.2. Four year fully phased crop rotation for organic and four no-till (NT) cropping systems at the Crop Rotation Diversification Study at the MSU Arthur H. Post Agronomy Farm, Bozeman, MT, 2000-2003.

System	Phase 1	Phase 2	Phase 3	Phase 4
Organic	winter pea manure‡	winter wheat	lentil	barley
NT Diverse	spring pea§	winter wheat	corn†	sunflower
NT Winter	winter pea§¶	winter wheat	dormant spring canola	winter wheat
NT Spring	spring pea§	spring wheat	spring canola	spring wheat
NT Cont Wheat	spring wheat	winter wheat	spring wheat	winter wheat

‡In 2000, winter pea green manure failed and was replaced in the spring with Chickling vetch (*Lathyrus sativus* L.).
§Spring pea replaced by lentil (*Lens culinaris* Medik.) in 2001.
†Corn (*Zea mays* L.) was replaced by proso millet (*Panicum milaceum* L.) in 2000-2001.
¶Winter pea sown to spring habit in all years except for 2002 due to overwinter mortality.

Table 4.3. Planned four year dual phased crop rotation for organic, pesticide free production (PFP), and seven no-till (NT) cropping systems at the Crop Rotation Diversification Study at the MSU Arthur H. Post Agronomy Farm, Bozeman, MT, 2004-2007.

Cropping System	Phase 1	Phase 2	Phase 3	Phase 4
Organic	winter pea/ fallow	winter wheat	lentil	barley
PFP	winter pea	winter wheat	lentil	barley
NT Diverse-low	spring pea	winter wheat	sunflower	OP corn
NT Diverse-high	spring pea	winter wheat	sunflower	hybrid corn
NT Winter-low	winter pea	winter wheat	dorm. mustard	winter triticale
NT Winter-high	winter pea	winter wheat	dorm. LL canola*	winter triticale
NT Spring-low	spring pea	spring wheat	mustard	triticale
NT Spring-high	spring pea	spring wheat	LL canola	triticale
NT Cont Wheat	spring/winter wheat			

*Liberty Link® herbicide resistant.

Table 4.4. Soil characteristics of contrasting organic (Org) and non-organic (NO) cropping systems in Organic and Non-organic Soil Fertility Comparison Study, north central Montana, 2007.*

Location/Field Site		pH	OM	Sand	Silt	Clay	Texture
			----------%----------				
Conrad, MT[1]							
Site 1 (C1)	Org	8	2.6	21.2	46.4	32.4	Clay loam
	NO	7.7	2.6	21.2	50.4	28.4	Clay loam
Site 2 (C2)	Org	8.3	2.6	23.2	40.4	36.4	Clay loam
	NO	7.7	2.7	19.2	48.4	32.4	Silty clay loam
W. Big Sandy, MT[2]							
	Org	6.3	1.5	51.2	32.4	16.6	Loam
Site 1 (WBS)	NO	7.7	1.3	55.2	30.4	14.4	Loam
S. Big Sandy, MT[3]							
	Org	6.2	2.4	43.2	38.4	18.4	Loam
Site 1 (SBS1)	NO	7.1	1.7	39.2	40.4	20.4	Loam
	Org	6.6	1.6	55.2	28.4	16.4	Sandy loam
Site 2 (SBS2)	NO	7.2	1.4	51.2	32.4	16.4	Loam
	Org	8.2	1.8	37.2	36.4	26.4	
Site 3 (SBS3)	NO	8	1.8	41.2	32.4	26.4	Loam Loam
	Org	7.9	1.9	37.2	40.4	22.4	
Site 4 (SBS4)	NO	7.7	1.7	31.2	44.4	24.4	Loam Loam

*Values are a single measurement based on seven individual soil samples with six surface (0-0.15 m) cores per sample.
[1]Farm located in Pondera county 32 km east of Conrad, MT.
[2]Farm located in Choteau county approx. 3.5 km west of Big Sandy, MT.
[3]Four fields sampled at 3 farms located in Choteau approx. 20 km south of Big Sandy, MT.

Table 4.5. Crop management factors for paired Organic (Org), and non-organic (NO) cropping systems in Organic and Non-organic Soil Fertility Comparison Study, north central Montana, 2007.

Location/Field ID	Rotation	2007 Crop	Year Organic	Fertilization
Conrad 1 (C1)[1]				
Org	wheat-fallow	winter wheat	1991	legume GM every 7-8 years
NO	wheat-fallow	winter wheat	----	70 lb/ac (½ urea, ½ 11-52-0)
Conrad 2 (C2)[1]				
Org	wheat-fallow	winter wheat	1991	legume GM every 7-8 years
NO	wheat-fallow	winter wheat	----	70 lb/ac (½ urea, ½ 11-52-0)
West Big Sandy (WSB)				
Org	diverse	spring wheat	2000	legume GM every 3-4 years
NO	wheat-fallow	winter wheat	----	80-100 lb/ac (urea and MAP)
South Big Sandy 1 (SBS1)				
Org	diverse	winter wheat	1991	legume in rotation 3-4 years
NO	wheat-fallow	winter wheat		no fertilization for past 3 years
South Big Sandy 2 (SBS2)				
Org	diverse	tilled pea[2]	1991	legume in rotation 3-4 years
NO	wheat-fallow	fallow		no fertilization for past 3 years
South Big Sandy 3 (SBS3)				
Org	diverse	fallow	1988	legume in rotation 3-4 years
NO	wheat-fallow	winter wheat	----	no fertilization for past 3 years
South Big Sandy 4 (SBS4)				
Org	diverse	kamut	1988	legume in rotation 3-4 years
NO	barley-fallow	fallow	----	not fertilized since 1985

[1]Rotation previously spring wheat-fallow, but changed to winter wheat habit due to drier conditions over the past several years.
[2]Plow down of GM (*Pisum sativum* L.) 10 d prior to soil sampling.

Table 4.6. Mean nutrient concentration comparison for organic and no-till cropping systems following 8 years of cropping at the Crop Rotation Diversification Study at the Montana State University Arthur H. Post Agronomy Farm, Bozeman, MT, 2007.

System	*n*	Olsen P 0-0.15 m	Nitrate 0-0.60 m	PMN‡ 0-0.60 m	TKN† 0-0.15 m
		----mg kg^{-1}---	----------kg ha^{-1}----------		-----%----
Organic	8	15.7	57	56.9	0.127
No-till	32	20.5	68	65.2	0.123
NT vs Org (*P* value)*		0.03	0.20	0.40	0.68

†Total Kjeldahl nitrogen.
‡Potentially mineralizable nitrogen.
*Planned orthogonal contrast considered significant at $P \leq 0.05$.

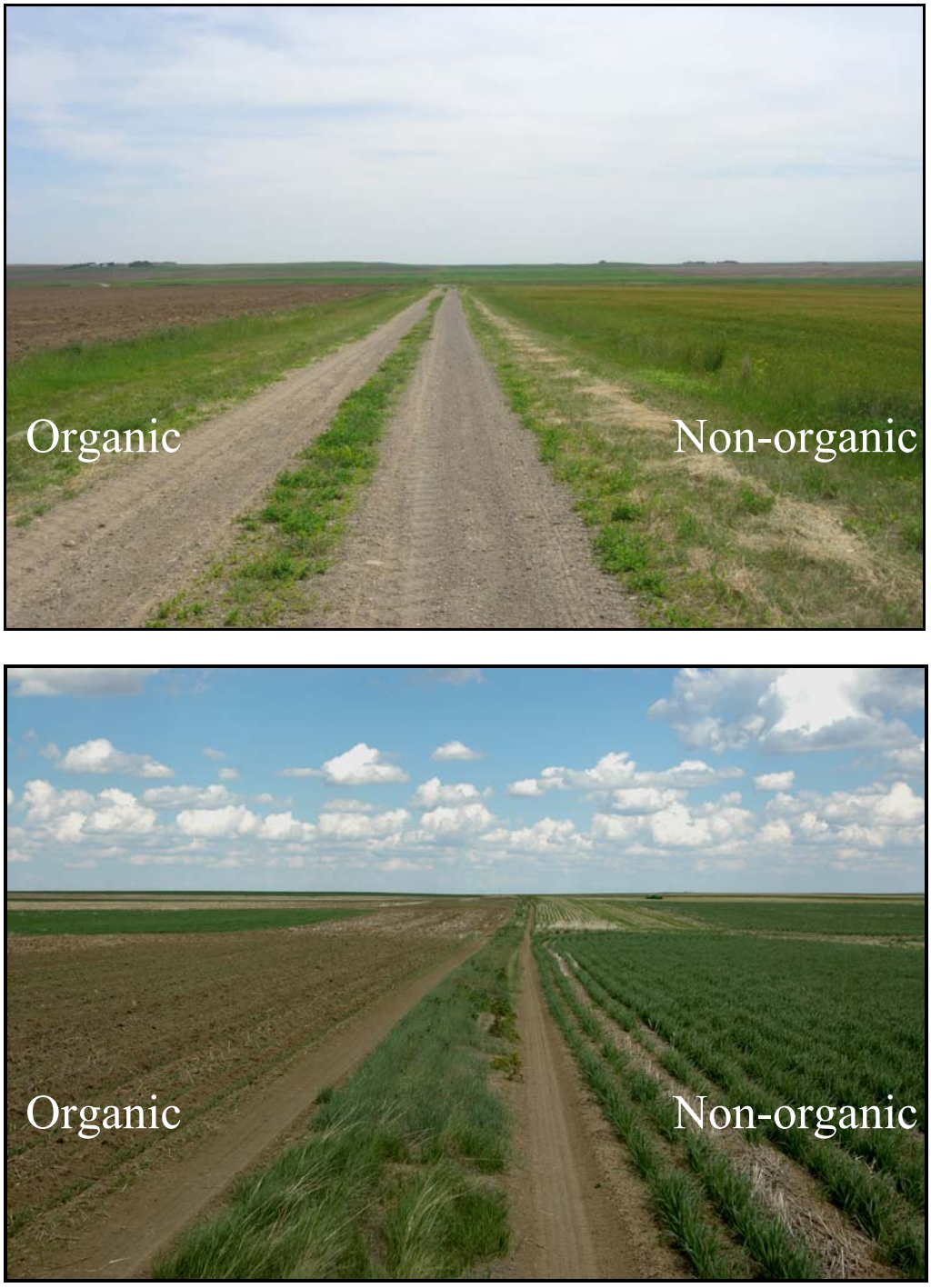

Figure 4.1. Farm lanes separating the contrasting Organic and Non-organic management systems in Organic - Non-Organic Soil Fertility Comparison Study, north central Montana. Upper photo taken of South Big Sandy Field 2 (SBS2). Lower photo of Conrad Field 1 (C1).

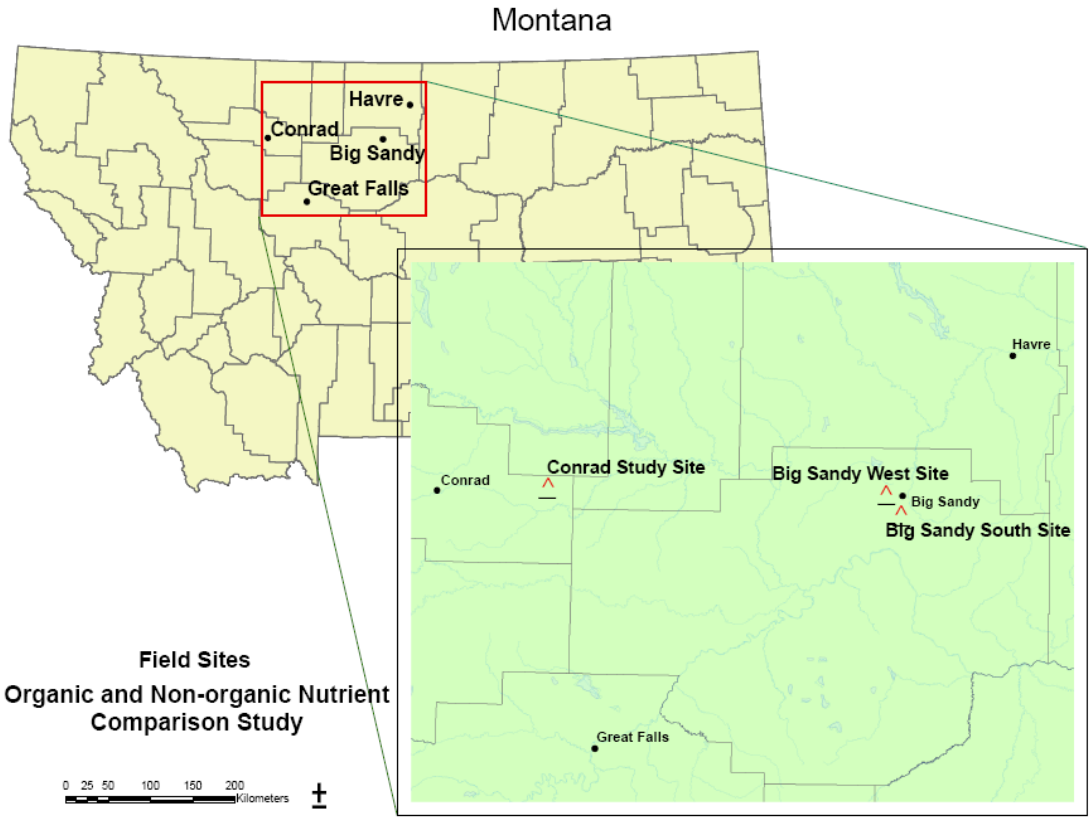

Figure 4.2. Field site locations for Organic and Non-organic Nutrient Comparison Study in north central Montana.

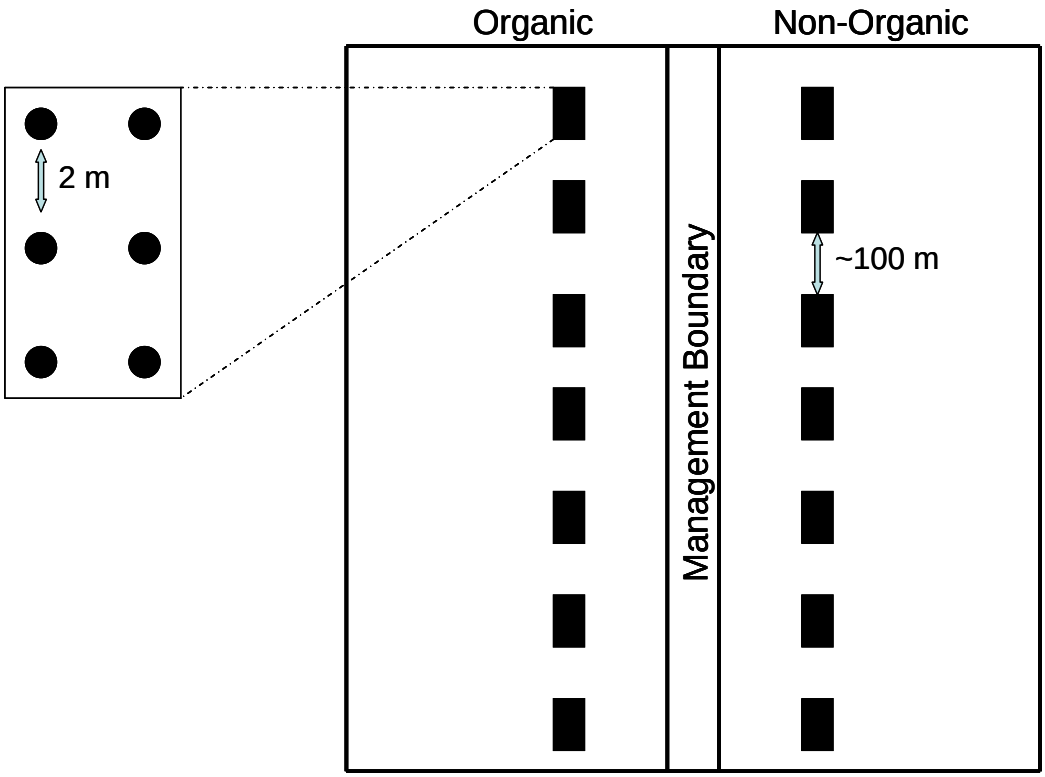

Figure 4.3. Schematic of sampling design for the Organic/Non-Organic Soil Fertility Comparison Study in north central Montana. Boxes represent paired sampling sites along both sides of the organic and non-organic management boundary. Circles show location of cores within a site used to create a composite sample.

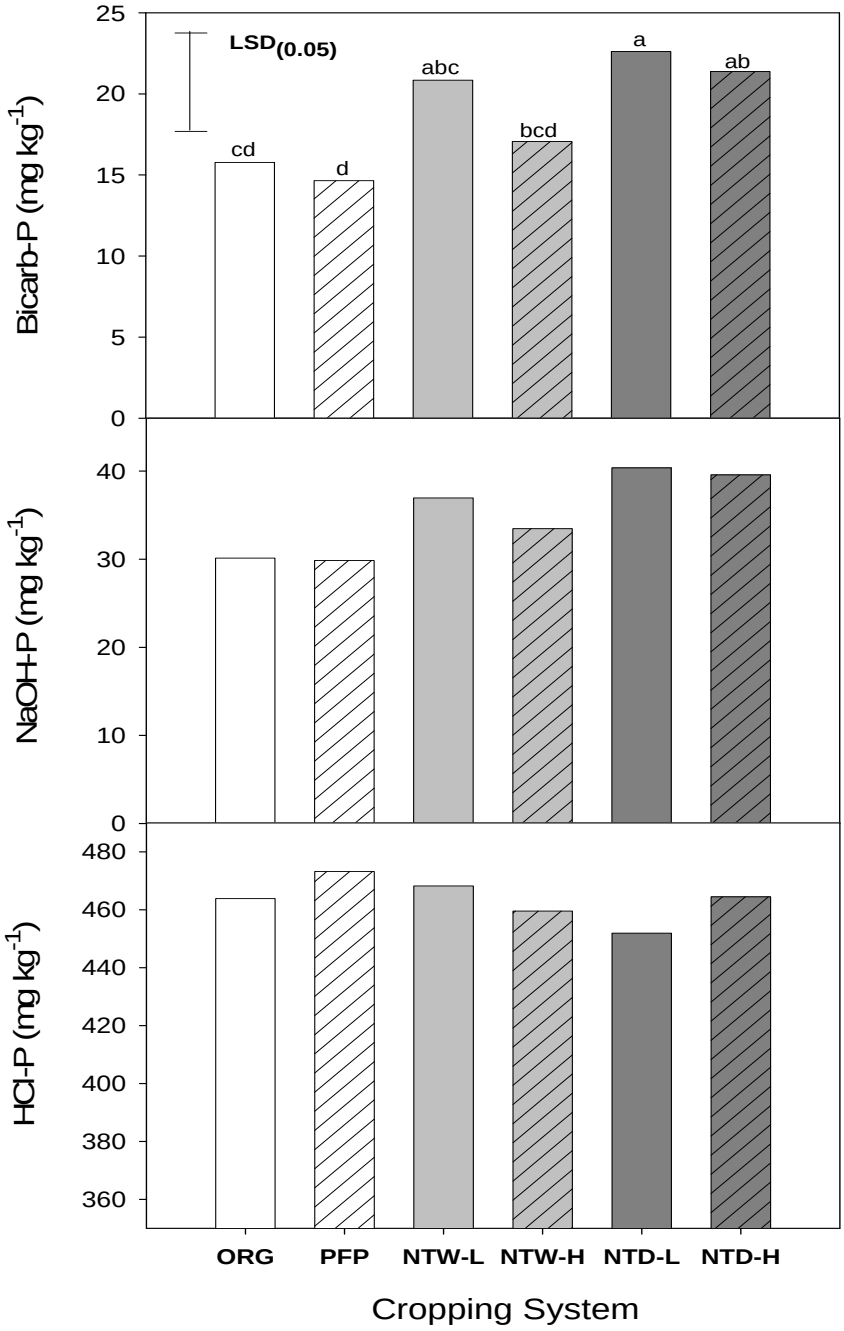

Figure 4.4. Mean soil inorganic P concentrations from sequential P fractionation analysis for cropping systems in the Crop Rotation Diversification Study. Each mean represents two phases with four replicates. Bars with same letter are not significantly different according to Fisher's Protected LSD at P= 0.05. Bicarb-P $LSD_{(0.05)}$=7.2 mg kg^{-1}; P concentrations in NaOH-P and HCl-P fractions were not significantly different among systems.

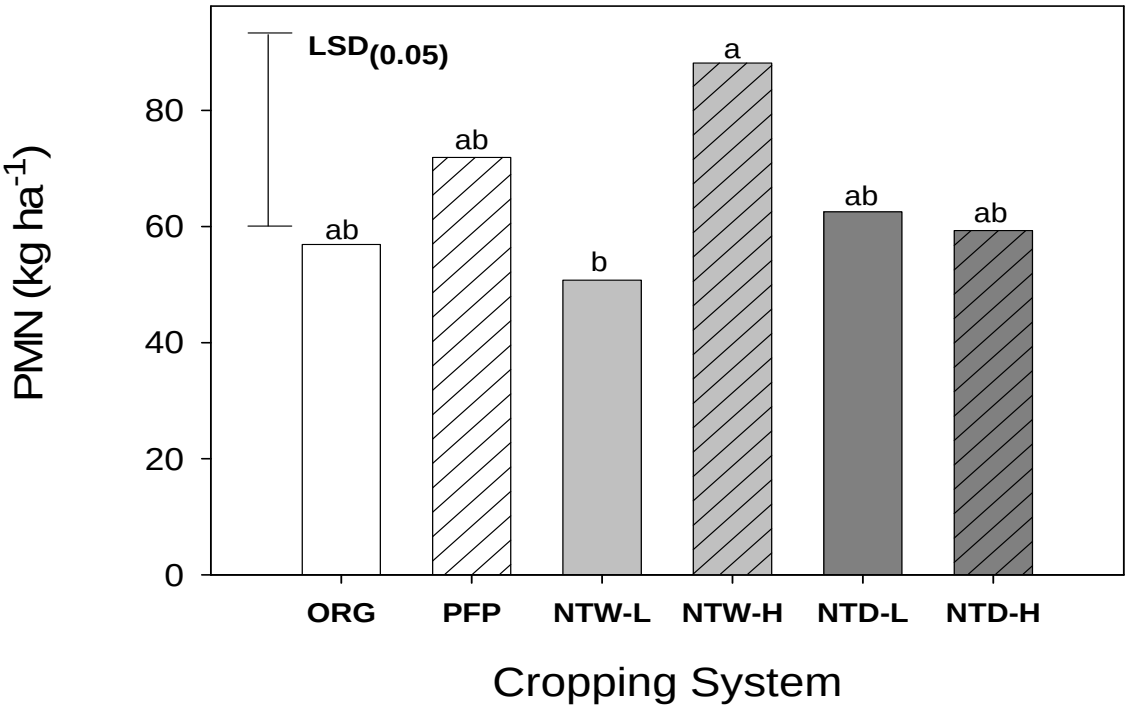

Figure 4.5. Mean potentially mineralizable nitrogen (PMN) concentrations for the 0-0.60 m depth for cropping systems in the Crop Diversification Rotation Study. Each mean represents four replicates of two phases. Bars with same letter are not significantly different according to Fisher's Protected LSD at *P*= 0.05. PMN $LSD_{(0.05)}$=34.7 kg ha^{-1}.

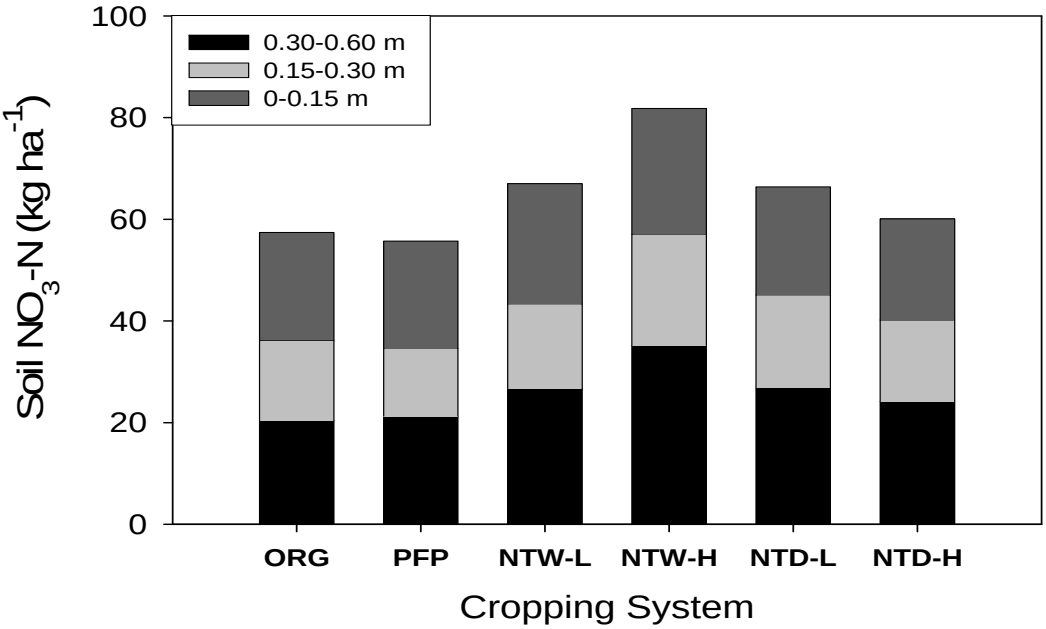

Figure 4.6. Mean soil nitrate (NO_3-N) concentrations for three depths (0-0.15 m, 0.15-0.30 m, 0.-0.60 m). Each mean represents two phases with four replicates. Analysis of variance conducted for total 0-0.60 m depth indicated no significant differences between systems at P= 0.05.

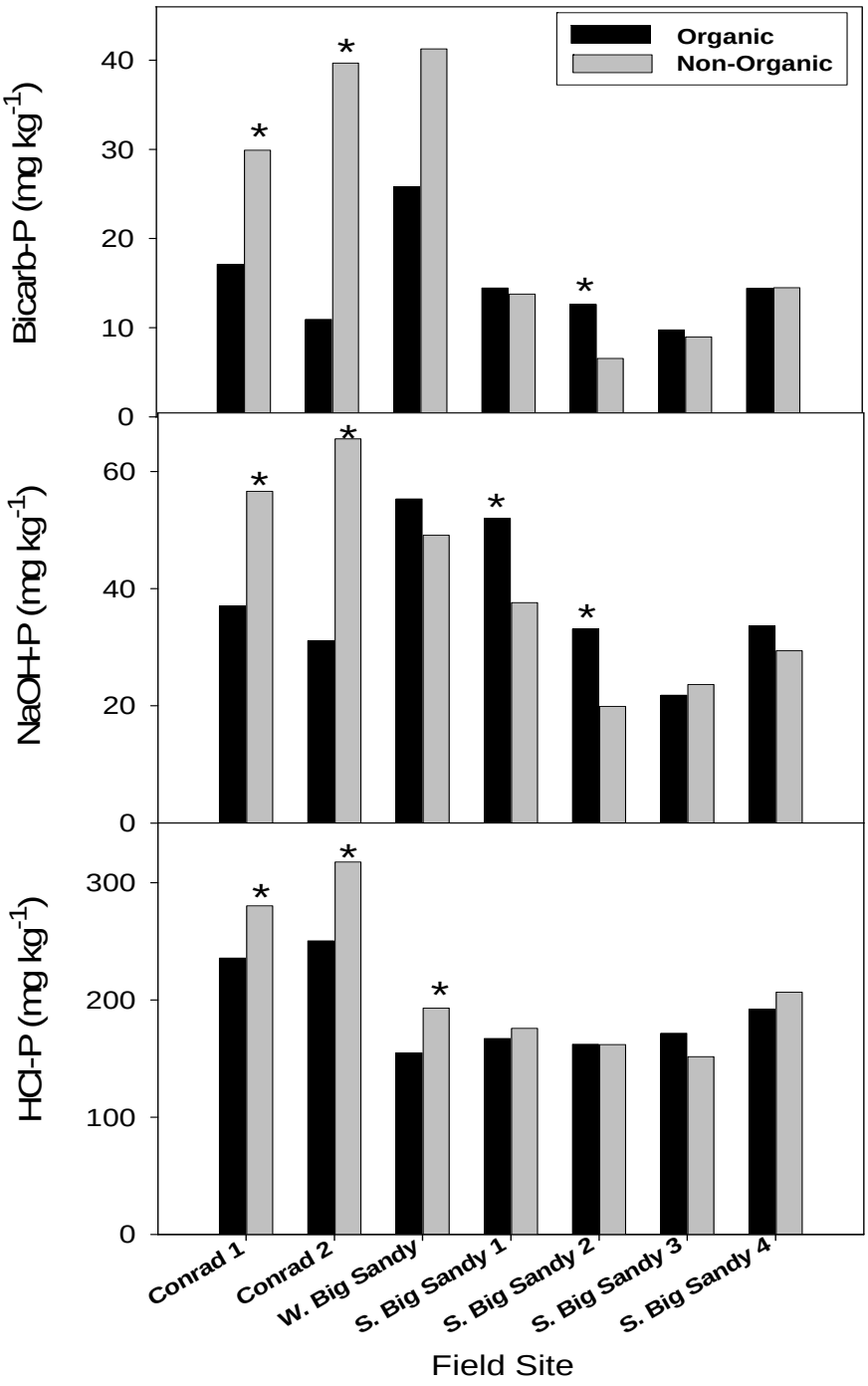

Figure 4.7. Mean soil inorganic P concentrations from sequential P fractionation in the Organic/Non-organic Soil Fertility Comparison Study, north-central Montana, 2007. Analysis of variance performed separately on paired organic and non-organic sites. Starred bars indicate cropping system mean is significantly different from its corresponding pair according to Fisher's Protected LSD at $\alpha = 0.05$.

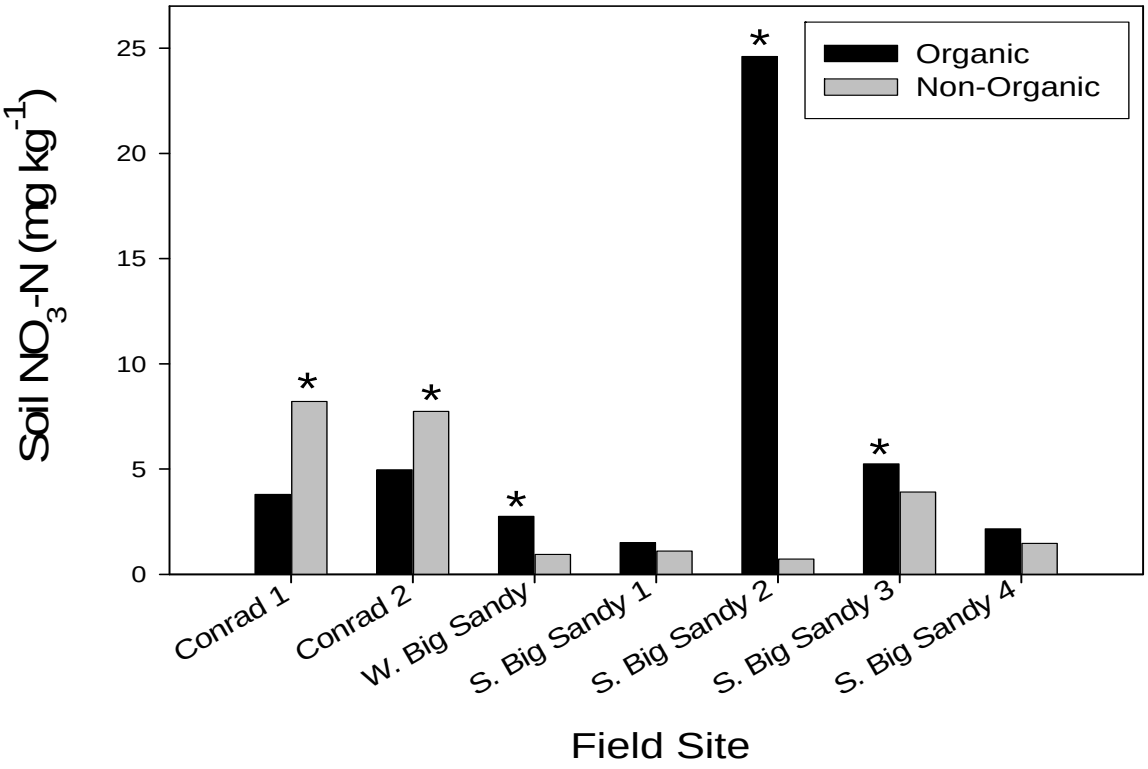

Figure 4.8. Mean soil nitrate (NO_3-N) concentrations for organic and non-organic cropping systems in the Organic/Non-organic Soil Fertility Comparison Study, north-central Montana, 2007. Analysis of variance performed separately on paired organic/non-organic sites. Starred bars indicate cropping system mean is significantly different according to Fisher's Protected LSD at $\alpha = 0.05$.

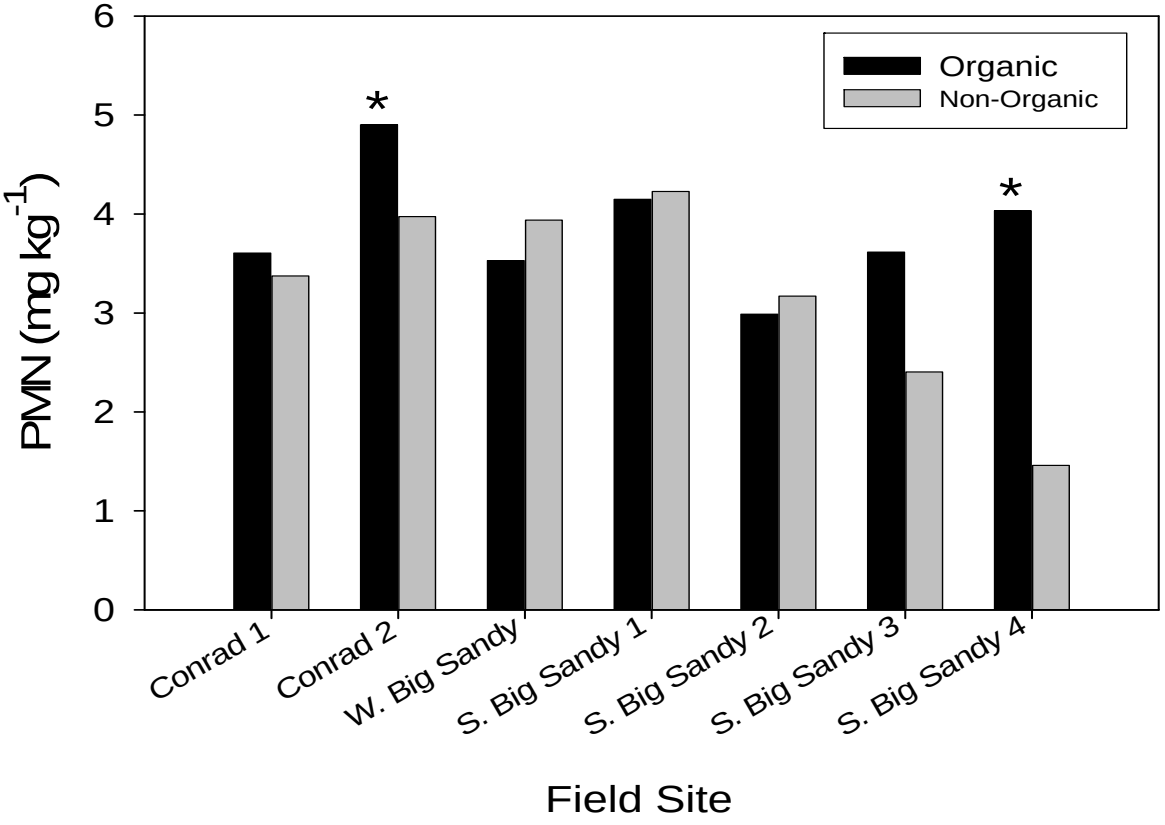

Figure 4.9. Mean soil potentially mineralizable nitrogen (PMN) concentrations for organic and non-organic cropping systems in the Organic/Non-organic Soil Fertility Comparison Study, north-central Montana, 2007. Analysis of variance performed separately on paired organic and non-organic sites. Starred bars indicate cropping system mean is significantly different from its corresponding pair according to Fisher's Protected LSD at $\alpha = 0.05$.

CHAPTER 5

SUMMARY

Soil fertility management remains one of the major challenges confronting organic producers in northern Great Plains (NGP) dryland organic cropping systems. Tools for maintaining soil fertility within the standards of organic production are limited for producers in the NGP. While nitrogen (N) fertility is managed through the inclusion of N-fixing legume green manures, mechanisms for replacing phosphorus (P) remain undeveloped. A better understanding of fertility management is essential to sustain crop yields and farm profitability in dryland organic cropping systems.

This research evaluated the efficacy of utilizing green manure (GM) crops in conjunction with unprocessed organic mineral phosphate fertilizers to enhance P fertility in NGP organic systems. In the Big Sandy field experiment, GM crops fertilized with rock phosphate (RP) were generally not effective at increasing the P nutrition of a subsequent wheat crop, with the possible exception of buckwheat fertilized at the higher rate of P. However, the results of this field study remain inconclusive due to multiple factors that may have impacted outcomes. Soil N deficiency, frost, and variable soil water levels were all factors that affected crop performance at this site. In addition, Olsen P values near or above the critical level, relatively high residual soil P, and low agronomic rates of applied P may have muted a measurable crop response.

As the dissolution of RP is enhanced by acidic soil conditions and adequate soil moisture, dissolution of RP in the NGP may not proceed rapidly enough to increase soil

solution P concentrations in the neutral to higher pH soil conditions common in the NGP region. Thus, RP may not be suitable for intensive agriculture because it cannot maintain sufficiently high solution P levels particularly in higher pH soils in semiarid regions. While the rate of total P applied is higher than available P in RP, it is not known whether the total P fraction would remain insoluble or become slowly available over time and serve as a reservoir to prevent future deficiency. Based exclusively on the results of the Big Sandy field study, RP combined with GM crops does not appear to represent a long-term strategy for maintaining P fertility in NGP organic systems. However, these results are based only on a single two year cropping sequence in a highly variable production environment with low soil N, and P concentrations near critical levels.

To ameliorate the variability of the production environment and high levels of available soil P, the greenhouse study was initiated using a low P soil in an effort to enhance responsiveness to applied P. Sparingly soluble RP was found to be effective at enhancing the P nutrition of a subsequent wheat crop following all crop treatments above their respective non-fertilized controls. Moreover, the P nutrition of wheat following buckwheat fertilized with all P sources was enhanced over the non-fertilized control. Phosphorus uptake of wheat following spring pea was not as effective as that of buckwheat. The weak P response of wheat following spring pea may reflect the N source (ammonium nitrate) used in this study. Added N can suppress biological N fixation, thereby reducing the acidifying effect of the rhizosphere observed in many experiments. Thus, it is important for effective P mobilization in pea to allow for natural biological N fixation. Adding a spring pea treatment without exogenous N fertilization treatment

would be beneficial in determining if spring pea could aid in the dissolution of low solubility organic P sources. The responsiveness of P uptake in wheat following all crops fertilized with RP indicates RP may have the potential for increasing the P fertility of organic cropping systems in neutral to alkaline pH soil common in the NGP.

As summarized in Chapter 4, studies have found P fertility generally declines over time in unfertilized organic cropping systems. Thus, this project also evaluated soil nutrient levels in contrasting non-organic no-tillage (NT) and organic cropping systems. In the Crop Diversification Rotation Study available P levels were significantly lower in the unfertilized organically managed systems compared to the fertilized NT systems. In comparison, the results of the Organic - Non-Organic Soil Fertility Comparison Study were less definitive due to the high level of management variability among systems. However, it was generally observed that available P levels were consistently lower in systems that were unfertilized regardless of management designation. If available P levels are indeed declining in organic systems, this would indicate that in the absence of a long-term strategy for replacing P exported through crop production, that soil P fertility will continue to decline and may ultimately affect crop yields and the long-term sustainability of organic systems in the NGP.

Studies of short duration may not adequately reveal the long-term viability of using organic mineral P sources in organic systems since organic systems rely heavily on dynamic soil biological process to build, store and cycle nutrients; thus short-term studies may not adequately capture the long-term effect of nutrients cycled from organic matter. Since the use of green manure crops is currently the foundation of nutrient management

in organic systems in the NGP, it is necessary to understand the dynamic between P uptake and the mineralization of P in residues on the availability of P for subsequent crops. The studies in this project did not measure the organic P fraction of the soil; therefore, it is unknown what long-term contribution organic mineral P fertilizers combined with GM crops may provide to future crops.

To best manage our agricultural systems it is important to develop sustainable soil fertility management practices. Phosphorus reserves are finite and require energy to extract, refine and export, and are essentially non-renewable resources that must be managed efficiently. As organic markets expand nationally and globally, it will be important to provide farmers with the tools necessary to sustain a more profitable and stable farm income by reducing the dependence on non-renewable resources, such as synthetic fertilizers and pesticides, and by promoting the environmental integrity of our agricultural systems. As organic farmers intensify and diversify organic systems to meet the increased demand for organic products, organic farming may exhaust soil P reserves. Therefore, it is critical to better understand P dynamics in organic farming systems and the P use efficiency of sparingly soluble P fertilizers used in organic systems. A greater understanding of P nutrition in biologically based organic systems may require a long-term multidisciplinary research approach to evaluate complex P transformations inherent in soil-plant system.

In the NGP where P availability is complicated by high pH soils and low soil moisture regimes, perhaps the efficacy of sparingly soluble calcium phosphate (Ca-P) sources, such as RP or bone meal (BM) may be enhanced through the use of acidifying

microorganisms. This approach may increase the acidification in the rhizosphere and enhance the dissolution of sparingly soluble P fertilizers. The investigation of the relationship between Mycorrhizae, GM crops, and organic P fertilizers may be another important avenue of P nutrition research in organic farming systems in the NGP.

APPENDICES

APPENDIX A

STATISTICAL TABLES REFERENCED IN CHAPTER 2

Table A.1. Analysis of variance (ANOVA) of pre-experimental Olsen P across the field site based on *proposed* main plot (crop) and sub-plot (P rate) treatments, Big Sandy, MT, 2006.

Source	df	Mean squares	*P* > F
		Olsen P (mg kg^{-1})	
Block (B)	3	77.72	<0.001
Proposed green manure crop (C)	3	18.93	0.038
Block x crop (Error A)	9	31.06	<0.001
Proposed P rate (R)	2	6.05	0.368
Crop x rate (C x R)	6	12.08	0.053
Residual error (Error B)	24	5.80	

Table A.2. Analysis of variance (ANOVA) of green manure biomass for main plot (crop) and sub-plot (P rate) treatments, Big Sandy, MT, 2006.

Source	df	Mean squares	*P* > F
		Shoot biomass (Mg ha^{-1})	
Block (B)	3	0.09	0.280
Green manure crop (C)	2	40.59	<0.001
Block x crop (Error A)	6	0.19	0.042
P rate (R)	2	0.16	0.139
Crop x rate (C x R)	4	0.04	0.062
Residual error (Error B)	18	0.07	

Table A.3. Analysis of variance (ANOVA) of green manure tissue P concentration for main plot (crop) and sub-plot (P rate) treatments, Big Sandy, MT, 2006.

Source	df	Mean squares	*P* > F
		Tissue P (%)	
Block (B)	3	0.0024	<0.001
Green manure crop (C)	2	0.0771	<0.001
Block x crop (Error A)	6	0.0001	0.010
P rate (R)	2	<0.0001	0.460
Crop x rate (C x R)	4	<0.0001	0.566
Residual error (Error B)	18	0.0003	

Table A.4. Analysis of variance (ANOVA) of green manure P uptake for main plot (crop) and sub-plot (P rate) treatments, Big Sandy, MT, 2006.

Source	df	Mean squares	*P* > F
		P Uptake (kg ha^{-1})	
Block (B)	3	4.79	<0.001
Green manure crop (C)	2	90.28	<0.001
Block x crop (Error A)	6	2.01	<0.002
P rate (R)	2	1.41	0.034
Crop x rate (C x R)	4	0.47	0.028
Residual error (Error B)	18	0.34	

Table A.5. Analysis of variance (ANOVA) of winter wheat grain yield for main plot (crop) and sub-plot (P rate) treatments, Big Sandy, MT, 2007.

Source	df	Mean squares	*P* > F
		Wheat grain yield (Mg ha^{-1})	
Block (B)	3	0.43	<0.001
Previous green manure crop (C)	3	0.22	<0.007
Block x crop (Error A)	9	0.09	0.059
P rate (R)	2	0.19	0.026
Crop x rate (C x R)	6	0.03	0.523
Residual error (Error B)	24	0.04	

Table A.6. Analysis of variance (ANOVA) of winter wheat total P uptake (grain plus biomass) for main plot (crop) and sub-plot (P rate) treatments, Big Sandy, MT, 2007.

Source	df	Mean squares	*P* > F
		Wheat grain yield (kg ha^{-1})	
Block (B)	3	21.89	<0.001
Previous green manure crop (C)	3	1.82	0.148
Block x crop (Error A)	9	0.96	0.447
P rate (R)	2	2.03	0.135
Crop x rate (C x R)	6	0.51	0.766
Residual error (Error B)	24	0.94	

Table A.7. Analysis of variance (ANOVA) of Bicarb-P fraction across the field site for main plot (crop) and sub-plot (P rate) treatments, Big Sandy, MT, 2007.

Source	df	Mean squares	*P* > F
		Olsen P (mg kg^{-1})	
Block (B)	3	107.32	<0.001
Green manure crop (C)	3	6.86	0.168
Block x crop (Error A)	9	20.58	<0.001
P rate (R)	2	7.36	0.162
Crop x rate (C x R)	6	12.11	0.018
Residual error (Error B)	24	3.75	

Table A.8. Analysis of variance (ANOVA) of NaOH-P fraction across field site for main plot (crop) and sub-plot (P rate) treatments, Big Sandy, MT, 2007.

Source	df	Mean squares	*P* > F
		NaOH-P (mg kg^{-1})	
Block (B)	3	173.59	0.021
Green manure crop (C)	3	66.78	0.238
Block x crop (Error A)	9	168.08	<0.005
P rate (R)	2	11.24	0.778
Crop x rate (C x R)	6	146.72	0.016
Residual error (Error B)	24	44.29	

Table A.9. Analysis of variance (ANOVA) of HCl-P fraction across the field site for main plot (crop) and sub-plot (P rate) treatments, Big Sandy, MT, 2007.

Source	df	Mean squares	*P* > F
		HCl-P (mg kg^{-1})	
Block (B)	3	1172.22	<0.001
Green manure crop (C)	3	547.86	0.269
Block x crop (Error A)	9	540.66	0.253
P rate (R)	2	985.00	0.102
Crop x rate (C x R)	6	147.51	0.887
Residual error (Error B)	24	392.68	

APPENDIX B

STATISTICAL TABLES REFERENCED IN CHAPTER 3

Table B.1. Analysis of variance (ANOVA) of buckwheat shoot biomass in greenhouse experiment, 2006. ¶

Source	df	Mean squares	*P* > F
		Shoot biomass (g pot^{-1})	
Block (B)	3	3.46	0.152
Phosphorus treatment (P)	6	3.14	0.015
Residual	18	1.74	

¶ Non-constant variance across crop types, therefore ANOVA completed individually per crop.

Table B..2. Analysis of variance (ANOVA) of spring pea shoot biomass in greenhouse experiment, 2006. ¶

Source	df	Mean squares	*P* > F
		Shoot biomass (g pot^{-1})	
Block (B)	3	2.28	0.105
Phosphorus treatment (P)	6	3.41	0.017
Residual	18	0.96	

¶ Non-constant variance across crop types, therefore ANOVA completed individually per crop.

Table B..3. Analysis of variance (ANOVA) of spring wheat pea shoot biomass in greenhouse experiment, 2006. ¶

Source	df	Mean squares	*P* > F
		Shoot biomass (g pot^{-1})	
Block (B)	3	0.01	0.973
Phosphorus treatment (P)	6	0.74	0.005
Residual	18	0.16	

¶ Non-constant variance across crop types, therefore ANOVA completed individually per crop.

Table B.4. Analysis of variance (ANOVA) of buckwheat P uptake in greenhouse experiment, 2006. ¶

Source	df	Mean squares	*P* > F
		P Uptake (mg pot^{-1})	
Block (B)	3	30.2	0.027
Phosphorus treatment (P)	6	38.61	0.003
Residual	18	7.82	

¶ Non-constant variance across crop types, therefore ANOVA completed individually per crop.

Table B.5. Analysis of variance (ANOVA) of spring pea P uptake in greenhouse experiment, 2006. ¶

Source	df	Mean squares	*P* > F
		P Uptake (mg pot^{-1})	
Block (B)	3	16.02	<0.001
Phosphorus treatment (P)	6	16.88	<0.001
Residual	18	1.48	

¶ Non-constant variance across crop types, therefore ANOVA completed individually per crop.

Table B.6. Analysis of variance (ANOVA) of spring wheat P uptake in greenhouse experiment, 2006. ¶

Source	df	Mean squares	*P* > F
		P Uptake (mg pot^{-1})	
Block (B)	3	0.33	0.689
Phosphorus treatment (P)	6	2.08	0.028
Residual	18	0.67	

¶ Non-constant variance across crop types, therefore ANOVA completed individually per crop.

Table B.7. Analysis of variance (ANOVA) of shoot biomass production in wheat from the wheat phase in the greenhouse experiment, 2006.

Source	df	Mean squares	*P* > F
		Shoot biomass (g pot^{-1})	
Block (B)	3	0.11	0.789
Previous Crop (C)	3	2.93	<0.001
Phosphorus treatment (P)	6	5.84	<0.001
Crop x treatment (C x P)	18	0.46	0.143
Residual	81	0.32	

Table B.8. Analysis of variance (ANOVA) of P uptake in wheat from the wheat phase in the greenhouse experiment, 2006.

Source	df	Mean squares	*P* > F
		P Uptake (mg pot^{-1})	
Block (B)	3	7.37	0.002
Previous Crop (C)	3	99.21	<0.001
Phosphorus treatment (P)	6	40.55	<0.001
Crop x treatment (C x P)	18	2.67	0.029
Residual	81	1.42	

Table B.9. Analysis of variance (ANOVA) of tissue P concentration in wheat from the wheat phase in the greenhouse experiment, 2006.

Source	df	Mean squares	*P* > F
		Tissue P (%)	
Block (B)	3	0.00146	<0.001
Previous Crop (C)	3	0.01161	<0.001
Phosphorus treatment (P)	6	0.00138	<0.001
Crop x treatment (C x P)	18	0.00018	0.093
Residual	81	0.00011	