IMPACT OF ROTATION, COVER CROP AND MANURE INPUTS ON PRODUCTIVITY, SOIL ORGANIC MATTER FRACTIONS AND SOIL NITROGEN IN IRRIGATED MICHIGAN POTATO CROPPING SYSTEMS

By

Kathleen A. O'Neil

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ABSTRACT

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Michigan growers have begun to integrate winter rye (*Secale cereale*) cover crops and manure amendments into potato (*Solanum tuberosum*) cropping systems to decrease soil erosion and nutrient losses and to improve soil organic matter (SOM). Information about cover crop biomass accumulation and effects within the constraints of a Michigan potato cropping system is limited. Objectives of these studies were to 1) quantify winter cover crop biomass accumulation on commercial potato farms and in controlled potato cropping field studies, 2) understand effect of maturity on important cover crop biochemical qualities, 3) compare productivity, soil organic matter fractions and nutrient pools in field studies where potatoes were rotated with wheat, corn or snap beans with and without manure amendments. Mid-April above-ground rye biomass on commercial farms ranged from 10 to 2600 kg ha^{-1} over two years and averaged about 900 kg ha^{-1}. Root biomass was typically 2 to 5 times greater than shoot biomass in these fields. Most commercial Michigan potato farms are achieving sufficient winter rye cover crop maturity and biomass for weed suppression and erosion and nutrient loss reduction, but are probably not generating sufficient biomass to restore SOM without additional inputs. A field experiment demonstrated that mid-September to mid-October cover crop planting can increase winter rye and rye-hairy vetch (*Vicia villosa* L. Roth) biomass compared with biomass measured in commercial fields. An additional 4 to 6 weeks of fall growth can double above-ground rye biomass in the spring. During early spring growth (from 416 to 532 GDD) above ground

biomass was accumulated at 144, 232 and 39 kg ha^{-1} per 10 GDD for rye, rye-hairy vetch and hairy vetch cover crops, respectively. For the 532 to 962 GDD growing period, above-ground biomass accumulated at 97 and 218 kg ha-1 per 10 GDD (across all cover crops) for zero and 30 kg N ha^{-1} treatments. Below-ground biomass changes for 6 cover crop-soil inorganic N content combinations were smaller and more variable. Above-ground cover crop tissue organic matter (OM), neutral detergent fiber (NDF) and acid detergent lignin (ADL) content were significantly affected by species and soil N fertility on some sampling dates. Both NDF and ADL fractions increased with maturity across species and N treatment. Early June soil macro-POM-C and –N pools reflected biomass and quality of cover crops, but these fractions did not persist through the growing season. By late October, Potato-Wheat/Clover rotation plots had higher macro-POM fractions than Potato-Snap bean rotations, regardless of winter cover crop, despite having low macro-POM fractions in early June. Across 3 sampling dates at both locations, Potato-Wheat/Clover rotation plots were consistently among the treatments with the highest POM-C and -N fractions and the lowest POM C:N ratios. Potato-Wheat/Clover rotation plots and all non-potato phase plots had the greatest inorganic N availability. Residual inorganic N after crop removal was generally higher for potato phase plots than for non-potato phase plots to a depth of 51 cm. In a production trial, cover crop treatment did not affect total or US No. 1 tuber yields consistently, but 5.6 Mg ha^{-1} poultry manure amendment with fertilizer reduction consistently increased US No. 1 tuber yield by an average of 17.6%. Rye cover crop, with and without poultry manure, were the only treatment combinations to produce positive marginal revenues compared with an unamended bare control treatment.

DEDICATION

I dedicate this volume of work and the years it has required to my partner, Becky, for her love, support and infinite patience and for her unselfish commitment to my pursuit and completion of graduate research and studies. I owe her countless hours, knee-deep in northern Michigan, New York and Montana trout streams, in return.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

AREA AND VALUE OF POTATO PRODUCTION IN MICHIGAN

Potatoes (*Solanum tuberosum*) are an important and historical part of Michigan agriculture and its economy. European settlers came to what is now the State of Michigan and began cultivating potatoes on land following hardwood timber removal. The 1860 Michigan census reports 5,261,245 bushels of potatoes produced, equivalent to more than 3.1 million hundredweight (cwt) or more than 143 Mg (Figure I.1). In 1899, Michigan's Montcalm, Kent and Oakland counties were among the top ten counties nationwide in potato production; each county produced over 1.35 million bushels (810,000 cwt, 36,700 Mg) of potatoes on over 20,000 acres (8000 ha) each. The 1910 census reveals a peak in Michigan potato production with more than 365,000 acres (147,906 ha) planted, over 35 million bushels (21 million cwt, 960,000 Mg) harvested and valued at more than $13 million. Since the 1950s, land area in Michigan used for potato production has stabilized between 45,000 and 50,000 acres (18,200 to 20,200 ha) (USDA-NASS, 2008) (Figure I.1.). 1950 also marks the beginning of a continual increase in potato yields due to shifts in geographical areas of production, increased grower specialization, advances in technology, and improved cultural techniques such as the use of disease-free seed (Guenthner, 2010). Before 1950, reported potato yields for Michigan ranged from 35 to 70 cwt per acre (3.9 to 7.9 Mg ha^{-1}). In 2009, average potato yield was a record-high 360 cwt per acre or 40.35 Mg ha^{-1}. Also in 2009, 600 Michigan farms grew over 45,000 acres of potatoes in Michigan and represented over $164,000,000 in cash receipts. In 2010, the value of Michigan's potato crop was ranked 10th largest agricultural commodity in the state, behind milk, corn, soybeans, floriculture, cattle and calves, poultry and eggs, hogs, wheat and sugarbeets. The majority of potatoes grown in Michigan are round, white varieties, with Russet, yellow and red cultivars making up just 10-15% of the statewide crop (USDA-NASS, 2010b).

CLIMATE REQUIREMENTS FOR POTATO PRODUCTION

Though potatoes are an integral part of the global food system and are the world's number one non-grain food commodity (FAO, 2008), their production is not without significant challenges. Outside of Michigan, potatoes are grown in other regions of the U.S. and in more than 100 other countries under temperate, subtropical and tropical conditions. The potato's widespread popularity is due to its versatility as a carbohydrate- and micronutrient-rich food (FAO, 2008). Potato tubers develop at temperatures between 10°C (50°F) and 30°C (86°F) and optimal tuber yields are achieved when mean daily temperatures range from 18 to 20°C (64 to 68°F). Potential potato yield is determined by the availability of solar radiation, the length of the frost-free growing period and suitable moisture and temperature regimes. All other requirements can be met with proper management (Rosen, 2010). Michigan has a short growing season of 120 to 150 days and its potato-growing regions fall into USDA hardiness zones 4b to 6a. About 5% of Michigan's fall potato crop is planted by April 16 each year, and 95% of the crop has been planted by June 8. The most active time for planting is from the end of April through May. Harvesting begins in late July for a small percentage of the potato crop which is sold directly from the field to fresh market or processors. Most harvesting takes place from August through mid-October with 95% of potatoes dug by October 28 each year (USDA-NASS, 2010a).

SOIL TYPES AND FERTILITY PRACTICES FOR POTATO PRODUCTION

Ideal soils for potato production are deep, coarse, well-drained and friable (Rosen, 2010). The sandy loam and loamy sand soils used for potato cropping in Michigan meet these criteria and are also low in both clay and organic matter, ranging from 4 to 13% clay and from 0.40 to 1.9% SOM in the Ap horizon (Soil Survey Staff, 2012) and therefore have a low nutrient- and water-holding capacity. Because potatoes require large quantities of water and nutrients and these soils lack the intrinsic ability to supply them, most potato land is irrigated and fertilizer use is relatively high. (Gardner et al., 1985; Warncke et al., 2004). These coarse and relatively unstructured soils are particularly vulnerable to organic matter depletion under intensive crop management (Saini and Grant, 1980). High organic matter, muck soils, can also produce good yields of high quality potatoes if adequately drained, however these soil types are less commonly used for potato production in Michigan.

Soil acidity is extremely important to nutrient availability and therefore to potato plant growth and productivity. Potatoes tolerate slightly acidic soil, but grow best when soil pH is 5.2 to 6.5. Potatoes require 17 nutrients for proper growth and nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), boron (B) and molybdenum (Mo) are most available in mineral soils when the pH is between 6.0 and 7.0. Zinc (Zn), manganese (Mn), iron (Fe) and copper (Cu) availability is best when the soil pH is below 6.5. At soil pH below 5.0, aluminum (Al) and Mn become more soluble and toxic, which reduces plant vigor and tuber yield. From a fertility standpoint therefore, it is desirable to maintain the pH of mineral soils between 6.0 and 6.5 (Warncke et al., 2004). However, a pH of greater than 5.5 will generally increase incidence of common scab, a common tuber disease caused by *Streptomyces* bacteria that does not reduce yield but causes lesions which reduce tuber marketability. To balance these opposing concerns, mineral soils used for potato cropping are normally limed to pH 6.0 after fall potato harvest, to optimize nutrient availability and to minimize scab pressures. Growers use scab-tolerant varieties when possible to reduce scab severity.

Nitrogen, phosphorus and potassium are important nutrients for optimal potato production and quality and must be provided with fertilizer applications during the growing season. Nitrogen (N) is a critical nutrient for potatoes as it affects both tuber yield and quality. Insufficient N can dramatically reduce yield while excess N can reduce tuber quality and result in leaching losses to groundwater. Potatoes use soil phosphorus (P) inefficiently, especially in cool early season soils, so P is often applied at or just before planting. Potassium (K) can also affect potato tuber quality; though potatoes have a high K requirement, excessive soil K will lower tuber specific gravity. Most potatoes in Michigan are grown on sandy soils which do not hold sufficient amounts of K so growers must accurately provide K fertilization (Vitosh, 1990).

WATER REQUIREMENTS FOR POTATO PRODUCTION

Though most regions within Michigan typically receive adequate precipitation for many crops (71 to 94 cm per year), most all Michigan potatoes are grown under irrigation because water availability is one of the most important factors determining yield and quality of the crop. Overall potato yield, and prevalence of several tuber disorders and diseases, is directly related to water quantity and distribution pattern during the growing season. Seasonal water requirement for potato cultivars is considered to be from 46 to more than 91 cm of water, but exact water requirements for optimal potato growth depends on cultivar, soil type, relative humidity, solar radiation, day length, length of growing season, and other environmental factors (Shock, 2010). For Michigan’s low water-holding capacity soils, irrigation recommendations normally include frequent applications of small amounts to maintain an adequate water supply throughout all growth stages of the crop, most especially during tuber initiation and enlargement.

TRAFFIC AND TILLAGE OPERATIONS IN POTATO CROPPING SYSTEMS

Potato production requires more soil disturbance and field traffic than many other crops. In Michigan, potatoes are cultivated as a cool-season annual crop and are clonally propagated by planting disease-free seed tubers, or cut tuber pieces containing one or more eyes (Ewing, 1997). Seed tubers are buried in a shallow trench (10-15 cm deep) in the early spring as soon as soils are warmed and appropriately moist for soil conditioning. Spring tillage is typically done with a plow or disk and serves to prepare the seedbed, aerate soil, control weeds, to incorporate cover crops, fertilizers, lime, organic amendments and other pre-planting treatments. Potatoes require soil temperatures of at least 7°C (45°F) to germinate and can tolerate a light frost, so in Michigan, most potatoes are planted in early spring between April 20 and May 15. During the first 30 to 40 days after planting and before canopy closure, soil is ridged or hilled over the base of the plants as they grow, to enhance stolon development, prevent 'greening' of the developing tubers, and to reduce weed populations and facilitate harvest. Hilling is normally accomplished with one or two successive tillage operations (Pierce and Burpee, 1995) and also serves to incorporate fertilizer applications. Herbicide and pesticide applications are applied before and during the growing season, usually via ground implements, but may alternatively be applied via airplane or overhead irrigation systems. Near the end of the growing season, potato vines senesce and are typically killed completely 10 to 14 days before harvest with either a mechanical method or a chemical desiccant treatment to stop tuber growth and promote tuber maturation and skin set (Johnson, 2010; Stark and Love, 2003). When tubers have matured, they are removed from slightly moist soil with a specialized potato harvester implement. A potato harvester digs beneath the potato row and lifts tubers and soil over a vibrating chain which separates tubers from soil and plant debris. As they are harvested, tubers are typically transferred directly into a field truck moving alongside the harvester and these trucks transport tubers from the field to packing sheds, processing plants or storages (Thornton and Johnson, 2010). After tubers are harvested, fields may be disked and planted with a winter cover crop as the final field operations of the season. In total, a potato field may be subjected to many more tillage and traffic operations than is required for most other crops. Frequent and intensive soil disturbance in potato rotations destroys soil aggregation, reducing SOM and particulate organic matter (POM) (Lal et al., 1994; Six et al., 1999). Intensive tillage and heavy field traffic has also been shown to damage soil structure, compact soil, limit rooting depth and reduce potato yields and quality (Lesczynski and Tanner, 1976; Young et al., 1993).

ROTATION CROPS USED IN POTATO PRODUCTION

Potato cropping systems in Michigan have become less diverse and more intensively managed in response to increased land values in rural areas resulting from the pressures of urbanization, and to ever-increasing demands to sustain long-term and short-term profitability. Potatoes are an important commodity in Michigan, representing 26% of the state's 175,000 vegetable acres (United States Department of Agriculture, 2004). From 1982 to 2001, 10 million acres of prime farmland was converted to new, non-farm developments within the contiguous United States and, in the Great Lakes basin, cropland acreage declined by 11 percent over a similar period (NRI,(2003). To maximize returns under these land availability constraints, today Michigan potato producers typically utilize simplified 2-year rotations of potatoes with corn, wheat, short-season vegetables or other annual crops. Few to no perennial crops are included in Michigan potato crop rotations.

RISKS TO POTATO PRODUCTION

Similar to other regions, Michigan potato cropping systems are managed with intensive tillage and heavy field traffic, low organic inputs, chemical fumigation, multiple fertilizer applications, overhead irrigation, and chemical weed and pest controls. Additionally, the coarse, well-drained, low organic matter soils typically used for potato production are particularly vulnerable to structural damage and organic matter degradation (Saini and Grant, 1980). As a result of all these conditions, soil structure, biological resilience, and general soil quality have been degraded over 30-50 years under this intensive cropping system More and more potato producers in Michigan are growing concerned about declining yields and long-term sustainability (Michigan Potato Industry (Commission, 2012).

Maintaining or improving soil quality is essential for sustaining agricultural productivity and valuable environmental services. SOM or soil organic carbon (SOC) imparts several important characteristics central to soil function and productivity and is a primary factor in soil quality. SOM is a source and a sink for nutrients necessary for plant growth, it maintains soil structure and tilth, increases water and nutrient retention, provides an energy source for soil biota, and provides physical protection from erosion at the soil surface (Sikora and Stott, 1996). SOM, or SOC, is a critical parameter in a minimum set of indicators for describing condition, health or quality of soil (Doran and Parkin, 1996). Plant residues are the primary resources for SOM or SOC formation. Amount of plant litter, its biochemical composition and physical properties are the main factors controlling formation of SOM and its decomposition in terrestrial systems (Oades, 1988; Scholes et al., 1997; Swift et al., 1979). The potato and main rotation crops used in these Michigan potato cropping systems return little crop residue to the soil and do not provide cover during winter months when risks of erosion and nutrient losses are the greatest. Typical Michigan potato cropping systems use a bare fallow or a winter rye (*Secale cereale*) cover crop during the winter months, between growing seasons. In recent years, discussions with Michigan potato growers and preliminary observations of their fields indicate that use of a winter rye cover crop has become much more commonplace as growers attempt to increase plant residue inputs and to reduce erosion and leaching losses of SOM and nutrients. In potato rotations however, rye cover crop seeding rate is variable and is often delayed until after potatoes are harvested in October. Late seeding can result in poor growth and minimal ground cover over the winter. The potato and main rotation crops used in these Michigan potato cropping systems return little crop residue to the soil and do not provide cover during winter months when risks of erosion and nutrient losses are the greatest.

The growing soil quality challenges and interest in the use of cover crops and organic amendments by Michigan potato farmers for improving soil quality and nutrient cycling justifies research to investigate their effectiveness. The studies included in this volume attempted to investigate impacts of rotation, cover crop and poultry manure amendment in a typical Michigan potato cropping system. Cover crop biomass accumulation within the constraints of a potato rotation were investigated both on commercial potato farms and within controlled experiments conducted at field stations. Because biochemical properties of plant residues dictate their decomposition and mineralization, changes in biochemical parameters of commonly used cover crops were monitored as plants matured in spring. Responses in soil organic fractions, N mineralization potential and residual N to rotation and cover crop alternatives were also examined in a 6-year field experiment. And finally, potato yields and tuber quality, as well as whole-rotation productivity and economic returns were compared in a field study conducted at two locations.

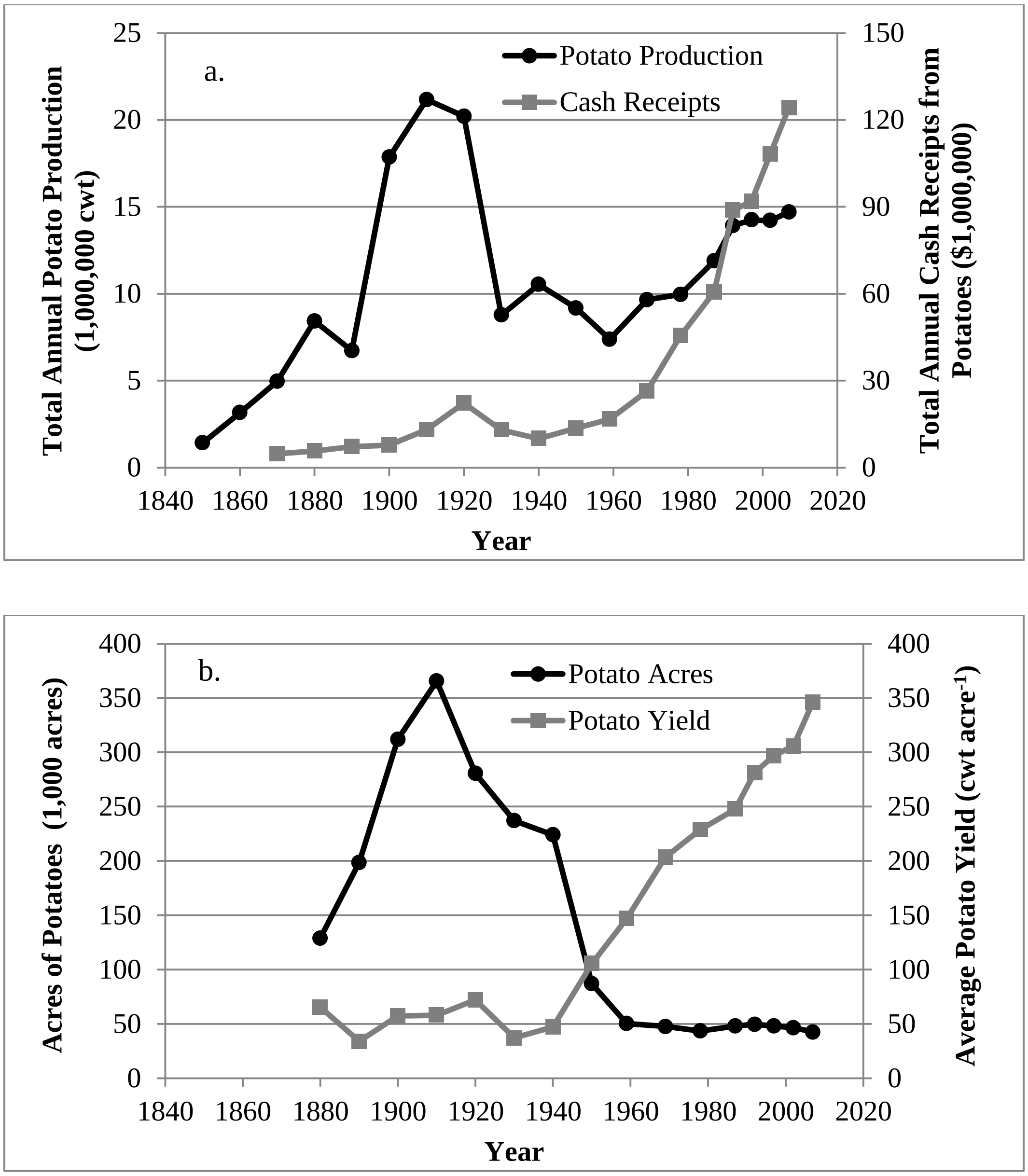

Figure I.1. Fluctuations in a.) total potato production and cash receipts from potato sales and b.) potato acreage and yield per acre in Michigan from 1840 to 2010.

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CHAPTER 1:

SPECIES, MATURITY AND SOIL INORGANIC NITROGEN INFLUENCE BIOCHEMICAL QUALITIES OF WINTER COVER CROP RESIDUES

ABSTRACT

It is widely recognized that biochemical composition or quality governs patterns of decomposition and mineralization of plant residues in soil. Accurate prediction of decomposition and subsequent mineralization of plant available nutrients remains imperfect, yet accurate prediction of nutrients availability is critically important for growers and land managers for whom efficient nutrient use and tight nutrient cycling are goals. The aims of this explorative study were to monitor changes in plant biomass and biochemical composition of winter cover crops during Upper Midwest springtime vegetative growth. Winter rye (Rye, *Secale cereale*), hairy vetch (Vetch, *Vicia villosa* Roth) and a rye – hairy vetch biculture (Rye+Vetch) were grown with (+30N) and without (+0N) an additional fall-applied 30 kg ha^{-1} of soil inorganic N on a coarse, loamy sand site typical of land used for production of a wide range of vegetable crops in Michigan. Following fall planting, plants were sampled 3 times during early spring at 416, 532 and 962 growing-degree-days (GDD) post-planting. Rye and hairy vetch species within Rye, Rye+Vetch and Vetch cover crop cultures responded differently to soil inorganic N treatment. The fall applied 30kg N ha^{-1} generally enhanced C and N accumulation for Rye, but not for Vetch. The additional N depressed hairy vetch population and biomass accumulation and therefore yield of hairy vetch N and C fractions in both the Rye+Vetch and Vetch cultures. This was most likely artifactual seedling damage caused by ammonia toxicity or salt injury form recently applied NH_4NO_3. Hairy vetch above-ground biomass accumulation was delayed compared with winter rye. Above-ground tissue organic matter (OM), neutral detergent fiber

(NDF) and acid detergent lignin (ADL) content were significantly affected by cover crop species and soil N fertility on some sampling dates. Both NDF and ADL fractions increased with maturity across species and N treatment. Hairy vetch and winter rye biochemical qualities were similar at 416 GDD, but diverged as growth and development progressed. C:N ratio for Vetch plots was consistently much lower, always below 20, than for Rye and Rye+Vetch plots throughout the experiment. Distribution of C and N among soluble NDS or structural NDF forms shifted dramatically between 416 and 532 GDD resulting in a large increase in C:N ratio of the NDF fraction with a minor impact on C:N ratio of NDS fraction across cover crop species and soil N fertility treatments. This shift in C allocation occurred quickly, in just 20 days and 115 GDD, and was combined with an average 55% increase in NDF content for Rye and Rye+Vetch and a 19% increase in Vetch above-ground tissues. These changes would be expected to dramatically reduce the rate of decomposition in soil and yield of microbe- and plant-available nutrients. This fairly rapid increase in expected recalcitrance of plant residues may enhance long term soil C restoration potential but result in greater risk of in-season immobilization of N. Winter rye is recommended when cover crops are planted late and when biomass will be terminated in the early spring, before hairy vetch biomass can accumulate appreciably and express its biochemical quality advantages over rye.

INTRODUCTION

Growers and land managers have multiple reasons for growing winter cover crops. Some of these goals are met by the presence of vegetative plant cover – erosion control, reduced leaching and loss of nutrients to ground and surface water. Other goals are met through the biochemical and microbiological transformations occurring during plant residue decomposition within the soil. Soil organic matter restoration, provision of nutrients to a subsequent crop, improved soil aggregation, structure and water infiltration are examples of these cover crop effects. The rate of biochemical and microbiological transformations during decomposition of plant materials depends on environmental conditions, soil characteristics and the initial biochemical characteristics of the plant residues. Estimation of the rate of residue decomposition and nutrient release is important for accurate and synchronous provision of fertilizer nutrients to crops. To capture the full benefit of plant available nutrients provided by decomposing winter cover crop residues and to optimize nutrient use efficiency, supplemental fertilizer applications must be reduced proportionately. This is a complex and challenging task, especially when the cover crop is in a rapidly growing vegetative state in the early spring. During this early growth phase, even small accumulations in GDD can cause significant changes in growth stage and biomass quantity (Mirsky et al., 2009; Nuttonson, 1958; Teasdale et al., 2004). Variable fall seeding dates and rates also produce a wide range of winter cover crop biomass and quality in commercial potato fields just prior to spring tillage (Chapter 2).

Winter rye cover crops have become more common in Michigan potato cropping systems as growers attempt to reduce erosion and overwinter N leaching on coarse, low OM, soils (Snapp and Rohrbach, 2001). However, fertilizer N applications to potato or other cash crops are not always reduced to account for cover crop N due to concerns of insufficient or asynchronous N supply. Without reliable residue quantity and quality estimates, growers may choose not to reduce synthetic fertilizer application rather than risk insufficient fertilizer application and subsequent reduced crop performance. Nutrient release from decomposing tissues is expected to be determined by environmental conditions and plant tissue biochemistry (Scholes et al., 1997; Schomberg and Endale, 2004; Swift et al., 1979; Vanlauwe et al., 1996). Plant residues are also the primary source for organic matter formation in soil (Kogel-Knabner, 2002; Oades, 1988). To properly optimize SOM formation, a better understanding of plant residue quality is needed. Plant tissue degradation in soil has been linked to biochemical composition, specifically cellulose, hemicellulose, lignin and tannin fractions, C:N ratio as well as spatial organization of these biochemical components within the plant tissues (Chesson, 1997).

Plant tissue biochemical components can be categorized according to biochemistry and location within the structure of plant tissues and cells. Organic fraction of plant residues serve as a source of nutrients for growing plants and soil biota, as building materials for soil organic matter, and residue OM permits organomineral interactions necessary for soil aggregation (Oades, 1988). Inorganic plant fractions provide mineral nutrients to growing plants and soil biota as residues decompose. Intracellular and storage compounds of plants such as proteins, starches, organic acids and fructans, are easily and quickly degraded and are important energy and nutrient sources for soil microorganisms (Kogel-Knabner, 2002; Martin and Haider, 1986). Most vascular plant proteins, polypeptides and non-protein nitrogenous compounds are water-soluble and are found within cell protoplasm. Primary and secondary plant cell walls and the middle lamella are comprised mainly of high-molecular weight cellulose and hemicellulose polymers and have been found to degrade slowly in soil (Martin and Haider, 1986). Middle lamella and primary cell wall also contain pectins which, unlike other cell wall polysaccharides, are degraded at faster rates, similar to protoplasmic components. Dicot primary cell walls can contain up to 30-50% of dry weight as pectins whereas monocots typically contain only 2-3% (Evert and Esau, 2006). Lignin is a high-molecular weight 3-dimensional network composed primarily of phenyl propane subunits found in middle lamella, primary and secondary cell walls (Evert and Esau, 2006; Kogel-Knabner, 2002). Lignin content is negatively correlated with degradation rate of plant tissues as it decomposes very slowly and, through its covalent associations with cell wall cellulose and hemicelluloses, limits the degradation rate of these plant cell wall polysaccharides as well (Grabber, 2005). In grasses, cell wall typically represents a larger proportion of total dry matter than for legumes, but legume cell walls are typically more highly lignified. Lignin structures within grass and legume cell walls are also understood to differ in composition (Moore and Jung, 2001).

Numerous proximate analytical methods have been developed to estimate biochemical components and qualities of plants. An analytical system was developed in the 1960s for estimating forage quality for ruminant feed and continues to be widely used (Goering and Van Soest, 1970; Van Soest, 1963). The Van Soest analytical system employs a sequence of extractions of dried and ground plant tissue preparations. The sample is first extracted with amylase and a buffered pH 7 sodium lauryl sulfate and EDTA reagent which solubilizes plant cell protoplasm, starches and cell wall pectins (NDS) and leaves an insoluble residue (NDF) containing cell wall polysaccharides and lignin (Van Soest, 1967). NDS therefore represents the most easily degraded portion of plant tissue and NDF represents a heterogeneous fraction including hemicelluloses, cellulose and lignin, varying in degradation rate. Carbon and N associated with NDS would be expected to be available to growing plants and soil biota over a short time frame of weeks to months while NDF-C and –N would be expected to be mineralized more slowly. NDF residue may be further extracted with a 1.0 N sulfuric acid and cetyl trimethylammonium bromide solution which solubilizes hemicelluloses leaving cellulose and lignin in the insoluble residue (ADF). ADF may then be extracted with 72% sulfuric acid to solubilize cellulose and leave lignin as an insoluble residue (ADL) (Van Soest, 1967). ADL therefore represents the most slowly degradable or recalcitrant fraction of plant cell wall materials.

Growers and land managers continually search for strategies to estimate plant available N from cover crops and plant residues so that exogenous inorganic fertilizer applications may be reduced accurately. Our goal was to provide a comparison of biochemical characteristics of three winter cover alternatives grown with two varying levels of soil inorganic N in a field experiment conducted in Michigan on sandy, low OM soils. We designed an experiment to examine the effect of cover crop species, maturity and soil N fertility on biochemical qualities of cover crops appropriate for Michigan potato cropping systems. Objectives of this experiment were to a.) compare dry matter (DM), C and N accumulation in rye and hairy vetch monoculture winter cover crops and a rye-hairy vetch biculture combination as affected by soil inorganic N, and b.) determine the effects of maturity and soil N on rye and hairy vetch cover crops on biochemical characteristics of plant tissues.

MATERIALS AND METHODS

Site Description

A field experiment was conducted at the Michigan State University Horticulture Research Farm near East Lansing, Michigan (42°40'N, 84°28'W) from October 2005 through June 2006 to quantify biomass accumulation and changes in biochemical quality for winter rye and hairy vetch winter cover crops. Soil at the field site is a Metea loamy sand (loamy, mixed, active, mesic Arenic Hapludalfs) similar to the coarse, well-drained soils commonly used for production of a wide range of vegetable crops in Michigan. Chemical and physical description of soil is listed in Table 1.1. Precipitation and temperature patterns at the experimental site during the 2005 to 2006 seasons are depicted in Figure 1.1. Cumulative growing degree-days (GDD) from October 2005 through June 2006 at the MSU Horticulture Research Farm are summarized in Figure 1.2. GDD were calculated using a base temperature of 4 ºC as appropriate for winter rye (Nuttonson, 1958).

Experimental Design

The field study was a two-factor split plot randomized complete block design with 4 field replications. Whole plot (4.6 x 24.4 m) treatments were winter cover crop of winter rye (Rye), hairy vetch (Vetch) or a rye-hairy vetch biculture (Rye+Vetch). Each whole plot was split for a single +0N (0 kg/ha) or +30N (30 kg/ha) N fertilizer application in the fall. Before planting cover crops, N in the form of ammonium nitrate fertilizer was manually broadcast as a split-plot treatment (4.6 x 12.2 m) to simulate a high post-harvest residual N that could occur following crop failure, asynchronous plant demand or excessive N application. Plots were prepared by disking with an offset disk prior to establishment. On September 30, 2005, 30 kg ha^{-1} N was manually broadcast and incorporated with a field-scale soil finisher (Kongskilde Industries Inc., Hudson, IL, model 0111) set to a depth of 5 cm. Cover crop whole plot treatments were subsequently seeded on October 3, 2005 by manually broadcasting seed and incorporating with the same field-scale soil finisher to a depth of 2.5 cm. Rye (cv. Wheeler) seed was planted at 100 kg ha^{-1}, hairy vetch (cv. Common) at 55 kg ha^{-1} and the rye and hairy vetch biculture was seeded at 60 and 30 kg ha^{-1} respectively. No irrigation, weed, pest or pathogen management was used during the duration of the experiment. Cover crops in all plots were observed to be fully emerged on 13 October 2005. On 19 October 2005, Rye and Vetch plant populations were counted within duplicate, randomly placed 0.25 x 0.25 m quadrat areas within each split-plot.

Soils were sampled for inorganic N analysis on April 21, 2006. Eight 1.9 cm diameter x 20 cm depth soil cores were collected and combined within each split-plot. Samples were allowed to air dry and then were sieved and mixed. A 20 g subsample was extracted with 100 ml 1M KCl. The KCl extracts were filtered and stored at -20 °C until inorganic N analysis. Inorganic N (NH_4-N + NO_3-N) was quantified using colorimetric methods through an autoanalyzer (Lachat Instruments, Milwaukee, WI). Gravimetric soil water content was determined by weighing a subsample, drying at 105 °C for 24 h and reweighing.

Yields of both above- and below-ground plant biomass were determined on April 25, May 15, and June 15, 2006. On each of the 3 sampling dates, above-ground cover crop biomass was sampled in duplicate by clipping aerial plant materials to a 0.5 - 1 cm stubble height within each of two 0.5 m x 0.5 m quadrats within each split-plot. Above-ground plants were separated by species and Rye and Vetch biomass were handled and analyzed separately. Below-ground plant material was quantified by collecting four 5.7 cm diameter x 60 cm depth soil cores within one of the 0.25 m^2 quadrat areas within each split-plot. Soil cores were separated into 0-30 and 30-60 cm depths. Root biomass was separated from soil material by wet-sieving each sample through a 3.2 mm sieve (Seedburo seed sieve No. I, Seedburo Equipment Co., Chicago, Illinois) using tap water. Root tissues were manually separated from soil mineral material and other plant residues remaining on the sieve, however root tissues were not separated by plant species. Above- and below-ground plant tissues were dried at 65 °C and dry weights were recorded. Shoot:root ratio was calculated by dividing above-ground dry biomass, expressed on a per-hectare basis, by corresponding below-ground dry biomass, also expressed on a per-hectare basis.

Biochemical quality was determined on dry, above-ground plant tissue samples. Below-ground plant tissue samples were not large enough to permit further preparation and analysis. Dry above-ground plant tissues were ground in a cutting mill (Wiley Model 4, Thomas Scientific, Swedesboro, NJ USA) to pass a 1 mm screen before dry matter (DM), organic matter and fiber analysis. Dry matter content was determined gravimetrically on duplicate 0.5 g ground tissue samples by weighing before and after drying at 105 °C for a minimum of 12 hours. Organic matter (OM) was quantified on the same 0.5 g sample by loss-on-ignition at 500 °C for 5 hours followed by 12 h at 105 °C and reweighing. NDF, ADF and ADL (ash-free) were determined sequentially on duplicate 1.0 g samples of dry, ground plant tissue (Goering and Van Soest, 1970). NDF and ADL fractions are expressed as a percentage of OM to eliminate excess variation and bias due to variable soil mineral contamination of above-ground plant tissues with time and species. Total C and N were analyzed by dry combustion (PDZ Europa ANCA-GSL elemental analyzer, Sercon Ltd, Cheshire, UK) on a subsample of dry, ground above-ground plant tissues which was prepared by grinding in a small cutting mill to pass a 60-mesh screen (Wiley Mini-Mill, Thomas Scientific, Swedesboro, NJ USA). Total C and N content was also similarly determined on a second sample of NDF residue prepared by extracting a separate 1.0 g sample of dry plant tissue. NDF residue was dried at 105 °C for a minimum of 12 hours before it was ground in a cutting mill to pass a 60-mesh screen and analyzed for C and N content. Total C and N content of NDS fraction was calculated by subtracting C and N content of NDF fraction from C and N content of whole tissue.

Statistical Analysis

Treatment differences due to plant species, nitrogen, and plant species x nitrogen interaction were identified using an ANOVA with PROC MIXED procedure in SAS (SAS, 2008). Where there were significant ($p<0.05$) plant species, nitrogen or sampling date main effects or interactions, means were separated with a least squares means calculation using the LSMEANS statement. Superscript letters indicating differences between means were assigned using the PDMIX800 SAS macro (Saxton, 1998).

RESULTS AND DISCUSSION

Soil inorganic N was low in late April, averaging 5.97 mg kg^{-1} across all treatments, however the +30N split-plots contained significantly more inorganic soil N in the top 20 cm than the unfertilized plots, confirming a treatment difference (6.7 versus 5.2 mg kg^{-1} respectively, Table 1.2). This additional 1.5 mg kg^{-1} inorganic N in +30N split-plots is equivalent to about 4 kg inorganic N per hectare in the upper 20 cm.

Winter populations of both rye and hairy vetch were reduced by the fall application of 30 kg ha^{-1} of inorganic N in the form of ammonium nitrate fertilizer. Rye stands were reduced by 32 and 16% in the Rye and Rye+Vetch treatments. Hairy vetch population was reduced by 25% in the Rye+Vetch treatment but was unaffected by N in the Vetch only treatment. Observed decrease in emergence of rye and hairy vetch is most likely due to injury to seedlings by ammonia toxicity or salt damage (Bremner, 1995; Bremner and Krogmeier, 1989). Seedling damage is often greater on coarse, low OM and dry soils (Havlin et al., 1999). This damage may have been averted by incorporating N fertilizer more deeply and/or by allowing more time between application and seeding the cover crops. Reduced emergence of rye and hairy vetch in the presence of inorganic N in this experiment is an artifact of the experimental design and would not be expected if the additional soil inorganic N were truly residual after a previously harvested crop.

Above- and below-ground biomass yields

Above- and below-ground plant biomass was determined on April 25, May 15 and June 15, 2006 representing 416, 532 and 962 GDD post-planting. Cover crops are typically terminated around April 25 to plant an early crop such as potatoes, sugarbeets, corn or some spring cereals, and between May 15 and June 15 is a typical planting window in Michigan for later crops such as soybeans, dry beans and fresh market vegetables (USDA-NASS, 2007; USDA-NASS, 2010).

Above-ground biomass accumulation was significantly affected by cover crop species, soil inorganic N and sample date (Tables 1.3 through 1.5). At the earliest sample date, after just 202 days and 416 GDD post-planting, above-ground biomass was significantly affected by soil N and cover crop species. Rye and Rye+Vetch plots with additional N produced significantly more above-ground biomass, 1571 and 1614 kg ha^{-1} respectively, than the other 4 treatments (Table 1.3). Vetch monoculture plots produced the least above-ground biomass regardless of N fertility. Above-ground biomass was reduced in the Vetch only cover despite similar plant population in +0N and +30N plots (Table 1.2). Rye and Rye+Vetch +30N plots produced 40% more rye biomass than +0N plots. Hairy vetch biomass was reduced 80% by presence of a rye companion crop in the Rye+Vetch treatment at this early sample date though the hairy vetch seeding rate was 55% of the rate used in the Vetch monoculture. Of the 1462 kg ha^{-1} of total DM produced in the Rye+Vetch treatment, 91% was from Rye and only 9% was contributed by Vetch. These early above-ground biomass yields are within the relatively wide range of yields observed by other researchers in North America in late April and early May for Rye (Bundy and Andraski, 2005; Clark et al., 1997; Miguez and Bollero, 2006), Rye+Vetch (Clark et al., 2007; Miguez and Bollero, 2006) and Vetch (Clark, 2007; Teasdale et al., 2004).

At the second sampling on May 15, 20 days and 115 GDD after the first, cover crop species and soil N continued to significantly impact above-ground biomass accumulation (Table 1.4). Rye biomass in the Rye and Rye+Vetch plots doubled to 3003 and 3732 kg ha^{-1} respectively. Vetch biomass in the Rye+Vetch and Vetch plots increased to 400 and 1064 kg ha^{-1} respectively, representing 203% and 74% increases from 416 GDD. Total biomass in the Rye+Vetch +30N treatment remained the highest at 4726 kg ha^{-1}. At 532 GDD, soil inorganic N was still a significant factor in above-ground biomass accumulation of both rye and hairy vetch. Rye biomass in the +30N treatments was 54% greater while hairy vetch biomass was 70% lower in the +30N treatments. Mid-May above ground biomass for Rye was higher than many previous research findings (Andraski and Bundy, 2005; De Bruin et al., 2005; Vyn et al., 2000) while, Rye+Vetch and Vetch were within similar ranges (Clark et al., 1997; Jannink et al., 1997; Miguez and Bollero, 2006). Total biomass produced by the Rye+Vetch plots was still 90% Rye and 10% Vetch.

Above-ground biomass was sampled a third and final time 31 days and 430 GDD after the second sample date. At the 962 GDD sampling point on June 15, cover crop species significantly affected above-ground biomass accumulation for hairy vetch, but was not a significant factor in rye biomass accumulation (Table 1.5). Rye and Rye+Vetch plots yielded a statistically similar quantity of rye biomass, 4716 and 5306 kg ha^{-1}, respectively, similar to yields observed previously (Clark et al., 1997; Duiker and Curran, 2005; Krueger et al., 2011). Hairy vetch DM was reduced by the rye companion crop in the Rye+Vetch biculture and produced significantly less hairy vetch biomass than the Vetch monoculture, 859 kg ha^{-1} versus 2738 kg ha^{-1}. Both figures are near the lower end of the very wide range of spring hairy vetch winter cover crop yields observed in North America, ranging from less than 1 to more than 7 Mg ha^{-1} (Frye et al., 1982; Jannink et al., 1997; Teasdale et al., 2004). Vetch DM increased from the previous sample date to 16% of total above-ground biomass of 5576 kg ha^{-1} in the Rye+Vetch biculture plots. Additional inorganic soil N no longer reduced Vetch monoculture biomass compared to the +0N control; the Vetch with +30N were able to compensate for poor early growth such that the overall Vetch average for +0N and +30N were statistically similar. Hairy vetch biomass in the Rye+Vetch plots still yielded a reduced vetch biomass with additional N. Additional soil inorganic N significantly increased rye biomass in the Rye and Rye+Vetch treatments. Total above-ground biomass was greatest at this latest sampling date for the Rye and Rye+Vetch plots with additional N. The other four treatment combinations produced less biomass and were statistically similar.

Rye+Vetch, with and without additional soil inorganic N, gained above-ground biomass most quickly between 416 and 532 GDD at an average rate of 133 kg ha^{-1} per day or 232 kg ha^{-1} per 10 GDD. Vetch plots accumulated above-ground biomass slowly, averaging 23 kg ha^{-1} per day or 39 kg ha^{-1} per 10 GDD, and at 83 kg ha^{-1} per day and 144 kg ha^{-1} per 10 GDD between the last 2 sample dates. Research conducted in Maryland and New York, USA showed that, across cultivar, hairy vetch accumulated 41 kg ha^{-1} of above-ground biomass per 10 GDD over its entire growth period from fall planting to spring sampling, and that a minimum of 655 GDD were required for hairy vetch to achieve 50% cover. (Teasdale et al., 2004). Rye plots gained biomass at an intermediate rate between the first two sampling dates. Between 532 and 962

GDD, rye in the +30N plots had the greatest rates of above-ground biomass accumulation at 125 kg ha^{-1} per day and 218 kg ha^{-1} per 10 GDD while the +0N plots produced just 56 kg ha^{-1} per day or 97 kg ha^{-1} per 10 GDD.

Below-ground biomass accumulation was significantly affected by cover crop species at mid- and late-season and shoot:root ratio increased significantly with advancing sampling date (Tables 1.6 through 1.8). Root biomass measurement methodologies employed in this experiment included more inherent variation than above-ground biomass measurements, due to lack of duplication and smaller sample sizes. Standard errors for some treatment means within a sample date were as large as 80 to 100% of treatment mean and therefore fewer significant effects or trends were detected. Across 3 sampling dates, below-ground root DM averaged 1562, 1717 and 528 kg ha^{-1} for Rye, Rye+Vetch and Vetch treatments respectively. Total root biomass in the 0 – 60 cm zone at the last sampling date was 1467, 1399 and 787 kg ha^{-1} for Rye, Rye+Vetch and Vetch cover crops respectively (Table 1.8). Vetch produced significantly less root biomass in surface 0-30 cm, from 30-60 cm and in total 0-60 cm than Rye and Rye+Vetch plots. The majority of 0-60 cm root biomass was detected in the surface 30 cm. About 13% of Rye roots were found from 30-60 cm whereas only 9% of Rye+Vetch and Vetch roots were present between 30 and 60 cm. Sample date, across species and N fertility, was the only significant factor affecting shoot:root ratio. Shoot:root ratio more than doubled, from 1.83 to 4.86, from the first sample date to the last, indicating that as the cover crops developed toward reproductive growth, above ground tissues far out grew below-ground roots. By mid-June roots made up only 17% of total DM. Early in the spring, roots comprised about 35% of total plant biomass present, across species and N fertility.

At the earliest sample date, 416 GDD after planting, no significant cover crop species or N fertility effects were detected in below-ground biomass among the 3 cover crop species despite the nearly 8-fold difference (Table 1.6). Vetch produced the least quantity of roots, 308 kg ha^{-1}, while Rye+Vetch plots yielded 2431 kg ha^{-1}. The Vetch +30N combination yielded the fewest total roots, 99 kg ha^{-1} and the Rye+Vetch +30N treatment combination produced the most, 3142 kg ha^{-1} which was also the most variable mean for all treatment combinations in the experiment and, therefore, may be a high estimate. Rye +30N also produced a high quantity of total roots, 1866 kg ha^{-1}. Shoot:root ratios for the 6 treatment combinations ranged from 0.72 for Rye+Vetch +0N to 2.87 for Rye +0N.

At the second sampling point, 532 GDD, crop species significantly impacted 0-30 cm root biomass and total below-ground biomass. For both parameters, Vetch monoculture produced significantly less root biomass than either Rye or Rye+Vetch. Quantities of root biomass at 532 GDD were similar to the 432GDD sampling point, but less variation at 532 GDD permitted detection of some differences (Table 1.7). Again, the Vetch +30N combination yielded the fewest roots, 182 kg ha^{-1}. The Rye +30N treatment combination produced the most root biomass, 2039 kg ha^{-1}. Rye +0N plots yielded 1795 kg ha^{-1} of below-ground biomass at 532 GDD, similar to Rye+Vetch. Shoot:root ratios for the 6 treatment combinations were generally higher than at 432 GDD and ranged from 2.13 for Rye +0N to 6.19 for Rye+Vetch +0N. At the final sampling point, 962 GDD, no significant crop species or N fertility effects were detected at $P \leq 0.05$, however Vetch again produced the least 0-60 cm root biomass (P=0.07) compared with Rye and Rye+Vetch (Table 1.8). From 532 to 962 GDD sampling points, Rye plots lost an average of 39 kg roots ha^{-1} per day, Rye+Vetch plots accumulated an average of 7 kg ha^{-1} per day, and Vetch plots gained an average of 42 kg ha^{-1} per day. Across treatments, rye plants were apparently losing roots while Vetch plants continued to increase root biomass. Research conducted in Georgia, USA found that root length density for both rye and vetch winter cover crops decreased in early spring from maxima achieved in fall or winter (Sainju et al., 1998).

About 89% of root biomass was found in the surface 30 cm across all treatments. N fertility had a small impact on shoot:root ratio; the +30N treatment plots had a shoot:root ratio of 6.4 where the control +0N had only a 3.29 ratio (P=0.08). Shoot:root ratios for the 6 treatment combinations at 962 GDD were the largest of the 3 sampling dates and ranged from 3.21 for Rye+Vetch +0N to 8.11 for Vetch +30N, reflecting the relatively large increase in above-ground biomass between the last 2 sampling dates for Vetch +30N.

Above-ground OM, NDF and ADL composition

Above-ground plant tissue biochemical composition was significantly affected by cover crop species, N fertility and sampling date (Tables 1.9 through 1.11). Plant tissues averaged 91% OM, however both cover crop species and N fertility affected OM content. Vetch tissues averaged just 82.9% OM across N fertility and sampling dates, while Rye and Rye+Vetch tissues contained 94% OM. Average OM content increased with sample date, from 87.3% at 416 GDD to 90.4 and 94.6% at 532 and 962 GDD respectively. Though legumes may have a 1 percentage point higher mineral content compared with grasses (National Research Council, 1982; National Research Council, 2001), the most plausible reason for both significant impacts of both crop species and sample date is soil mineral contamination. Additionally, this mineral contamination not only lowers % OM, it also increases the SE of these means as it contributes substantial variation. Though steps were taken to minimize soil contamination as above-ground samples were collected, soil minerals occasionally adhered to plant samples, especially hairy vetch samples since it has a prostrate and sprawling growth habit which results in more soil contact than the tall and upright profile of rye plants. In the presence of companion cereal grain, hairy vetch climbs upward and away from the soil surface. Additionally, mineral contamination on smaller, younger plants is a larger proportion of their lower DM, thus lowering %OM by dilution, and increasing SE, for the earlier sampled plants. At 416 GDD, crop species, soil inorganic N and the crop species x N interaction were all highly significant ($P<0.0001$) (Table 1.9). Vetch biomass contained significantly less OM%, 74.8%, compared with Rye or Rye+Vetch which contained 93.9 and 93.2% OM. Rye and Rye+Vetch, both with and without added soil N, all contained similar OM fractions. The Vetch +0N samples were quite low in OM, 66.2 ± 1.6% and the Vetch +30N samples were intermediate with 83.3 ± 0.5% OM. The low OM mean due to soil contamination and high ash content for some Vetch +0N samples was enough to cause the inorganic soil N factor to be significant. At 532 GDD, soil contamination on the Vetch samples continued to lower OM fraction means and increase SE of those means, however neither crop species nor soil inorganic N treatment significantly affected OM fraction (Table 1.10). Rye and Rye+Vetch means were consistent, about 94.8% OM, while Vetch OM was 81.6%. At 962 GDD post-planting, OM% was much more uniform across treatment groups, however, Vetch %OM was significantly lower, 92.5% compared to 96% and 95.4% for Rye and Rye+Vetch, respectively (Table 1.11). Soil inorganic N treatment did not affect OM at 962 GDD; all treatments averaged 94.7% OM.

Fibrous cell wall fraction (NDF) in above-ground plant tissues were significantly impacted by cover crop species, soil inorganic N and sampling date (Tables 1.9 to 1.11). Across species and N treatment, NDF increased with maturity and was significantly lower for Vetch than for Rye and Rye+Vetch above-ground tissues. ADL also increased, across species and N fertility over the duration of the experiment. These changes in NDF and ADL over time are typical of grass and legume development. (National Research Council, 1982; National Research Council, 2001). Unlike the effect of cover crop species on NDF, ADL was higher for Vetch above-ground tissues and lower for Rye and Rye+Vetch tissues. Legume tissues typically contain significantly less NDF and more lignin than grasses at similar maturities (National Research Council, 1982; National Research Council, 2001). Legumes typically contain less cell wall than grasses when fractionated in this way, but cellulose and lignin comprise a higher proportion of legume cell walls than for grasses. Vetch maintained these typical differences relative to Rye and Rye+Vetch tissues throughout the experiment, though differences in ADL content were not always significant. NDF content in above-ground plant residue was unaffected by soil inorganic N content. Both +0N and +30N treatment groups averaged 51.7% NDF across species and sampling date. ADL content was significantly lowered by 0.5 units from 5.4% to 4.9% with additional soil inorganic N (Tables 1.9 -2.11).

At the first sampling date at 416 GDD post-planting, NDF was significantly lower for Vetch than for Rye and Rye+Vetch tissues. Rye and Rye+Vetch above-ground tissues contained about 41% NDF whereas Vetch tissues contained 33.7%. Vetch with and without added soil N contained more ADL, 5.0%, than Rye and Rye+Vetch tissues at 1.2 and 1.7% respectively, but these differences were only significant at $p=0.089$ due to the larger variation inherent in this ADL measurement.

At 532 GDD similar trends in cell wall fractions were observed (Table 1.10). NDF content in above-ground tissues was significantly impacted by cover crop species but not soil N. Vetch was again the lowest of the 3 crop species in NDF, with 39.8%. Rye monoculture tissues contained the most NDF, 65.2%, and at this point Rye+Vetch contained enough hairy vetch biomass to have significantly less NDF, 61.2%, than the Rye monoculture. ADL concentration was highest for Vetch, both with and without additional soil N, compared to Rye and Rye+Vetch with or without extra N. Mean ADL content for Rye+Vetch above-ground tissues were intermediate to the two monocultures, but these differences were only significant for the +0N treatments. The +30N Rye and Rye+Vetch ADL concentrations were statistically different.

At the last sampling date, 962 GDD on June 15, Vetch again had lower NDF content and higher ADL concentration than Rye and Rye+Vetch, which were not different from each other for any of these cell wall components (Table 1.11). Soil inorganic N treatment did not significantly impact NDF fractions, but ADL was reduced for the +30N plots compared with the +0N plots, 6.9 versus 7.8%. In terms of NDF and ADL, the Rye+Vetch mixtures generally were more similar to Rye than to Vetch treatments throughout the experiment.

Above-ground total C and N content and yield

Carbon and N content, and especially the ratio of C to N have been associated with short-term degradability of plant residues (Swift et al., 1979). A general guideline is that, in soil, a C:N ratio in plant litter >20 will result initially in net immobilization of N and that mineralization of N will begin when the ratio is below 20 (Brady and Weil, 1996). Concentration and yield of C and N in above-ground plant tissues was significantly affected by cover crop species and sampling date, and at some sample dates, by N fertility (Tables A1.4 and 2.12 through 2.14). Across sample dates, total N content was highest for Vetch tissues, 3.68%, compared with Rye or Rye+Vetch above-ground tissues which contained 1.34 and 1.61% N. N fraction also decreased, across soil N treatment, for each species over the duration of the experiment. Total N content of above-ground tissues was unaffected by soil N fertility, perhaps due to a significant crop species x N fertility interaction. Rye +30N contained slightly more total N than Rye +0N, but because hairy vetch biomass was reduced with the inorganic N treatment, Rye+Vetch and Vetch cover crops accumulated a lower total N fraction in above-ground tissues. Total N above-ground yield was significantly affected by sample date but crop species and soil N were not significant factors. Yield of above-ground N increased significantly at each sampling date from an average across species of 27.9 kg ha^{-1} at 416 GDD to 46.2 kg ha^{-1} at 532 GDD to 59.6 kg ha^{-1} at 962 GDD.

Over the duration of the experiment, total C concentration varied little and was only impacted significantly by sampling date. C concentration in above-ground tissues was significantly lower at 416 GDD, 43.9%, than at 532 and 962 GDD when tissues contained 47.3 and 46.8% respectively. Yield of above-ground C was significantly affected by crop species, N fertility and sample date. Carbon yields were proportional to biomass yields of above-ground residues. Across all species yield of C increased significantly at each sampling date from 499 kg ha^{-1} at 416 GDD to 1306 kg ha^{-1} at 532 GDD to 2138 kg ha^{-1} at 962 GDD. Vetch yielded less C per hectare than Rye or Rye+Vetch. C:N ratio was also significantly affected by cover crop species, N fertility and sampling date. Cover crops with additional soil N actually had a significantly higher C:N ratio, 30.4, versus 28 for +0N plots. C:N ratio consistently increased with advancing maturity across species and N fertility. At 416 GDD, C:N ratio averaged 17.7 across crop and N treatments, at 532 GDD C:N increased to 28.1 and by 962 C:N had increased to an average of 41.8.

At the earliest sample date, 416 GDD on April 25, Vetch plots contained the highest content of above-ground tissue N, 4.03%, but the least kg N per hectare, 23.4 kg N ha^{-1} (Table 1.12). Rye and Rye+Vetch with and without high soil N averaged about 2.13% N and 30.2 kg N ha^{-1} and were not significantly different. The highest yield of above-ground tissue N was observed in the Vetch +0N plots which produced 39.8 kg N ha^{-1}. The Vetch +30N plots showed reduced growth, presumably due to poorer stand. No significant differences due to cover crop species, N fertility or sample date were observed for C as a percentage of DM; however yield of C was proportional to above-ground biomass totals at 416 GDD. At 532 GDD, Vetch plots continued to contain the highest concentration of above-ground tissue N with 4.18% (Table 1.13). Rye and Rye+Vetch tissues contained significantly less, 1.38 and 1.33% respectively. The disparate N concentrations did not translate into a significant crop species effect on above-ground total N yield. Rye, Rye+Vetch and Vetch yielded statistically similar N, 40.0, 53.4 and 44.2 kg ha^{-1} respectively. Rye contained a significantly higher C content than Rye+Vetch or Vetch, which were similar. Rye+30N contained the highest %C with 51.7%. On a C yield basis, Vetch produced significantly less C per hectare than Rye or Rye+Vetch. Total C yield was generally proportional to total above-ground biomass yield where Vetch yielded significantly less C per hectare than Rye or Rye+Vetch treatments. Total C yield was also significantly increased with additional soil N across cover crop species at 532 GDD. C:N ratio was significantly affected by both crop species and soil N fertility. Vetch plots produced above-ground biomass with the lowest C:N ratio, 10.9, while Rye produced the highest, 38.0. Rye+Vetch was intermediate with a C:N ratio of 35.3. Additional soil inorganic N significantly increased C:N ratio for the only the Rye+Vetch plots. Rye and Vetch plots were unaffected by soil inorganic N treatment.

At 962 GDD, Vetch plots remained the crop species with the highest %N with 2.83% of DM (Table 1.14). Rye above-ground tissues were lowest with 0.71%N and Rye+Vetch were intermediate with 1.19%N. Soil inorganic N treatment did not significantly impact %N at 962

GDD. Vetch+30N plots contained the highest %N content with 3.1% and Rye with and without additional N and Rye+Vetch+30N all contained the lowest %N, 0.79% of DM. On a per-hectare basis across N levels, Vetch produced the most N, at 78.2 kg ha^{-1} N and Rye produced the least, 38.5 kg ha^{-1} N. Rye+Vetch was intermediate with 62.1 kg ha^{-1} above-ground N. The Vetch+30N treatment combination yielded the most N per hectare, 86.2 kg ha^{-1} N. Neither crop species nor soil inorganic N treatment significantly impacted C as a percentage of DM. All treatments averaged 46.8 % C. Carbon yield was greatest for Rye and Rye+Vetch plots, averaging 2578 kg ha, compared with Vetch which produced 1260 kg ha^{-1} C. Across species the +30N treatment produced more C than the +0N control, 2590 and 1686 kg ha^{-1} C respectively. The Rye+30N and Rye+Vetch+30N treatment combinations produced the most C per hectare, 3059 and 3418 kg ha^{-1} C respectively.

C:N ratio was significantly affected by both crop species and soil N fertility. Vetch plots produced above-ground biomass with the lowest C:N ratio, 16.4, while Rye produced the highest, 64.5. Rye+Vetch was intermediate with a C:N ratio of 44.5 (Table 1.14). Additional soil inorganic N increased the C:N ratio significantly to 44.5 compared with 39.1 for the +0N control across species. Vetch with and without additional N yielded the lowest C:N ratios, average of 16.4, while Rye with and without N yielded the highest ratios, average of 64.5.

Above-ground fractional C and N content and yield

Though the relationship between plant tissue C:N ratio and plant tissue degradation is widely accepted and utilized, some researchers conclude the reason for the relationship is more due to N availability in the soil (Mary et al., 1996). Nitrogen and C within above-ground vegetation may be associated with structural cell walls (NDF-N and NDF-C) or within the more soluble cell contents (NDS-N and NDS-C). NDF-N and –C and NDS-N and C results are shown in Tables A1.5 and A2.6 and Tables 1.15 through 2.20. Across 3 sampling dates, NDF-N concentration was impacted significantly by cover crop species, N fertility treatment and sampling date. NDF-N was higher in Vetch above-ground tissues compared with Rye and Rye+Vetch. Across species the +30N treatment increased NDF-N above +0N control plots. NDF-N concentration decreased with advancing maturity across species and N treatment from a high of 0.89% of NDF at 416 GDD to 0.34 and 0.42% at 532 and 962 GDD respectively. NDF-N yield per hectare increased significantly with GDD from 3.6 kg ha^{-1} to 9.7 kg ha^{-1} across species and N treatment. Concentration of NDF-C was significantly impacted by cover crop species and by sampling date. Vetch contained a significantly lower NDF-C fraction, 39.5%, compared with Rye and Rye+Vetch tissues, which both contained 45.2%. Across species and N treatment, NDF-C content increased significantly with advancing maturity from 39.5% at 416 GDD to 43.3% at 532 GDD and finally to 46.9% at 962 GDD. NDF-C production per hectare was also significantly affected by crop species, N treatment and sample date. Vetch produced the least NDF-C, 304 kg ha^{-1}, compared with Rye and Rye+Vetch which yielded 984 and 1116 kg ha^{-1} respectively. The C:N ratios of NDF tissues were generally high and were significantly affected by crop species and sample date, but was unaffected by inorganic soil N.

At the earliest sample date, 416 GDD, NDF-N content was affected significantly by crop species and by N fertility (Table 1.15). Vetch contained a greater NDF-N fraction than Rye or Rye+Vetch. Total yield of NDF-N was also significantly affected by crop species and by soil N fertility. Vetch plots yielded significantly less NDF-N per hectare, 1.7 kg ha^{-1}, than Rye or Rye+Vetch, 42.7 and 43.1 kg ha^{-1} respectively. The +30N treated plots, across crop species, yielded 40% more NDF-N than the +0N control plots. Additional soil inorganic N increased

NDF-N yield in Rye and Rye+Vetch plots and reduced yield in Vetch plots, reflecting the impact of N treatment on overall above-ground biomass at 416 GDD. NDF-C concentration at the earliest sampling date was significantly impacted by crop species but not by soil N fertility. Vetch tissues, with and without additional soil inorganic N, contained significantly lower NDF-C than Rye or Rye+Vetch tissues. Yield of NDF-C was lowest for Vetch plots whether treated with additional inorganic N or not. Rye and Rye+Vetch with +30N treatment produced the highest quantity of NDF-C per hectare, 272 and 308 kg ha^{-1} respectively. C:N ratios of NDF tissues ranged from 25 to 66 for the 6 cover crop species-N treatment combinations, and were significantly affected by both crop species and soil inorganic N.

At the second sampling on May 15, 20 days and 115 GDD after the first, NDF-N fraction was significantly decreased from initial concentrations across crop species and soil N treatment (Table 1.16). Only soil inorganic N treatment significantly affected NDF-N at this sampling point. Across crop species, +0N control NDF fractions contained 0.32% N and +30N contained 0.36% N. NDF-N yield per hectare was also impacted significantly by crop species. Rye+Vetch, with and without additional soil inorganic N, yielded the most NDF-N per hectare, 7.1 kg ha^{-1}, compared with Rye and Vetch which yielded 4.2 and 2.2 kg ha^{-1} respectively. At this middle sampling point, NDF-C concentration remained lowest for Vetch above-ground tissues, 39.3%, compared with Rye and Rye+Vetch tissues which contained 45.3%. NDF-C yield was significantly affected by cover crop species, but not by soil inorganic N treatment. Rye and Rye+Vetch produced significantly more NDF-C per hectare, 951 and 1162 kg, than Vetch which yielded 174 kg ha^{-1}. The C:N ratios of NDF tissues were higher than at 416 GDD and ranged from 68 to 261 for the 6 cover crop species-N treatment combinations, and were significantly affected by crop species but not soil inorganic N treatment.

At the final sampling date, 962 GDD after planting, the NDF-N concentration was similar to the 532 GDD concentrations and was affected significantly by cover crop species but not by soil inorganic N treatment (Table 1.17). Vetch NDF fraction, with and without added soil inorganic N, contained an average of 0.79% N while Rye and Rye+Vetch NDF fractions contained just 0.21 and 0.28% N. NDF-N yield averaged 9.8 kg ha^{-1} across all 6 treatment combinations and was unaffected by crop species or soil inorganic N content. NDF-C content was similar across all 6 treatment combinations and averaged 46.9%. Vetch plots yielded significantly less NDF-C per hectare, 675 kg ha^{-1}, than Rye or Rye-Vetch plots, which were similar and averaged 1796 kg ha^{-1}. C:N ratio of NDF tissues was significantly affected by crop species as well. Vetch NDF C:N, whether the crop was grown with or without high soil inorganic N, averaged 61 while Rye NDF C:N was 233 and Rye+Vetch C:N was intermediate with 183. All are well beyond the C:N ratio of 20 which is understood to result in soil N immobilization without additional sources of N (Brady and Weil, 1996).

Across 3 sampling dates, NDS-N concentration was impacted significantly by cover crop species and sampling date but not by soil inorganic N content. NDS-N concentration was elevated in Vetch above-ground tissues compared with Rye and Rye+Vetch. NDS-N concentration also varied with sample date across species.. NDS-N yield per hectare increased significantly with GDD from 24.5 kg ha^{-1} to 50.2 kg ha^{-1} across species and N treatment. Concentration of NDS-C was significantly impacted by sampling date but not by cover crop species or soil inorganic N treatment. Across species and N treatment, NDS-C content varied significantly with advancing maturity from 46.1% at 416 GDD to 52.5% at 532 GDD and finally to 46.6% at 962 GDD. NDS-C production per hectare was significantly affected by crop species, N treatment and sample date. Vetch produced the least NDS-C, 396 kg ha^{-1}, Rye+Vetch yielded the most NDS-C, 727 kg ha^{-1}, and Rye yielded an intermediate quantity, 575 kg ha^{-1}. Additional soil inorganic N significantly increased NDS-C per hectare across cover crop species and sample date. Control +0N yielded 501 kg ha^{-1} NDS-C while +30N plots produced 629 kg ha^{-1}. C:N ratios of NDS fractions were generally low and were significantly affected by cover crop species, soil inorganic N and sample date. Across sample date and N fertility treatment, Vetch NDS C:N ratio was the lowest, 8.6, Rye NDS C:N ratio was the highest, 19.2, and the Rye+Vetch NDS C:N ratio was intermediate, 16.1. Across crop species and sample date, NDS C:N was increased by +30N treatment from 14.1 for +0N control to 15.2. Across crop species and N treatment, NDS C:N was 13 at 416 GDD and 13.6 at 532 and 17.2 at 962 GDD.

At the earliest sample date, 416 GDD, NDS-N content was affected significantly by crop species but not by soil N fertility (Table 1.18). Vetch contained a greater NDS-N fraction than Rye or Rye+Vetch. Total yield of NDS-N was significantly affected by crop species and by soil N fertility. Rye+Vetch biculture plots yielded significantly more NDS-N per hectare, 29.2 kg ha^{-1}, than Rye or Vetch monocultures, 22.7 and 21.7 kg ha^{-1} respectively. The +30N treated plots, across crop species, yielded 17% less NDS-N than the +0N control plots due to reduced biomass production. The +30N inorganic N increased NDS-N yield in Rye and Rye+Vetch plots and reduced NDS-N yield in Vetch plots, reflecting the negative impact of N treatment on above-ground Vetch biomass at 416 GDD. NDS-C concentration at the earliest sampling date was not significantly affected by crop species or by soil N fertility. Yield of NDS-C was lowest for Vetch plots and Rye and Rye+Vetch with +30N treatment produced the highest quantity of NDS-C per hectare, 413 and 533 kg ha^{-1} respectively. C:N ratios of NDS fractions ranged from 8.6 to 17.1 for the 6 cover crop species-N treatment combinations, and were significantly affected by crop species but not soil inorganic N. All NDS C:N ratios are below the rule of thumb ratio of 20 and would be expected to yield net mineralization of N in soil (Brady and Weil, 1996).

At the second sampling on May 15 at 532 GDD, NDS-N fraction was significantly affected by cover crop species (Table 1.19). Across soil inorganic N treatment, Vetch NDS contained 6.6% N while Rye and Rye+Vetch NDS averaged 3.3 %N. NDS-N yield per hectare was not impacted significantly by crop species or by soil inorganic N treatment. All treatment combinations averaged 41.8 kg ha^{-1}. At this middle sampling point, NDS-C concentration was highest for Rye above-ground tissues with or without additional soil N, 61.7%, compared with Rye+Vetch and Vetch tissues which contained 47.9% on average. NDS-C yield was significantly affected by cover crop species, but not by soil inorganic N treatment. Rye and Rye+Vetch produced significantly more NDS-C per hectare, 682 and 748 kg, than Vetch which yielded 315 kg ha^{-1}. C:N ratios of NDS fractions were below 20 and were similar to those observed at 416 GDD and ranged from 7.4 to 18.1 for the 6 cover crop species-N treatment combinations, and were significantly affected by crop species. Vetch NDS fractions contained the lowest C:N ratio, 7.5, compared with Rye and Rye+Vetch which contained ratios of 17.5 and 15.8 respectively. The dramatic increase in NDF C:N ratio, concomitant with a very slight increase in NDS C:N ratio between 416 to 532 GDD is mainly due to a dramatic shift in C allocation from NDS to NDF components (NDS-C dropped from 64% to about 48% of total C across treatments) while N allocation between NDS and NDF remains relatively constant with NDS-N about 90% of total N. Between 416 and 532 GDD, above-ground N remains largely apportioned to protoplasm, while C is shifted toward less soluble and more slowly decomposable structural forms.

At the latest sampling date, 962 GDD after planting, the NDS-N concentration was decreased from the 532 GDD concentrations and was affected significantly by cover crop species but not by soil inorganic N treatment (Table 1.20). Vetch NDS fractions, with and without added soil inorganic N, contained an average of 4.7% N while Rye and Rye+Vetch NDS fractions contained 1.9 and 2.9% N. NDS-N yield averaged 50.2 kg ha^{-1} across all 6 treatment combinations and was significantly affected by both crop species and soil inorganic N treatment. Vetch NDS-N yield per hectare was 127% greater than Rye and 28% greater than Rye+Vetch plots. Additional soil inorganic N increased NDS-N yield to 56.4 kg ha^{-1} compared with 44 kg ha^{-1} for the +0N control. NDS-C content was similar across all 6 treatment combinations and averaged 46.6%. NDS-C production per hectare was also similar across treatments and averaged 791 kg ha^{-1}. C:N ratio of NDS fractions was significantly affected by crop species and soil N fertility. Vetch NDS C:N, whether the crop was grown with or without high soil inorganic N, averaged 9.7 while Rye NDF C:N was 23.7 and Rye+Vetch C:N was intermediate at 18.2. High soil inorganic N, on average, increased NDS C:N ratio to 18.3 compared with 16 for the +0N control. Across cover crop species and soil N fertility, C:N ratios for both NDS and NDF did not change significantly between 532 and 962 GDD. Generally, proportion of N allocated to NDF increased slightly, but fractional increase in C allocated to NDF increased similarly, so the overall impact on NDF and NDS C:N ratios was minimal between 532 and 962 GDD.

Yields of NDS- and NDF-C and –N fractions are combined and summarized in Figures 2.3 and 2.4. Hairy vetch yields of C and N are depressed within the +30N treatments, until the last sampling date where they caught up with the +0N control. The +30N soil inorganic N treatment enhanced rye production of both NDS and NDF fractions of both C and N. The bulk of N yield was in the form of NDS-N across cover crop treatments, though the NDF-N contribution was increased by the +30N treatment and by increasing maturity. Carbon yield was more evenly distributed between NDF and NDS fractions and generally reflected effects of cover crop species, N treatment and sample date on biomass accumulation.

SUMMARY

Rye and hairy vetch species within Rye, Rye+Vetch and Vetch cover crop treatments responded differently to soil inorganic N treatment. While the additional 4 kg N ha^{-1} in the +30N treatments generally enhanced rye accumulation of C and N , the additional N depressed hairy vetch population and biomass accumulation and therefore yield of C and N fractions. This effect on hairy vetch was most likely artifactual; due to seedling injury caused by ammonia toxicity or salt damage (Bremner, 1995; Bremner and Krogmeier, 1989) and may have been exacerbated by the coarse, low OM and dry soils (Havlin et al., 1999). Vetch above-ground biomass growth did not recover from this damage until after the 532 GDD sampling date.

Across soil inorganic N treatment, above-ground biomass accumulated between 416 and 532 GDD at rates of 144, 232 and 39 kg ha^{-1} per 10 GDD for Rye, Rye+Vetch and Vetch cover crops. Between 532 and 962 GDD above-ground biomass accumulation varied more distinctly by soil inorganic N treatment and accumulated at rates of 97 and 218 kg ha^{-1} per 10 GDD for +0N and +30N treatments respectively. Hairy vetch above-ground biomass accumulation was delayed compared with winter rye. Across soil inorganic N treatment, below-ground biomass changed between 416 and 532 GDD at rates of 54, -97 and -0.2 kg ha^{-1} per 10 GDD for Rye, Rye+Vetch and Vetch cover crops, indicating perhaps that maximum root biomass had already occurred near or before 416 GDD for Rye+Vetch and Vetch treatments.

Above-ground tissue OM, NDF and ADL content were significantly affected by cover crop species and soil N fertility on some sampling dates. Both NDF and ADL fractions increased with maturity across species and N treatment. Vetch above-ground tissues generally contained less NDF and more ADL than either Rye or Rye+Vetch samples at each sampling date, consistent with published values (National Research Council, 1982; National Research Council, 2001). In terms of NDF and ADL content, the Rye+Vetch mixtures generally were more similar to Rye than to Vetch treatments throughout the experiment. Between 416 and 962 GDD, NDF as a fraction of DM increased by 67%, 66% and 44% and ADL as a fraction of DM increased by factors of 4.3, 3.0 and 0.8 for Rye, Rye+Vetch and Vetch cover crops across soil fertility treatment with the majority of the increases occurring between 416 and 532 GDD. Hairy vetch and winter rye biochemical qualities diverged more greatly as growth and development progressed.

Total N concentration decreased for Rye and Rye+Vetch treatment combinations throughout the duration of the experiment, but %N in Vetch tissues, with and without additional soil inorganic N, remained at approximately 4%, from 416 to 532 GDD and then decreased to about 2.8% at 962 GDD. Total N yield however increased steadily over the 3 sampling dates for Rye+Vetch and Vetch, with and without additional soil inorganic N, but Rye treatments accumulated N from 416 to 532 GDD, then remained relatively constant through the final sampling at 962 GDD. C:N ratio increased for all cover crop-soil N fertility treatment combinations over each sampling interval. Soil inorganic N treatment increased C:N ratio across cover crop treatments at the 532 and 962 GDD sampling points by an average of 12%. C:N ratio for Vetch plots was consistently much lower, always below 20, than for Rye and Rye+Vetch plots throughout the experiment however differences in C:N ratio were small at 416 GDD and became much greater at 532 and 962 GDD. Residue quality of rye and hairy vetch are relatively similar during early growth and quality differences became more disparate beyond 416 GDD. Distribution of C and N among soluble NDS or structural NDF forms shifted dramatically between 416 and 532 GDD resulting in large increase in C:N ratio of the NDF fraction with a minor impact on C:N ratio of NDS fraction across cover crop species and soil N fertility treatments. This shift in C allocation occurred quickly, in just 20 days and 115 GDD, and was combined with an average 55% increase in NDF content for Rye and Rye+Vetch and a 19% increase in NDF concentration in Vetch above-ground tissue DM. These changes would be expected to dramatically reduce the rate of decomposition in soil and consequent release of plant-available nutrients (Trinsoutrot et al., 2000). This fairly rapid increase in expected recalcitrance of plant residues may enhance long term soil C restoration potential (Johnson et al., 2007; Oades, 1988) but result in greater risk of within-season N immobilization (Mary et al., 1996).

Table 1.1. Soil chemical and physical characteristics at the field experiment site on the Michigan State University Horticultural Research Farm, East Lansing, Michigan, USA.

Sand, %	80
Silt, %	10
Clay, %	10
Organic Matter, %	1.0
pH	5.9
CEC, meq/100g	3.1
NO3-N, ppm	5
P, ppm	63
K, ppm	88
Ca, ppm	313
Mg, ppm	45

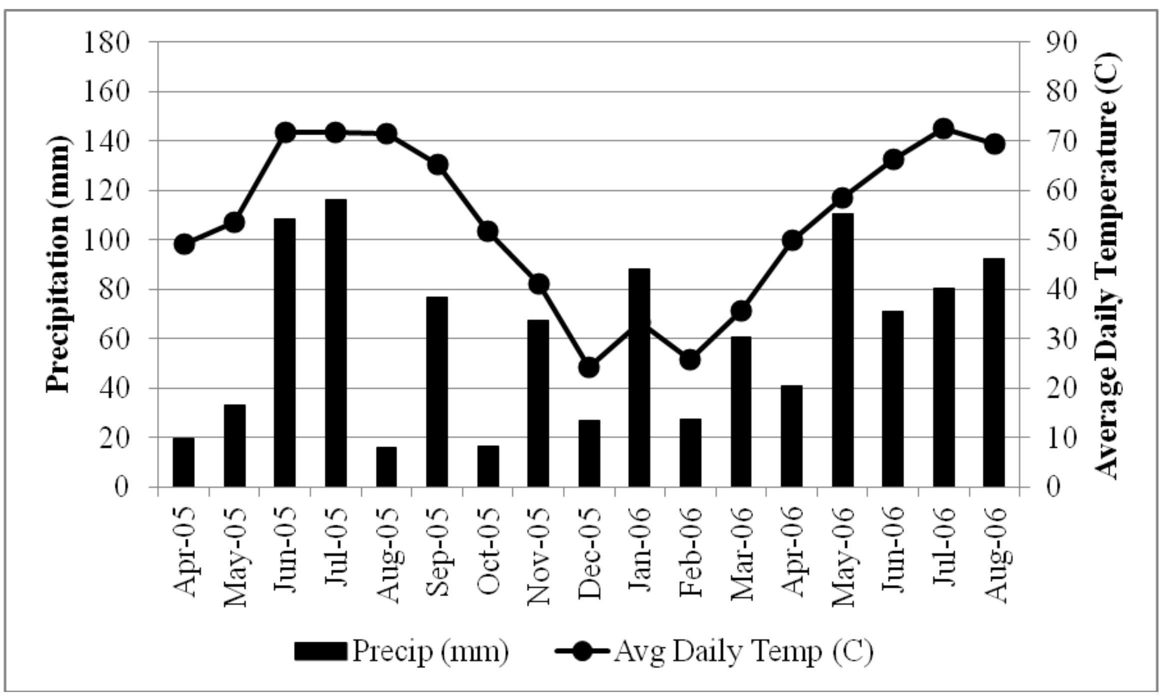

Figure 1.1. Monthly precipitation totals (mm) and average daily temperature (°C) recorded at the MSU Horticulture Research Farm for April 2005 to August 2006.

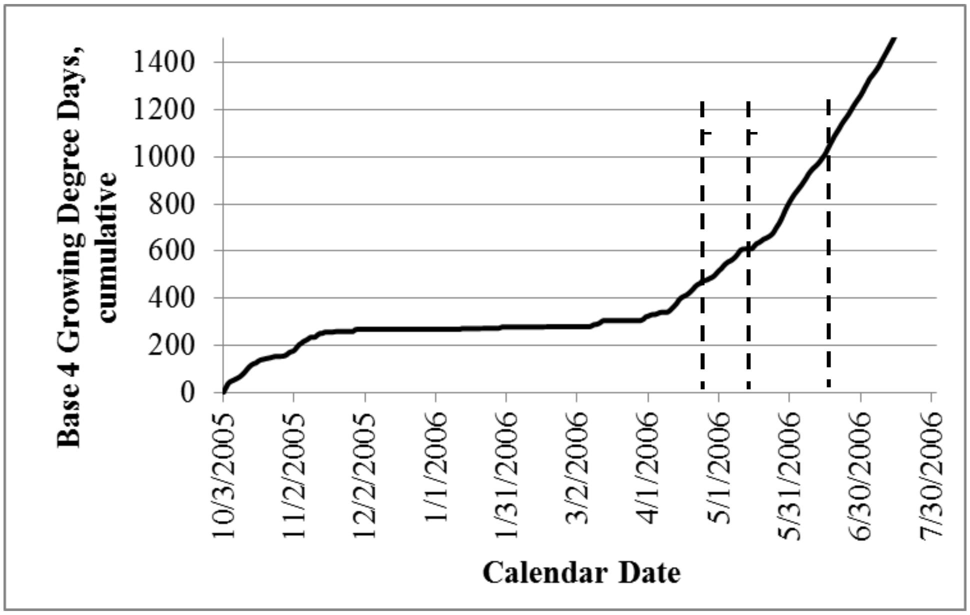

Figure 1.2. Accumulation of Base-4 Growing-Degree Days at the MSU Horticulture Research Farm in East Lansing, MI from October 2005 through July 2006. Plant sample collection points are indicated by dashed lines.

Table 1.2. Effect of plant species and nitrogen fertilization on spring soil inorganic N and plant populations in East Lansing, MI.

	Soil Inorganic N (mg kg^{-1})			Rye Population (no. m^{-2})			Hairy Vetch Population (no. m^{-2})		
	Mean		SE	Mean		SE	Mean		SE
Rye	5.4		0.5	98.8		10.7	---		
Rye-Vetch	5.9		0.3	64.5		7.8	54.8		5.5
Vetch	6.6		0.4	---			72.5		3.3
Crop effect, p-value	*0.080*			*0.137*			*0.101*		
+0N	5.2	b	0.3	93.8	a	12.1	70.0	a	4.0
+30N	6.7	a	0.3	69.5	b	6.9	57.3	b	5.5
N effect, p-value	*0.001*			*0.031*			*0.017*		
Rye +0N	4.6	c	0.6	117.5	a	17.0	---		
Rye +30N	6.2	b	0.5	80.0	ab	10.0	---		
Rye+Vetch +0N	5.3	bc	0.4	70.0	b	13.4	66.5	a	7.1
Rye+Vetch +30N	6.4	ab	0.3	59.0	b	8.4	43.0	b	6.1
Vetch +0N	5.8	bc	0.2	---			73.5	a	3.7
Vetch +30N	7.5	a	0.4	---			71.5	a	5.7
*Crop*N interaction, p-value*	*0.607*			*0.219*			*0.040*		

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 1.3. Effect of plant species and nitrogen fertilization on above-ground winter cover crop biomass, East Lansing at 416 GDD, MI.

	Rye ($kg\ ha^{-1}$)			Hairy Vetch ($kg\ ha^{-1}$)			Total Above-ground ($kg\ ha^{-1}$)		
416 GDD only	Mean		SE	Mean		SE	Mean		SE
Rye	1345		87	---		---	1345	a	87
Rye-Vetch	1330		100	132	b	30	1462	a	94
Vetch	---		---	613	a	144	613	b	144
Crop effect, p-value	*0.841*			*0.015*			*0.002*		
+0N	1107	b	76	633	a	139	1160		80
+30N	1568	a	70	112	b	29	1120		148
N effect, p-value	<.0001			<.0001			0.634		
Rye +0N	1120	b	102	---		---	1120	c	102
Rye +30N	1571	a	87	---		---	1571	ab	87
Rye+Vetch +0N	1095	b	119	216	b	39	1311	bc	125
Rye+Vetch +30N	1565	a	115	48	b	14	1614	a	124
Vetch +0N	---		---	1051	a	177	1051	c	177
Vetch +30N	---		---	175	b	48	175	d	48
*Crop*N interaction, p-value*	0.912			0.001			<.0001		

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 1.4. Effect of plant species and nitrogen fertilization on above-ground winter cover crop biomass at 532 GDD, East Lansing, MI.

	Rye (kg ha^{-1})			Hairy Vetch (kg ha^{-1})			Total Above-ground (kg ha^{-1})		
532 GDD only	Mean		SE	Mean		SE	Mean		SE
Rye	3003	b	238	---		---	3003	b	238
Rye-Vetch	3732	a	335	400	b	98	4132	a	293
Vetch	---		---	1064	a	200	1064	c	200
Crop effect, p-value	*0.044*			*0.014*			*<0.001*		
+0N	2653	b	196	1129	a	185	2521		228
+30N	4082	a	283	335	b	96	2944		404
N effect, p-value	*<0.001*			*<0.001*			*0.090*		
Rye +0N	2468	c	217	---		---	2468	c	217
Rye +30N	3537	b	337	---		---	3537	b	337
Rye+Vetch +0N	2838	bc	328	699	b	115	3537	b	325
Rye+Vetch +30N	4626	a	382	100	c	45	4726	a	401
Vetch +0N	---		---	1559	a	283	1559	d	283
Vetch +30N	---		---	570	b	148	570	e	148
*Crop*N interaction, p-value*	*0.289*			*0.277*			*0.001*		

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 1.5. Effect of plant species and nitrogen fertilization on above-ground winter cover crop biomass at 962 GDD, East Lansing, MI.

	Rye ($kg\ ha^{-1}$)			Hairy Vetch ($kg\ ha^{-1}$)			Total Above-ground ($kg\ ha^{-1}$)		
962 GDD only	Mean		SE	Mean		SE	Mean		SE
Rye	5306		393	---		---	5306	a	393
Rye-Vetch	4716		702	859	b	199	5576	a	691
Vetch	---		---	2738	a	292	2738	b	292
Crop effect, p-value	*0.445*			*0.006*			*0.003*		
+0N	3447	b	325	1998		290	3631	b	311
+30N	6575	a	477	1599		392	5449	a	535
N effect, p-value	*<.0001*			*0.225*			*<0.001*		
Rye +0N	4037	b	228	---		---	4037	b	228
Rye +30N	6575	a	389	---		---	6575	a	389
Rye+Vetch +0N	2858	b	548	1229	b	339	4087	b	817
Rye+Vetch +30N	6575	a	907	490	b	123	7065	a	865
Vetch +0N	---		---	2768	a	274	2768	b	274
Vetch +30N	---		---	2708	a	539	2708	b	539
*Crop*N interaction, p-value*	*0.316*			*0.301*			*0.021*		

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 1.6. Effect of cover crop treatment and nitrogen fertility on below-ground winter cover crop biomass and above:below ground biomass ratio at 416 GDD, East Lansing, MI.

	Roots 0-30 cm (kg ha^{-1})		Roots 30-60 cm (kg ha^{-1})		Total Below-Ground (kg ha^{-1})		Shoot:Root Ratio	
416 GDD only	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Rye	1172	266	130	26	1302	269	1.86	0.73
Rye-Vetch	2238	1069	193	84	2431	1049	1.08	0.33
Vetch	305	124	4	4	308	124	2.55	0.54
Crop effect, p-value	*0.216*		*0.265*		*0.149*		*0.222*	
+0N	912	184	79	21	991	192	1.95	0.50
+30N	1564	763	151	66	1703	762	1.71	0.45
N effect, p-value	*0.428*		*0.260*		*0.382*		*0.706*	
Rye +0N	630	283	107	19	737	273	2.87	1.34
Rye +30N	1714	232	153	50	1866	226	0.86	0.11
Rye+Vetch +0N	1591	130	130	37	1720	117	0.72	0.13
Rye+Vetch +30N	2886	2245	256	171	3142	2186	1.44	0.63
Vetch +0N	516	203	0	---	516	203	2.28	0.38
Vetch +30N	93	32	8	8	99	32	2.82	1.09
*Crop*N interaction, p-value*	*0.637*		*0.668*		*0.599*		*0.199*	

Table 1.7. Effect of cover crop treatment and nitrogen fertility on below-ground winter cover crop biomass and above:below ground biomass ratio at 532 GDD, East Lansing, MI.

	Roots 0-30 cm ($kg\ ha^{-1}$)			Roots 30-60 cm ($kg\ ha^{-1}$)		Total Below-Ground ($kg\ ha^{-1}$)			Shoot:Root Ratio	
532 GDD only	Mean		SE	Mean	SE	Mean		SE	Mean	SE
Rye	1631	a	376	286	151	1917	a	482	2.20	0.38
Rye-Vetch	1209	a	297	112	17	1321	a	306	5.06	1.75
Vetch	253	b	54	52	16	306	b	65	4.04	0.76
Crop effect, p-value	*0.007*			*0.260*		*0.012*			*0.290*	
+0N	977		257	182	105	1159		347	3.32	0.50
+30N	1085		305	118	24	1203		317	4.21	1.26
N effect, p-value	*0.777*			*0.557*		*0.922*			*0.505*	
Rye +0N	1406	ab	589	390	312	1795	ab	899	2.13	0.55
Rye +30N	1857	a	529	182	43	2039	ab	518	2.27	0.62
Rye+Vetch +0N	1165	abc	418	88	25	1253	abc	442	3.93	1.11
Rye+Vetch +30N	1253	abc	486	136	19	1389	abc	489	6.19	3.50
Vetch +0N	361	bc	67	68	25	429	bc	78	3.90	0.67
Vetch +30N	146	c	40	36	21	182	c	57	4.18	1.49
*Crop*N interaction, p-value*	*0.769*			*0.610*		*0.893*			*0.761*	

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 1.8. Effect of cover crop treatment and nitrogen fertility on below-ground winter cover crop biomass and above:below ground biomass ratio at 962 GDD, East Lansing, MI.

	Roots 0-30 cm (kg ha^{-1})		Roots 30-60 cm (kg ha^{-1})		Total Below-Ground (kg ha^{-1})		Shoot:Root Ratio	
962 GDD only	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Rye	1281	284	187	56	1467	271	4.26	0.69
Rye-Vetch	1237	192	162	28	1399	184	4.57	1.16
Vetch	726	183	70	27	787	192	5.76	1.70
Crop effect, p-value	*0.165*		*0.191*		*0.071*		*0.630*	
+0N	1139	189	176	38	1316	179	3.29	0.37
+30N	1023	198	106	28	1120	211	6.43	1.22
N effect, p-value	*0.567*		*0.108*		*0.362*		*0.076*	
Rye +0N	1227	459	256	100	1483	411	3.27	0.73
Rye +30N	1334	404	117	38	1451	418	5.26	1.01
Rye+Vetch +0N	1159	331	166	32	1324	317	3.21	0.53
Rye+Vetch +30N	1315	242	158	52	1473	234	5.92	2.18
Vetch +0N	1032	257	107	36	1139	254	3.40	0.83
Vetch +30N	419	164	22	22	435	157	8.11	3.03
*Crop*N interaction, p-value*	*0.255*		*0.438*		*0.252*		*0.769*	

Table 1.9. Effect of cover crop treatment and nitrogen fertility on total organic matter, NDF and ADL in the above-ground whole plant tissue at 416 GDD.

	Total OM % of DM			Total NDF % of DM			Total ADL % of DM	
416 GDD only	Mean		SE	Mean		SE	Mean	SE
Rye	93.9	a	0.2	41.4	a	0.3	1.2	0.2
Rye-Vetch	93.2	a	0.3	40.0	a	0.8	1.7	0.1
Vetch	74.8	b	3.3	33.7	b	0.8	5.0	0.2
Crop effect, p-value	*<.0001*			*<.0001*			*0.089*	
+0N	84.5	b	3.9	38.5		1.3	2.8	0.5
+30N	90.1	a	1.5	38.2		0.9	2.5	0.5
N effect, p-value	*<.0001*			*0.766*			*0.241*	
Rye +0N	94.1	a	0.3	41.9	a	0.4	1.3	0.0
Rye +30N	93.8	a	0.3	40.9	a	0.2	1.1	0.4
Rye+Vetch +0N	93.2	a	0.3	40.8	a	1.6	2.0	0.1
Rye+Vetch +30N	93.2	a	0.5	39.2	a	0.5	1.5	0.0
Vetch +0N	66.2	c	1.6	32.7	b	0.6	5.1	0.4
Vetch +30N	83.3	b	0.5	34.6	b	1.5	4.8	0.3
*Crop*N interaction, p-value*	*<.0001*			*0.195*			*0.921*	

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 1.10. Effect of cover crop treatment and nitrogen fertility on total organic matter, NDF and ADL in the above-ground whole plant tissue at 532 GDD.

	Total OM % of DM		Total NDF % of DM			Total ADL % of DM		
532 GDD only	Mean	SE	Mean		SE	Mean		SE
Rye	94.6	0.3	65.2	a	0.6	4.2	b	0.2
Rye-Vetch	95.0	0.2	61.2	b	1.1	4.8	b	0.1
Vetch	81.6	4.9	39.8	c	0.8	7.3	a	0.2
Crop effect, p-value	*0.251*		*<.0001*			*<.0001*		
+0N	92.2	1.1	55.0		3.0	5.6		0.5
+30N	88.6	3.9	55.8		3.8	5.3		0.4
N effect, p-value	*0.534*		*0.342*			*0.220*		
Rye +0N	94.2	0.6	64.6	a	0.7	4.1	c	0.2
Rye +30N	95.0	0.1	65.8	a	0.8	4.4	bc	0.3
Rye+Vetch +0N	94.6	0.2	58.9	b	1.2	5.0	b	0.1
Rye+Vetch +30N	95.3	0.1	63.5	a	0.9	4.7	bc	0.3
Vetch +0N	87.7	2.0	41.5	c	0.7	7.6	a	0.2
Vetch +30N	75.4	9.0	38.2	c	0.9	6.9	a	0.4
*Crop*N interaction, p-value*	*0.495*		*0.014*			*0.185*		

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 1.11. Effect of cover crop treatment and nitrogen fertility on total organic matter, NDF and ADL in the above-ground whole plant tissue at 962 GDD.

	Total OM % of DM			Total NDF % of DM			Total ADL % of DM		
962 GDD only	Mean		SE	Mean		SE	Mean		SE
Rye	96.0	a	0.1	69.4	a	0.5	6.4	b	0.2
Rye-Vetch	95.4	a	0.3	66.3	a	1.3	6.8	b	0.2
Vetch	92.5	b	0.5	48.4	b	1.9	8.8	a	0.6
Crop effect, p-value	*<.0001*			*<.0001*			*0.003*		
+0N	94.6		0.4	61.8		2.2	7.8	a	0.5
+30N	94.7		0.6	61.0		3.6	6.9	b	0.3
N effect, p-value	*0.725*			*0.249*			*0.003*		
Rye +0N	95.9	ab	0.1	69.3	a	0.5	6.4	c	0.3
Rye +30N	96.1	ab	0.1	69.5	a	0.9	6.4	c	0.3
Rye+Vetch +0N	94.7	b	0.2	63.6	b	1.8	7.1	bc	0.5
Rye+Vetch +30N	96.1	a	0.2	69.1	a	0.3	6.5	bc	0.1
Vetch +0N	93.0	c	0.5	52.5	c	1.7	9.9	a	0.7
Vetch +30N	91.9	c	0.8	44.3	d	1.6	7.7	b	0.5
*Crop*N interaction, p-value*	*0.052*			*<.0001*			*0.009*		

a, b, c, d Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 1.12. Effect of cover crop treatment and nitrogen fertility on total above-ground whole plant tissue C and N at 416 GDD.

	Total N % of DM			Total N (kg ha^{-1})			Total C % of DM		Total C (kg ha^{-1})			Total C:N		
416 GDD only	Mean		SE	Mean		SE	Mean	SE	Mea n		SE	Mean		SE
Rye	1.94	b	0.10	26.5	a	2.3	43.4	1.4	587	a	44	22.9	a	1.2
Rye-Vetch	2.31	b	0.11	33.9	a	2.2	45.2	1.0	656	a	38	19.6	a	0.7
Vetch	4.03	a	0.19	23.4	b	5.3	43.1	1.7	253	b	57	10.8	b	0.2
Crop effect, p-value	*<.0001*			*<.0001*			*0.606*		*<0.001*			*<.0001*		
+0N	2.64		0.28	30.1		2.9	43.2	0.9	497		32	18.3		1.8
+30N	2.88		0.31	25.8		3.1	44.6	1.3	501		68	17.1		1.5
N effect, p-value	*0.204*			*0.098*			*0.434*		*0.904*			*0.066*		
Rye +0N	1.80	b	0.11	20.6	c	2.5	42.7	1.9	476	c	41	24.2	a	2.1
Rye +30N	2.08	b	0.14	32.5	b	2.5	44.1	2.4	698	ab	54	21.5	b	1.0
Rye+Vetch +0N	2.25	b	0.17	29.9	bc	3.1	44.7	1.4	581	bc	46	20.0	b	1.4
Rye+Vetch +30N	2.38	b	0.15	38.0	bc	2.5	45.6	1.6	732	a	50	19.3	b	0.5
Vetch +0N	3.88	a	0.18	39.8	a	6.2	42.1	1.7	433	c	66	10.9	c	0.1
Vetch +30N	4.18	a	0.35	6.9	d	1.7	44.0	3.2	73	d	19	10.6	c	0.5
*Crop*N interaction, p-value*	*0.903*			*<.0001*			*0.970*		*<.0001*			*0.254*		

a, b, c, d Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 1.13. Effect of cover crop treatment and nitrogen fertility on total above-ground whole plant tissue C and N at 532 GDD.

	Total N % of DM			Total N (kg ha^{-1})			Total C % of DM			Total C (kg ha^{-1})			Total C:N		
532 GDD only	Mean		SE	Mean		SE	Mean		SE	Mean		SE	Mean		SE
Rye	1.38	b	0.06	40.9		3.8	50.9	a	1.1	1533	a	128	38.0	a	0.8
Rye-Vetch	1.33	b	0.08	53.4		3.4	45.7	b	0.7	1899	a	143	35.3	b	2.2
Vetch	4.18	a	0.14	44.2		8.5	45.4	b	0.9	487	b	94	10.9	c	0.2
Crop effect, p-value	*<.0001*			*0.279*			*0.011*			*<.0001*			*<.0001*		
+0N	2.32		0.39	49.9		5.2	46.9		1.0	1185	b	106	26.6	b	3.5
+30N	2.27		0.43	42.5		4.1	47.8		1.1	1427	a	196	29.5	a	4.1
N effect, p-value	*0.494*			*0.175*			*0.340*			*0.044*			*0.030*		
Rye +0N	1.33	bc	0.05	31.8	bc	2.9	50.1	ab	1.2	1236	c	107	38.9	a	0.5
Rye +30N	1.43	bc	0.13	49.9	ab	5.5	51.7	a	1.9	1830	ab	183	37.1	a	1.5
Rye+Vetch +0N	1.50	b	0.09	52.5	a	4.8	45.0	c	1.2	1603	bc	155	30.0	b	1.8
Rye+Vetch +30N	1.15	c	0.06	54.3	a	5.2	46.3	bc	0.8	2195	a	197	40.5	a	1.4
Vetch +0N	4.13	a	0.22	65.2	a	12.5	45.4	c	1.5	717	d	138	11.1	c	0.4
Vetch +30N	4.23	a	0.21	23.2	c	5.4	45.5	c	1.3	256	e	64	10.8	c	0.3
*Crop*N interaction, p-value*	*0.042*			*<0.001*			*0.785*			*0.001*			*0.003*		

a, b, c, d, e Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 1.14. Effect of cover crop treatment and nitrogen fertility on total above-ground whole plant tissue C and N at 962 GDD.

	Total N % of DM		Total N (kg ha^{-1})		Total C % of DM		Total C (kg ha^{-1})		Total C:N	
962 GDD only	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Rye	0.71 c	0.01	38.5 b	3.0	46.5	0.3	2468 a	183	64.5 a	0.8
Rye-Vetch	1.19 b	0.16	62.1 ab	7.5	48.1	0.6	2687 a	335	44.5 b	4.8
Vetch	2.83 a	0.12	78.2 a	9.7	45.8	1.0	1260 b	142	16.4 c	0.7
Crop effect, p-value	*<.0001*		*0.042*		*0.064*		*0.004*		*<.0001*	
+0N	1.57	0.24	52.4	6.2	46.1	0.7	1686 b	153	39.1 b	6.1
+30N	1.58	0.33	66.8	7.0	47.5	0.6	2590 a	255	44.5 a	6.5
N effect, p-value	*0.884*		*0.065*		*0.114*		*<0.001*		*0.050*	
Rye +0N	0.70 d	0.00	29.0 c	1.8	46.4	0.4	1877 b	110	65.0 a	0.7
Rye +30N	0.73 d	0.03	48.0 bc	2.9	46.6	0.6	3059 a	176	63.9 a	1.5
Rye+Vetch +0N	1.45 c	0.24	57.9 abc	13.9	47.6	0.7	1955 b	400	34.8 c	4.6
Rye+Vetch +30N	0.93 d	0.10	66.3 ab	6.3	48.7	1.1	3418 a	409	54.3 b	4.6
Vetch +0N	2.55 b	0.05	70.3 ab	7.1	44.3	1.5	1227 b	121	17.5 d	1.0
Vetch +30N	3.10 a	0.14	86.2 a	18.2	47.3	1.0	1292 b	266	15.3 d	0.5
*Crop*N interaction, p-value*	*0.011*		*0.841*		*0.376*		*0.028*		*0.008*	

a, b, c, d Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

Table 1.15. Effect of cover crop species and nitrogen fertility on total above-ground plant tissue NDF and NDF-C and -N fractions at 416 GDD.

	Total NDF-N % of NDF			Total NDF-N (kg ha^{-1})			Total NDF-C % of NDF			Total NDF-C (kg ha^{-1})			Total NDF C:N		
416 GDD only	Mean		SE	Mean		SE	Mean		SE	Mean		SE	Mean		SE
Rye	0.76	b	0.07	4.2	a	0.6	42.7	a	0.4	232	a	19	60	a	5
Rye-Vetch	0.80	b	0.03	4.9	a	0.5	43.1	a	0.2	254	a	27	54	a	2
Vetch	1.12	a	0.18	1.7	b	0.3	33.1	b	2.0	63	b	14	34	b	4
Crop effect, p-value	*0.025*			*<0.001*			*<.0001*			*<.0001*			*0.003*		
+0N	0.72	b	0.04	3.0	b	0.3	38.7		1.9	167	b	19	55	a	4
+30N	1.06	a	0.12	4.2	a	0.7	40.4		1.5	195	a	40	42	b	5
N effect, p-value	*0.006*			*0.005*			*0.210*			*0.002*			*0.001*		
Rye +0N	0.67	b	0.09	3.0	bc	0.2	42.4	a	0.6	193	c	17	66	a	7
Rye +30N	0.84	b	0.10	5.4	a	0.9	43.1	a	0.5	272	ab	18	53	bc	6
Rye+Vetch +0N	0.76	b	0.02	3.7	b	0.5	43.4	a	0.2	213	bc	29	58	ab	2
Rye+Vetch +30N	0.85	b	0.05	6.1	a	0.1	42.8	a	0.4	308	a	31	50	bc	4
Vetch +0N	0.75	b	0.09	2.3	cd	0.3	30.4	c	2.1	94	d	14	42	c	3
Vetch +30N	1.49	a	0.23	1.2	d	0.4	35.9	b	2.9	33	e	11	25	d	3
*Crop*N interaction, p-value*	*0.037*			*0.004*			*0.227*			*0.000*			*0.488*		

a, b, c, d, e Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 1.16. Effect of cover crop species and nitrogen fertility on total above-ground plant tissue NDF and NDF-C and -N fractions at 532 GDD.

	Total NDF-N % of NDF			Total NDF-N (kg ha^{-1})			Total NDF-C % of NDF			Total NDF-C (kg ha^{-1})			Total NDF C:N		
532 GDD only	Mean		SE	Mean		SE	Mean		SE	Mean		SE	Mean		SE
Rye	0.20		0.04	4.2	b	0.8	45.2	a	0.1	951	a	130	236	a	15
Rye-Vetch	0.28		0.04	7.1	a	0.9	45.3	a	0.1	1162	a	141	166	b	8
Vetch	0.54		0.04	2.2	b	0.5	39.3	b	2.0	174	b	46	75	c	5
Crop effect, p-value	*0.121*			*0.002*			*0.001*			*<.0001*			*<.0001*		
+0N	0.32	b	0.04	3.9		0.5	43.5		1.3	640		98	170		24
+30N	0.36	a	0.05	5.1		1.1	43.1		1.2	884		192	148		18
N effect, p-value	*0.042*			*0.109*			*0.821*			*0.075*			*0.089*		
Rye +0N	0.18	ab	0.02	2.8	c	0.4	45.1	a	0.2	712	b	105	261	a	23
Rye +30N	0.22	ab	0.01	5.7	b	1.0	45.2	a	0.1	1189	a	173	211	b	9
Rye+Vetch +0N	0.28	ab	0.02	5.7	b	0.6	45.3	a	0.2	947	ab	100	168	c	16
Rye+Vetch +30N	0.28	ab	0.01	8.5	a	1.6	45.4	a	0.1	1376	a	228	163	c	7
Vetch +0N	0.50	b	0.04	3.3	bc	0.8	40.1	ab	3.5	261	c	61	81	d	1
Vetch +30N	0.59	a	0.05	1.2	c	0.3	38.6	b	2.5	88	c	33	68	d	10
*Crop*N interaction, p-value*	*0.153*			*0.024*			*0.925*			*0.102*			*0.286*		

a, b, c, d Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 1.17. Effect of cover crop species and nitrogen fertility on total above-ground plant tissue NDF and NDF-C and -N fractions at 962 GDD.

	Total NDF-N % of NDF			Total NDF-N (kg ha^{-1})		Total NDF-C % of NDF		Total NDF-C (kg ha^{-1})			Total NDF C:N		
962 GDD only	Mean		SE	Mean	SE	Mean	SE	Mean		SE	Mean		SE
Rye	0.21	b	0.03	7.7	1.5	47.7	0.6	1768	a	205	233	a	19
Rye-Vetch	0.28	b	0.03	10.1	1.9	46.9	0.3	1825	a	350	183	b	17
Vetch	0.79	a	0.07	11.5	1.7	46.0	0.5	675	b	80	61	c	5
Crop effect, p-value	*<.0001*			*0.244*		*0.119*		*0.001*			*<.0001*		
+0N	0.43		0.09	9.2	1.6	46.9	0.2	1152		163	152		25
+30N	0.41		0.08	10.3	1.2	46.8	0.6	1693		289	166		25
N effect, p-value	*0.381*			*0.692*		*0.814*		*0.079*			*0.430*		
Rye +0N	0.18	b	0.02	5.1	0.8	47.2	0.4	1363	bc	158	250	a	17
Rye +30N	0.26	b	0.06	11.0	2.3	48.3	1.1	2173	ab	250	215	a	35
Rye+Vetch +0N	0.34	b	0.04	9.5	3.6	46.9	0.4	1286	c	454	144	b	18
Rye+Vetch +30N	0.22	b	0.01	10.7	1.9	46.8	0.4	2364	a	416	221	a	9
Vetch +0N	0.82	a	0.13	14.0	1.8	46.6	0.3	807	c	28	61	c	9
Vetch +30N	0.77	a	0.06	9.0	2.3	45.3	0.8	543	c	131	61	c	6
*Crop*N interaction, p-value*	*0.156*			*0.141*		*0.079*		*0.160*			*0.057*		

a, b, c Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

Table 1.18. Effect of cover crop species and nitrogen fertility on total above-ground plant tissue NDS and NDS-C and -N fractions at 416 GDD.

	Total NDS-N % of NDS			Total NDS-N (kg ha^{-1})			Total NDS-C % of NDS		Total NDS-C (kg ha^{-1})			Total NDS C:N		
416 GDD only	Mean		SE	Mean		SE	Mean	SE	Mean		SE	Mean		SE
Rye	2.8	b	0.2	22.7	b	2.1	43.9	2.3	342	a	40	16.3	a	1.1
Rye-Vetch	3.3	b	0.2	29.2	a	1.9	46.5	1.9	409	a	45	14.0	a	0.6
Vetch	5.5	a	0.2	21.7	c	5.0	47.9	2.7	187	b	50	8.7	b	0.4
Crop effect, p-value	*<.0001*			*<.0001*			*0.589*		*0.001*			*0.002*		
+0N	3.8		0.4	26.9	a	2.8	45.5	1.5	297		17	13.3		1.2
+30N	4.0		0.4	22.2	b	2.7	46.7	2.3	321		65	12.6		1.1
N effect, p-value	*0.449*			*0.020*			*0.630*		*0.093*			*0.402*		
Rye +0N	2.6	b	0.3	17.5	d	2.3	43.0	3.1	271	c	28	17.1	a	2.1
Rye +30N	2.9	b	0.2	27.9	c	2.3	44.8	3.8	413	b	57	15.5	a	1.1
Rye+Vetch +0N	3.3	b	0.2	25.8	c	2.7	45.5	2.3	316	bc	16	13.9	a	1.1
Rye+Vetch +30N	3.4	b	0.3	32.6	b	2.2	47.7	3.6	533	a	18	14.2	a	0.4
Vetch +0N	5.4	a	0.2	37.3	a	5.9	47.9	2.4	305	c	43	8.9	b	0.2
Vetch +30N	5.6	a	0.4	6.0	e	1.5	47.9	5.2	69	d	22	8.6	b	0.7
*Crop*N interaction, p-value*	*0.907*			*<.0001*			*0.938*		*<.0001*			*0.576*		

a, b, c, d, e Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 1.19. Effect of cover crop species and nitrogen fertility on total above-ground plant tissue NDS and NDS-C and -N fractions at 532 GDD.

	Total NDS-N % of NDS		Total NDS-N (kg ha^{-1})		Total NDS-C % of NDS		Total NDS-C (kg ha^{-1})		Total NDS C:N	
532 GDD only	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Rye	3.5 b	0.2	36.9	3.4	61.7 a	3.4	682 a	92	17.5 a	0.4
Rye-Vetch	3.0 b	0.1	46.5	3.0	46.5 b	1.9	748 a	92	15.8 b	0.9
Vetch	6.6 a	0.2	42.0	8.1	49.3 b	1.5	315 b	81	7.5 c	0.3
Crop effect, p-value	*<.0001*		*0.400*		*0.004*		*0.010*		*<.0001*	
+0N	4.4	0.5	46.0	5.0	51.0	2.4	538	49	12.9 b	1.3
+30N	4.3	0.5	37.6	3.5	54.0	3.0	625	117	14.3 a	1.4
N effect, p-value	*0.293*		*0.102*		*0.319*		*0.271*		*0.042*	
Rye +0N	3.3 bc	0.1	28.8 bc	2.6	59.1 ab	3.7	500 b	45	17.8 a	0.8
Rye +30N	3.7 bc	0.4	44.9 ab	4.9	64.4 a	5.8	864 a	123	17.3 a	0.4
Rye+Vetch +0N	3.3 b	0.1	47.2 ab	4.1	44.8 c	3.0	648 ab	71	13.6 b	0.7
Rye+Vetch +30N	2.7 c	0.1	45.9 ab	4.5	48.1 c	2.3	848 a	167	18.1 a	0.4
Vetch +0N	6.7 a	0.4	61.9 a	11.8	49.1 bc	2.2	467 b	116	7.4 c	0.6
Vetch +30N	6.5 a	0.3	22.0 c	5.1	49.5 bc	2.2	164 c	40	7.6 c	0.2
*Crop*N interaction, p-value*	*0.042*		*<0.001*		*0.786*		*0.013*		*0.018*	

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 1.20. Effect of cover crop species and nitrogen fertility on total above-ground plant tissue NDS and NDS-C and -N fractions.

	Total NDS-N % of NDS			Total NDS-N (kg ha^{-1})			Total NDS-C % of NDS		Total NDS-C (kg ha^{-1})		Total NDS C:N		
962 GDD only	Mean		SE	Mean		SE	Mean	SE	Mean	SE	Mean		SE
Rye	1.9	c	0.1	29.9	c	2.2	43.8	1.5	702	66	23.7	a	0.8
Rye-Vetch	2.9	b	0.3	53.0	b	6.4	50.6	2.2	985	187	18.2	b	1.5
Vetch	4.7	a	0.2	67.8	a	8.9	45.4	2.2	686	82	9.7	c	0.4
Crop effect, p-value	*<.0001*			*<.0001*			*0.100*		*0.153*		*<.0001*		
+0N	3.2		0.3	44.0	b	5.3	45.0	1.4	667	95	16.0	b	1.8
+30N	3.1		0.4	56.4	a	6.7	48.2	2.0	914	106	18.3	a	1.9
N effect, p-value	*0.583*			*0.004*			*0.161*		*0.133*		*0.033*		
Rye +0N	1.9	c	0.1	23.8	d	1.4	44.8	0.9	570	51	23.7	a	0.6
Rye +30N	1.8	c	0.2	35.9	d	2.9	42.8	3.0	834	79	23.7	a	1.5
Rye+Vetch +0N	3.4	b	0.4	49.9	c	11.9	48.3	2.2	779	295	14.8	b	1.1
Rye+Vetch +30N	2.5	c	0.3	56.0	c	5.4	52.8	3.8	1191	218	21.5	a	1.2
Vetch +0N	4.4	a	0.1	58.4	b	6.2	41.9	3.0	653	36	9.5	c	0.6
Vetch +30N	5.0	a	0.3	77.3	a	16.6	48.9	2.4	718	170	9.9	c	0.6
*Crop*N interaction, p-value*	*0.062*			*<.0001*			*0.232*		*0.650*		*0.030*		

a, b, c, d Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

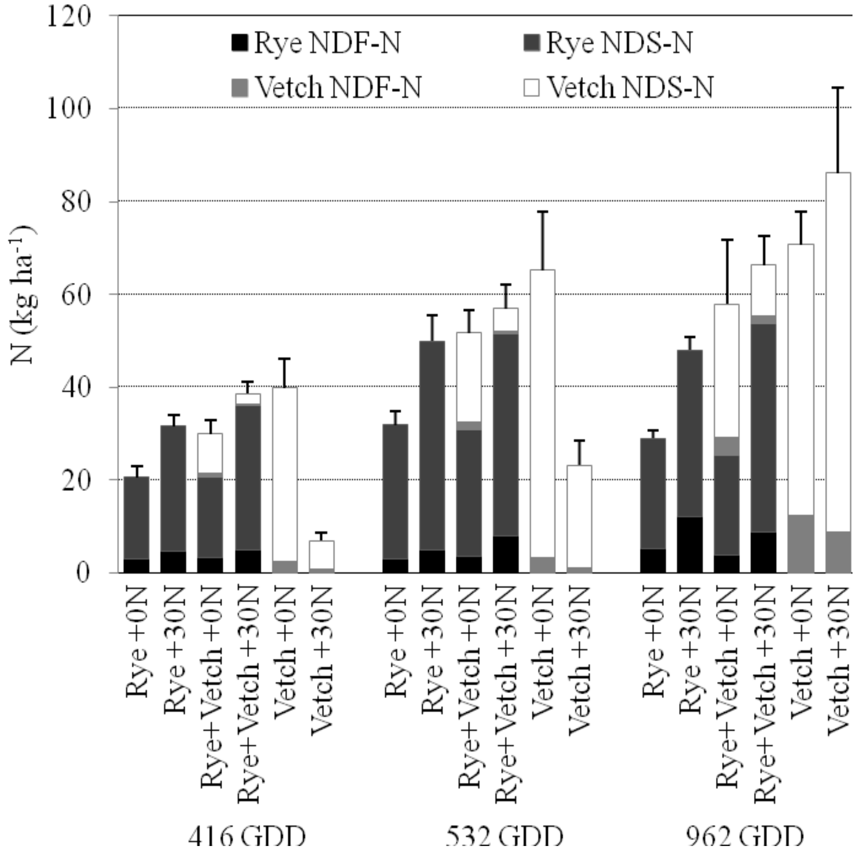

Figure 1.3 Nitrogen yield (kg ha^{-1}) in NDF and NDS fractions of rye and hairy vetch species at three sampling dates within Rye, Vetch and Rye+Vetch cover crop treatments with and without additional N.

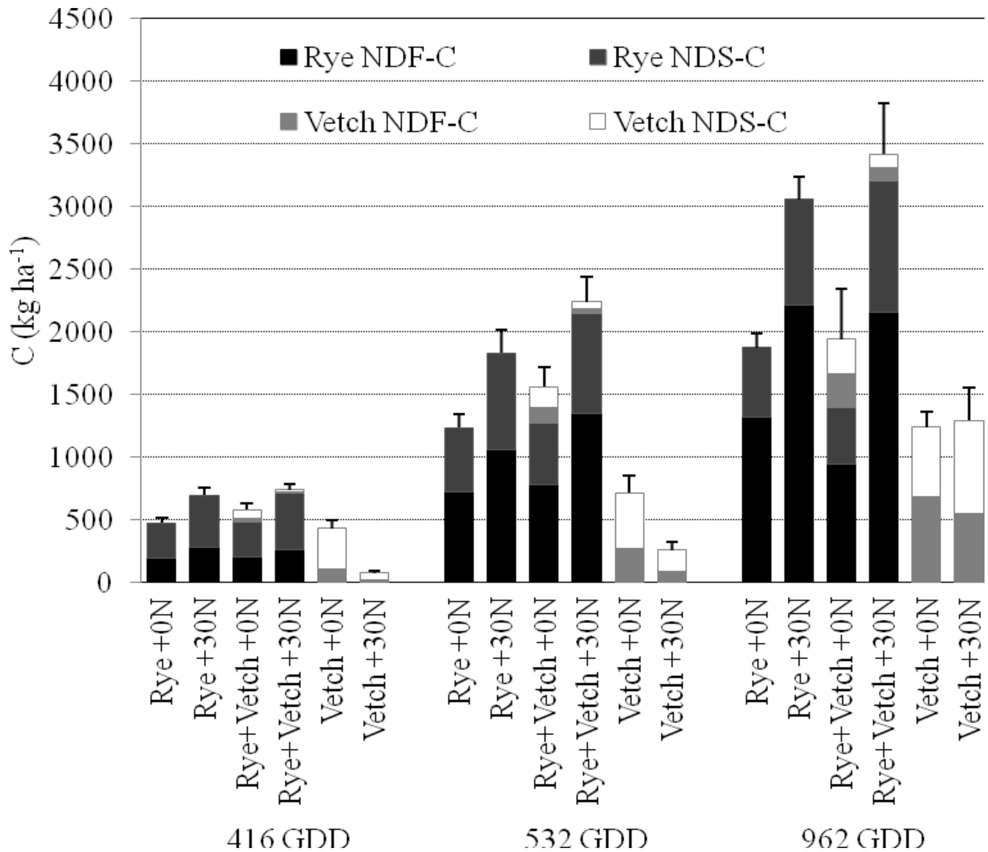

Figure 1.4 Carbon yield (kg ha^{-1}) in NDF and NDS fractions of rye and hairy vetch species at three sampling dates within Rye, Vetch and Rye+Vetch cover crop treatments with and without additional N.

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CHAPTER 2:

IMPACT OF COVER CROPS AND MANURE AMENDMENT ON PERFORMANCE OF A POTATO-SNAP BEAN CROP ROTATION

ABSTRACT

Winter rye cover crops have become more common in Michigan potato (*Solanum tuberosum*) cropping systems as growers attempt to reduce erosion and overwinter N leaching on coarse, low organic matter (SOM) soils. However fertilizer N applications to subsequent potato or other cash crops are not always reduced to account for cover crop N due to perceived risk of insufficient or asynchronous N supply. A 3-year field experiment was conducted in 2 important potato-growing regions in Michigan to compare yields and economic returns for a 2-year potato-snap bean (*Phaseolus vulgaris*) rotation with winter rye (*Secale cereale*, Rye), a winter rye-hairy vetch (*Vicia villosa* L. Roth) biculture or no winter cover crop (Bare). Each cover crop treatment was conducted with and without an annual amendment of 5.6 Mg ha^{-1} poultry manure and each cover crop-manure amendment combination was replicated 4 times at each location. Nitrogen fertilizer applications were reduced appropriately for each treatment combination. Partial budgets of variable costs and benefits and net marginal returns were calculated for each field replicate at each location. Yield of above-ground cover crop biomass averaged about 1.6 and 0.9 Mg ha^{-1} at Entrican and Benton Harbor locations respectively and was unaffected by cover crop species. Bare plots accumulated about 0.2 Mg ha^{-1} of winter annual weed biomass. Manure amendment had no significant effect on cover crop biomass or N accumulation. Poultry manure amendment with N fertilizer reduction consistently increased US No. 1 tuber yield by 17.6%. Cover crop treatment did not affect total or US No. 1 tuber yields. The combination of bare winter fallow or rye cover crop with manure produced the highest yields on average across all 6 site-years. Rye cover crop, with and without poultry manure, were the only treatment

combinations to produce positive marginal revenues compared with unamended bare control treatment. Post-harvest soil inorganic N in surface soils (0-20 cm) of poultry manure-amended plots was elevated by 17%, on average, above non-amended plots. Potatoes grown on these plots yielded 16% more tuber weight, on average. Bare and rye-vetch plots, without manure, had the highest average inorganic N in the 20-51 cm layer. Across treatments and site-years, inorganic N averaged 6.9 mg kg^{-1} and 4.5 mg kg^{-1} soil after a snap bean crop, in the 0-20 cm and 20-51 cm layers respectively. After a potato crop, inorganic N averaged 5.92 mg kg^{-1} and 6.65 mg kg^{-1} soil, in the 0-20 cm and 20-51 cm layers respectively across 5 site-years. Manure increased soil N mineralization potential (NMP) after potatoes by an average of 20% at Entrican in all 3 years. NMP after potatoes was unaffected by manure amendment in both years at Benton Harbor. In site-years with significant manure or cover crop effects, the bare control without manure amendment resulted in the lowest NMP. Total soil C and N, measured in the fall of 2006, were unaffected by manure amendment or cover crop. Soil C and N averaged 0.73% and 0.06% at Entrican and 0.60% and 0.05% at Benton Harbor. This moderate annual amendment of poultry manure significantly increased Bray P by 26% at Entrican and by 37% at Benton Harbor. Rye cover crop, with or without manure, is recommended as it did not negatively affect potato or snap bean production, improved residual soil inorganic N and provided a positive marginal return on variable costs. Rye can be combined with manure on low- or moderate-P soil following a P-based application plan.

INTRODUCTION

Potato production in Michigan is typically accomplished with short 2-year rotations of potatoes with corn, wheat or other vegetables; with supplemental irrigation, extensive tillage, split applications of soluble inorganic fertilizer and nominal crop residue inputs. Additionally, Michigan potato cropping is concentrated on coarse, well-drained soils which are very low in soil organic matter (SOM), often below 1%. Michigan potato growers have begun to integrate winter cover crops, usually winter rye (*Secale cereale*), into potato cropping systems (Snapp and Rohrbach, 2001) to reduce overwinter nutrient leaching and erosion, to restore depleted SOM and to recover residual inorganic N, which may be subsequently provided to the cash crop as incorporated cover crop residues decompose and mineralize during the spring and summer growing season. This plant available, mineralized N may replace a significant portion of exogenous fertilizer N if its availability coincides sufficiently with cash crop demand (Griffin et al., 2000). However, survey results show that the perceived risk of insufficient or asynchronous N supply following cover crops often causes growers to opt not to reduce N fertilizer application to a cash crop following a winter cover crop (Snapp and Rohrbach, 2001).

Few cover crops are appropriate for integration into an Upper Midwest potato cropping system. Most potatoes are harvested in late September and October when available heat units are insufficient for establishment of many cover crops. Winter rye is a popular cover crop choice for potato systems due to its winter hardiness and tolerance of late planting dates. A rye cover crop has been found to dramatically reduce leaching of NO_3-N in sandy soils (Prunty and Greenland, 1997) and , once established, the rye root system can take up residual inorganic nutrients more quickly than other winter cereal alternatives (Clark, 2007; Sarrantonio, 1994). Combining a legume with the winter rye cover crop could provide additional organic N to the cash crop and further reduce fertilizer N requirements (Ranells and Wagger, 1997) and reduce N leaching losses (Tonitto et al., 2006). Additionally, researchers have shown that legumes can improve SOM faster than grass alone (Drinkwater et al., 1998; Robertson et al., 2000). Hairy vetch (*Vicia* *villosa* L. Roth) is the most cold-tolerant of winter annual legumes and has been found to perform well in northern US cropping systems (Clark, 2007; Jannink et al., 1997; Sarrantonio, 1994). Furthermore, a grass-hairy vetch biculture can provide greater mineralized N to subsequent cash crops than a grass alone (Ranells and Wagger, 1997).

Application of animal manure can also ameliorate a degraded soil through direct organic C and N inputs (Larney and Janzen, 1996). Michigan potato growers have begun to expand application of animal manures to restore SOM and to provide a source of organic N to potato and rotation crops. Poultry manure is available in Michigan potato growing regions and, because it is typically lower in moisture than cattle or hog manure, it is more efficient to transport. Poultry manure has been found to improve SOM sequestration (Franzluebbers, 2005) and provide a good source of plant available N to subsequent crops (Bowden et al., 2007). Rye cover crop combined with manure was found to reduce leaching of inorganic N compared with manure alone (Parkin et al., 2006). Organic amendments have also been found to reduce incidence and severity of root rot in snap beans (Rotenberg et al., 2005; Stone et al., 2003).

The objectives of the following experiment were to compare yields and economic returns for a 2-year potato-snap bean rotation with three winter cover alternatives: a bare winter fallow, winter rye, or a rye + hairy vetch mixture winter cover crop. All three cover crop cropping systems were managed with or without moderate annual amendment of poultry manure. We also monitored residual soil inorganic N, extractable P and effects on soil organic C and N resulting from all 6 treatment combinations.

MATERIALS AND METHODS

Site Descriptions

A 6-year potato cropping systems field study was conducted at 2 locations in Michigan from 2001 through 2007 comparing potato crop rotation sequences and winter cover crop alternatives. Both sites are well-drained, loamy sand to sandy loam soils that are common soil types used for production of a wide range of vegetable crops in Michigan. The experimental site at the Montcalm Research Farm, near Entrican, MI (43°20' N, 85°01' W), was first established in the spring of 2001 with planting of main crops. The Entrican location is on Montcalm/McBride loamy sand to sandy loam (coarse-loamy, mixed, semiactive, frigid Alfic Haplorthods; and coarse-loamy, mixed, semiactive, frigid Alfic Fragiorthods). The experiment was established in the fall of 2001, at the Southwest Michigan Research and Extension Center, near Benton Harbor, MI (42°6' N, 86°24' W) beginning with cover crops. At the Benton Harbor site, the soil is an Oakville series fine sand (mixed, mesic Typic Udipsamment). Monthly precipitation and irrigation totals and average monthly ambient temperature for each location are depicted in Figure 2.1. All plots at both locations were sampled in 2001 for initial soil chemical and physical parameters listed in Table 2.1.

Eight crop rotation-winter cover crop combinations, listed in Table 2.2, were included as whole plot treatments to represent common and potentially improved systems for Michigan potato production. The experiment was a randomized complete block design and whole plot (5.5 x 17 m) treatments were 2-year rotations of potato with snap bean, sweet corn or wheat and one 3-year potato-sweet corn-wheat rotation. After removal of main crops, whole plots were either left as a bare fallow (Bare) or were planted with rye (Rye) or rye-hairy vetch biculture (Rye+Vetch) winter cover crop in October of each year. Annual poultry manure amendment was applied as a split-plot factor only to the Potato-Snap Bean rotation plots, at a rate of 5.6 Mg ha^{-1}. Both experimental sites were conventionally tilled and managed with field-scale machinery throughout the experiment and included 4 field replications of all treatment combinations. Weeds, pests and pathogens affecting potato and snap bean crops were treated with conventional herbicides and pesticides according to standard recommended practices. This paper focuses on the Potato-Snap Bean rotation treatments only, with (+M) and without annual poultry manure amendment, during the 2003, 2004 and 2005 growing seasons.

Experimental Design and Crop Management

Dates of cover crop and main crop agronomic practices for 2003 through 2006 are listed in Table 2.3. Cover crops and winter wheat were planted in the late fall and allowed to overwinter and accumulate in the spring before spring tillage and planting of main crops. Winter rye (cv. Wheeler) was drilled at 18 cm row spacing with 101 kg ha^{-1} and the rye-hairy vetch (cv. Common) biculture was also drilled using 67 and 34 kg ha^{-1} respectively. Prior to spring incorporation of cover crop residues with a field-scale disk, two 0.25 m^2 samples of aboveground cover crop biomass were collected from each split-plot to estimate dry matter and total N content. Dried poultry manure was applied each spring to potato-snap bean split-plots (5.5 x 8.5 m) at both locations after cover crop sampling and just prior to spring tillage. Poultry manure was first applied to the Entrican site in the spring of 2002 and to the Benton Harbor site in spring of 2003. The poultry manure composition varied slightly but contained an average of 235 g kg^{-1}organic C, 35 g kg^{-1} total N, and 0.87 g kg^{-1} inorganic N content (NH_4–N + NO_3–N), representing 2.5% of total N. The manure also contained 1240 mg kg^{-1} P, 6275 mg kg^{-1} K, 6600 mg kg^{-1} Ca, and 450 mg kg^{-1} Mg, and had a pH of 8.9 (Nyiraneza and Snapp, 2007).

Potatoes were rotated with snap beans, corn or wheat in all whole plots with both potato and rotation crop phases present each year. Cut potato tuber (cv. Snowden) pieces were planted in May of each year with a field-scale 2-row planter at a within-row spacing of 31 cm and 86 cm between rows for a population of approximately 38000 ha^{-1}. Potassium (0-0-60) was broadcast before planting at the rate of 201.6 kg ha−1. Phosphorus (19-19-19) was applied to the Entrican plots at a rate of 37.5 kg ha^{-1} at potato planting while none was applied to Benton Harbor plots. Nitrogen fertilizer was applied to potatoes in applications at planting, at hilling and at tuberization, totaling 224 kg ha^{-1}. Nitrogen fertilizer applications were reduced by 56 kg ha^{-1} in manure-treated split-plots based on 120-d lab incubation studies showing approximately 40% mineralization of total N (Nyiraneza and Snapp, 2007). Fertilizer reductions were applied to late N applications while planting and hilling applications were not modified from applications to bare control. Reductions averaged 11, 34 and 60 kg ha^{-1} N for rye , rye-vetch and red clover cover crops based on previous studies (Nyiraneza and Snapp, 2007). Nitrogen fertilizer reductions for cover crop treatments were dependent upon cover crop species, maturity and total biomass yields. Biomass N was assumed to be 50% available to the subsequent crop. Potato vines were killed with diquat dibromide on the dates indicated in Table 2.3, approximately 105 days after planting. Two to three weeks later, when vines were fully desiccated, two central rows within each split-plot were dug with a field scale potato digger and tubers were sampled, sized and evaluated manually. All tubers within two 1.5 m row sections per split plot were collected and total tuber fresh weight was determined, as well as tuber size distribution, as follows: oversize > 8.3 cm, U.S. No. 1 > 5.1 cm, B < 5.1 cm. Tubers with external physiological defects were excluded from the US No. 1 grade category. Each tuber sample was also visually inspected for common scab and tubers with deep pitted lesions or with 3 or more lesions > 0.5

cm in diameter were categorized as having scab and were separated and weighed. Specific gravity was determined using the weight-in-air/weight-in-water method for a subsample of U.S. No. 1 tubers, weighing approximately 3.5 kg.

Snap beans (cv. HyStyle, Harris Moran) were planted in late May or early June of each year with a field-scale planter at a within-row spacing of 10.1 cm and 51 cm between rows for a population of 194,000 ha^{-1}. Potassium (0-0-60) was broadcast before planting at the rate of 202 kg ha^{-1}. Fifty-six kg ha^{-1} N in the form of ammonium nitrate fertilizer was applied to snap beans at planting. Nitrogen fertilizer was not applied to manure-treated split-plots. At maturity, approximately 62 days after planting, bean plants were sampled manually from center plot rows within each split plot by collecting all above-ground plant biomass in two 1.5 m row sections. Bean pods were separated from leaf and stem biomass and both fractions were weighed. Pods and vegetative leaf and stem biomass were also dried and weighed for dry biomass estimates.

Winter wheat (cv. Caledonia) was drilled at 18 cm row spacing at a rate 168 kg ha^{-1} at both locations. In late March at both locations, potassium (0-0-60) was broadcast onto wheat plots at the rate of 202 kg ha^{-1} and urea was broadcast at the rate of 84 kg N ha^{-1}. Red clover was frost-seeded into standing wheat plots in late March at the rate of 28 kg ha^{-1}. At maturity, in mid-July, wheat plants were sampled by collecting all above-ground plant biomass within two 0.5 x 0.5 m quadrat areas. Grain was separated from leaf and stem biomass and both fractions were weighed. Grain and leaf and stem biomass were also dried and weighed for dry biomass estimates.

Sweet corn (cv. Jackpot, Siegers Seed Co.) was planted in late May or early June of each year with a field-scale planter at a within-row spacing of 10 cm and 86 cm between rows for a population of 27,000 ha^{-1}. Potassium (0-0-60) was broadcast before planting at the rate of 202 kg ha^{-1}. Ammonium nitrate fertilizer was applied to corn at planting to provide 101 kg N ha^{-1}. At maturity, approximately 82 days after planting, corn plants were sampled manually from center rows within each plot by collecting all above-ground plant biomass in two 1.5 m row lengths. Ears were separated from leaf and stem biomass and both fractions were weighed. Ears and leaf and stem biomass were also dried and weighed for dry biomass estimates.

Soils were sampled with a 6.4 cm enclosed bucket auger to a depth of 51 cm in all plots and all treatment combinations after fall crop harvests. Four soil cores were collected from each split plot and cores were segmented into 0-20 cm and 20-51 cm depths. Four additional cores were taken to a depth of 20 cm. Cores were combined by depth, were mixed, sieved (6 mm) and subsampled and were stored at 5 °C for 0-3 days before KCl extraction. Gravimetric soil water content was determined by weighing a subsample, drying at 105 °C for 24 h and reweighing. Soil subsamples were extracted with 1M KCl and extracts were filtered and stored at -20 °C until inorganic N analysis. Inorganic N (NH_4-N + NO_3-N) was quantified using colorimetric methods and an autoanalyzer (Lachat Instruments, Milwaukee, WI). An aerobic N mineralization potential assay was performed by incubating field-moist soil subsamples at 25 °C for 30d. Soil moisture was adjusted to 60% of field capacity before incubation if necessary. Net N mineralized (NMP) was calculated by subtracting the day 0 inorganic N content from the inorganic N content after 30 d of incubation. After subsampling for moisture and KCl extraction, soils were air-dried. Air-dried soil subsamples were extracted with Bray-1 extractant and filtered. Bray extracts were stored at -20 °C until P analysis with a Lachat autoanalyzer instrument.

Economic Analysis

Partial budgets were calculated for each potato-snap bean treatment combination including only the variable costs and benefits that varied among 6 cover crop-manure treatment combinations. Not all production costs are included in the partial budget and non-economic benefits are excluded. Only those costs that are affected by the alternative treatments are considered. Two-season gross revenues were simulated by summing potato and snap bean performance within each field replication-site-year for each cover crop-manure treatment combination. Measured yields were multiplied by current prices to get gross income/revenue. Revenues generated by sale of measured potato and snap bean marketable yields were summed to get the two-year gross revenue. Costs for all variable factors for both the potato and snap bean phases for each treatment combination within each field replication in each site-year were subtracted from the gross revenue to determine the partial net income. The variable factors were nitrogen fertilizer, manure, cover crop seed, application of manure and seeding of the cover crop. Current farm gate prices for chip potatoes and fresh snap beans, and the current costs of the input variables are listed in Table 2.4. Partial net revenue for each treatment replicate was calculated by subtracting variable costs from gross revenues. Marginal returns and marginal rate of return were calculated by difference in partial net revenues over unamended bare cover crop control cost (CIMMYT, 1988). All gross revenue, partial net revenue and marginal return data were subjected to both one-tailed and two-tailed ANOVA.

Statistical Analysis

Because this experiment was first established at two sites in different seasons of different years, the 6 site-years included in this summary were analyzed separately. Treatment differences due to cover crop, manure, and cover crop x manure interaction were identified using an

ANOVA with either PROC MIXED or PROC GLIMMIX in SAS (SAS, 2008). PROC MIXED was used for normally distributed variables. When non-normally distributed data were encountered, a log(n+1) transformation was applied and transformed data were subjected to ANOVA using PROC GLIMMIX. Data were back-transformed within PROC GLIMMIX using the 'ILINK' command for reporting and presentation. Where there were significant ($p<0.05$) cover crop or manure main effects, or cover crop x manure interaction, means were separated with a least squares means calculation using the LSMEANS statement within PROC GLIMMIX. Superscript letters indicating differences between means were assigned using the PDMIX800 SAS macro (Saxton, 1998). A non-parametric one way ANOVA was applied to yield and economic return data to identify differences in medians of treatment groups across years and location. Within SAS, the PROC NPAR1WAY was used with the WILCOXON option (SAS, 2008) to perform a Kruskal-Wallis test. Where a significant ($p<0.05$) treatment effects, ranks were compared and separated using the K_WMC SAS macro (Elliott and Hynan, 2011).

RESULTS AND DISCUSSION

Crop Productivity

Above-ground cover crop biomass averaged about 1.6 and 0.9 Mg ha^{-1} at Entrican and Benton Harbor locations respectively (Table 2.5). Springtime accumulations of rye and rye-vetch biomass were unaffected by cover crop species. Yield of cover crop ranged from 0.6 to almost 2.0 Mg ha^{-1} and was largely dependent upon planting date and fall temperatures. Rye-vetch biculture occasionally resulted in higher biomass, but this difference was only significant for Benton Harbor in 2003. This was perhaps due to the relatively early seeding date for Benton Harbor cover crops in the fall of 2002. Manure amendment also had little impact on cover crop biomass except for Benton Harbor in 2005 where poultry manure decreased cover crop biomass by 27%. At Benton Harbor in 2005 the rye + manure combination resulted in only 0.47 Mg ha^{-1} compared with an average of 0.71 Mg ha^{-1} for the other 3 cover crop treatments. Plots in the bare winter fallow treatment accumulated a small amount of biomass each winter as a mixture of winter annual weed species. Bare plots averaged 0.2 Mg ha^{-1} across all 6 site-locations, and were unaffected by manure treatment.

Above-ground cover crop biomass N yield is listed in Table 2.6. Cover crop N accumulation averaged 20 and 26 kg ha^{-1} for rye and rye-vetch covers at Entrican and 16 and 18 kg ha^{-1} at Benton Harbor. Rye-hairy vetch biculture yielded approximately 20% more above-ground biomass N, though this effect was not significant for 5 of the 6 site-years included in this experiment. Cover crop N accumulation was unaffected by manure amendment and the cover crop x manure interaction was also non-significant in each of the 6 site-years.

Total and U.S. No. 1 potato tuber yields ranged from 20 to 43 Mg ha^{-1} across all treatments and locations within this experiment (Tables 2.7, 2.8 and 2.9). For comparison, the state average potato yield for Michigan in 2002 was about 35 Mg ha^{-1} (United States Department of Agriculture, 2004). Tuber yields were slightly lower at the Benton Harbor site than the Entrican, site, mainly due to marginally sufficient irrigation at Benton Harbor. Manure amendment, with fertilizer reduction, consistently increased U.S. No. 1 tuber yield over unmanured plots by an average of 17.6%. Tuber yield increases were significantly greater in 4 out of 6 site-years included in this paper. Manure-amended plots yielded slightly less than control plots in Benton Harbor in 2004, but this difference was not significant. Differences in U.S. No. 1 tuber yield were generally due to overall differences in total tuber yield rather than to a shift in tuber size distribution. U.S. No. 1 tuber yield as a percentage of total tuber yield was improved with manure amendment in only 1 of 6 site-years, in Benton Harbor in 2005. Cover crop treatment did not affect Total or U.S. No. 1 tuber yields or U.S. No. 1 percentage consistently. At Entrican in 2004, both rye and rye-vetch cover crops reduced tuber yield but this difference was not quite significant at the $p<0.05$ level. The early portion of the growing season for this individual site-year was extraordinarily cool and wet, possibly delaying cover crop tissue N mineralization and causing asynchrony with plant demand (Quemada and Cabrera, 1997). At Entrican in 2005, rye cover crop increased total tuber yield by 18% above bare and rye-vetch treatments. The combinations of manure amendments with either a bare fallow or rye cover crop produced highest yields on average, across all 6 site-years.

Tuber specific gravity was largely unaffected by manure or winter cover crop treatments (Table 2.10). Overall, specific gravity of tubers grown at Entrican averaged 1.074 and those grown at Benton Harbor averaged 1.070, both slightly low for Snowden variety (Sinha et al., 1992). While low specific gravity can be indicative of excess N or K or low soil P (Laboski and Kelling, 2007), in this experiment the cause is most likely due to observed air bubbles trapped inside numerous scab lesions during the underwater tuber sample weight determination. Manure significantly increased specific gravity of tubers in one site-year out of 6 in this experiment. Tubers grown in Entrican in 2003 with manure amendment had a specific gravity of 1.083 compared with the bare non-manured treatments that yielded tubers with 1.079. Rye and rye-vetch cover crops did not significantly impact specific gravity in any of the 6 site-years.

Incidence of common scab expressed as a percentage of tuber weight was quite high (Table 2.11). The Entrican site produced a very high proportion of tubers exhibiting scab lesions, almost 70%, while the Benton Harbor site averaged 18% across all 3 years included in this paper. The Entrican site has a long history of potato production while 2003 was the first year potatoes had been planted on the Benton Harbor plots. Scab was significantly increased by manure amendment in 1 of 6 site-years. Cover crop treatment did not significantly affect proportion of tubers affected by scab lesions.

Fresh snap bean pod yields averaged 14.5 Mg ha^{-1} at Entrican and significantly less, 5.3 Mg ha^{-1} at Benton Harbor across the 3 years included in this study (Table 2.12). Benton Harbor snap bean pod yields were consistently reduced by vigorous weed competition and insufficient soil moisture. Manure amended plots consistently yielded 5 to 10% more pod fresh weight at Entrican, though this effect was not statistically significant. Cover crop did not affect bean pod yield significantly or consistently. Rye-vetch reduced yields slightly in 2003 at Entrican, and rye and rye-vetch cover crops increased pod yields slightly at Benton Harbor in 2004 and 2005 possibly due to reduced weed pressure, but neither effect was significant. In 2 of 6 site-years, the manure x cover crop interaction was significant but no consistent trend is evident.

Dry weight of above-ground leaves and stems biomass is presented in Table 2.13a and b. Benton Harbor snap bean plants were smaller and less vigorous than those at Entrican, mainly due to weed pressures and insufficient soil moisture, and this is reflected in a reduced leaves and stems biomass compared with Entrican plants. Manure amendment significantly increased leaves and stems biomass at Entrican in 2 of 3 years compared with fertilized control. Cover crop treatment did not affect leaf and stem biomass significantly, though at Entrican in 2003, the rye-vetch cover crop without manure amendment produced significantly less leaf and stem biomass, and less pod yield, than all the other treatment combinations. Other researchers have observed reduction in snap bean yield after a cereal rye cover crop (Masiunas et al., 1997) and with intercropped rye or hairy vetch (Mwaja et al., 1996) compared with conventionally tilled and managed snap bean crops. Studies have linked snap bean yield reductions to an increased incidence or severity of root rot. New York researchers found that cereal rye increased bean yield and reduced root rot severity while hairy vetch increased root rot and depressed bean yield (Abawi and Widmer, 2000) in a greenhouse experiment.

Economic Analysis

Whole cropping system gross and partial net revenues, simulated by summing potato and snap bean performance within each field replication-site-year, are listed in Tables 2.14a and b and 2.15 respectively. Average total gross revenues ranged from $30,900 to $10,400 per 2 years while average partial net revenues ranged from $30,000 to $9500. On average, over all site years, the cover crop-manure treatments produced over twice the partial net return at Entrican than at Benton Harbor, $23,200 compared with $11,700 for a two crop, 2 year rotation. The value of snap bean was about 62% of the per-hectare gross revenue over 2 years. Snap beans comprised roughly 70% at of the gross returns at Entrican and 55% at Benton Harbor. Manure amendment increased gross and partial net revenues over unamended treatments in 2003 and 2004 at the Entrican location. In 2003 at Entrican the unamended rye-hairy vetch biculture cover crop significantly reduced gross and net revenues compared with other cover crop and manure treatment combinations. At the Benton Harbor site, manure amendment had no effect on gross and net revenues in all 3 years. Manure amended plots produced about 10% more marketable potato tubers and 17% less marketable snap beans at Benton Harbor but did not significantly reduce partial net revenues. In 2004 at Benton Harbor the manure-amended bare fallow treatment generated the greatest loss in partial net revenue in comparison with the bare fallow treatment ($p<0.04$). It is important to note that, in the ANOVA for these data, all the seasonal and analytical variability is contributed by the revenue side of the calculation. No variation in the cost portion of the calculation is included as all cover crop-manure treatment costs would be treatment-dependent. The statistical variation in each of the economic variables is proportional to the variation in the yield data.

Total marginal revenue and marginal rate of return for each treatment combination across 6 site-years are listed in Table 2.16a and b and in 2.17. Marginal revenue was calculated by subtracting the average partial net revenue for the unamended bare winter fallow treatment, for each site-year, from the partial net revenue for each split-plot for the remaining 5 treatment combinations. The marginal revenue represents the economic benefit or cost for adopting each manure-cover crop treatment combination compared with the use of no manure and no cover crop. The marginal rate of return expresses this benefit or cost as a percentage of the variable costs necessary to accomplish the benefit. At the Entrican location, the unamended rye-vetch treatment consistently produced the lowest marginal revenue over a 2-year crop rotation compared with the other treatment combinations, though this effect is only significant in 1 of the 3 seasons in Entrican. This marginal revenue decrease is mainly due to the high costs of hairy vetch seed (\$212 ha^{-1}) and to the fact that this treatment did not improve potato and snap bean yields. At the Benton Harbor location, the amended bare and rye-vetch treatments produced negative marginal revenue all 3 seasons. The unamended rye treatment produced a significantly higher marginal revenue than all other treatments in 2004. Across all 6 site years, rye cover crop with, and without manure, were the only treatment combinations to result in positive marginal returns compared with unamended bare control (Table 2.17) however a Wilcoxon rank test performed on marginal revenue across site-years was non-significant indicating no consistent ranking of the treatment combinations.

Residual Soil Nutrients

Residual inorganic soil N was monitored in the fall, to a depth of 51 cm, and results are listed in Tables 2.18 through 2.21. Analyses of samples taken 0 to 20 cm and from 20 to 51 cm are presented separately; and results of soil analyses following a potato crop are listed separately from those following a snap bean crop. Throughout the 51-cm profile, more inorganic soil N was detected after a potato crop than after snap beans, where less fertilizer N was applied. And more post-harvest N was measured in the slightly finer-textured Entrican soil than at Benton Harbor, where soil texture is coarser. Following a potato crop, residual inorganic N in surface soils (0-20 cm) of manure-amended plots were elevated by an average of 17% over unamended treatments across the 5 site-years sampled (Table 2.18). This increase is evident in each of the 5 site years but was significant only for Entrican in 2003 and 2005. Potatoes grown on these amended plots generally yielded 16% more total tuber weight but residual surface soil inorganic N was elevated compared with fertilized control suggesting that surplus N was supplied by the poultry manure or that manure N was released too late for plant uptake. Residual inorganic N in the 20-51 cm layer was higher than in the surface 0-20 cm layer following a potato crop across all treatments and site-years (Tables 2.18 and 2.19) and has an enhanced risk of overwinter leaching loss (Cameron et al., 1978). Compared with unamended soils, manure treatment reduced inorganic N content in the 20-51 cm layer in 4 of 5 site-years, however none of these reductions were significant at $p<0.05$. Cover crop treatments generally increased residual inorganic N in the 0-20 cm layer over bare winter fallow control, though this effect is very small and is only significant for Benton Harbor in 2005. Cover crop effect on the inorganic N in the 20-51 cm layer is less consistent. In some site-years rye cover crop reduced inorganic N in this deeper layer, but in Benton Harbor, rye resulted in small, non-significant increases in both years soils were sampled. Bare fallow and rye-vetch plots, without manure amendment had the lowest average total potato yields. Bare fallow plots without manure amendment had the highest average inorganic N in this deeper layer, but the unamended rye-vetch plots did not contain higher than average inorganic N after potato harvest.

Less total N was applied to snap bean plots compared with potato plots, and residual inorganic N in the entire soil profile (0-51 cm) after snap beans was slightly less than after harvest of potatoes (5.77 vs 6.28 g N kg^{-1} soil). In the 0-20 cm layer, residual inorganic N was not significantly affected by manure or cover crop main treatments in snap bean plots. Across treatments and site-years, inorganic N in this 0-20 cm layer averaged 6.8 mg kg^{-1} after a snap bean crop. Rye-vetch cover crop resulted in 10 to 15% more residual inorganic N content in the 0-20 cm layer, on average, compared with bare or rye cover crop across site-years, but this difference was not significant. This increase may be due to decomposition of vetch root nodules following their termination (Mohr et al., 1998). Residual inorganic N after snap beans in the deeper, 20-51 cm layer averaged 4.5 mg kg^{-1} soil and was lower than in the surface 0-20 cm layer and was also lower than the same layer after removal of a potato crop (4.71 vs 6.65 g N kg^{-1} soil). The effect of manure was slight and somewhat inconsistent, decreasing residual inorganic N in the 20-51 cm layer in 1 out of 5 site years significantly. Rye and rye-vetch cover crops reduced residual N in this layer by approximately 14% on average compared with bare winter fallow control, though this effect was not consistent nor significant in any of the 5 site-years. Others have observed a similar reduction in soil mineral N to a depth of 180 cm for a rye cover crop compared with bare fallow (Weinert et al., 2002). Though all of this residual inorganic N is within the rooting zone of the subsequent crop, it is at risk of overwinter leaching to a deeper zone, out of the reach of potato and snap bean roots.

Nitrogen mineralization potential (NMP), expressed as g N mineralized per kg soil per day, is presented in Table 2.22, after a potato crop, and in Table 2.23, after snap bean harvest. Manure increased NMP after potatoes at Entrican in all 3 site-years by an average of 20%. This effect was statistically significant in the 2004 and 2005 seasons at Entrican, but not for the earlier 2003 season. NMP after potatoes was unaffected by manure amendment in both years at Benton Harbor. Cover crop treatments did not significantly alter NMP compared with bare control, though a non-significant reduction of almost 18% was observed across all 5 site-years after potatoes due to rye and rye-vetch cover crop. Manure increased average NMP after snap beans across all 5 site-years by 24%. This effect was statistically significant for the 2004 seasons at Entrican and Benton Harbor while non-significant increases were observed in the remaining 3 site-years. Cover crops significantly enhanced NMP above bare control in Benton Harbor in 2004 and non-significantly in 2005, while NMP response to cover crops was inconsistent at Entrican. In site-years with significant manure or cover crop effects, the bare control without manure amendment resulted in the lowest NMP.

Total soil C and N, measured in the fall of 2006, were unaffected by manure amendment or cover crop and the manure x cover crop interaction was also not significant (data not shown). Soil C and N averaged 0.73% and 0.06% at Entrican and 0.60% and 0.05% at Benton Harbor. Bray P was significantly increased in manure amended plots (Table 2.24) at each location in 2006, after 5 annual springtime amendments at Entrican and 4 at Benton Harbor. Annual poultry manure amendment increased Bray P by 26% at Entrican (363 vs. 288 ppm, 75 ppm difference, $p=0.005$) and by 37% at Benton Harbor (202 vs. 147 ppm, 55 ppm difference, $p<0.0001$). Rye and rye-vetch cover crops did not significantly affect Bray P at either location although a non-significant decrease of approximately 10% for both cover crops, compared with bare control, was observed across both sites. Soils at both Entrican and Benton Harbor sites were sufficient in P, containing The poultry manure amendment of 5.6 Mg ha^{-1} added 6.95 kg P ha^{-1} annually. A potato crop removes about 0.6 kg P per Mg of tubers harvested (Warncke et al., 2004), so manure amendment would need to result in a 12.2 Mg ha^{-1} increase in tuber yield to remove all manure P. Manure only increased potato yield by about 5 Mg ha^{-1} across all 6 site-years, so this moderate quantity of manure could not be added every year. Annual manure application must be reduced or it must be applied only every 2 or 3 years. Using a P-based manure application strategy, supplemental N fertilizer would need to be increased for potato and snap bean crops. Virginia researchers found that application of more than 22 and less than 67 kg ha-1 broiler litter resulted in similar bean pod yields as conventional fertilizer without increasing soil P on an irrigated sandy loam soil (Phillips et al., 2002).

SUMMARY AND CONCLUSION

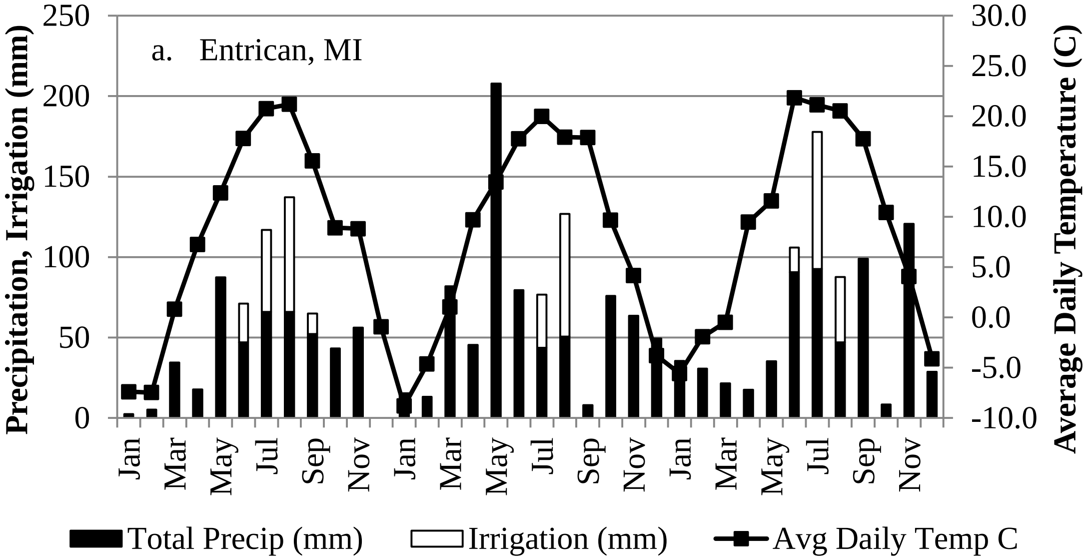
This experiment compared the productivity of potato-snap bean rotations with 3 winter cover crop alternatives and with or without a moderate poultry manure amendment at 2 sites on sandy, low OM soils. Yield of above-ground cover crop biomass averaged about 1.6 and 0.9 Mg ha^{-1} at Entrican and Benton Harbor locations respectively and was unaffected by cover crop species. Manure had no significant impact on cover crop biomass. Bare plots accumulated about 0.2 Mg ha-1 of winter annual weed biomass. Cover crop N averaged 18 kg ha^{-1} for rye and 22 kg ha^{-1} for rye-hairy vetch biculture, though this difference was not significant for 5 of 6 site-years. Manure amendment had no significant effect on cover crop N accumulation. Poultry manure amendment with fertilizer reduction consistently increased US No. 1 tuber yield by 17.6%. Cover crop treatment did not affect total or US No. 1 tuber yields consistently. The combination of bare winter fallow or rye cover crop with manure produced the highest yields on average across all 6 site-years. Manure and cover crop had no consistent effect on scab incidence, but scab was fairly high at both sites in 5 of 6 site-years. Manure-amended plots yielded 5-10% greater fresh snap bean pod weight at Entrican, though this effect was not significant. Cover crop affected pod yields and leaf and stem biomass inconsistently. Bean plants and yields were lower at Benton Harbor due to weed competition and low soil moisture.

Net revenues ranged from \$9500 to \$30,000 per hectare for 2 growing seasons at 2 locations and Entrican produced over twice the net returns of the Benton Harbor plots. Snap beans were responsible for 70% of gross revenue at Entrican and 55% at Benton Harbor. Manure resulted in reduced gross and net revenues in all 3 years, but this effect was only significant in 2004. Rye cover crop, with and without poultry manure, were the only treatment combinations to produce positive marginal revenues compared with unamended bare control treatment. No one cover crop-manure combination consistently outperformed the alternatives economically.

Post-harvest soil inorganic N in surface soils (0-20 cm) of poultry manure-amended plots was elevated by 17%, on average, above non-amended plots. Potatoes grown on these plots yielded 16% more tuber weight, on average, indicating that surplus N was supplied by the poultry manure or that manure N mineralized after crop demand subsided. Residual inorganic N in the sub-surface soil (20-51 cm) was higher than in surface soils and is at risk of leaching loss over the winter months. Manure amendment, with fertilizer N reduction, reduced inorganic N in the sub-surface zone in 4 of 5 site-years, however none of these differences were significant ($p<0.05$). Cover crops generally increased inorganic N in the 0-20 cm layer but the effect on the 20-51 cm zone was inconsistent. Bare and rye-vetch plots, without manure, had the highest average inorganic N in the deeper layer. After a snap bean crop, residual inorganic N in the 0-20 cm layer was not significantly affected by manure or cover crop main treatments. Across treatments and site-years, inorganic N in this 0-20 cm layer averaged 6.9 mg kg $^{-1}$ after a snap bean crop. Residual inorganic N after snap beans in the deeper, 20-51 cm layer averaged 4.5 mg kg^{-1} soil and was also lower than the same layer after removal of a potato crop. After a potato crop, inorganic N averaged 5.92 mg kg $^{-1}$ and 6.65 mg kg^{-1} soil, in the 0-20 cm and 20-51 cm layers respectively across 5 site-years.

Manure increased NMP after potatoes at Entrican in all 3 site-years by an average of 20%. NMP after potatoes was unaffected by manure amendment in both years at Benton Harbor. Manure increased average NMP after snap beans across all 5 site-years by 24%, however this effect was only significant in 2 of 5 site-years analyzed. Cover crops significantly enhanced NMP above bare control in Benton Harbor in 2004 and non-significantly in 2005, while NMP response to cover crops was inconsistent at Entrican. In site-years with significant manure or cover crop effects, the bare control without manure amendment resulted in the lowest NMP. Total soil C and N, measured in the fall of 2006, were unaffected by manure amendment or cover crop. Soil C and N averaged 0.73% and 0.06% at Entrican and 0.60% and 0.05% at Benton Harbor. This moderate annual amendment of poultry manure significantly increased Bray P was at both locations. Manure increased Bray P by 26% at Entrican and by 37% at Benton Harbor.

Rye cover crop, with or without manure, is recommended as it did not negatively affect potato or snap bean production, improved residual soil inorganic N and provided a positive marginal return on variable costs. Rye can be combined with manure on low- or moderate-P soil following a P-based application plan.



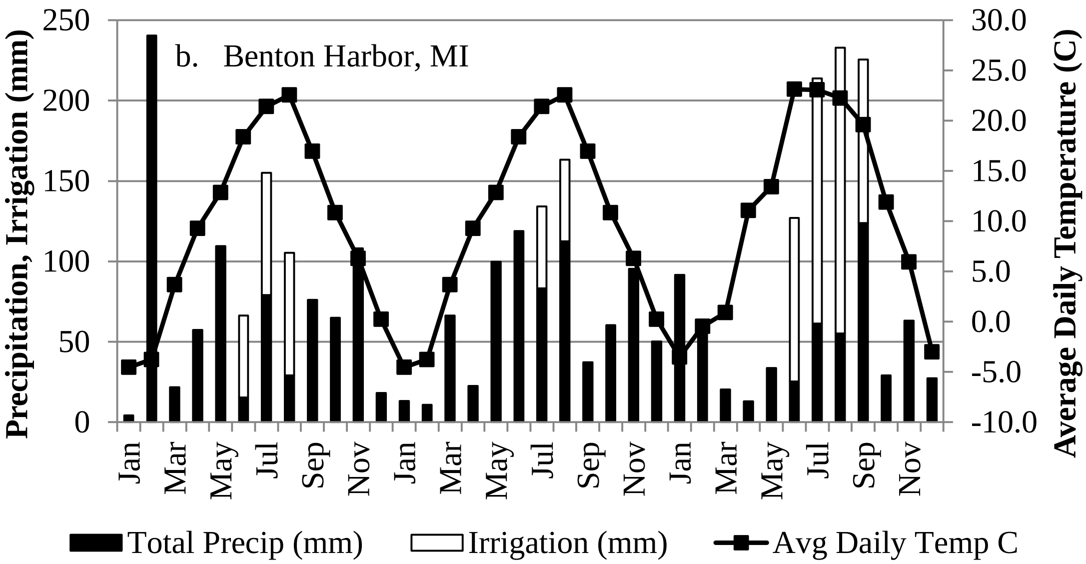


Figure 2.1. Monthly precipitation and irrigation totals (mm) and average daily temperature (°C) recorded at Montcalm Research Farm (a. Entrican, MI) and Southwest Michigan Research and Extension Center (b. Benton Harbor, MI) for January 2003 to December 2005.

Table 2.1. Soil chemical and physical characteristics at the Entrican, MI and Benton Harbor, MI field experiment locations.

	Entrican	Benton Harbor
Texture		
Sand, %	75	88
Silt, %	16	6
Clay, %	9	6
Class	sandy loam	fine sand
Organic C, %	0.8	0.6
pH	6.2	6.4
CEC, meq/100g	3.5	3.1
Ca, ppm	359	477
K, ppm	122	121
P, ppm	200	150

Table 2.2 Rotation, cover crop and manure treatments used in long-term potato rotation experiment at Entrican and Benton Harbor, MI.

Rotation	Winter Cover Crop	Manure
Potato-Snap Bean	Bare (no cover crop)	+ or - manure
Potato-Snap Bean	Rye	+ or - manure
Potato-Snap Bean	Rye+Hairy Vetch	+ or - manure
Potato-Corn	Rye after Potatoes, Bare after Corn	
Potato-Corn	Rye+Hairy Vetch	
Potato-Wheat	Wheat after Potatoes, Rye after Wheat	
Potato-Wheat	Wheat after Potatoes, Red Clover after Wheat	
Potato- Corn-Wheat	Rye+Hairy Vetch or Wheat+Clover	

Table 2.3. Dates of field experiment agronomic operations for 2003 through 2006.

	2003		2004		2005		2006	
	Entrican	Benton Harbor	Entrican	Benton Harbor	Entrican	Benton Harbor	Entrican	Benton Harbor
Plant Fall 2002 cover crops, wheat	10/10	9/17	- - -	- - -	- - -	- - -	- - -	- - -
Frost-seed Red Clover	3/11	3/12	3/15	3/18	3/24	3/25	3/30	3/31
Wheat N application	4/29	4/30	4/14	4/15	4/11	3/31	4/6	4/7
Sample cover crops	5/21	5/16	5/19	5/6	5/17	5/16	5/16	5/10
Manure amendment	5/21	5/18	5/19	5/7	5/17	5/16	5/16	5/10
Spring tillage	5/23	5/23	5/20	5/10	5/18	5/18	5/21	5/23
Plant potatoes	5/30	5/29	5/28	5/14	5/25	5/24	6/1	5/30
Plant corn	6/3	5/29	5/31	5/18	5/27	6/2	6/1	5/31
Plant snap beans	6/16	6/11	6/16	5/24	6/10	6/16	6/13	6/6
Potato N applications	5/30, 6/3, 7/2	5/29, 7/2, 7/23	5/28, 6/9, 7/3	5/14, 6/9, 6/29	5/25, 6/7, 6/28	5/24, 6/8, 7/15	6/1, 6/30, 7/25	5/30, 7/8, 7/24
Harvest wheat	7/22	7/23	7/22	7/13	7/21	7/15	7/11	7/10
Harvest snap beans	8/20	8/12	8/17	8/2	8/5	8/16	9/9	9/8
Harvest corn	8/26	8/22	8/24	8/20	8/15	8/24	8/30	8/25
Vine kill potatoes	9/11	- - -	9/14	9/21	8/30	9/8	9/14	9/7
Harvest potatoes	10/1	10/6	9/27	10/14	9/19	10/7, 10/10	10/15	10/6
Fall tillage	10/6	10/10	10/18	10/22	8/22, 9/30	8/31, 10/11	9/11, 10/23	9/8, 10/16
Plant cover crops	10/15	10/16	10/20	10/27	8/23, 10/12	9/7, 10/17	9/21, 10/25	9/20, 10/20
Plant wheat	10/15	10/16	10/20	10/27	8/23	9/7	9/21	9/20
Soil sample	11/10	- - -	11/10	11/22	11/21	11/11	11/1	11/15

Table 2.4. Prices (US Dollars) used for gross and net revenue and marginal return calculations.

Item	Price ($)	Source
Potatoes, chipping	231 per Mg	(USDA-NASS, 2009)
Snap beans, fresh	1168 per Mg	(USDA-NASS, 2009)
N Fertilizer	1.56 per kg N	(United States Department of Agriculture, 2008)
Poultry manure	73 per Mg	Herbrucks Poultry Farm, MI
Manure application	15 per ha	(Ward and Freytag, 2008)
Rye seed (Wheeler)	0.39 per kg	Moore Seed Farm, MI
Hairy vetch seed (Common)	5.47 per kg	Southern Michigan Seed, MI
Cover crop establishment	42 per ha	(Ward and Freytag, 2008)

Table 2.5. Effect of cover crop and manure amendment on yield of above-ground cover crop biomass (Mg ha^{-1}) in 3 rotation cycles at Entrican and Benton Harbor, MI.

	Above-ground cover crop biomass, Mg ha^{-1}											
	Entrican, MI						Benton Harbor, MI					
	2003		2004		2005		2003		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Rye	0.88	0.10	1.82	0.14	1.97	0.10	1.11 b	0.09	0.80	0.07	0.60	0.08
Rye-Vetch	0.91	0.08	1.96	0.10	1.93	0.07	1.29 a	0.10	0.68	0.06	0.70	0.07
Crop effect, p	*0.885*		*0.505*		*0.793*		*0.002*		*0.453*		*0.307*	
No Manure	0.89	0.09	1.87	0.11	1.88	0.09	1.20	0.07	0.78	0.07	0.75 a	0.07
Manure	0.91	0.09	1.91	0.13	2.02	0.08	---		0.71	0.06	0.55 b	0.08
Manure effect, p	*0.907*		*0.782*		*0.232*		---		*0.423*		*0.049*	
Rye	0.88	0.13	1.79	0.16	1.86	0.16	1.11 b	0.09	0.93	0.11	0.73 ab	0.12
Rye + M	0.89	0.16	1.85	0.22	2.09	0.11	---		0.68	0.09	0.47 b	0.11
Rye-Vetch	0.90	0.13	1.95	0.16	1.90	0.08	1.29 a	0.10	0.63	0.09	0.78 a	0.09
Rye-Vetch + M	0.93	0.11	1.97	0.13	1.96	0.11	---		0.73	0.08	0.63 ab	0.11
*Crop*Manure interaction, p*	*0.938*		*0.905*		*0.466*		---		*0.050*		*0.604*	
Bare	0.06	0.03	0.08	0.08	0.64	0.22	0.23	0.05	0.02	0.02	0.20	0.11
Bare + Manure	0.12	0.05	0.07	0.07	0.55	0.22	---		0.02	0.02	0.20	0.13
Manure effect, p	*0.316*		*0.922*		*0.555*		---		*0.931*		*0.977*	

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.6. Effect of cover crop and manure amendment on yield of above-ground cover crop N (kg ha^{-1}) in 3 rotation cycles at Entrican and Benton Harbor, MI.

	Above-ground cover crop N, kg ha^{-1}											
	Entrican, MI						Benton Harbor, MI					
	2003		2004		2005		2003		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Rye	14.90	1.63	22.75	1.85	23.40	1.27	17.98 b	1.55	15.39	1.30	13.24	2.37
Rye-Vetch	18.51	1.55	29.30	1.73	29.26	1.11	23.58 a	2.10	14.12	1.25	15.51	1.62
Crop effect, p	*0.260*		*0.069*		*0.123*		*0.006*		*0.708*		*0.495*	
No Manure	16.63	1.61	25.97	2.00	25.17	1.30	20.78	1.38	15.45	1.40	17.10	2.30
Manure	16.78	1.63	26.07	1.77	27.49	1.27	---		14.06	1.13	11.65	1.59
Manure effect, p	*0.948*		*0.969*		*0.157*		---		*0.422*		*0.053*	
Rye	15.03	2.01	22.49	2.55	21.83	1.91	17.98 b	1.55	17.74	1.88	16.95	4.07
Rye + M	14.77	2.64	23.01	2.77	24.96	1.66	---		13.04	1.63	9.53	2.19
Rye-Vetch	18.23	2.53	29.45	2.90	28.51	1.37	23.58 a	2.10	13.16	1.97	17.25	2.31
Rye-Vetch + M	18.79	1.87	29.14	2.00	30.01	1.77	---		15.09	1.58	13.77	2.26
*Crop*Manure interaction, p*	*0.858*		*0.876*		*0.614*		---		*0.058*		*0.477*	
Bare	0.99	0.51	1.12	1.12	8.05	2.82	2.62	0.48	0.25	0.25	2.61	1.38
Bare + Manure	1.96	0.85	1.06	1.06	6.86	2.72	---		0.24	0.24	3.20	1.99
Manure effect, p	*0.318*		*0.967*		*0.510*		---		*0.967*		*0.811*	

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.7. Effect of cover crop and manure amendment on US No. 1 potato tuber yield in 3 rotation cycles at Entrican and Benton Harbor, MI.

	US No. 1 Tuber Yield, Mg ha^{-1}											
	Entrican, MI						Benton Harbor, MI					
	2003		2004		2005		2003		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bare	35.8	2.3	35.0	2.7	27.3	1.6	30.1	2.5	22.9	1.9	24.6	2.6
Rye	37.1	2.5	25.1	2.7	33.9	1.4	35.7	1.8	22.4	1.7	31.5	2.3
Rye-Vetch	36.0	2.4	20.1	1.5	27.9	1.8	34.4	2.5	21.9	2.3	28.8	2.4
Crop effect, p	*0.912*		*0.058*		*0.078*		*0.450*		*0.823*		*0.085*	
No Manure	32.7 b	1.9	23.4 b	2.0	26.2 b	1.3	31.3 b	1.8	23.0	1.3	26.0	2.0
Manure	39.9 a	1.7	30.1 a	2.3	33.2 a	1.2	35.5 a	2.0	21.8	1.9	30.7	1.9
Manure effect, p	*0.002*		*0.001*		*<0.001*		*0.046*		*0.515*		*0.055*	
Bare	31.2 b	3.1	30.1 b	3.6	24.7 c	2.5	25.6 b	2.8	23.3	2.3	21.2 b	2.7
Bare + M	40.3 a	2.7	39.9 a	3.4	29.9 bc	1.7	34.5 a	3.8	22.4	3.2	28.0 ab	4.2
Rye	34.5 ab	3.2	22.0 b	3.5	30.1 bc	1.3	35.2 ab	3.3	23.9	2.1	27.4 ab	3.3
Rye + M	39.6 ab	3.9	28.2 ab	3.9	37.7 a	1.7	36.2 ab	1.8	20.9	2.8	35.7 a	2.5
Rye-Vetch	32.2 ab	3.8	18.1 b	2.0	23.8 c	2.6	33.2 ab	2.2	21.7	2.6	29.2 a	4.3
Rye-Vetch + M	39.7 ab	2.5	22.1 b	1.9	32.0 ab	1.8	35.7 ab	4.6	22.1	4.0	28.4 ab	2.7
*Crop*Manure interaction, p*	*0.762*		*0.428*		*0.668*		*0.250*		*0.733*		*0.260*	

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.8. Effect of cover crop and manure amendment on total potato tuber yield in 3 rotation cycles at Entrican and Benton Harbor, MI.

	Total Tuber Yield, Mg ha^{-1}											
	Entrican, MI						Benton Harbor, MI					
	2003		2004		2005		2003		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bare	37.9	2.3	36.5	2.8	31.9 b	1.7	33.0	2.4	26.2	2.0	28.4	2.3
Rye	39.9	2.4	26.3	2.7	37.1 a	1.5	38.3	1.8	25.1	1.7	34.6	2.4
Rye-Vetch	39.6	2.7	20.7	1.5	30.6 b	1.9	37.0	2.4	24.5	2.4	32.3	2.4
Crop effect, p	*0.833*		*0.053*		*0.039*		*0.476*		*0.625*		*0.130*	
No Manure	35.4 b	1.9	24.5 b	2.1	29.3 b	1.3	34.1 b	1.7	26.0	1.4	29.7	2.0
Manure	42.9 a	1.8	31.2 a	2.4	37.1 a	1.2	38.1 a	1.9	24.5	1.9	33.8	1.8
Manure effect, p	*0.003*		*0.001*		*<0.001*		*0.046*		*0.396*		*0.098*	
Bare	33.3 b	3.0	31.7 bc	3.8	28.4 cd	2.1	28.9 b	2.6	26.9	2.3	25.8	2.4
Bare + M	42.4 a	2.9	41.4 a	3.5	35.4 b	2.0	37.1 a	3.6	25.4	3.5	30.9	3.8
Rye	36.9 ab	3.1	23.0 ce	3.5	32.7 bc	1.4	38.1 ab	3.3	26.3	2.3	31.1	4.0
Rye + M	42.9 ab	3.6	29.6 abd	4.0	41.5 a	1.4	38.5 ab	1.7	23.9	2.7	38.0	2.2
Rye-Vetch	36.0 ab	4.0	18.9 de	2.2	26.9 d	2.7	35.3 ab	2.3	24.7	2.7	32.2	4.1
Rye-Vetch + M	43.2 a	3.2	22.5 bcd	2.0	34.3 b	1.9	38.7 ab	4.4	24.3	4.2	32.4	2.8
*Crop*Manure interaction, p*	*0.856*		*0.426*		*0.880*		*0.268*		*0.885*		*0.498*	

a, b, c, d, e Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.9. Effect of cover crop and manure amendment on US No. 1 potato tuber yield as a percentage of total tuber yield in 3 rotation cycles at Entrican and Benton Harbor, MI.

	US No. 1 Yield, % of Total Yield											
	Entrican, MI						Benton Harbor, MI					
	2003		2004		2005		2003		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bare	94.3	0.92	95.7	0.56	85.4	2.15	89.9	1.49	87.2	1.59	84.4	2.77
Rye	92.2	1.53	95.1	0.83	91.3	1.08	93.2	1.42	91.1	1.47	90.9	1.46
Rye-Vetch	90.8	1.40	97.3	0.51	90.8	0.99	92.5	1.05	88.5	1.54	88.5	1.40
Crop effect, p	*0.205*		*0.127*		*0.255*		*0.430*		*0.325*		*0.224*	
No Manure	91.8	1.13	95.6	0.63	88.7	1.23	91.3	1.23	89.3	1.19	86.0 b	1.85
Manure	93.0	1.06	96.4	0.45	89.6	1.43	92.5	0.98	88.6	1.37	89.8 a	1.41
Manure effect, p	*0.410*		*0.272*		*0.420*		*0.356*		*0.690*		*0.046*	
Bare	93.4	1.52	95.2	0.94	86.1	3.09	87.6	2.00	87.6	2.52	80.1 b	4.12
Bare + M	95.2	1.06	96.2	0.63	84.7	3.18	92.3	2.00	86.8	2.12	88.7 ab	3.27
Rye	93.0	1.68	95.4	1.60	92.0	1.16	92.6	2.74	92.7	1.24	88.3 ab	2.30
Rye + M	91.5	2.66	94.8	0.60	90.6	1.88	93.9	1.03	89.5	2.65	93.4 a	1.41
Rye-Vetch	89.2	2.43	96.3	0.65	88.1	1.19	93.8	0.55	87.5	1.87	89.5 ab	2.00
Rye-Vetch + M	92.3	1.35	98.3	0.64	93.5	0.88	91.2	1.98	89.5	2.53	87.4 ab	2.00
*Crop*Manure interaction, p*	*0.397*		*0.391*		*0.018*		*0.058*		*0.454*		*0.068*	

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.10. Effect of cover crop and manure amendment on potato specific gravity in 3 rotation cycles at Entrican and Benton Harbor, MI.

	Tuber Specific Gravity											
	Entrican, MI						Benton Harbor, MI					
	2003		2004		2005		2003		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bare	1.081	0.001	1.078	0.001	1.064	0.001	1.070	0.002	1.067	0.002	1.072	0.001
Rye	1.081	0.002	1.077	0.001	1.064	0.001	1.070	0.002	1.069	0.001	1.072	0.002
Rye-Vetch	1.081	0.003	1.076	0.002	1.063	0.002	1.068	0.001	1.068	0.001	1.072	0.002
Crop effect, p	*0.994*		*0.664*		*0.757*		*0.564*		*0.512*		*0.949*	
No Manure	1.079 b	0.001	1.077	0.001	1.063	0.001	1.069	0.001	1.068	0.001	1.072	0.001
Manure	1.083 a	0.002	1.077	0.001	1.064	0.001	1.070	0.001	1.069	0.001	1.072	0.002
Manure effect, p	*0.017*		*0.866*		*0.416*		*0.631*		*0.285*		*0.897*	
Bare	1.080 abc	0.001	1.079	0.002	1.064	0.001	1.070	0.002	1.066	0.001	1.073	0.001
Bare + M	1.082 abc	0.002	1.076	0.002	1.063	0.002	1.070	0.003	1.068	0.003	1.070	0.002
Rye	1.078 bd	0.002	1.077	0.001	1.064	0.001	1.068	0.002	1.069	0.001	1.071	0.003
Rye + M	1.084 ac	0.003	1.076	0.001	1.063	0.001	1.072	0.002	1.069	0.000	1.073	0.003
Rye-Vetch	1.078 cd	0.003	1.075	0.002	1.060	0.002	1.068	0.001	1.067	0.001	1.072	0.001
Rye-Vetch + M	1.085 ab	0.004	1.078	0.002	1.066	0.003	1.069	0.001	1.069	0.002	1.072	0.005
*Crop*Manure interaction, p*	*0.347*		*0.070*		*0.205*		*0.717*		*0.424*		*0.600*	

a, b, c, d Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.11. Effect of cover crop and manure amendment on potato tubers affected by common scab in 3 rotation cycles at Entrican and Benton Harbor, MI.

	Common Scab, % of affected tubers, by weight											
	Entrican, MI						Benton Harbor, MI					
	2003		2004		2005		2003		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bare	57.6	4.8	58.4	5.0	82.5	2.9	3.1	1.0	19.8	2.7	28.6	1.4
Rye	60.8	3.7	68.4	5.9	84.0	3.4	3.4	0.9	23.9	2.9	29.4	1.8
Rye-Vetch	57.2	5.1	63.4	5.6	88.7	1.7	3.8	0.9	25.3	3.5	27.5	3.3
Crop effect, p	*0.897*		*0.329*		*0.404*		*0.902*		*0.449*		*0.356*	
No Manure	60.4	3.0	61.8	3.9	82.0 b	2.2	3.7	0.8	20.5	2.1	27.9	1.9
Manure	56.7	4.3	65.0	5.0	88.1 a	2.2	3.1	0.7	25.5	2.8	29.2	2.0
Manure effect, p	*0.417*		*0.412*		*0.010*		*0.531*		*0.170*		*0.679*	
Bare	61.6	4.9	48.4 b	5.8	79.9 ab	2.9	3.8	1.9	14.4	2.3	25.5	1.9
Bare + M	53.6	8.3	68.5 a	6.6	85.0 ab	5.1	2.4	1.0	25.3	4.1	31.8	0.6
Rye	55.6	4.2	72.2 a	6.6	76.5 b	4.6	5.1	1.4	26.0	3.6	28.7	3.3
Rye + M	66.1	5.8	64.7 ab	9.9	90.4 a	3.5	1.9	0.8	21.7	4.8	30.2	1.9
Rye-Vetch	64.0	6.3	65.0 a	5.3	88.6 a	1.7	2.4	0.9	21.2	3.9	29.6	4.4
Rye-Vetch + M	50.5	7.5	61.9 ab	10.2	88.9 a	3.0	5.4	1.5	29.4	5.7	25.5	5.0
*Crop*Manure interaction, p*	*0.089*		*0.014*		*0.067*		*0.037*		*0.189*		*0.387*	

a, b Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

Table 2.12. Effect of cover crop and manure amendment on fresh snap bean pod yield in 3 rotation cycles at Entrican and Benton Harbor, MI.

	Snap Bean Pods, fresh (Mg/ha)											
	Entrican, MI						Benton Harbor, MI					
	2003		2004		2005		2003		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bare	20.7	0.9	16.4	0.7	6.4	1.1	7.9	0.6	3.9	0.4	3.6	1.4
Rye	20.0	1.0	17.3	0.8	7.7	1.0	7.0	0.6	4.8	0.3	4.2	0.8
Rye-Vetch	17.1	1.1	16.8	0.8	7.7	0.5	6.9	0.5	4.5	0.3	4.7	0.9
Crop effect, p	*0.087*		*0.763*		*0.775*		*0.404*		*0.143*		*0.915*	
No Manure	18.6	1.0	16.0	0.6	7.1	0.8	7.7	0.4	4.5	0.3	5.1	1.0
Manure	19.9	0.8	17.6	0.6	7.4	0.6	6.8	0.4	4.3	0.3	3.2	0.8
Manure effect, p	*0.105*		*0.072*		*0.721*		*0.134*		*0.459*		*0.061*	
Bare	20.2 ab	1.1	16.8	0.8	6.4	1.6	8.5	0.8	4.7 a	0.5	6.0	2.5
Bare + M	21.2 ab	1.4	16.1	1.3	7.0	1.5	7.2	0.8	3.0 b	0.3	1.2	1.0
Rye	21.4 a	1.6	16.1	1.3	8.1	1.7	7.4	0.8	4.8 a	0.7	4.4	0.9
Rye + M	18.6 b	1.3	18.5	0.5	7.3	1.1	6.7	0.9	4.7 a	0.3	4.0	1.5
Rye-Vetch	14.4 c	1.2	15.2	1.0	7.1	0.5	7.3	0.7	4.0 ab	0.2	4.9	1.3
Rye-Vetch + M	19.9 ab	1.4	18.4	1.1	8.2	0.9	6.5	0.6	5.1 a	0.4	4.5	1.3
*Crop*Manure interaction, p*	*<0.0001*		*0.151*		*0.531*		*0.893*		*0.006*		*0.117*	

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.13a. Effect of cover crop and manure amendment on yield of dried snap bean above-ground vegetative tissues in 3 rotation cycles at Entrican, MI.

	Snap Bean Leaves & Stems, dry (Mg/ha)								
	Entrican, MI								
	2003			2004			2005		
	Mean		SE	Mean		SE	Mean		SE
Bare	2.33		0.08	2.53		0.15	1.33		0.12
Rye	2.32		0.12	2.93		0.14	1.32		0.09
Rye-Vetch	2.01		0.13	2.79		0.16	1.38		0.10
Crop effect, p	*0.160*			*0.111*			*0.951*		
No Manure	2.06	b	0.08	2.42	b	0.09	1.23	b	0.14
Manure	2.38	a	0.10	3.08	a	0.12	1.45	a	0.07
Manure effect, p	*0.001*			*<0.001*			*0.038*		
Bare	2.19	a	0.06	2.32	b	0.12	1.28	ab	0.21
Bare + M	2.47	a	0.14	2.75	ab	0.27	1.39	ab	0.14
Rye	2.30	a	0.12	2.60	b	0.20	1.24	ab	0.16
Rye + M	2.34	a	0.21	3.25	a	0.11	1.40	ab	0.07
Rye-Vetch	1.69	b	0.12	2.35	b	0.13	1.18	b	0.11
Rye-Vetch + M	2.32	a	0.16	3.24	a	0.19	1.57	a	0.14
*Crop*Manure interaction, p*	*0.029*			*0.474*			*0.456*		

a, b, c, d Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.13b. Effect of cover crop and manure amendment on yield of dried snap bean above-ground vegetative tissues in 3 rotation cycles at Benton Harbor, MI.

	Snap Bean Leaves & Stems, dry (Mg/ha)							
	Benton Harbor, MI							
	2003		2004			2005		
	Mean	SE	Mean		SE	Mean		SE
Bare	1.78	0.08	1.42		0.08	1.37		0.20
Rye	1.85	0.09	1.40		0.06	1.78		0.12
Rye-Vetch	1.91	0.04	1.37		0.05	1.68		0.17
Crop effect, p	*0.587*		*0.866*			*0.554*		
No Manure	1.89	0.07	1.46	a	0.06	1.59		0.14
Manure	1.81	0.08	1.33	b	0.05	1.64		0.14
Manure effect, p	*0.429*		*0.018*			*0.773*		
Bare	1.93	0.07	1.68	a	0.08	1.42		0.32
Bare + M	1.62	0.14	1.15	d	0.06	1.32		0.28
Rye	1.80	0.13	1.46	abd	0.11	1.86		0.17
Rye + M	1.90	0.13	1.34	bcd	0.06	1.70		0.17
Rye-Vetch	1.93	0.17	1.25	cd	0.05	1.48		0.22
Rye-Vetch + M	1.90	0.12	1.49	ab	0.07	1.89		0.25
*Crop*Manure interaction, p*	*0.255*		*<0.001*			*0.321*		

a, b, c, d Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.14a. Effect of cover crop and manure amendment on partial gross revenue from combined potato and snap bean crops in 3 rotation cycles at Entrican, MI.

	Partial Gross Revenue (\$ ha^{-1} $2yr^{-1}$)					
	Entrican, MI					
	2003		2004		2005	
	Mean	SE	Mean	SE	Mean	SE
Bare	32438	973	27311	1136	14477	1428
Rye	31963	1228	26012	1107	16830	1159
Rye-Vetch	28355	1674	24242	1101	15408	905
Crop effect, p	*0.118*		*0.333*		*0.599*	
No Manure	29352 b	1208	24156 b	846	14757	971
Manure	32485 a	950	27554 a	890	16586	881
Manure effect, p	*0.001*		*0.004*		*0.084*	
Bare	30790 a	1096	26624	1109	13723	2099
Bare + M	34085 a	1443	27998	2041	15232	2082
Rye	33028 a	1934	23945	1525	16449	1938
Rye + M	30899 a	1548	28080	1306	17212	1401
Rye-Vetch	24237 b	1864	21898	1377	13841	981
Rye-Vetch + M	32473 a	1921	26585	1316	16974	1360
*Crop*Manure interaction, p*	*<0.0001*		*0.425*		*0.593*	

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.14b. Effect of cover crop and manure amendment on partial gross revenue from combined potato and snap bean crops in 3 rotation cycles at Benton Harbor, MI.

	Partial Gross Revenue ($ ha⁻¹ 2yr⁻¹)								
	Benton Harbor, MI								
	2003		2004				2005		
	Mean	SE	Mean		SE		Mean	SE	
Bare	16143	720	9811		576		9908	1721	
Rye	16472	585	11022		739		12169	896	
Rye-Vetch	16055	713	10373		730		12174	1253	
Crop effect, p	*0.953*		*0.366*				*0.657*		
No Manure	16297	467	10766		546		11963	1171	
Manure	16150	616	10028		565		10871	1010	
Manure effect, p	*0.831*		*0.144*				*0.404*		
Bare	15905	984	10900	ab	829		11919	2762	
Bare + M	16382	1113	8722	b	629		7898	1978	
Rye	16739	752	11836	a	1257		11467	979	
Rye + M	16204	937	10311	ab	841		12871	1530	
Rye-Vetch	16246	754	9694	ab	716		12503	2205	
Rye-Vetch + M	15865	1265	11051	ab	1281		11845	1357	
*Crop*Manure interaction, p*	*0.808*		*0.035*				*0.238*		

Table 2.15. Effect of cover crop and manure amendment on partial net revenue from combined potato and snap bean crops in 3 rotation cycles at Entrican and Benton Harbor, MI.

	Partial Net Revenue (\$ ha^{-1} $2yr^{-1}$)											
	Entrican, MI						Benton Harbor, MI					
	2003		2004		2005		2003		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bare	31668	939	26541	1126	13707	1415	15374	718	9041	623	9138	1749
Rye	31056	1251	25105	1067	15923	1155	15564	601	10092	769	11262	882
Rye-Vetch	27155	1616	23042	1053	14208	868	14856	725	9173	714	10974	1263
Crop effect, p	*0.088*		*0.255*		*0.606*		*0.876*		*0.377*		*0.718*	
No Manure	28738 b	1227	23542 b	863	14128	971	15683	468	10150 a	556	11350	1170
Manure	31181 a	954	26249 a	897	15263	877	14846	620	8723 b	553	9567	1001
Manure effect, p	*0.009*		*0.019*		*0.279*		*0.227*		*0.012*		*0.177*	
Bare	30354 a	1096	26624	1109	13287	2099	15469	984	10464 ab	829	11483	2762
Bare + M	32981 a	1443	26894	2041	14128	2082	15278	1113	7618 b	629	6794	1978
Rye	32463 a	1934	23380	1525	15884	1938	16175	752	11272 a	1257	10903	979
Rye + M	29649 ab	1548	26830	1306	17212	1401	14954	937	9061 ab	841	11621	1530
Rye-Vetch	23397 b	1864	21059	1377	13002	981	15406	754	8855 ab	716	11663	2205
Rye-Vetch + M	30912 a	1921	25025	1316	15414	1360	14305	1265	9491 ab	1281	10285	1357
*Crop*Manure interaction, p*	*<0.0001*		*0.434*		*0.603*		*0.796*		*0.038*		*0.241*	

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.16a. Comparison of partial marginal revenue and marginal rate of return for 5 alternate cover crop and manure amendment cropping systems compared with unamended bare control for each 3 rotation cycles at Entrican, MI.

	Entrican, MI								
	2003			2004				2005	
Partial Marginal Revenue ($ ha^{-1} $2yr^{-1}$)									
	Mean		SE	Mean		SE		Mean	SE
Bare	- - -		- - -	- - -		- - -		- - -	- - -
Bare + M	2,626	a	1,443	706		2,041		842	2,082
Rye	2,109	a	1,934	(2,808)		1,525		2,597	1,938
Rye + M	(705)	ab	1,548	641		1,306		2,675	1,401
Rye-Vetch	(6,958)	b	1,864	(5,130)		1,377		(285)	981
Rye-Vetch + M	558	a	1,921	(1,164)		1,316		2,127	1,360
Marginal Rate of Return (%)									
Bare	- - -		- - -	- - -		- - -		- - -	- - -
Bare + M	3.9	ab	2.2	1.3	ab	3.1		1.3	3.1
Rye	16.1	a	15.0	(21.8)	b	11.9		20.3	15.0
Rye + M	(0.9)	ab	1.9	0.8	a	1.6		3.3	1.6
Rye-Vetch	(17.3)	b	4.6	(12.6)	ab	3.4		(0.6)	2.4
Rye-Vetch + M	0.5	ab	1.7	(1.0)	ab	1.2		1.9	1.3

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.16b. Comparison of partial marginal revenue and marginal rate of return for 5 alternate cover crop and manure amendment cropping systems compared with unamended bare control for each 3 rotation cycles at Benton Harbor, MI.

	Benton Harbor, MI						
	2003		2004			2005	
Partial Marginal Revenue (\$ ha^{-1} $2yr^{-1}$)							
	Mean	SE	Mean		SE	Mean	SE
Bare	- - -	- - -	- - -		- - -	- - -	- - -
Bare + M	(191)	1,112	(2,847)	b	629	(4,689)	1,978
Rye	706	752	807	a	1,257	(581)	979
Rye + M	(515)	937	(1,404)	ab	841	138	1,530
Rye-Vetch	(63)	754	(1,610)	ab	716	180	2,205
Rye-Vetch + M	(1,164)	1,265	(973)	ab	1,281	(1,198)	1,357
Marginal Rate of Return (%)							
Bare	- - -	- - -	- - -		- - -	- - -	- - -
Bare + M	(0.3)	1.7	(4.1)		1.0	(6.8)	3.0
Rye	5.5	5.8	6.3		9.8	(4.8)	7.6
Rye + M	(0.8)	1.1	(1.6)		1.0	0.1	1.9
Rye-Vetch	(0.3)	1.9	(4.0)		1.8	0.4	5.5
Rye-Vetch + M	(1.0)	1.1	(0.9)		1.1	(1.3)	1.2

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.17. Comparison of 2-year partial marginal revenues and marginal rates of return for 5 alternate cover crop and manure amendment cropping systems compared with unamended bare control across 3 rotation cycles and 2 experimental sites, Entrican and Benton Harbor, MI.

	Partial Marginal Revenue ($ ha^{-1} 2yr^{-1})			Marginal Rate of Return (%)		
	Entrican	Benton Harbor	Mean	Entrican	Benton Harbor	Mean
Bare	- - -	- - -	- - -	- - -	- - -	- - -
Bare + M	1,391	(2,576)	(592)	2.2	(3.7)	(0.8)
Rye	633	311	472	4.9	2.3	3.6
Rye + M	870	(594)	138	1.0	(0.8)	0.1
Rye-Vetch	(4,124)	(498)	(2,311)	(10.2)	(1.3)	(5.7)
Rye-Vetch + M	507	(1,112)	(302)	0.5	(1.0)	(0.3)

Table 2.18. Effect of cover crop and manure amendment on soil (0-20 cm) inorganic N content (NO_3-N + NH_4-N) after a potato crop in 3 rotation cycles at Entrican and Benton Harbor, MI.

	Inorganic Soil N (g N/kg soil) 0-20 cm depth, after potato crop									
	Entrican, MI						Benton Harbor, MI			
	2003		2004		2005		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bare	5.67	1.15	5.84	0.61	7.40	0.67	5.63	0.44	5.01 b	0.33
Rye	4.62	0.99	6.87	0.78	5.56	0.28	5.97	0.42	6.19 a	0.50
Rye-Vetch	5.00	1.04	6.98	1.12	5.90	0.46	5.70	0.51	6.33 a	0.63
Crop effect, p	*0.808*		*0.642*		*0.269*		*0.922*		*0.045*	
No Manure	4.44 b	0.55	6.22	0.82	5.94 b	0.44	5.37	0.27	5.48	0.41
Manure	5.81 a	0.65	6.91	0.53	6.64 a	0.47	6.16	0.37	6.20	0.44
Manure effect, p	*0.021*		*0.369*		*0.009*		*0.297*		*0.174*	
Bare	5.55	1.20	5.81	0.79	7.22 ab	0.92	5.42	0.56	4.45 b	0.24
Bare + M	5.79	1.24	5.87	1.05	7.59 ab	1.10	5.84	1.00	5.57 ab	0.48
Rye	3.80	0.93	6.84	1.22	5.30 ab	0.53	5.77	0.73	6.11 a	0.32
Rye + M	5.63	1.23	6.90	1.17	5.81 ab	0.18	6.16	0.35	6.27 a	1.03
Rye-Vetch	4.16	0.99	6.00	0.88	5.29 b	0.65	4.91	0.73	5.89 ab	1.19
Rye-Vetch + M	6.01	1.28	7.97	2.42	6.52 a	0.55	6.50	0.48	6.77 a	0.54
*Crop*Manure interaction, p*	*0.260*		*0.529*		*0.255*		*0.625*		*0.713*	

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.19. Effect of cover crop and manure amendment on soil (20-51 cm) inorganic N content (NO_3-N + NH_4-N) after a potato crop in 3 rotation cycles at Entrican and Benton Harbor, MI.

	Inorganic Soil N (g N/kg soil) 20-51 cm depth, after potato crop														
	Entrican, MI								Benton Harbor, MI						
	2003			2004		2005			2004			2005			
	Mean		SE	Mean	SE	Mean	SE		Mean		SE	Mean	SE		
Bare	9.91		1.78	10.19	1.80	5.44	0.33		3.44		0.26	5.62	0.68		
Rye	8.46		1.60	7.90	1.03	5.66	0.57		4.08		0.55	6.29	0.73		
Rye-Vetch	8.13		2.22	10.37	1.03	5.16	0.68		3.66		0.18	5.39	0.51		
Crop effect, p	*0.706*			*0.484*		*0.866*			*0.657*			*0.556*			
No Manure	9.09		1.57	10.80	0.79	5.12	0.40		3.93		0.29	6.16	0.32		
Manure	8.57		1.46	8.17	1.25	5.72	0.46		3.53		0.30	5.37	0.65		
Manure effect, p	*0.703*			*0.118*		*0.274*			*0.055*			*0.417*			
Bare	14.01	a	1.63	12.20	3.29	5.14	0.52		3.39	ab	0.30	6.08	1.35		
Bare + M	5.80	b	0.91	8.18	1.23	5.73	0.41		3.49	ab	0.53	5.15	0.46		
Rye	7.56	b	1.71	9.03	1.34	5.66	0.56		4.96	a	0.58	6.82	1.37		
Rye + M	9.37	ab	2.91	6.77	1.52	5.67	1.09		3.20	b	0.82	5.77	0.64		
Rye-Vetch	5.72	a	2.27	11.18	1.67	4.57	1.25		3.44	ab	0.08	5.58	0.85		
Rye-Vetch + M	10.54	ab	3.73	9.55	1.32	5.75	0.62		3.89	ab	0.33	5.20	0.67		
*Crop*Manure interaction, p*	*0.007*			*0.807*		*0.662*			*0.003*			*0.951*			

a, b Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

Table 2.20. Effect of cover crop and manure amendment on soil (0-20 cm) inorganic N content (NO_3-N + NH_4-N) after a snap bean crop in 3 rotation cycles at Entrican and Benton Harbor, MI.

	Inorganic Soil N (g N/kg soil) 0-20 cm depth, after snap bean crop									
	Entrican, MI						Benton Harbor, MI			
	2003		2004		2005		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bare	5.71	0.67	8.13	1.51	6.50	0.37	8.53	0.83	4.93	0.35
Rye	6.75	1.38	6.89	0.60	5.95	0.68	8.25	0.49	4.20	0.31
Rye-Vetch	6.71	0.94	8.26	0.85	6.12	0.24	9.99	1.25	5.60	0.28
Crop effect, p	*0.821*		*0.643*		*0.864*		*0.546*		*0.096*	
No Manure	6.46	0.88	8.43	0.97	5.95	0.44	8.58	0.84	5.09	0.30
Manure	6.32	0.81	7.08	0.69	6.43	0.29	9.27	0.65	4.73	0.30
Manure effect, p	*0.821*		*0.329*		*0.155*		*0.246*		*0.214*	
Bare	5.38	0.61	7.08	0.84	6.01	0.42	9.05 ab	1.45	4.43	0.52
Bare + M	6.04	1.29	9.17	3.02	7.00	0.54	8.01 b	0.95	5.43	0.37
Rye	7.01	2.28	5.76	0.54	5.89	0.75	8.79 ab	0.77	4.27	0.55
Rye + M	6.50	1.90	8.02	0.74	6.01	1.27	7.71 b	0.58	4.14	0.38
Rye-Vetch	6.99	1.00	8.40	1.74	5.95	0.40	7.89 b	1.33	5.49	0.33
Rye-Vetch + M	6.43	1.77	8.11	0.54	6.29	0.32	12.10 a	1.60	5.70	0.51
*Crop*Manure interaction, p*	*0.652*		*0.684*		*0.527*		*0.005*		*0.264*	

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.21. Effect of cover crop and manure amendment on soil (20-51 cm) inorganic N content (NO_3-N + NH_4-N) after a snap bean crop in 3 rotation cycles at Entrican and Benton Harbor, MI.

	Inorganic Soil N (g N/kg soil) 20-51 cm depth, after snap bean crop									
	Entrican, MI						Benton Harbor, MI			
	2003		2004		2005		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bare	6.26	0.67	5.46	0.90	5.84 a	0.68	3.53	0.15	4.84 a	0.64
Rye	7.44	1.69	4.75	0.65	3.18 b	0.34	3.97	0.28	3.09 b	0.34
Rye-Vetch	6.76	0.84	5.74	0.43	2.69 b	0.11	4.18	0.46	2.89 b	0.17
Crop effect, p	*0.853*		*0.659*		*0.022*		*0.474*		*0.046*	
No Manure	6.45	0.71	6.13 a	0.54	4.01	0.49	3.69	0.31	3.71	0.49
Manure	7.19	1.11	4.50 b	0.47	3.80	0.60	4.09	0.21	3.51	0.35
Manure effect, p	*0.450*		*0.001*		*0.670*		*0.241*		*0.619*	
Bare	5.08	0.85	4.35	1.08	5.94	1.29	3.68	0.21	4.54	0.65
Bare + M	7.45	0.64	6.57	1.34	5.74	0.71	3.39	0.22	5.15	1.18
Rye	8.25	3.18	4.28	0.95	3.29	0.58	3.77	0.56	3.16	0.55
Rye + M	6.63	1.69	5.22	0.95	3.08	0.45	4.18	0.17	3.03	0.46
Rye-Vetch	6.03	0.93	4.87	0.53	2.80	0.18	3.63	0.38	2.82	0.31
Rye-Vetch + M	7.49	1.44	6.61	0.29	2.59	0.12	4.72	0.81	2.97	0.18
*Crop*Manure interaction, p*	*0.242*		*0.340*		*1.000*		*0.259*		*0.762*	

a, b, c, d Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.22. Effect of cover crop and manure amendment on soil (0-20 cm) N mineralization (NO_3-N + NH_4-N) after a potato crop in 3 rotation cycles at Entrican and Benton Harbor, MI.

	Soil N Mineralization Potential (g N/kg soil/day), 0-20 cm depth, after potato crop									
	Entrican, MI						Benton Harbor, MI			
	2003		2004		2005		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bare	0.59	0.12	0.28	0.03	0.49	0.06	0.16	0.03	0.12	0.02
Rye	0.34	0.08	0.28	0.03	0.36	0.06	0.19	0.04	0.09	0.02
Rye-Vetch	0.34	0.08	0.31	0.02	0.32	0.03	0.23	0.02	0.15	0.02
Crop effect, p	*0.280*		*0.731*		*0.149*		*0.182*		*0.294*	
No Manure	0.40	0.10	0.26 b	0.02	0.33 b	0.03	0.20	0.02	0.11	0.02
Manure	0.44	0.07	0.32 a	0.02	0.44 a	0.05	0.21	0.04	0.13	0.02
Manure effect, p	*0.649*		*0.025*		*0.039*		*0.627*		*0.459*	
Bare	0.59	0.24	0.27 ab	0.05	0.40 ab	0.05	0.15	0.03	0.10	0.01
Bare + M	0.59	0.10	0.30 ab	0.03	0.57 a	0.09	0.23	0.15	0.14	0.05
Rye	0.30	0.08	0.24 b	0.03	0.28 b	0.06	0.20	0.01	0.07	0.02
Rye + M	0.38	0.13	0.33 a	0.04	0.44 ab	0.08	0.16	0.11	0.12	0.04
Rye-Vetch	0.32	0.12	0.28 ab	0.03	0.32 b	0.06	0.24	0.04	0.16	0.02
Rye-Vetch + M	0.35	0.12	0.34 ab	0.03	0.32 b	0.03	0.23	0.03	0.15	0.05
*Crop*Manure interaction, p*	*0.936*		*0.630*		*0.284*		*0.447*		*0.644*	

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.23. Effect of cover crop and manure amendment on soil (0-20 cm) N mineralization (NO_3-N + NH_4-N) after a snap bean crop in 3 rotation cycles at Entrican and Benton Harbor, MI.

	Soil N Mineralization Potential (g N/kg soil/day), 0-20 cm depth, after snap bean crop									
	Entrican, MI						Benton Harbor, MI			
	2003		2004		2005		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bare	0.57	0.07	0.31	0.02	0.56	0.11	0.17 b	0.02	0.07	0.03
Rye	0.48	0.12	0.32	0.03	0.51	0.11	0.28 a	0.04	0.09	0.02
Rye-Vetch	0.36	0.07	0.32	0.03	0.58	0.05	0.28 a	0.02	0.16	0.04
Crop effect, p	*0.445*		*0.966*		*0.945*		*0.014*		*0.139*	
No Manure	0.41	0.07	0.28 b	0.01	0.50	0.07	0.22 b	0.03	0.09	0.02
Manure	0.52	0.07	0.36 a	0.02	0.60	0.08	0.27 a	0.03	0.12	0.03
Manure effect, p	*0.122*		*0.001*		*0.088*		*0.045*		*0.660*	
Bare	0.46	0.07	0.28 b	0.01	0.47	0.15	0.12 c	0.02	0.07	0.03
Bare + M	0.67	0.09	0.34 ab	0.05	0.64	0.16	0.22 b	0.02	0.08	0.05
Rye	0.50	0.18	0.30 ab	0.03	0.48	0.15	0.23 b	0.03	0.11	0.02
Rye + M	0.46	0.19	0.35 ab	0.06	0.54	0.19	0.34 a	0.06	0.06	0.02
Rye-Vetch	0.33	0.12	0.26 b	0.01	0.54	0.06	0.30 ab	0.04	0.11	0.06
Rye-Vetch + M	0.44	0.09	0.39 a	0.02	0.62	0.07	0.26 ab	0.03	0.21	0.03
*Crop*Manure interaction, p*	*0.254*		*0.089*		*0.631*		*0.044*		*0.174*	

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 2.24. Effect of cover crop and manure amendment on soil (0-20 cm) phosphorus in 2006 at Entrican and Benton Harbor, MI.

	Bray P (g P/kg soil, 0-20 cm depth)			
	Entrican, MI		Benton Harbor, MI	
	2006		2006	
	Mean	SE	Mean	SE
Bare	347	32	190	16
Rye	321	30	164	11
Rye-Vetch	307	24	171	14
Crop effect, p	*0.433*		*0.141*	
No Manure	288 b	23	147 b	6
Manure	363 a	21	202 a	13
Manure effect, p	*0.005*		*<.0001*	
Bare	290	44	162	16
Bare + M	405	38	218	24
Rye	305	49	141	9
Rye + M	338	36	188	18
Rye-Vetch	268	23	140	5
Rye-Vetch + M	346	37	202	24
*Crop*Manure interaction, p*	*0.410*		*0.872*	

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

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CHAPTER 3:

ABOVE- AND BELOW-GROUND BIOMASS FOR WINTER COVER CROPS IN MICHIGAN POTATO CROPPING SYSTEMS

ABSTRACT

Michigan growers have begun to integrate winter rye cover crops into potato (*Solanum tuberosum*) cropping systems to decrease soil erosion and nutrient losses through leaching, and to improve soil organic matter (SOM) (Snapp and Rohrbach, 2001). Some Michigan growers have combined animal manure amendments with cover crops to improve N efficiency and to ameliorate SOM. Information about cover crop biomass accumulation within the constraints of a Michigan potato cropping system is limited. Our objectives were to examine above- and below-ground cover crop productivity across several potato rotation systems. Quantity of above-ground cover crop biomass produced by mid-October-planted winter rye (1600 to 2500 kg/ha) was greater than biomass measured in commercial fields, and the late-August/early-September planted rye yielded significantly more than the commercial potato farms (3000 to 5000 kg/ha). Commercial Michigan potato farms may be achieving sufficient winter rye cover crop maturity and biomass for weed suppression and reduction of erosion and nutrient loss, but are probably not generating sufficient biomass to restore soil C without additional inputs. A Michigan field experiment demonstrated that increased winter rye and rye-hairy vetch (*Vicia villosa* L. Roth) biomass is possible for potato rotations on similar soils if cover crops can be planted by mid-September to mid-October. An additional 4 to 6 weeks of fall growing season can double above-ground rye biomass in the spring.

INTRODUCTION

Concern about the sustainability of intensive annual cropping systems and their effects on soil and water quality has led to an increased interest in alternative strategies, including the use of winter cover crops. Vegetative cover between main crops has been shown to reduce erosion by wind (Fryrear, 1985) and water (Fryrear, 1985; Hussein and Laflen, 1982; Kaspar et al., 2001), to improve soil quality (Karlen et al., 1992) and restore SOM (Karlen and Cambardella, 1996; Nyakatawa et al., 2001), to reduce leaching loss of soil nutrients (Askegaard and Eriksen, 2008), and to suppress weeds (Bàrberi and Mazzoncini, 2001; Campiglia et al., 2009). These concerns are especially important in potato cropping systems, where potatoes are typically grown with irrigation and large inputs of supplemental fertilizers on sandy, well-drained soils low in soil organic matter (SOM). Additionally, potatoes supply minimal plant residue to replace or restore SOM. Few cover crops are suitable for integration into an Upper Midwest potato cropping system. In Michigan, potatoes are typically grown in short, 2-year rotations with corn, wheat or a shorter-season vegetable. Long season crops, such as potatoes and corn, are typically planted in late April or May and harvested in September through October when available heat units are insufficient for establishment of many cover crop species (Bollero and Bullock, 1994). Short-season rotation crops such as wheat or a fresh vegetable often leave time for sufficient cover crop growth after main crop removal in July or August. Small grains such as wheat (*Triticum aestivum* L.), oat (*Avena sativa* L.), or rye seem to have the best potential as winter cover crops in these Upper Midwest full season crop rotations (Snapp et al., 2005). Winter rye is a popular cover crop choice for northern climates due to its winter hardiness and tolerance of late, cool weather planting dates. Rye requires only 1.1 to 4.4 ºC soil temperatures to germinate (Clark, 2007; Sarrantonio, 1994). A rye cover crop has been found to dramatically reduce leaching of NO_3-N in sandy soils (Prunty and Greenland, 1997) and, once established, the rye root system can take up residual inorganic nutrients more quickly than other winter cereal alternatives (Clark, 2007; Sarrantonio, 1994).

Legume cover crop species must be planted earlier in the fall in order to establish and survive the winter (Clark, 2007) and they tend to produce most of their biomass in the spring. A legume cover crop, or a legume-winter cereal mixture, can be feasible following an early-harvested main crop. Combining a legume with the winter rye cover crop can provide additional organic N to a subsequent cash crop and reduce fertilizer N requirements (Ranells and Wagger, 1997) and reduce N leaching losses (Tonitto et al., 2006). Additionally, researchers have shown that legumes can improve SOM faster than grass alone (Drinkwater et al., 1998; Robertson et al., 2000). Hairy vetch (*Vicia villosa* L. Roth) is the most cold-tolerant of winter annual legumes and has been found to perform well in northern US cropping systems (Clark, 2007; Jannink et al., 1997; Sarrantonio, 1994). Furthermore, a grass-hairy vetch biculture can provide greater mineralized N to subsequent cash crops than a grass monoculture (Ranells and Wagger, 1997). Red clover (*Trifolium pratense* L.) is a winter-hardy legume that can be frost-seeded into dormant winter wheat in late winter or early spring to allow earlier establishment. Red clover is used as a winter cover crop most commonly in regions where small grain production dominates.

Winter cover crop biomass accumulation varies widely within North America, due mainly to variable fall planting and spring termination dates and environmental temperatures. Table 3.1 summarizes above-ground biomass accumulations reported in North America for fall-planted rye, hairy vetch, rye-hairy vetch mixtures and frost-seeded red clover winter cover crops. Several studies conducted in the Midwestern U.S. report winter rye above-ground yields below 1 Mg ha^{-1} while larger yields of 3.7 to 4.7 Mg ha^{-1} were reported in moderated climates in

Maryland and California. Hairy vetch cover crop biomass accumulations range from less than 0.2 Mg ha^{-1} in some northern experiments, to as much as 7.7 Mg ha^{-1} in a Kentucky study. Winter rye-hairy vetch mixtures have produced winter cover crop yields from 0.8 to over 6 Mg ha^{-1}. Seeded into standing wheat in the spring, red clover accumulates biomass after wheat harvest and can produce from less than 1 to more than 3 Mg ha^{-1} of above-ground biomass (Blaser et al., 2007; Blaser et al., 2006) and 100 to 225 kg N ha^{-1} (Hesterman et al., 1992; Vyn et al., 1999) by May of the following year.

A study conducted in Michigan in 2004 and 2005 measured winter cover crop biomass on commercial potato farm fields just prior to spring tillage. All cover crop biomass encountered on these commercial potato farms was winter rye. The Feekes growth stage of the standing rye in mid- to late April of both 2004 and 2005 ranged from 2 to 4 with a mean of 3.1. In 2004, mid-April above-ground biomass ranged from 132 to 2640 kg ha^{-1}, and from 11 to 1757 kg ha^{-1} in 2005. Below-ground biomass varied similarly, ranging from 208 to 5197 kg ha^{-1} in 2004 and from 0 (undetectable) to 4287 kg ha^{-1} in 2005 (O'Neil and Snapp, 2006).

Michigan potato growers have begun to integrate winter rye cover crops in attempt to reduce erosion and winter N leaching, and to provide plant residue input to improve SOM (Snapp and Rohrbach, 2001). Michigan growers have also begun to combine animal manure amendments with cover crops to improve N efficiency and to ameliorate SOM. Few cover crop research trials have been conducted within the short time frame afforded in a northern potato rotation and often compare fully- or nearly-mature cover crops. As a result, information about cover crop biomass accumulation within the constraints of a Michigan potato cropping system is limited. Our objectives were to examine the effect of fall planting date on above- and below-ground cover crop yield and variability within several Michigan potato cropping systems.

MATERIALS AND METHODS

Site Descriptions

A 6-year potato cropping systems field study was conducted at 2 locations in Michigan from 2001 through 2007. Data from the 2005-2006 season is presented in this paper. Both sites are well-drained, loamy sand to sandy loam soils that are common soil types used for production of a wide range of vegetable crops in Michigan. At the Entrican, MI location (43°20' N, 85°01' W), the soil is a Montcalm/McBride loamy sand to sandy loam (coarse-loamy, mixed, semiactive, frigid Alfic Haplorthods; and coarse-loamy, mixed, semiactive, frigid Alfic Fragiorthods). At the Benton Harbor, MI site (42°6' N, 86°24' W) the soil is an Oakville series fine sand (mixed, mesic Typic Udipsamment). Chemical and physical descriptions of soils at both sites are listed in Chapter 2. Average daily temperature and monthly precipitation and irrigation totals from January 2005 through December 2006 are summarized in Figure 3.1 for Entrican and Benton Harbor locations. GDD were calculated using a base temperature of 4 ºC (Nuttonson, 1958) and actual and 10-year average monthly winter GDD accumulations for both Entrican and Benton Harbor locations from September to May are shown in Table 3.2.

Experimental Design

The field study at both Entrican and Benton Harbor locations was designed as a randomized complete block with 4 field replications, and the main experimental factor at both sites was a combination of crop rotation and winter cover crop (Table 3.3). Crop rotation-winter cover crop combinations were chosen to represent common and potentially improved systems for Michigan potato production. Whole plot (5.5 x 17 m) treatments at both locations included 2-year rotations of potato with snap bean, sweet corn or wheat and one 3-year potato-sweet corn-wheat rotation. For all 2-year rotation treatments, both rotation phases were present each year. Only two rotation phases of the 3-year potato-sweet corn-wheat rotation treatment were present in any one season, however. Wheat and sweet corn phases of the 3-year rotation treatment were present during the 2005 growing season. After removal of potato, snap bean and sweet corn main crops, whole plots were disked and either left as a bare fallow (Bare) or were planted with rye (Rye) or rye+hairy vetch (Rye+Vetch) winter cover crop. Red Clover was frost-seeded into wheat in mid-March of each year and allowed to grow after wheat harvest and remain through winter. All main crops and cover crops were conventionally managed with field-scale equipment per standard practices as described in Chapter 2, with one important modification. In fall of 2005, cover crops were planted early after short-season rotation crops (snap bean, wheat or sweet corn), or late after longer season potato crop. In previous seasons, all cover crops were planted late, after long-season crops were harvested and removed. In fall of 2005, early planting of cover crops took place on August 23 and September 7, 2005 after snap beans, wheat or sweet corn harvest (Early) at Entrican and Benton Harbor respectively. Late plantings took place on October 12 and 17, 2005 at Entrican and Benton Harbor, respectively, after potatoes were harvested. Winter rye (cv. Wheeler) and hairy vetch (cv. Common) were drilled at the same rates for both planting dates, 101 kg ha^{-1} for Rye alone and for the Rye+Vetch biculture, 67 kg ha^{-1} rye + 34 kg ha^{-1} hairy vetch. At both Entrican and Benton Harbor sites, potato-snap bean rotation plots only were split for a manure amendment split-plot treatment, as described in Chapter 2. One half of each potato-snap bean plot was amended annually with 2.5 ton ha^{-1} dried poultry manure (from egg-laying hens) each spring after cover crop sampling and prior to spring tillage. Poultry manure (5.6 Mg ha^{-1}) was first applied to the Entrican site in the spring of 2002 and to the Benton Harbor site in spring of 2003.

Prior to spring 2006 incorporation of cover crop residues, duplicate 0.25 m^2 samples of aboveground cover crop biomass were collected from each plot to estimate dry matter and total N content. Below-ground plant material was also quantified by collecting four 5.7 cm diameter x 20.3 cm depth soil cores within each of the same 0.25 m^2 quadrat areas. Above- and below-ground sampling occurred on May 16, 2006 at Entrican and on May 10, 2006 at Benton Harbor. Soil samples and above- and below-ground plant tissue samples were handled in the same manner as in the commercial field study.

Statistical Analysis

Main effects of plant species, planting date, and manure application, and their interactions, were identified using an ANOVA with the PROC MIXED procedure in SAS software (SAS, 2008). Because of their significantly different variances, Bare plots were analyzed separately from other cover crop treatments. The cover crop species main effect was determined on a subset of data of non-manured plots only because Red Clover was only planted without manure. The main effect of planting date was determined by analyzing a subset of data from Rye and Rye+Vetch plots because red clover plots were not planted at both planting dates. The manure amendment main effect was determined on a data subset of Rye and Rye+Vetch plots only, because manure amendment treatment was not applied to all rotation plots. Where significant ($p<0.05$) main effects or interactions were detected, treatment means were separated with a least squares means calculation using the LSMEANS statement within PROC MIXED. Superscript letters indicating differences between means were assigned using the PDMIX800 SAS macro (Saxton, 1998).

RESULTS AND DISCUSSION

Above-ground weed biomass for bare winter fallow plots at Entrican and Benton Harbor locations is presented in Table 3.4. No cover crops were planted on these plots but some winter annual weed biomass were present. Bare plots were disked in the fall when other crops were planted to cover crops. The biomass sampled from these plots ranged from 0 to 1200 kg ha^{-1} and was a mixture of winter annual weeds including common chickweed (*Stellaria media*), field pennycress (*Thlaspi arvense*), shepherd's purse (*Capsella bursa-pastoris*) and henbit (*Lamium amplexicaule*). More weed biomass accumulated at the slightly warmer Benton Harbor location than at Entrican. Early tilled plots accumulated more weed biomass than later tilled plots at both locations. Late tilled plots were cultivated during cooler weather, when fewer GDD were available for subsequent germination and establishment of weed seedlings. Manure application had no significant effect on weed biomass accumulation, though average above-ground weed biomass was slightly greater on manured spilt-plots than on non-manured split-plots at both locations. Even when manure is not a source of weed seeds, manure amendment has been observed to occasionally produce more vigorous and competitive weeds as a result of increased nutrient availability (Blackshaw et al., 2003). Slower or later nutrient release from organic nutrient sources such as poultry manure can favor late season weed emergence which can then increase the weed seed bank and subsequent weed pressure in following years (Bàrberi, 2002). For this reason, combining cover crops with manure amendment may be important for suppression of late season weeds.

Above-ground biomass accumulations for cover crop plots, with and without manure amendment, are shown in Table 3.5. Red clover, a cold-tolerant but slower-growing legume, produced significantly less above-ground biomass, by half, than Rye and Rye+Vetch treatments across both locations ($p<0.001$). Rye and Rye+Vetch plots were statistically similar, producing an average of 2600 and 3500 kg ha^{-1} at Entrican and Benton Harbor respectively. Early-planted Rye and Rye+Vetch cover crops produced significantly more spring biomass than Late-planted covers across both locations. Entrican Early plots were planted 50 days earlier in the fall and produced more than double the biomass of Late plots; Early plots produced 4487 kg ha^{-1} while Late plots produced 1913 kg ha^{-1}. At Benton Harbor, Early plots were planted 40 days before Late plots and produced 91% more above-ground biomass than Late plots (5190 kg ha^{-1} versus 2721 kg ha^{-1}). The highest above-ground biomass yielding treatment combination at both locations was Rye+Vetch amended with poultry manure and planted Early ($p<0.05$). Red clover and all Late-planted covers yielded the least above-ground biomass across location ($p<0.05$).

A subset of plots listed in Table 3.5 were used to investigate accumulation of both above- and below-ground biomass at each location. This subset included 4 field replicate plots of frost-seeded Red Clover and Late-planted Rye and Rye+Vetch with and without manure amendment (Tables 3.6 through 3.9). Within this subset, manure amendment did not significantly affect above- or below-ground biomass, total biomass or shoot:root ratio at either location. Above-ground biomass was statistically similar for all treatments at each location within this subset and averaged 1831 kg ha^{-1} at Entrican and 2231 kg ha^{-1} at Benton Harbor. Below-ground biomass averaged 1773 kg ha^{-1} at Entrican and 1412 kg ha^{-1} at Benton Harbor. At Entrican, below-ground biomass was significantly greater for the Red Clover treatment than for all Rye and Rye+Vetch treatments ($p=0.013$). Red Clover yielded 4229 kg ha^{-1} below-ground biomass while the other cover crops averaged 1159 kg ha^{-1}. At Benton Harbor, no significant differences in below-ground biomass were detected. Red Clover did not establish as well on the sandier soil at Benton Harbor resulting in an uneven stand. Red clover generally establishes better on finer-textured soils (Sarrantonio, 1994). The only significant difference in total biomass at either location reflects the significantly greater production of below-ground biomass for Red Clover at Entrican. Red Clover plots produced an average total biomass of 5688 kg ha^{-1} at Entrican while Rye and Rye+Vetch averaged 3083 kg ha^{-1}. Total biomass for all treatments at Benton Harbor was similar, averaging 3643 kg ha^{-1} across all 5 treatment combinations. Shoot:root ratios averaged 1.5 for all treatments across locations. At each location, Red Clover had a lower shoot:root ratio than the other 4 treatments (0.54 versus 1.74 across locations), indicating proportionally greater root tissue production, however this difference was only significant at Entrican (Table 3.15).

Though Feekes growth stage was not recorded for experimental plots, plants were more advanced than those encountered on commercial potato farms due to the later spring termination date (O'Neil and Snapp, 2006). Entrican and Benton Harbor plots were sampled at approximately rye Feekes stages 5 to 7 whereas growth stage of rye examined on commercial fields averaged 3.1 in each of 2 years. Early-planted cover crops in this experiment yielded substantially more above-ground and total biomass than commercial farm cover crops. Even the Late-planted cover crops at Entrican yielded more above-ground biomass than the majority of winter cover crops sampled on commercial farms. The lowest above-ground cover crop yields in the field experiment were 1429 kg ha^{-1} for Red Clover and 1592 kg ha^{-1} for Late-planted Rye+Vetch without manure amendment at Entrican. These results are similar to the highest yields measured on commercial farms. In both 2004 and 2005, 7 of 10 commercial fields sampled yielded less above-ground cover crop biomass than the lowest yielding field experiment plots (O'Neil and Snapp, 2006).

The objective for planting winter cover crops is to produce sufficient plant biomass or vegetative ground cover during the weeks between harvest and replanting of main crops to prevent land degradation via soil loss by wind and water erosion, loss of soil organic matter, loss of nutrients to surface and ground water, and for suppression of weeds and pests. It is unclear what minimum winter biomass, ground cover or growth stage is needed to achieve these goals. Weed suppressing allelochemicals appear to be most concentrated in young, vegetative rye plants. In 10 winter rye cultivars, allelochemicals declined with advancing maturity from a maximum at Feeke's stage 4, the youngest plants sampled in the experiment (Reberg-Horton et al., 2005). Beyond stage 4, allelochemical concentrations declined but biomass continued to increase which resulted in a maximum per hectare allelochemical rate at about Feeke's stage 8. In an Arkansas study, peak allelochemical concentration was observed at 60 days, but the growth stage was not reported (Burgos et al., 1999). None of the Michigan commercial potato farm cover crops sampled matured beyond Feeke's stage 4 and the more advanced research station cover crops were approximately Feeke's stage 5 to 7.

Erosion may be significantly reduced with very little plant biomass. California researchers concluded that 17.5% vegetative cover was sufficient to reduce wind erosion of a sandy soil by 95% compared to a bare soil (Lancaster and Baas, 1998). And in Iowa, researchers significantly reduced erosion with only 220 kg ha^{-1} of above-ground small grain cover crop biomass (Kaspar et al., 2001). A simple comparison of annual soil loss resulting from a long-season potato-corn cropping system with or without a winter rye cover crop was conducted using the Revised Universal Soil Loss Equation (RUSLE2) (Renard et al., 1996; USDA-ARS, 2010). This RUSLE2 simulation included potatoes planted in April and harvested in September and with corn planted in April and harvested in October on 2 soils typical for commercial potato production in Michigan, a Mancelona loamy sand (sandy, mixed, frigid Alfic Haplorthods) and a Montcalm/McBride sandy loam (coarse-loamy, mixed, semiactive, frigid Alfic Haplorthods). Addition of a winter rye cover crop following both main crops in this simulation effectively reduced soil loss by 35% on both soil types.

Researchers in Iowa detected a significant reduction of nitrate-N in tile drainage under 250 to 2740 kg ha^{-1} of rye cover crop in a 4-year corn-soybean experiment (Kaspar et al., 2007). These USDA scientists are now recommending that growers target 500 kg ha^{-1} of above-ground cover crop biomass as a reasonably achievable minimum to safely provide positive nutrient loss and erosion benefits. (Kaspar, personal communication, 2011). Seven of 10 commercial farm fields surpassed this minimum cover crop biomass in each of 2 years sampled, while all research station cover crop treatments accumulated much more biomass than this minimum target.

Analysis of soil C losses in a 20-year study in Michigan revealed that up to 190 kg C ha^{-1} may be lost per year in a conventionally tilled corn-soybean rotation on a sandy loam soil (Senthilkumar et al., 2009). Typical, conventional-tillage potato cropping operations generally entail more soil disturbance than typical corn-soybean systems and may result in C losses at or beyond the upper end of these findings. To replace this quantity of soil C per year, plant residue inputs of 1000 to 2000 kg ha^{-1} or more would likely be required (Kludze et al., 2010; VandenBygaart et al., 2003). This high rate of winter cover crop biomass production does not appear to be presently achieved within a commercial Upper Midwestern US potato cropping system; however, greater biomass yield could be achieved with earlier cover crop planting following a shorter season rotation crop.

Commercial potato producers in Michigan may be achieving sufficient winter rye cover crop maturity and biomass for weed suppression and for protection from erosion and nitrate loss, but are probably not producing sufficient biomass to permit soil C restoration without additional C inputs. Our field experiment demonstrated that increased winter rye and rye-hairy vetch biomass is possible for potato rotations on similar soils in Michigan if cover crops can be planted from mid-September to mid-October. It may be possible for Michigan potato growers to simply prioritize fall cover crop planting more highly, but elsewhere in the Midwest, cash crop growers have listed economic barriers to increasing their use of winter cover crops (Carpita and Gibeaut, 1993).

CONCLUSIONS

In a potato cropping systems field experiment, quantity of above-ground cover crop biomass produced by mid-October-planted winter rye (1600 to 2500 kg/ha) was greater than biomass measured in commercial potato fields in Michigan, and the late-August/early-September planted rye yielded significantly more than the commercial potato farms (3000 to 5000 kg/ha). Commercial Michigan potato farms may be achieving sufficient winter rye cover crop maturity and biomass for weed suppression and reduction of erosion and nutrient loss, but are probably not generating sufficient biomass to restore soil C without additional inputs. A Michigan field experiment demonstrated that increased winter rye and rye-hairy vetch biomass is possible for potato rotations on similar soils if cover crops can be planted by mid-September to mid-October. An additional 4 to 6 weeks of fall growing season can double above-ground rye biomass in the spring.

Table 3.1. Summary of above ground biomass yields for winter cover crops in North America.

Location	Plant Date	Termination Date	Average Biomass Yield (Mg ha^{-1})	Reference
Rye				
Minnesota, USA	Mid- to Late October	Early May, Late May	0.61, 2.20	(De Bruin et al., 2005)
Ontario, Canada	Mid-August	Early May	0.65 to 2.12	(Vyn et al., 2000)
Wisconsin, USA	Late August	Early May	0.57 to 1.44	(Andraski and Bundy, 2005)
Wisconsin, USA	Late August to Late September	Late April	0.28 to 0.93	(Bundy and Andraski, 2005)
Illinois, USA	Late September to Late October	Early to Mid-April	0.61 to 2.43	(Miguez and Bollero, 2006)
Iowa, USA	Late August to early Oct	Late April to early May	0.25 to 2.74	(Kaspar et al., 2007)
Washington, USA	Early October	Late April	4.05	(Kuo et al., 1997)
California, USA	Late November	Early March	3.73	(Wyland et al., 1996)
Maryland, USA	Late September, early October	Late March, Early April, and Late April	1.29, 1.99, 3.21	(Clark et al., 1997)
Maryland, USA	Early October	Late March, Early May	2.41, 4.67	(Clark et al., 2007)
Nebraska, USA	After soybean harvest	Early May	0.26 to 1.62	(Kessavalou and Walters, 1997)
Hairy Vetch				
Maine, USA	Mid-August, Early September	Late May	0.08 to 1.55	(Jannink et al., 1997)
Maine, USA	Early, Late August	Mid, Late May	0.01 to .58	(Jannink et al., 1997)
New York, USA	Late August, Mid-September	Early May, Early June	1.70, 3.65	(Teasdale et al., 2004)
Illinois, USA	Late September to Late October	Early to mid-April	0.12 to 2.2	(Miguez and Bollero, 2006)
Washington, USA	Early October	Late April	2.7	(Kuo et al., 1997)

Table 3.1 continued on next page

Table 3.1 (cont'd)

Location	Plant Date	Termination Date	Average Biomass Yield (Mg ha^{-1})	Reference
Hairy Vetch, continued				
Kentucky, USA	Mid-September	Mid-May	5.90 to 7.72	(Frye et al., 1982)
Maryland, USA	Late September, Early October	Late March, Early April, Late April, and Early May	1.89, 2.84, 3.35, 4.50	(Clark et al., 1997)
Maryland, USA	Early October	Late March, Early May	2.98, 5.69	(Clark et al., 2007)
Maryland, USA	Late September to Late October	Late April to Early June	1.70 to 6.67	(Teasdale et al., 2004)
Rye + Vetch				
Maine, USA	Mid-August, Early September	Late May	1.76 to 3.97	(Jannink et al., 1997)
Maine, USA	Mid- to Late August	Late May to Early June	2.1 to 4.5	(Griffin et al., 2000)
Illinois, USA	Late September to Late October	Early to Mid-April	0.83 to 4.1	(Miguez and Bollero, 2006)
Maryland, USA	Late September, Early October	Late March, Early April, Late April, Early May	2.59, 3.48, 5.06, 6.09	(Clark et al., 1997)
Maryland, USA	Early October	Late March, Early May	3.13, 4.87	(Clark et al., 2007)
Red Clover				
Maine, USA	Mid-May	Late May	2.3 to 5.0	(Sarrantonio and Molloy, 2003)
Ontario, Canada	Late April to Late May	Mid-May	0.82 to 3.67	(Vyn et al., 1999)
Ontario, Canada	March	Early May	1.24 to 3.59	(Vyn et al., 2000)
Ontario, Canada	Mid-March to Late April	Late September to Early October	0.7 to 2.8	(Queen et al., 2009)
Iowa, USA	Mid- and Late March	Early May	2.27 to 3.15	(Blaser et al., 2007)

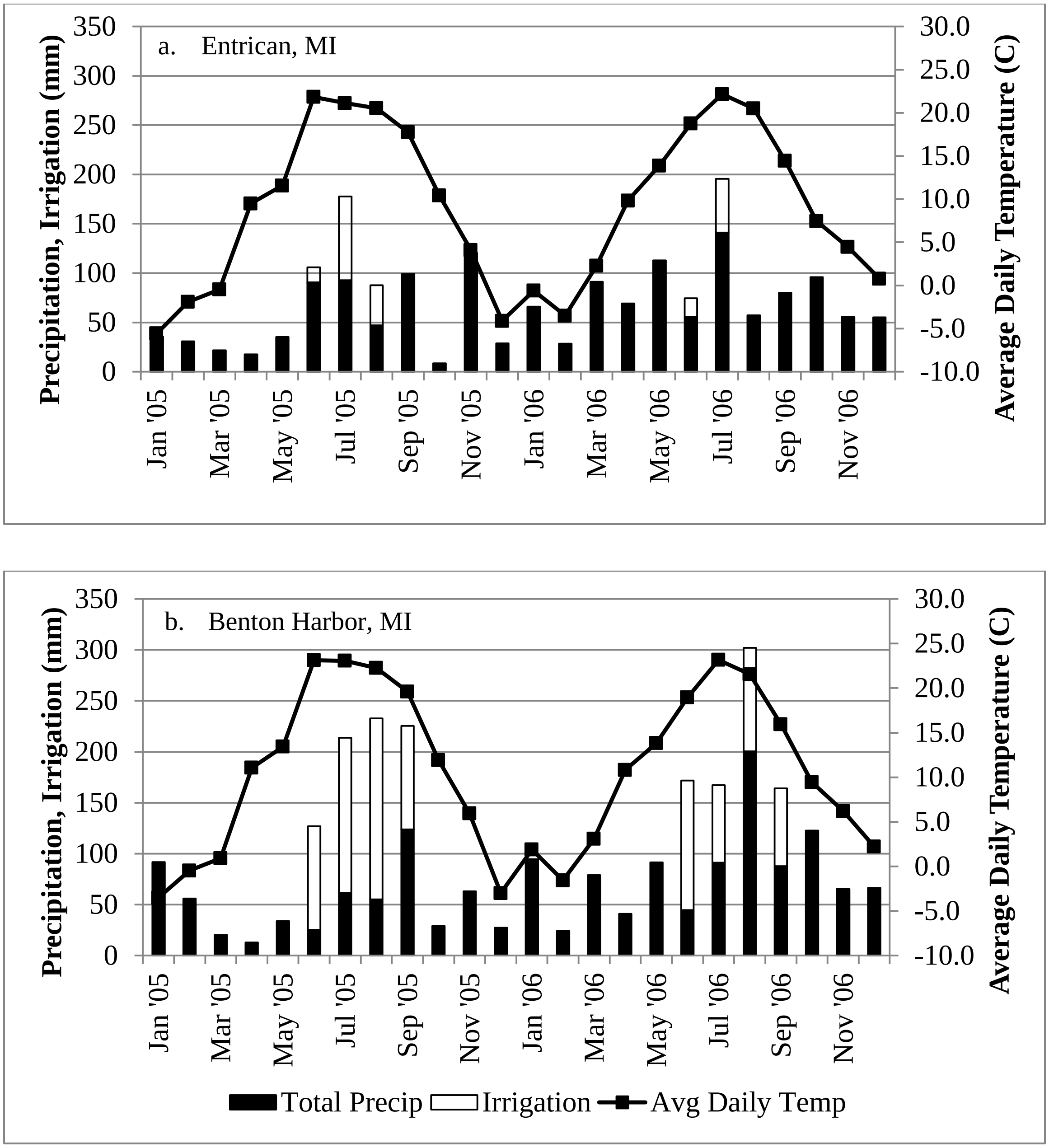

Figure 3.1. Monthly precipitation and irrigation totals (mm) and average daily temperature (°C) recorded at Montcalm Research Farm (a. Entrican, MI) and Southwest Michigan Research and Extension Center (b. Benton Harbor, MI) for January 2005 to December 2006.

Table 3.2. Monthly winter growing degree-day (base 4) accumulations for Entrican and Benton Harbor, MI from September 2005 to May 2006. 10-year average is calculated from daily ambient temperatures from 2000 through 2010.

	Entrican, MI			Benton Harbor, MI		
	2005-06	10-Year Average	SE	2005-06	10-Year Average	SE
September	413	370	21	469	419	23
October	199	167	12	245	227	11
November	67	22	4	115	59	3
December	0	0	0	0	0	0
January	3	0	1	15	0	0
February	0	0	0	3	0	0
March	32	6	4	56	21	1
April	167	130	8	209	169	10
May	307	278	17	305	324	17

Table 3.3. Rotation, cover crop and manure treatments used in long-term potato rotation experiment at Entrican and Benton Harbor locations.

Whole Plot Treatment		Split-plot Treatment
Crop Rotation	Winter Cover Crop	Manure (M)
Potato / Snap Bean	Bare (no cover crop)	+ or - manure
Potato / Snap Bean	Rye	+ or - manure
Potato / Snap Bean	Rye + Hairy Vetch	+ or - manure
Potato / Sweet Corn	Rye + Hairy Vetch	
Potato / Sweet Corn	Rye after Potatoes, Bare after Corn	
Potato / Winter Wheat	Wheat + Red Clover (frost seeded)	
Potato / Winter Wheat	Wheat after Potatoes, Rye after Wheat	
Potato / Corn / Wheat	Rye+Hairy Vetch or Wheat+Clover	

Table 3.4. Effect of fall tillage date and manure amendment on yield of above-ground cover crop biomass (kg ha^{-1}) in bare plots only at Entrican and Benton Harbor, MI.

	Entrican, MI				Benton Harbor, MI			
	n	Mean		SE	n	Mean		SE
Early Planted	16	350	a	159	16	1039	a	111
Late Planted	24	0	b	0	24	523	b	123
Plant Date Effect, p		*0.003*				*0.002*		
No Manure	24	100		69	24	709		125
Manure	16	200		137	16	759		148
Manure Effect, p		*0.653*				*0.953*		
Early, No Manure	8	300	ab	197	8	869	ab	134
Early, Manure	8	400	a	262	8	1209	a	164
Late, No Manure	16	0	c	0	16	630	bc	175
Late, Manure	8	0	bc	0	8	310	c	92
*Plant Date * Manure Interaction, p*		*0.053*				*0.058*		

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 3.5. Effect of cover crop species, fall planting date and manure amendment on yield of above-ground cover crop biomass (kg ha^{-1}) at Entrican and Benton Harbor, MI.

	Entrican				Benton Harbor			
	n	Mean		SE	n	Mean		SE
Rye[1]	31	2780	a	249	32	3280	a	223
Rye-Vetch	32	2496	a	305	32	3697	a	347
Red Clover	16	1429	b	163	16	1729	b	195
Cover Crop Effect, p		*<0.001*				*<0.001*		
Early-planted[2]	39	4487	a	305	40	5190	a	280
Late-planted	56	1913	b	82	56	2721	b	162
Plant Date (Cover Crop) Effect, p		*<0.0001*				*<0.0001*		
No Manure[3]	63	2635	b	197	64	3489	b	207
Manure	32	3627	a	374	32	4272	a	402
Manure (Cover Crop) Effect, p		*0.035*				*0.234*		
Rye, No Manure, Early	15	3304	c	460	16	4072	c	316
Rye, Manure, Early	8	4087	c	516	8	4906	bc	598
Rye-Vetch, No Manure Early	8	5206	b	402	8	5706	b	462
Rye-Vetch, Manure Early	8	6385	a	505	8	7195	a	453
Red Clover, No Manure, Early	16	1429	e	163	16	1729	e	195
Rye, No Manure, Late	16	2288	d	150	16	2488	de	150
Rye, Manure, Late	8	2009	de	293	8	2758	de	231
Rye-Vetch, No Manure Late	24	1592	e	92	24	3028	d	343
Rye-Vetch, Manure Late	8	2028	de	117	8	2228	de	229
*Plant Date * Manure(Cover Crop) Interaction, p*		*0.122*				*0.013*		

a, b, c, d, e Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

[1] Cover crop species effect was determined on a data subset of non-manured plots only because red clover was only planted without manure.
[2] Rye and rye-vetch plots only were included in the planting date comparison because red clover plots were not planted at both early and late.
[3] Manure amendment effect was determined on a data subset of rye and rye-vetch plots only, because manure amendment treatment was not applied to red clover plots.

Table 3.6. Effect of cover crop species and manure amendment on yield of above-ground cover crop biomass (kg ha^{-1}) at Entrican and Benton Harbor, MI.

Above-ground	Entrican			Benton Harbor		
	n	Mean	SE	n	Mean	SE
No Manure[1]	8	1879	232	8	2208	172
Manure	8	1969	150	8	2588	267
Cover Crop Effect, p		*0.149*			*0.372*	
Red Clover, No Manure, Early	4	1459	416	4	1559	519
Rye, No Manure, Late	4	1999	295	4	2538	140
Rye, Manure, Late	4	1979	262	4	3118	228
Rye-Vetch, No Manure Late	4	1759	393	4	1879	213
Rye-Vetch, Manure Late	4	1959	192	4	2059	305
Manure (Cover Crop) Effect, p		*0.832*			*0.687*	

a, b, c, d, e Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

[1] Manure amendment effect was determined on a data subset of rye and rye-vetch plots only, because manure amendment treatment was not applied to red clover plots.

Table 3.7. Effect of cover crop species and manure amendment on yield of below-ground cover crop biomass (kg ha^{-1}) at Entrican and Benton Harbor, MI.

Below-ground	Entrican				Benton Harbor		
	n	Mean		SE	n	Mean	SE
No Manure[1]	8	1033		206	8	1422	225
Manure	8	1285		253	8	1358	201
Manure Effect, p		*0.717*				*0.687*	
Red Clover, No Manure, Early	4	4229	a	1172	4	1501	527
Rye, No Manure, Late	4	1463	b	231	4	1436	358
Rye, Manure, Late	4	989	b	284	4	1542	345
Rye-Vetch, No Manure Late	4	602	b	147	4	1408	330
Rye-Vetch, Manure Late	4	1582	b	400	4	1173	215
Manure (Cover Crop) Effect, p		*0.013*				*0.372*	

a, b, c, d, e Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

[1] Manure amendment effect was determined on a data subset of rye and rye-vetch plots only, because manure amendment treatment was not applied to red clover plots.

Table 3.8. Effect of cover crop species and manure amendment on yield of total cover crop biomass (kg ha^{-1}) at Entrican and Benton Harbor, MI.

Above plus below-ground	Entrican				Benton Harbor		
	n	Mean		SE	n	Mean	SE
No Manure[1]	8	2911		328	8	3630	347
Manure	8	3254		374	8	3946	392
Manure Effect, p		*0.138*				*0.514*	
Red Clover, No Manure, Early	4	5688	a	1368	4	3060	672
Rye, No Manure, Late	4	3462	ab	397	4	3974	476
Rye, Manure, Late	4	2967	b	541	4	4660	509
Rye-Vetch, No Manure Late	4	2361	b	378	4	3287	506
Rye-Vetch, Manure Late	4	3540	b	552	4	3232	345
Manure (Cover Crop) Effect, p		*0.050*				*0.213*	

a, b, c, d, e Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

[1] Manure amendment effect was determined on a data subset of rye and rye-vetch plots only, because manure amendment treatment was not applied to red clover plots.

Table 3.9. Effect of cover crop species and manure amendment on yield of total cover crop shoot:root ratio at Entrican and Benton Harbor, MI.

Shoot:Root ratio	Entrican				Benton Harbor		
	n	Mean		SE	n	Mean	SE
No Manure[1]	8	1.69		0.34	8	1.56	0.21
Manure	8	1.59		0.25	8	1.81	0.29
Manure Effect, p		*0.955*				*0.949*	
Red Clover, No Manure, Early	4	0.25	a	0.08	4	0.82	0.25
Rye, No Manure, Late	4	1.30	b	0.22	4	1.81	0.39
Rye, Manure, Late	4	2.14	b	0.44	4	2.04	0.37
Rye-Vetch, No Manure Late	4	2.39	b	1.01	4	1.37	0.22
Rye-Vetch, Manure Late	4	1.26	b	0.22	4	1.62	0.44
Manure (Cover Crop) Effect, p		*0.014*				*0.073*	

a, b, c, d, e Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

[1] Manure amendment effect was determined on a data subset of rye and rye-vetch plots only, because manure amendment treatment was not applied to red clover plots.

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CHAPTER 4:

WITHIN-SEASON CHANGES IN *IN SITU* SOIL MACRO-ORGANIC MATTER, PARTICULATE ORGANIC MATTER AND NITROGEN AVAILABILITY IN FOUR CONVENTIONAL MICHIGAN POTATO CROPPING SYSTEMS

ABSTRACT

Winter cover crops have become commonplace in Michigan potato (*Solanum tuberosum*) cropping systems as growers attempt to increase plant residue inputs in efforts to maintain or improve soil organic matter (SOM) content, nutrient retention, soil structure and productivity. It is not clear whether cover crop residues alone can substantially improve SOM pools in a potato rotation, however. This study examined how rotation and cover crop management may alter the size, composition and within-season dynamics of young SOM pools in a potato-wheat (*Triticum aestivum*) rotation with a frost-seeded red clover (*Trifolium pratense*) cover crop and 3 potato-snap bean (*Phaseolus vulgaris*) cropping rotations without a winter cover crop, or with rye (*Secale cereale*) or a rye-hairy vetch (*Vicia villosa* L. Roth) cover crop. Cover crops were planted either in late August-early September (Early) or in mid- to late-October (Late) in 2 important potato-growing regions in Michigan on coarse, well-drained soils. The difference in GDD exposure for Early- vs. Late-planted cover crops was reflected in above-ground biomass yield and quality. Cover crop biomass accumulation ranged from 1139 to 5706 kg ha^{-1} across sites. At both locations, earlier planted winter rye (Rye) and rye-hairy vetch biculture (RV) cover crops yielded almost double the above-ground biomass of Clover or late-planted Rye and RV. Quantities of neutral detergent fiber (NDF) and acid detergent lignin (ADL) contributed per hectare were greatest for Early-planted Rye and RV while Clover produced one of the smaller yields of NDF and ADL. Early June macro-particulate organic matter (POM) –C and –N pools reflected variable biomass and quality of cover crops, but these fractions did not persist through

the growing season. In late October, Potato-Wheat/Clover rotation plots had the highest macro-POM fractions despite having low macro-POM fractions in early June. POM-C and –N pools were more stable than macro-POM pools during the growing season. Across 3 sampling dates at both locations, Potato-Wheat/Clover rotation plots were consistently among the treatments with the highest POM-C and -N fractions and the lowest POM C:N ratios. Presence of winter wheat and frost-seeded red clover in this cropping system eliminates the need for spring tillage and therefore these plots were tilled much less intensively than all the potato-snapbean cropping system plots. Measurement of NO_3-N accumulation on anion exchange resin probes detected a sharp decline in soil NO_3-N availability over the latter month of the growing season, but few significant treatment effects were noted. Inorganic N availability estimated with an aerobic laboratory mineralization assay revealed greatest availability in the Potato-Wheat/Clover plots at Entrican and in the non-potato phase plots on the coarser soils of Benton Harbor. Residual inorganic N after crop removal was generally higher for potato phase plots than for non-potato phase plots to a depth of 51 cm. Though the soil health benefits of cover crops are numerous and widely accepted, it appears that, regardless of species, cover crops alone are unlikely to provide enough organic input to improve soil organic matter fractions in fields used for short-rotation potato production. Soil organic matter fractions can be improved where potatoes can be rotated with main crops that permit use of cover crops and reduced tillage frequency and intensity, such as winter wheat.

INTRODUCTION

Potatoes are typically cultivated on light-textured, well-drained soils in Michigan, U.S.A. Potato production employs frequent tillage operations and heavy traffic during planting and harvesting seasons, which can result in physical breakdown of soil structure and loss of SOM (Grandy and Robertson, 2007; Janzen et al., 1998; Paustian et al., 1997) Maintenance of SOM and productivity on land under potato production is a concern for Michigan potato growers (Michigan Potato Industry Commission, 2012). Plant residues serve as a source of building materials for soil organic matter, and residue OM permits organomineral interactions necessary for soil aggregation and structure (Oades, 1988).

It is widely recognized that biochemical composition or quality determines rate of decomposition and mineralization of plant residues in soil. Nutrient release from decomposing plant tissues is expected to be determined both by plant tissue biochemistry and environmental conditions (Scholes et al., 1997; Schomberg and Endale, 2004; Swift et al., 1979; Vanlauwe et al., 1996). Plant residues are also the primary source for organic matter formation in soil (Kogel-Knabner, 2002; Oades, 1988). To properly enhance SOM formation, a better understanding of the impact of plant residue quality on SOM fractions is needed. Plant tissue degradation in soil has been linked to biochemical composition, specifically cell wall carbohydrate and lignin fractions, to C:N ratio as well as to relationships among biochemical components within the plant tissues (Chesson, 1997).

Most current models of SOM dynamics describe 2 to 5 discrete, kinetically-defined pools. Models typically include a labile pool, generally associated with microbial biomass and high turnover rate, and one or more other more stable, recalcitrant pools with slower turnover rates (Jenkinson and Rayner, 1977; Parton et al., 1987). Physical and chemical fractionation of these theoretical SOM pools has been attempted by many soil researchers. Physical fractionation of SOM based on particle size and/or density allows separation of the mineral-bound SOM from a larger macro-organic matter fraction composed mainly of decaying plant residues and an associated microbial biomass (Cambardella and Elliott, 1992; Christensen, 2001). Isotopic ^{13}C experiments have shown that the macro-organic matter fraction is typically younger and more degradable than the more recalcitrant mineral-associated SOM (Balesdent et al., 1987; Cambardella and Elliott, 1992).

Particulate organic matter (POM), a labile component of SOM defined physically as the organic matter separated with the sand fraction (> 53 μm), is comprised primarily of partially decomposed plant material and responds more quickly to crop and soil management alternatives than do other SOM pools (Wander, 2004). POM is not closely associated with mineral particles, but is an important indicator of soil physical condition, biological activity and of capacity for N retention and availability (Wander and Bollero, 1999). This is especially true for sandy soils because the proportion of total soil C and N in the POM fraction is higher than in more finely textured soils (Hook and Burke, 2000). Concentration of POM in bulk soil changes during the growing season (Spycher et al., 1983; Willson et al., 2001) and is a good indicator of potentially mineralizable N and C (Wander and Bidhart, 2000). Organic soil inputs such as plant residues, manures or composts directly contribute to the POM pool and are positively related to soil quality and function (Marriott and Wander, 2006; Wander et al., 1994).

POM pool sizes and dynamics are indicative of organic amendment efficacy and decomposition of POM releases plant available nutrients (Marriott and Wander, 2006). Initial plant residue biochemistry has been related to eventual POM pool size in container studies. Researchers found that POM-C pool size 56 days after plant residue incorporation was positively correlated with both cellulose and lignin content of the original plant residues (Bending and Turner, 1999). Mineralization of plant tissue N was faster for potato shoot residues and for Brussels sprout shoots than for ryegrass roots and wheat straw, which both caused a net N immobilization. Some attempts to further partition POM into subclasses have employed shape, size and density fractionation techniques. Research focused on studying dynamics of recent plant residues have defined macro-POM or macro-OM as particles as large as 200 to 8000 μm (Hassink et al., 1993; Willson et al., 2001).

Here we present data collected during the sixth growing season of a 6-year potato cropping systems experiment conducted to examine the impact of winter cover crop and rotation sequence on SOM pools and N availability. Though data were collected during a single growing season, results reflect both within-season dynamics and the cumulative effects resulting from cropping system management over the 6-year duration of the experiment. Objectives for this experiment were 1) to determine how long-term rotation and cover crop management alter the size, composition and within-season dynamics of POM and macro-POM fractions; and 2) to examine the relationship between macro-POM and POM pool sizes during the season and soil NO_3-N availability, N mineralization potential and residual NO_3-N in potato-snap bean and potato-wheat rotations with different winter cover crop alternatives.

MATERIALS AND METHODS

Site Descriptions

A field experiment comparing potato crop rotation sequences and winter cover crop alternatives was conducted from 2001 to 2006 in two important potato-producing regions in Michigan. The experimental site at the Montcalm Research Farm, near Entrican, MI (43°20' N, 85°01' W), was first established in the spring of 2001 with planting of potato, wheat and snap bean main crops. The experiment was established in the fall of 2001, at the Southwest Michigan

Research and Extension Center, near Benton Harbor, MI (42°6' N, 86°24' W) beginning with cover crops.

The Entrican site is a Montcalm/McBride sandy loam (coarse-loamy, mixed, semiactive, frigid Alfic Haplorthods; and coarse-loamy, mixed, semiactive, frigid Alfic Fragiorthods). The Benton Harbor site is an Oakville fine sand (mixed, mesic Typic Udipsamment). All plots were sampled in 2001 and 2002 for an initial soil chemical and texture descriptions to provide a context for the experimental outcomes. Chemical and physical descriptions of soils at both sites are listed in Table 4.1. Precipitation, temperature and irrigation patterns for each site during 2005 and 2006 are depicted in Figure 4.1. Cumulative growing degree-days (GDD), shown in Table 4.2, were calculated using a base temperature of 4 ºC as appropriate for winter rye (Nuttonson, 1958).

This experiment was designed as a randomized complete block with crop rotation as the main experimental factor at both sites. Main plots measured 5.5 x 17 m. All treatment combinations were replicated 4 times at each field site and are listed in Table 4.3.

Experimental Design and Crop Management

Cover crops were seeded in fall 2005 at 2 different dates due to differing season length of the preceding crop. See Table 4.3. Cover crops were seeded in September, after short-season wheat and snap beans, while those seeded after potatoes were planted in mid-October at both sites. Specific planting dates for each experimental site are listed in Table 4.4. Winter rye (cv. Wheeler, Rye) was drilled in 18 cm row spacing at 101 kg ha^{-1} and the rye-hairy vetch (cv. Common) biculture (RV) was drilled using 67 and 34 kg ha^{-1} of rye and hairy vetch, respectively. All cover crops were allowed to overwinter and accumulate until spring field conditioning for subsequent crops. Both field sites were conventionally tilled and managed with field-scale machinery throughout the experiment and included both main crop rotation phases and 4 field replications of all rotation-winter cover crop combinations. Weeds, pests and pathogens affecting potato and snap bean crops were treated with conventional herbicides and pesticides according to standard recommended practices.

Winter wheat (cv. Caledonia) was drilled at 18 cm row spacing at a rate 168 kg ha^{-1} in mid-October 2004 at both locations. Specific planting dates are listed in Table 4.4. In late March at both locations, potassium (0-0-60) was broadcast onto plots at the rate of 202 kg ha^{-1} and N, in the form of urea, was broadcast at the rate of 84 kg N ha^{-1}. Red clover was frost-seeded into standing wheat plots in late March 2006 at both locations at the rate of 28 kg ha^{-1}.

Potatoes were rotated with wheat or snap beans in all main plots in a 2-year rotation with both potato and rotation crop phases present each year. Cut potato tuber (cv. Snowden) pieces were planted on June 1 and May 30, 2006 at Entrican and Benton Harbor locations respectively. Both locations were planted with a field-scale 2-row potato planter and a within-row spacing of 31 cm and 86 cm between rows for a population of approximately 38000 ha^{-1}. Potassium (0-0-60) was broadcast before planting at the rate of 202 kg K_2O ha^{-1}. Phosphorus (19-19-19) was applied to the Entrican plots at a rate of 37.5 kg ha^{-1} at potato planting while none was applied to Benton Harbor plots. Nitrogen fertilizer was applied to potatoes in applications at planting, at hilling and in late July, totaling 224 kg ha^{-1}. Nitrogen fertilizer reductions for rye, rye-vetch and red cover crops were dependent upon spring biomass accumulations and ranged from 34 to 78 kg ha^{-1} N based on biomass, estimated N content and previous studies (Nyiraneza and Snapp, 2007). See Table 4.3. Fertilizer reductions were applied to late N applications while planting and hilling applications were not modified from bare control.

Snap beans (cv. HyStyle, Harris Moran) were planted in early June (Table 4.4) with a field-scale planter at a within-row spacing of 10.1 cm and 51 cm between rows for a population of 194,000 ha^{-1}. Potassium (0-0-60) was broadcast before planting at the rate of 202 kg K_2O ha^{-1}. Fifty-six kg N ha^{-1} was applied to snap beans at planting with appropriate fertilizer credits applied for cover crop biomass (Table 4.3).

Analytical Methods

Prior to spring incorporation of cover crop residues with a field-scale disk, samples of aboveground cover crop biomass were collected from two 0.25 m^2 areas within each plot to estimate dry matter and total N content. Biomass samples were not sorted by plant species. Below-ground plant material was also quantified by collecting four 5.7 cm diameter x 20.3 cm depth soil cores within each of the same 0.25 m^2 quadrat areas. Above- and below-ground sampling occurred on May 16, 2006 at Entrican and on May 10, 2006 at Benton Harbor. Soil cores were combined and stored at 4.4 ºC for up to 3 days before root tissues were separated. Root biomass was separated from soil material by wet-sieving each sample through a 3.2 mm sieve (Seedburo seed sieve No. I, Seedburo Equipment Co., Chicago, Illinois) using tap water. Root tissues were manually separated from soil mineral material and other plant residues remaining on the sieve. Above- and below-ground plant tissues were dried at 65 °C and dry weights were recorded. Total C and N of above-ground tissues were analyzed by dry combustion (PDZ Europa ANCA-GSL elemental analyzer, Sercon Ltd, Cheshire, UK) on a subsample of dry, ground plant tissues prepared by grinding in a small cutting mill to pass a 60-mesh screen (Wiley Mini-Mill, Thomas Scientific, Swedesboro, NJ USA). Above-ground tissues were also analyzed for neutral detergent fiber (NDF) and acid detergent lignin (ADL)

(Goering and Van Soest, 1970). NDF is an insoluble, high C:N residue containing hemicelluloses, cellulose and lignin that comprise cell walls, and though it varies in decomposition rate, NDF degrades significantly slower than cell contents (Jung and Allen, 1995). ADL represents a very slowly degradable or recalcitrant fraction of plant cell wall materials (Van Soest, 1967).

Soil Ap horizons (20 cm depth) were sampled at 3 points during the growing season for POM and macro-POM analyses. POM soil samples were collected immediately after cover crops were incorporated but before main crops were planted, at mid-season, and again after main crops were harvested and plots were disked but before cover crops were planted again. Specific sampling dates for each location are listed in Table 4.5. At each sampling date, eight 6.4 cm diameter by 20 cm depth soil cores were collected within each plot with an enclosed bucket auger specifically for POM and macro-POM analysis. These soil cores were combined, mixed and dried at ambient temperature. Air-dried soil samples were manually passed through a 6mm sieve and plant shoot and root particles larger than 6mm were separated to quantify macro-POM. Macro-POM samples were dried 65 °C and dry weights were recorded. Macro-POM was analyzed for total C and N, NDF, and NDF-N using the same methods as were used for above-ground biomass. After macro-POM removal, soil samples were subjected to POM analysis (Cambardella and Elliott, 1992). A 40 g subsample was dispersed by shaking (120 rpm) in 100 ml of a 5.0 g L^{-1} sodium hexametaphosphate solution for 18 h. An 18 h dispersal time was chosen based on results of a preliminary study of the soils used in this experiment. Immediately following dispersal, soil samples were passed through a 53 μm sieve and rinsed with tap water. Particles smaller than 53 μm were discarded and particles remaining on the sieve were dried in a 105 °C forced air oven for 24 to 48 hours to a constant weight. Weight of POM was recorded.

Dry whole soil samples and POM residues were pulverized in a shatterbox mill (Shatterbox Model 8530, SPEX CertiPrep, Metuchen, NJ) before a 30 to 100 μg sample was analyzed for total C and N (PDZ Europa ANCA-GSL elemental analyzer, Sercon Ltd, Cheshire, UK).

Available soil nitrate was assessed during the growing season using anion exchange resin strips (3 per plot) in the potato phase only of the listed crop rotation treatments. Anion exchange resin (Ionics AR204-SZRA Anion Exchange Membrane, Waterville, Massachusetts, USA), as applied in this study, provides an integrated quantification of soil NO_3-N content with time, temperature and soil water content. After all fertilizer applications for the season were completed, triplicate 2.5 x 10 cm resin strips were charged (shaken 1 h in 0.5 mol/L HCl and 5 h in 0.5 mol/L $NaHCO_3$ then rinsed in deionized water), and installed at a 0-10cm depth at 4 points in time and were left in place for 10 days at each time point. Resin strips were placed within the potato row, between plants, without root exclusion devices and were oriented in a vertical position. Anion strip removal dates are listed in Table 4.5. Anion resin strips were inserted into the soil by making vertical slots in the soil with a knife, placing the strips into the slot, and firming soil around the strip to ensure close contact between the soil and strip. After 10 days, the anion strips were removed from the soil, rinsed with deionized water to remove any adhering soil, placed in individual and labeled zip-close plastic bags for return to the laboratory, and new strips were placed in an adjacent location. At the laboratory, 70 mL of 2 M KCl was added to each labeled plastic bag. Strips and KCl were shaken for 1 h, extract decanted into a scintillation vial, and frozen until analysis. Before reuse, anion strips were recharged as described with HCl and $NaHCO_3$. Anion exchange strip extracts were analyzed for NO_3-N using a SmartChem 140 discrete analyzer (Unity Scientific, Brookfield, CT, USA).

Soil inorganic N availability was assessed at the end of the growing season by quantifying both soluble N and N mineralization potential. Soils were sampled with a 6.4 cm enclosed bucket auger to a depth of 51 cm in all plots of all treatment combinations after fall crop harvests. Four soil cores were collected from each split plot and cores were segmented into 0-20 cm and 20-51 cm depths. Four additional 0-20 cm cores were collected from each plot. Cores were combined by depth, were mixed, sieved (6 mm) and subsampled and were stored at 5 °C for up to 3 days before subsampling and KCl extraction. Gravimetric soil water content was determined by weighing a subsample, drying at 105 °C for 24 h and reweighing. Soil subsamples were extracted with 1M KCl and extracts were filtered and stored at -20 °C until inorganic N analysis. Inorganic N (NH_4-N + NO_3-N) was quantified using a SmartChem 140 discrete analyzer (Unity Scientific, Brookfield, CT, USA). An aerobic N mineralization potential assay was performed by incubating field-moist soil subsamples at 25 °C for 30d. Soil moisture was adjusted to 60% of field capacity before incubation if necessary. Net N mineralized (NMP) was calculated by subtracting the day 0 inorganic N content from the inorganic N content after 30 d of incubation.

Statistical Analysis

Because the 2 field sites included in this experiment differ in both soil type and climate, data from each site was analyzed separately. Treatment differences due to cropping system were identified using an ANOVA with the PROC MIXED procedure in SAS software (SAS, 2008) when variables were distributed normally. When non-normally distributed data were encountered, a suitable mathematical transformation was applied, resulting in normally distributed data, which were then subjected to ANOVA using PROC GLIMMIX. Data were back-transformed within PROC GLIMMIX using the 'ILINK' command for reporting and presentation. For some parameters, suitable transformations were not possible, however. Due to significantly different variances for some cover crop parameters, rotation treatments using a bare winter fallow were analyzed separately from rotations with winter cover crops. Where significant ($p<0.05$) main effects or interactions were detected, an LSD test and the PDMIX800 macro (Saxton, 1998) were used to separate means. A non-parametric one way ANOVA was applied to POM and macro-POM data to identify differences in medians of treatment groups across years and location. Within SAS, the PROC NPAR1WAY was used with the WILCOXON option (SAS, 2008) to perform a Kruskal-Wallis test. Where a significant ($p<0.05$) treatment effects, ranks were compared and separated using the K_WMC SAS macro (Elliott and Hynan, 2011).

RESULTS AND DISCUSSION

Above- and Below-ground Biomass Yields

Fall, winter and early spring temperatures were slightly warmer than the 10-year average at both Entrican and Benton Harbor sites, and resulted in a slightly larger accumulation of GDD by winter cover crops (Table 4.2). Early-planted Rye and RV cover crops received 1171 GDD at Entrican, and to 1187 GDD at Benton Harbor, from fall planting to spring termination. Late-planted Rye and RV covers received about half as many GDD, just 515 and 629 GDD at Entrican and Benton Harbor respectively. This difference in GDD exposure is reflected in above-ground biomass yields for Rye and RV cover crops. Spring above-ground cover crop biomass accumulation ranged from 1139 to 5206 kg ha^{-1} at Entrican and from 1359 to 5706 kg ha^{-1} at Benton Harbor (Table 4.6). At both locations, earlier planted Rye and RV cover crops yielded almost double the above-ground biomass of Clover or late-planted Rye and RV. Red clover, frost-seeded into wheat following potatoes, typically established well at Entrican, but poorly in the coarser soils at Benton Harbor. Clover plots at Benton Harbor had a greater presence of weed biomass. Legumes often establish better on finer textured soils than on sandy soils (Hesterman et al., 1992; Martens et al., 2001). Despite its lengthy growing window (March to May), only 1139 and 1359 kg ha^{-1} of above-ground Clover biomass accumulated at Entrican and Benton Harbor respectively. Early Bare plots accumulated more weed biomass than Late bare plots at both locations (Table 4.6). Late Bare plots were tilled during cooler fall weather, when fewer GDD were available for subsequent germination and establishment of weed seedlings. Weed biomass in Bare plots was a mixture of winter annual species at both Entrican and Benton Harbor including common chickweed (*Stellaria media*), field pennycress (*Thlaspi arvense*), shepherd's purse (*Capsella bursa-pastoris*) and henbit (*Lamium amplexicaule*). More weed biomass accumulated at the slightly warmer Benton Harbor location than at Entrican. A subset of plots was sampled to investigate accumulation of both above- and below-ground biomass at each location. This subset included 4 field replicate plots of frost-seeded Red Clover and Late-planted Rye and RV only. Clover plots produced the greatest amount of root biomass at Entrican, 4229 kg ha^{-1}, versus 1463 and 602 kg ha^{-1} for Rye and RV respectively. All 3 treatments yielded a similar quantity of root biomass at Benton Harbor, about 1450 kg ha^{-1} (Table 4.6). Total biomass and shoot:root ratio were calculated only for those treatments for which both above- and below-ground biomass was quantified and are listed in Table 4.7. Clover, undersown into wheat following potatoes, yielded significantly greater total biomass than Late-planted Rye or RV at Entrican mainly due to its large root biomass accumulation. Large root biomass for Clover is also reflected in its low shoot:root ratio. At Entrican, RV yielded the least total biomass, 2361 kg ha^{-1}, and had the highest shoot:root ratio, 3.56. Clover, Rye and RV total biomass and shoot:root ratios were similar at Benton Harbor and averaged 3440 kg ha^{-1} and 1.68 shoot:root ratio. Bare plots, following potatoes, at Entrican produced no total biomass, and at Benton Harbor a yield of 162 kg ha^{-1} total biomass was measured with a relatively high shoot:root ratio of 3.34.

The long term impact, beyond a single growing season, of Late vs. Early cover crop seeding in this experiment would be expected to be negligible, as in each of these 2-year potato rotations, Late seeding after potatoes would be followed by Early seeding after snap beans or wheat the subsequent season. Late and Early cover crop seeding was present in all rotations.

Above-ground Biomass Biochemical Quality

Neutral-detergent fiber content of above ground cover crop biomass varied widely and revealed similar trends at both Entrican and Benton Harbor. The NDF fraction represents a heterogeneous set of interrelated plant cell wall biomolecules including hemicelluloses, cellulose and lignin, varying in degradation rate. Non-NDF fraction, referred to as neutral-detergent soluble material, contains more soluble protoplasmic molecules and pectin. Carbon and N associated this neutral-detergent soluble fraction would be expected to be available to growing plants and soil biota over a short time frame of weeks to months while NDF-C and –N would be expected to be mineralized more slowly (Van Soest, 1967). Neutral detergent fiber residue may be further extracted with a 1.0 N sulfuric acid and cetyl trimethylammonium bromide solution which solubilizes hemicelluloses leaving cellulose and lignin in the insoluble residue. This residue may then be extracted with 72% sulfuric acid to solubilize cellulose and leave lignin as an insoluble residue (ADL) (Van Soest, 1967). ADL therefore represents the most slowly degradable or recalcitrant fraction of plant cell wall materials. At both locations, NDF concentration was greatest for Early Rye, 69% average, and least for Clover, 45% average, and for weed biomass, 43% average, in above ground cover crop tissues (Table 4.8 and 3.9). Early RV and Late Rye and RV NDF content were intermediate and ranged from 53 to 61 NDF % at both locations. Lignin content also varied widely and showed similar trends at both Entrican and Benton Harbor, with the exception of Clover following wheat. Clover established poorly at Benton Harbor, but the small biomass that was present contained 8% ADL, which was significantly higher than other cover crops. Generally, weed and legume species exhibited the highest ADL content while Rye contained the least ADL and early planted cover crops contained a higher ADL fraction compared with Late planted covers, across location. At similar maturities, legume tissues typically contain significantly less NDF and more lignin than grasses, and grasses normally increase NDF and lignin as proportion of dry matter as they mature from vegetative to reproductive stages (National Research Council, 1982; National Research Council, 2001). Lignin is generally accepted as a primary component limiting the degradation of plant cell wall tissues (Besle et al., 1994; Grabber, 2005). The ADL to NDF ratio roughly represents the proportion of cell wall that may be associated with lignin and has been linked to increased recalcitrance and decreased enzymatic and microbial degradation of plant tissues (Jung and Casler, 2006; Traxler et al., 1998). Legumes typically contain less NDF than grasses, but lignin generally comprises a higher proportion of the legume NDF fraction than for grasses (Buxton and Russell, 1988). The ADL:NDF ratio ranged from 0.052 to 0.128 at Entrican and from 0.066 to 0.163 at Benton Harbor. A low ADL:NDF ratio indicates that lignin comprises a smaller fraction of plant cell wall tissues, while a high ratio indicates a greater extent of cell wall lignification, though the exact nature of lignin association with cell wall carbohydrates cannot be inferred from this simple ratio. In this experiment ADL:NDF ratios are higher, across location, for Bare plot weeds and for Early planted legumes than for grasses and Late planted cover crops. These plant cell wall fractions can be expected to degrade more slowly than residues with lower ADL:NDF ratios. At Entrican, Clover ADL:NDF ratio was 0.072, one of the lowest treatment ratios, while at Benton Harbor where clover did not establish well, the ratio was quite high, 0.159, and was similar to Bare plot weed biomass ratios. The high ratio at Benton Harbor may be due to higher moisture stress and weed contamination in plots where Clover established and grew poorly. Total yield of cover crop NDF and ADL at both Entrican and Benton Harbor experimental sites are listed in Table 4.10. Early planted Rye and RV produced significantly more NDF and ADL per hectare than Clover, Bare plots or Late planted Rye or RV. Differences in total NDF and ADL production are due mainly to differences in above-ground yield and less due to differences in NDF and ADL content. Rye and RV plots at Entrican and Benton Harbor yielded 2 to 10 times more NDF and ADL than other treatments.

Unharvested aerial wheat, potato and snap bean biomass were not sampled in this experiment; their yields and compositions are unknown. These data, had they been collected, would help to completely quantify and characterize annual above-ground biomass C and N inputs for each cropping system. Reference tables list typical mature wheat straw as containing 75-85 % NDF, 9-14% ADL, 0.6 to 0.7% N and a C:N ratio of over 60 (National Research Council, 1982; National Research Council, 2001). Mature, non-senescent potato vines have been found to contain 61% NDF, 11% ADL, 1.8% N with a C:N ratio of approximately 24 (Parfitt et al., 1982). Analysis of mature *Phaseolus vulgaris* stem and leaf tissues revealed that they contained 51% NDF, 5.4% ADL, 1.1% N and a C:N ratio of about 40 (López et al., 2005).

Macro-POM-C and -N

Tables 4.11 and 4.12 list macro-POM-C, the C fraction measured in large (> 6 mm) plant residue particles separated from the Ap horizon soil samples on 3 dates during the growing season. Macro-POM-C pools varied with time, crop rotation and cover crop treatment and were more variable than other SOM fractions because pool size of macro-POM-C reflects quantity of recently incorporated plant tissues. The first sampling date at Entrican, June 1, was 10 days after cover crops were terminated and incorporated, while the first sampling at Benton Harbor occurred on May 26, just 3 days after cover crop termination and incorporation. At the first sampling date, macro-POM-C ranged from 15 to 1971 mg kg^{-1} soil at Entrican and from 127 to 2923 mg kg^{-1} at Benton Harbor. Early planted Rye plots held the most macro-POM-C on the first sampling date at Entrican, while Early and Late planted Rye and Early planted RV each had the most macro-POM-C at Benton Harbor at the first sampling. These same treatments also yielded the most above-ground biomass at each location. Early planted covers contributed more macro-POM-C at this first sampling date than their Late planted counterparts. Though the quantity of macro-POM-C at the first sampling was somewhat proportional to quantity of measured cover crop biomass, the actual correlations between above-ground or total biomass and quantity of macro-POM-C measured in each plot at the first sampling date were poor for both locations ($R^2 < 0.2$, data not shown). If all above-ground plant material were quantitatively recovered as macro-POM-C, Entrican plots would have contained between 24 mg macro-POM-C kg^{-1} soil for Early Bare and 1698 mg macro-POM-C kg^{-1} soil for Early RV. Benton Harbor plots would have contained approximately 94 mg macro-POM-C kg^{-1} soil for Early Bare and 1637 mg macro-POM-C kg^{-1} soil for Early RV. Addition of below-ground, root biomass would raise these expected macro-POM-C ranges markedly. A number of factors may be responsible for this weak relationship between measured above-ground biomass and recovered macro-POM-C. Error associated with plant biomass and macro-POM sample collection can contribute variation, as can error associated with separating macro-POM from soil samples. Analytical error in quantifying plant biomass and C in macro-POM samples can also contribute to a poor relationship. Additionally, quantity of root biomass was not measured for all treatments and the effect of incorporating standing cover crops with a disk could also have had differential effects on different crops and different maturities, resulting in different residue particle size distributions.

From the first to the second soil sampling date, on 7 August at Entrican and on 4 August at Benton Harbor, soil macro-POM-C fraction decreased in most experimental treatments but not in all (Tables 4.11 and 4.12). Bare and Wheat/Clover plots were the exception to this generalization at each location. As sampled and quantified in this experiment, the macro-POM-C fraction may include dead, decomposing tissues and living plant biomass on the soil surface or within the Ap horizon, so increased recovery of macro-POM-C during the growing season is reasonable, especially in plots where little biomass was present at the beginning of the growing season and where main crops were growing. At the second sampling date, much less variation between treatments was evident. At Entrican, the Bare plots, whether potatoes or beans were presently growing, both increased macro-POM-C fraction by an average of 167%, while Early and Late Rye and RV plots decreased macro-POM-C fraction by an average of 86%. Wheat/Clover plots had a 19% increase in macro-POM-C and yielded the most macro-POM-C of all treatments at the second sampling with 469 mg macro-POM-C kg^{-1} soil. At Benton Harbor, Wheat/clover plots also increased, by 3%, to 807 mg macro-POM-C kg^{-1} soil, the most of any cover crop treatment at the second sampling date at Benton Harbor. Benton Harbor Late Bare plots, with a bean crop present, also increased in macro-POM-C, by 36%. All other cover crop treatments lost an average of 71% of initial macro-POM-C by the second sampling. Wheat and Early and Late RV plots contained the most macro-POM-C at the second sampling date at Benton Harbor.

The third and final soil POM sampling took place on 27 October at Entrican. At Entrican, no significant difference was detected among cover crop treatments at the 27 October sampling. All Entrican plots with a main crop of snap beans in 2006 increased macro-POM-C, by an average of 78% from the 2nd to the 3rd soil POM sampling date. Bean harvest had occurred in early September 2006 and cover crops were planted in these plots in late September, so incorporated senescent plants and root biomass of small cover crop seedlings were present in Bean plot soil for POM sampling on 27 October. Wheat plots were harvested in July and Clover was allowed to grow for 3 months prior to soil POM sampling. Presence of clover root biomass, dead wheat stubble and roots and weed biomass contributed to the 202 mg macro-POM-C kg^{-1} soil measured in these plots but this fraction decreased 57% from 469 mg macro-POM-C kg^{-1} soil detected at the 2nd sampling date. All plots with Potato main crops decreased macro-POM-C fraction from the 2nd to the 3rd sampling date. Potatoes following Wheat/Clover dropped only 8% while Bare, Rye and RV cover crop plots decreased macro-POM-C by an average of 47% from the 2nd sampling date. Potato main crop plots were harvested at Entrican on 15 October and fall tillage and cover crop planting occurred on 23 and 25 October, just days prior to sampling. No seedlings were present to contribute to macro-POM-C in these plots, but the relatively small amount of residual potato or weed biomass was disked in and contributed to macro-POM-C.

The last soil POM sampling took place on 26 October at Benton Harbor and all other field operations were sequenced similar to the Entrican site. All Late plots containing Beans or

Wheat were already tilled and seeded with cover crops in September. On 26 October at Benton Harbor, the Wheat/Clover after Potatoes plots yielded the most macro-POM-C, 519 mg macro-POM-C kg^{-1} soil, and all other treatments were similar, averaging 176 mg macro-POM-C kg^{-1} soil. Macro-POM-C fractions decreased in all plots at Benton Harbor from the 2nd to the 3rd soil POM sampling date. Declines ranged from 25% to 79%, averaging a 50% decrease in macro-POM-C. Generally,

Macro-POM-N is the N pool present in large (> 6 mm) plant residue particles separated from the top 20 cm of soil at 3 sampling dates during the growing season. Macro-POM-data are listed in Tables 4.13 and 4.14 for Entrican and Benton Harbor locations. Macro-POM-N trends over the season are similar to those observed with macro-POM-C. At the first sampling date, just after cover crop incorporation, macro-POM-N fractions ranged from 0.7 to 49.1 mg macro-POM-N kg^{-1} soil at Entrican and from 4.3 to 66.1 mg macro-POM-N kg^{-1} soil at Benton Harbor. At Entrican, Early Rye, RV and Clover macro-POM-N was greater than other treatments. At Benton Harbor, Bare and Clover plots yielded the least macro-POM-N compared with Rye and RV plots. Legume cover crop plots did not yield more initial macro-POM-N than non-legumes at either location. At the second sampling at Entrican, Late Wheat plots yielded significantly more macro-POM-N than all other treatments. Early and Late Bare plots increased macro-POM-N content dramatically, by 145 and 239%, respectively. Wheat plots also increased macro-POM-N fraction but more marginally, by just 16%, to 20.4 from 17.1 mg macro-POM-N kg^{-1} soil. All other treatments decreased macro-POM-N fraction from the first to the second sample date by an average of 77%. At Benton Harbor, no significant treatment effect on macro-POM-N was detected at the second sampling. Macro-POM-N pool decreased in all treatments at Benton Harbor from the first to second sample dates except for Late Bare, which increased by 96%, from

4.3 to 8.3 mg macro-POM-N kg^{-1} soil. All other treatments decreased by an average of 59% from the first sampling to the second. At the third and final sampling date at Entrican, macro-POM-N ranged from 1.9 to 10.3 mg kg^{-1} soil, but rotation and cover crop treatment had no significant effect. Clover and Late Bare, Rye and RV increased macro-POM-N pool size by an average of 22%, while Early Bare, Rye, RV and Late Wheat all decreased in macro-POM-N by an average of 62% at Entrican. At Benton Harbor, macro-POM-N at the last sample date ranged from 2.9 to 18.1 mg kg^{-1} soil. Late Wheat plots contained significantly more than the other cover crop treatments. Late Wheat was also the only treatment to increase macro-POM-N pool size from the second to the third sampling date. Macro-POM-N pool size decreased for all other cover crop treatments from the second to the third sampling date at Benton Harbor.

Generally, rotation and cover crop were both important factors in quantity and persistence of macro-POM-C and –N. Rye and Wheat/Clover plots consistently contained more macro-POM-C and –N than Bare plots across location and planting date, as detected with a nonparametric Wilcoxon rank test ($p \leq 0.0017$). Early vs. Late cover crop planting date yielded no significant ranking effect for macro-POM-C or –N.

Carbon:nitrogen ratios in macro-POM fractions are listed for both locations in Tables 4.15 and 4.16. At the first POM sampling date, C:N ratio of macro-POM fractions were slightly higher at Benton Harbor than at Entrican, apparently due to greater accumulation of GDD and more advanced development of cover crops at Benton Harbor. Carbon:N ranged from 14.8 to 40.8 at Entrican and from 17.2 to 46.1 at Benton Harbor. At both locations, initial macro-POM C:N ratios, at the first POM sampling date just after cover crop termination and incorporation, were lowest for Bare and Clover plots and higher for Rye and RV plots. Decomposition rates for plant tissues has been shown to be correlated with C:N ratio, or with N concentration (Enríquez et al., 1993). A C:N ratio in plant tissues of greater than 20 is expected to result in initial net immobilization of N and net mineralization of N generally begins when the ratio is below 20 (Brady and Weil, 1996). According to this criteria, the only plant residue to initially mineralize N was Early Bare. All other biomass would have caused an initial immobilization of N as their C:N ratios were above 20.

At the second sampling date in early August, C:N ratios generally decreased from the initial sampling date just after cover crop incorporation, but not for every treatment combination. By early August, only Clover, Late RV and Wheat plots contained macro-POM with C:N ratios above 20 at Entrican, for all other treatments C:N ratio decreased below 20. C:N ratio can decrease due to loss of C, or to enrichment in N, perhaps as a result of microbial colonization and assimilation of N. Macro-POM in Early Bare and Clover plots at Entrican increased C:N ratio while C:N ratio for all other treatments decreased. At Benton Harbor, early August macro-POM C:N ratios were overall slightly higher than at Entrican and were generally decreased from initial ratios, except for the Late Wheat plots. In the Wheat plots at Benton Harbor, C:N ratio of macro-POM increased from the first to the second sampling by 248%.

The last soil POM sampling occurred in late October at both sites. At Entrican, C:N ratio of macro-POM in Early Bare plots was the highest, at 37.6. Early RV and Clover and Late Bare were the lowest, with ratios of 20.7, 18.2 and 20.9 respectively. Early Rye and Late Rye, RV and Wheat all had intermediate ratios at the final sampling, ranging from 24 to 28.6. Macro-POM C:N ratio increased by an average of 47% from the second to the third sampling date for all treatments at Entrican except Early Clover, which decreased by 29%. C:N ratios in macro-POM at Benton Harbor were again slightly higher overall than at Entrican at the last sampling date. At Benton Harbor, Late Bare, RV and Wheat had the highest macro-POM C:N ratios at this last sampling, with 39.1, 33.4 and 29.9 respectively. Early Bare macro-POM samples were too small to analyze and Early Rye, RV, Clover and Late Rye all had lower ratios, ranging from 18.0 to 25.1. Macro-POM C:N ratio increased for Early Clover and for Late Bare and RV treatments from the second to the third sampling date at Benton Harbor while the C:N ratio decreased for all other treatments.

A nonparametric Wilcoxon rank test performed across location and cover crop planting date showed that Bare plots consistently contained less macro-POM-C and -N than Rye or Wheat/Clover plots ($p \leq 0.0017$) however no significant ranking effect was detected for macro-POM C:N ratio. Early vs. Late cover crop planting date yielded no significant ranking effect for macro-POM-C;N ratio either.

POM-C and -N

Tables 4.17 and 4.18 list POM-C for the Entrican and Benton Harbor locations, respectively. POM-C is the C measured in the sand fraction (> 53 μm) of Ap horizon soil samples, after macro-POM was removed, at 3 sampling dates during the 2006 growing season. POM-C pool size was more stable over time than macro-POM-C and was 3 to 6 times greater than macro-POM-C pools across treatments and locations. At Entrican across 3 sampling dates, the 2 phases of the Potato-Wheat/Clover rotation numerically had the most POM-C, though no significant cropping system effect was detected. Early Rye and RV and Late Bare were also among the treatments with at least 1880 mg kg^{-1} POM-C. Significant cropping system effects on POM-C were detected at Benton Harbor across 3 sampling dates. Similar to Entrican, both phases of the Potato-Wheat/Clover rotation were among the highest treatments, along with Early RV and Late Rye. At Entrican on June 1, 10 days after cover crops were terminated, POM-C treatment averages ranged from 1161 to 2533 mg kg^{-1} and were significantly affected by rotation and cover crop treatment. At Benton Harbor on May 26, 3 days after cover crop termination and incorporation, POM-C ranged similarly from 1308 to 2253 mg kg^{-1} but was not significantly affected by rotation and cover crop treatment. Early Rye, RV and Clover, and Late Wheat plot soils contained the most POM-C on the first sampling date at Entrican, while Early RV and Clover and Late planted Rye and Wheat were the top 4 treatments for POM-C at Benton Harbor at the first sampling. With the exception of Late RV, all cropping system combinations that included a legume cover crop were in the top 4 treatments with the most POM-C at both locations. A nonparametric Wilcoxon rank test showed that Wheat/Clover plots consistently contained more POM-C than Bare or RV plots ($p \leq 0.0009$) across location and rotation phase., while Wheat/Clover plots and Rye plots were similarly ranked.

From the first to the second soil sampling date, on 7 August at Entrican and on 4 August at Benton Harbor, POM-C fraction decreased in some experimental treatments and increased in others. At Entrican, the four treatments with the highest POM-C fraction (Early Rye, Early RV and Early Clover and Late Wheat) at the first sampling date remained the highest at the second sampling date, though there were no significant differences between treatments at the second sampling date. Overall, POM-C fraction increased by 6% between the first two sampling dates at Entrican, but half the treatments increased slightly and half decreased slightly. At Benton Harbor, average POM-C fraction decreased by 2% between the first two sampling dates. Similar to Entrican, the four treatments with the highest POM-C fraction at the first sampling date remained the highest at the second sampling date. POM-C increased slightly in half the treatments at Benton Harbor and half the treatments decreased slightly between the first two sampling dates. Late Wheat plots contained significantly more POM-C than other treatments at Benton Harbor on the 4 August sampling date.

From the second to the third soil sampling date, on 27 October at Entrican and on 26 October at Benton Harbor, POM-C fraction again decreased in some experimental treatments while increasing in others. Across all treatments, POM-C fraction decreased by 9% between the last two sampling dates at Entrican; potato phase plots decreased by an average of 16% and non-potato phase plots increased POM-C by an average of 6%. At Benton Harbor, average POM-C fraction again decreased by 2% between the second and third sampling dates. At Entrican, Early Clover and Late Wheat remained among the treatments with the highest POM-C fraction there were no significant differences between treatments at the 27 October sampling date. Late Bare and Early Rye and RV also had greater than 1700 mg POM-C kg^{-1} soil at the end of the growing season at Entrican. Early Clover, Late Rye and Late Wheat plots continued to yield the highest POM-C fractions and Late RV increased to greater than 1800 mg POM-C kg^{-1} soil at the end of the growing season to round out the top four treatments at Benton Harbor. Early Bare, Rye, RV and Late Bare treatments had significantly less POM-C at the end of the growing season than Late Rye and Late Wheat at Benton Harbor. Between the second and third sampling dates at Benton Harbor, potato phase plots lost an average of 6% and non-potato plots gained an average of 3% POM-C. Over the entire growing season from early June to late October, soil POM-C fraction decreased in potato phase plots by an average of 7% and 13% at Entrican and Benton Harbor respectively, while POM-C in non-potato phase plots increased by an average of 7% and 9% respectively. In contrast, macro-POM-C decreased over the same time period by an average of 83% across treatments at each location.

Tables 4.19 and 4.20 list POM-N for the Entrican and Benton Harbor locations, respectively. POM-N is the N associated with the sand fraction (> 53 μm) of Ap horizon soil samples, after macro-POM removal. The POM-N pool sizes were more stable over time than macro-POM-N and were 5 to 10 times greater than macro-POM-N pools across treatments and locations. A nonparametric Wilcoxon rank test showed that Wheat/Clover plots consistently contained more POM-N than Bare, Rye or RV plots ($p < 0.0001$) across rotation phase. At Entrican across 3 sampling dates, no significant cropping system effect was detected. Two phases of the Potato-Wheat/Clover rotation along with Early Rye and RV and Late Bare had the most POM-N. Significant cropping system effects on POM-N were detected at Benton Harbor across 3 sampling dates. Similar to Entrican, both phases of the Potato-Wheat/Clover rotation were among the treatments with the largest POM-N pool size, along with Early RV and Late Rye. At the first sampling date shortly after cover crops were terminated and incorporated, cropping system treatments at Entrican ranged from 69.2 to 149.0 mg POM-N kg^{-1} soil and from 79.6 to 142.1 mg POM-N kg^{-1} soil at Benton Harbor. At Entrican on the first sampling date, just after cover crop termination and incorporation, Early Rye, RV and Clover and Late Bare and Wheat plots yielded the most POM-N and were statistically similar, averaging 119.2 mg POM-N kg^{-1} soil. The remaining 3 treatment combinations, Early Bare, Late Rye and Late RV contained the least POM-N at the first sampling date, averaging 74.5 mg POM-N kg^{-1} soil. At the first sampling date at Benton Harbor, the largest POM-N pool was detected in Late Wheat plots, but Early Bare, RV, Clover and Late Rye plots were statistically similar and averaged 124.6 mg POM-N kg^{-1} soil. Soils from the Early Rye, Late Bare and Late RV plots contained the least POM-N, averaging 92.5 mg kg^{-1} soil. Early RV and both phases of the potato-wheat/clover rotation were among the treatments with the largest POM-N pool at each location.

At the second sampling date at Entrican on 7 August, all cropping system treatments were statistically similar, but Early Rye, and both phases of the potato-wheat/clover rotation contained the numerically highest POM-N fractions. At Entrican, POM-N rose from the first to the second sampling date by 3% across treatments. At Benton Harbor on the second sampling date, both potato-wheat/clover phases continued to yield the most POM-N, averaging 146.1 mg POM-N kg^{-1} soil, while the two Bare treatments yielded the least, 91.2 mg POM-N kg^{-1} average. Other treatments were intermediate. Across treatments, POM-N increased by 3% from the first to the second sampling date at Benton Harbor.

At Entrican at the third sampling date on 27 October, no significant differences between cropping system treatments were detected and the average POM-N fraction across treatments decreased by 3% to be approximately equivalent to the 1 June average. Both phases of the potato-wheat/clover rotation continued to have higher than average POM-N content at Entrican at the last sample date along with the Late Bare plots. Early Bare and Late Rye and RV remained below 100 mg POM-N kg^{-1} soil. At Benton Harbor at the 26 October sample date both phases of the potato-wheat/clover cropping system had the highest POM-N contents, along with the Late Rye plots. This group averaged 142 mg POM-N kg^{-1} soil while the remaining 5 treatments averaged 102.5 mg kg^{-1} POM-N. Over the entire growing season from early June to late October, soil POM-N fraction decreased in potato phase plots by an average of 2% and 4% at Entrican and Benton Harbor respectively, while POM-N in non-potato phase plots increased by an average of 9% and 14% respectively. In contrast, macro-POM-N decreased over the same time period by an average of 70% across treatments at each location, excluding Late Bare at Entrican which had the least initial macro-POM-N and was the only treatment for which macro-

POM-N increased. For this treatment, macro-POM-N increased 343%, from 0.7 to 3.1 mg kg^{-1} soil over the duration of the growing season.

Early-planted Rye and RV produced the most NDF and ADL per hectare and caused the highest early-season macro-POM-C and –N at the first sampling date in June. However, across locations, both phases of the Potato-Wheat/Clover rotation treatment had the most persistent and one of the highest macro-POM- and POM-C and –N through the last sampling date in late October. Because the winter wheat and frost seeded clover portion of the rotation is planted with one tillage operation, the Potato-Wh/Clover treatment was tilled less frequently than the Potato-Bean rotations which required an extra tillage prior to bean planting and prior to a winter cover crop. In a 10-year potato rotation study, Anger et al (1999) found that total soil C and light fraction-C (light fraction C is comparable to macro-POM-C + POM-C) were sensitive to potato cropping rotation sequence. Inclusion of perennial legume forages in at least 4 of the 10 crop years resulted in higher total C and N and light fraction-C and –N at the end of the experiment, than a continuous potato rotation. Researchers in this study attributed the increased light fraction-N content to an increase in N-rich root residues in rotations including legumes. In this same study, decreasing frequency of potato crop in the rotation also increased light fraction-C and –N, reportedly by reducing the frequency and intensity of tillage operations (Angers et al., 1999). Grandy et al (2002) concluded that a effects of a leguminous green manure crop on SOM and LF in potato cropping systems were much smaller than continuous or periodic amendments of compost or animal manure. In this study, even a single manure or compost application of 5 to 22 Mg ha^{-1} dry matter caused a rapid increase light fraction- and total soil C in a potato rotation. For long-term retention of these SOM improvements, these scientists recommended reduction of soil disturbances and tillage or reducing the frequency of potatoes in the rotation sequence (Grandy et al., 2002).

Carbon:N ratio in POM fractions for Entrican and Benton Harbor soils are listed in tables 4.21 and 4.22, respectively. POM-C:N ratios were remarkably stable, averaging 17.1 over the duration of the growing season at Entrican and 15.9 at Benton Harbor. A nonparametric Wilcoxon rank test yielded no significant effect of crop rotation or winter cover crop. At Entrican on 1 June just after termination and incorporation of cover crops, POM C:N ratios ranged from 16.8 to 18.6, averaged 17.4 and did not differ significantly among treatment combinations. On the first sample date, 26 May, at Benton Harbor, POM C:N ratios ranged from 15.3 to 18.3, averaged 16.5 and no significant differences between treatments were detected. At Benton Harbor, both phases of the potato-wheat/clover rotation had the lowest POM C:N, averaging 15.4.

At the second sampling date at Entrican on 7 August, significant treatment effects were detected. Generally, plots in potato phases had a higher C:N than plots in non-potato phases, despite the fact that potato plots received more fertilizer N. Potato plots also generally had more mature cover crop biomass with higher NDF and ADL yields than non-potato plots. This effect was not evident at Benton Harbor at the second sampling, however. Significant treatment differences were detected at Benton Harbor at the second sampling, but no clear distinction between Early and Late plots existed. Early RV and Clover had the lowest POM C:N ratios, with 15.2 and 14.4 respectively. All other treatments were statistically similar with an average POM C:N ratio of 16.2.

On the third and last sampling date on 27 October at Entrican, no significant differences were found among the 8 cropping system treatments and POM C:N ratios ranged from 16.0 to

17.3. At Benton Harbor, significant cropping system effects were detected at the last sampling date on 26 October. POM C:N ratios at Benton Harbor ranged from a low of 13.9 for Early Clover to 16.3 for Early Bare. Lowest POM C:N ratios were found in Early RV, Clover and Late Wheat plots, averaging 14.5. C:N ratio in POM for the other 5 treatments were higher, averaging 15.9. Average POM C:N ratio for all treatments was lower at Benton Harbor than at Entrican and average ratios decreased steadily over the growing season at both locations.

Particulate organic matter C:N ratio can decrease as C is respired and removed, or as N increases, perhaps due to colonization by microbes rich in N from multiple sources. Conversely, C:N ratio of POM or macro-POM can increase as C is added, by actively photosynthesizing plants or from another C fraction, or as N is removed to another pool. A laboratory study, where growing plants were excluded while plant residue decomposition was monitored, light fraction-C:N ratio decreased steadily for all plant residues, regardless of initial C:N ratio (Bending and Turner, 1999). Willson et al (2001) studied C and N in POM fractions in field-scale corn-soybean rotations during one full growing season and found that though both C and N increased through mid-season and then declined again, the C:N ratio of both coarse (> 250 μm) POM and fine (53 to 250 μm) POM fractions remained fairly constant throughout the growing season (Willson et al., 2001). Coarse POM generally had a slightly higher C:N ratio than fine POM.

Soil Nitrogen

Soil N availability in each treatment combination was estimated in two different ways: with anion-exchange resin probes at 3 points during the growing season, and with an aerobic N mineralization assay performed on post-harvest soil samples. Tables 4.23 and 4.24 list available soil nitrate measured with anion-exchange resin probes in potato phase plots only from mid-

August through mid-September at Entrican and Benton Harbor sites, after all N fertilizer applications were complete. Available soil nitrate, as quantified within 0-10 cm depth with anion exchange resin strips, is expressed in µg NO_3-N cm^{-2} of resin day^{-1}, and provides an integrated measure of soil NO_3-N content with time, soil temperature and moisture. Available NO_3-N evaluation began 16 and 21 days after the last N fertilizer application at Entrican and Benton Harbor, respectively. Few significant treatment effects were detected, possibly due to a relatively large pool size of inorganic fertilizer-N relative to organic N sources. Initially, on 10 August, NO_3-N availability ranged from 5.23 µg NO_3-N cm^{-2} day^{-1} for Bean-RV-Potato, to 8.63 µg NO_3-N cm^{-2} day^{-1} for Bean-Bare-Potato. At Entrican, Bare plots consistently had a numerically higher NO_3-N availability than Rye, RV or Clover plots until the last sampling period, though this difference was not significant at any point during the experiment. At the last sampling period ending on 15 September, all 4 treatments sampled had similarly low NO_3-N availability, ranging from 0.21 to 0.47 µg NO_3-N cm^{-2} day^{-1}. Entrican plots decreased in NO_3-N availability by an average of 89% over the duration of the NO_3-N sampling period from 10 August to 15 September. Availability of NO_3-N in surface soils was overall lower in the coarser soils at Benton Harbor. Bare cover crop plots did not exhibit higher NO_3-N availability at Benton Harbor as they did at Entrican. Benton Harbor Bare plots provided just 1.50 µg NO_3-N cm^{-2} day^{-1} during the sampling period ending on 15 August, while RV plots yielded 3.29 µg NO_3-N cm^{-2} day^{-1}. Rye and Clover plots were intermediate. NO_3-N availability decreased steadily over the course of the experiment for all 4 treatments, by an average of 73% from the first to the last sampling period. At the last sampling period, ending on 7 September, RV plots had the highest available NO_3-N, 0.50 µg NO_3-N cm^{-2} day^{-1} and Rye plots had the least available NO_3-N, 0.24 µg NO_3-N cm^{-2} day^{-1}. It should be noted that estimates of N availability measured with ion exchange are influenced by soluble soil N, soil temperature, moisture and time. Soil temperature can increase rate of ion diffusion and rate of nutrient mineralization by soil biota. The effect of soil moisture has been shown to be greater than temperature, reducing diffusion of ions as soils become drier (Qian and Schoenau, 2002). In this study, the large difference between Entrican and Benton Harbor NO_3-N uptake by exchange resin may be due to moisture limitation in the sandier soils at Benton Harbor.

Ap horizon soils (0-20 cm) were sampled in early November and evaluated aerobically for N mineralization potential and results are listed in Tables 4.25 and 4.26. Entrican soils mineralized roughly twice as much N per day as did Benton Harbor soils, 0.20 vs. 0.09 μg N g^{-1} soil day^{-1}. Early Bare, Clover and Late Wheat treatments mineralized the most N at Entrican, averaging 0.22 to 0.24 μg N g^{-1} soil day^{-1}. Late Bare had the least available N, at 0.18 μg N g^{-1} soil day^{-1}. At Benton Harbor, the non-potato phase plots, with Late planted cover crops, mineralized the most N, averaging 0.103 μg N g^{-1} soil day^{-1}, and the potato phase treatments released an average 0.075 μg N g^{-1} soil day^{-1}. No consistent ranking effect among rotations or cover crop treatments was detected with a nonparametric Wilcoxon rank test. In a field experiment examining the effect of a winter rye cover crop on N availability in a corn-soybean rotation. McSwiney et al (2010) found a 60% greater mid-season N mineralization potential for cover cropped plots. However, N availability estimated for 14 days with exchange resins did not differ for cover crops vs. no cover crops in that experiment (McSwiney et al., 2010). It is possible that a briefer deployment of resin probes may have permitted detection of N availability differences in both experiments.

Residual inorganic N was quantified at 0-20 cm and 20-51 cm depths at each experimental site in early November, after all main crops were removed, soil was tilled and cover crops were planted. Inorganic N results are listed in Tables 4.25 and 4.26. At each location, residual NO_3-N fraction was low, but slightly higher in potato phase plots than in non-potato phase plots at both depths. More N fertilizer was applied to potato plots than to snap bean and wheat plots and may have contributed to the elevated NO_3-N in the 20-51 cm layer in potato plots. At Entrican, significant differences in residual NO_3-N were detected at both depths. Nitrate-N in the 0-20 cm layer ranged from 3.95 to 7.21 μg NO_3-N g^{-1} soil and from 3.71 to 6.24 μg NO_3-N g^{-1} in the 20-51 cm depth. Cropping system treatments with the least residual NO_3-N in the 0-20 cm layer were Early Bare and Late Rye and RV. Late Rye and RV were also among the treatment combinations with the least NO_3-N in the 20-51 cm layer along with Late Wheat/Clover. At the 20-51 cm depth all potato phase treatments, and Late Bare, had residual NO_3-N pools of 5.25 μg NO_3-N g^{-1} soil or greater. At Benton Harbor, the largest 0-20 cm NO_3-N pools, 5.95 and 6.40 μg NO_3-N g^{-1} soil, were found in Early RV and Clover plots, while the smallest pools were measured in Late Rye and RV treatments, 4.82 and 4.75 μg NO_3-N g^{-1} soil, respectively. Early RV and Clover also had the largest residual NO_3-N pool in the 20-51 cm layer with 4.75 and 4.55 μg NO_3-N g^{-1} soil, respectively. In this deeper layer, Late Bare, Rye and RV had the least residual NO_3-N with 3.00 μg NO_3-N g^{-1} soil or less. Increases in soil NO_3-N have been linked to decomposition of legume root nodules following crop termination (Mohr et al., 1998) though time would be required for this nodule-N to move to deeper horizons.

SUMMARY

The difference in GDD exposure for Early- vs. Late-planted cover crops was reflected in above-ground yield and quality. Cover crop biomass accumulation ranged from 1139 to 5706 kg ha^{-1} across 2 experimental sites. At both locations, earlier planted Rye and RV cover crops yielded almost double the above-ground biomass of Clover or late-planted Rye and RV. Quantities of NDF and ADL contributed per hectare were greatest for Early-planted Rye and RV while Clover produced one of the smaller yields of NDF and ADL. Early June macro-POM-C and –N pools reflected biomass and quality of cover crops, but these fractions did not persist through the growing season. In late October, Potato-Wheat/Clover rotation plots had the highest macro-POM fractions despite having low macro-POM fractions in early June. Rye and Wheat/Clover plots consistently contained more macro-POM-C and –N than Bare plots across location and planting date, while planting date had no significant ranking effect. POM-C and –N pools were more stable than macro-POM pools during the growing season. Across 3 sampling dates at both locations, Potato-Wheat/Clover rotation plots were consistently among the treatments with the highest POM-C and -N fractions and the lowest POM C:N ratios. Presence of winter wheat and frost-seeded red clover in this cropping system eliminates the need for spring tillage and therefore these plots were tilled much less intensively than all the Potato-Bean cropping system plots. Measurement of NO_3-N availability with anion exchange resin probes detected a sharp decline in soil NO_3-N availability over the last month of the growing season, but few significant cropping system effects were noted. Inorganic N availability estimated with a laboratory mineralization assay revealed greatest availability in the Potato-Wheat/Clover plots at Entrican and in the non-potato phase plots on the coarser soils of Benton Harbor, but no consistent rotation or cover crop effects were detected with a nonparametric rank test. Residual inorganic N after crop removal was generally higher for potato phase plots than for non-potato phase plots to a depth of 51 cm. It is likely that reduced frequency or intensity of soil disturbance and tillage in 6 years of potato-wheat/clover rotation is responsible for increased POM fractions and mineralizable N. Though the soil health benefits of cover crops are numerous and widely accepted, it appears that, regardless of species, cover crops are unlikely to provide enough organic input to improve soil organic matter fractions in fields used for short-rotation potato production. Soil organic matter fractions may possibly be improved where potatoes can be rotated with main crops that permit reduced tillage frequency and intensity.

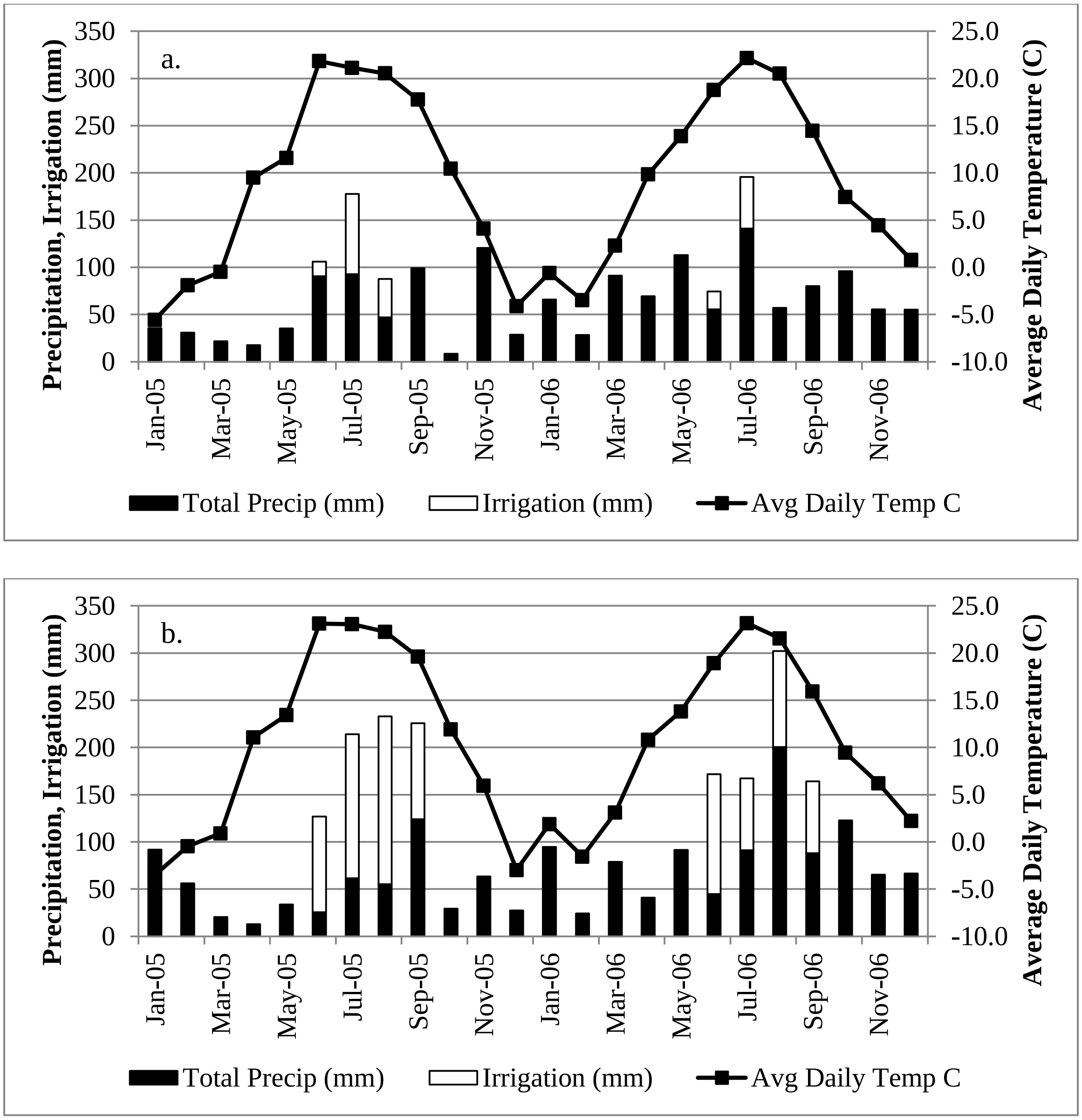

Figure 4.1. Monthly precipitation and irrigation totals (mm) and average daily temperature (°C) recorded at Montcalm Research Farm (a. Entrican, MI) and Southwest Michigan Research and Extension Center (b. Benton Harbor, MI) for January 2005 to December 2006.

Table 4.1. Soil chemical and physical characteristics at the Entrican, MI and Benton Harbor, MI field experiment locations.

	Entrican, MI	Benton Harbor, MI
Texture		
Sand, %	75	88
Silt, %	16	6
Clay, %	9	6
Organic C, %	0.8	0.6
pH	6.2	6.4
CEC, meq/100g	3.5	3.1
Ca, ppm	359	477
K, ppm	122	121
P, ppm	200	150

Table 4.2. Monthly growing degree-day (base 4) accumulations for Entrican and Benton Harbor, MI winter cover crops from September 2005 to May 2006. 10-year average is calculated from daily ambient temperatures from 2000 through 2010.

	Entrican, MI			Benton Harbor, MI		
	2005-06	10-Year Average	SE	2005-06	10-Year Average	SE
September	413	370	21	469	419	23
October	199	167	12	245	227	11
November	67	22	4	115	59	3
December	0	0	0	0	0	0
January	3	0	1	15	0	0
February	0	0	0	3	0	0
March	32	6	4	56	21	1
April	167	130	8	209	169	10
May	307	278	17	305	324	17

Table 4.3. Cropping system treatment identification.

Cropping System (2005 Crop-Winter Cover-2006 Crop)	Fall 2005 Cover Crop Planting	Fall 2005 Cover Crop	Treatment Identification	N fertilizer credit (kg ha^{-1})[b]
Bean-Bare-Potato	Early	Bare Fallow	Early Bare	0
Bean-Rye-Potato	Early	Rye	Early Rye	50
Bean-RV-Potato[a]	Early	Rye+Vetch	Early RV	78
Wheat/Clover-Potato	Early	Clover	Early Clover	56
Pot-Bare-Bean[a]	Late	Bare Fallow	Late Bare	0
Pot-Rye-Bean	Late	Rye	Late Rye	45
Pot-RV-Bean	Late	Rye+Vetch	Late RV	34
Pot-Wheat/Clover	Late	Wheat	Late Wheat	--

[a] Pot = potato; RV = rye-hairy vetch biculture
[b] based on results from Nyiraneza and Snapp (2007)

Table 4.4. Main and cover crop species and variety names.

Crop	**Species**	**Variety**
Potato	*Solanum tuberosum*	Snowden
Snap bean	*Phaseolus vulgaris*	HyStyle
Wheat	*Triticum aestivum*	Caledonia
Rye	*Secale cereale*	Wheeler
Hairy Vetch	*Vicia villosa* Roth	Common
Red Clover	*Trifolium pratense*	Mammoth

Table 4.5. Dates of field experiment agronomic and experimental operations for 2005 and 2006.

	2005		2006	
	Entrican	Benton Harbor	Entrican	Benton Harbor
Fall 2004 wheat and cover crop planting	10/20/04	10/27/04	---	---
Frost-seed red clover	3/24	3/25	3/30	3/31
Sample cover crops	5/17	5/16	5/16	5/10
Spring tillage	5/18	5/18	5/21	5/23
Sample soil, POM	---	---	6/1, 8/3, 10/27	5/26, 8/4, 10/26
Plant potatoes	5/25	5/24	6/1	5/30
Plant snap beans	6/10	6/16	6/13	6/6
Potato split N applications	6/7, 6/28	6/8, 7/15	6/30, 7/25	7/8, 7/24
Harvest wheat	7/15	7/14	7/11	7/10
Install anion resin strips	---	---	7/31, 8/10, 8/21, 8/31	8/4, 8/15, 8/25
Remove anion resin strips	---	---	8/10, 8/21, 8/31, 9/11	8/15, 8/25, 9/6
Harvest snap beans	8/5	8/16	9/9	9/8
Vine kill potatoes	8/30	9/8	9/14	9/7
Harvest potatoes	9/19	10/7, 10/10	10/15	10/6
Fall tillage	8/22, 9/30	8/31, 10/11	9/11, 10/23	9/8, 10/16
Plant wheat	8/23	9/7	9/21	9/20
Plant cover crops	8/23, 10/12	9/7, 10/17	9/21, 10/25	9/20, 10/20
Soil sample	11/21	11/11	11/1	11/15

Table 4.6. Effect of cropping system on yield of above- and below-ground cover crop biomass in spring 2006 at Entrican (16 May 2006) and Benton Harbor, MI (10 May 2006).

			Entrican, MI						Benton Harbor, MI					
Cropping System	Cover Crop Planting	Cover Crop	Above-ground biomass, kg ha^{-1}			Below-ground biomass, kg ha^{-1}			Above-ground biomass, kg ha^{-1}			Below-ground biomass, kg ha^{-1}		
			Mean		SE	Mean		SE	Mean		SE	Mean		SE
Bean-Rye-Potato	Early	Rye	4431	a	772	- - -		- - -	4786	a	495	- - -		- - -
Bean-RV-Potato	Early	Rye+Vetch	5206	a	402	- - -		- - -	5706	a	462	- - -		- - -
Wh/Clover-Potato	Early	Clover	1139	b	256	4229	a	1172	1359	c	272	1501		527
Pot-Rye-Bean	Late	Rye	1989	b	213	1463	b	231	2488	b	204	1436		358
Pot-RV-Bean	Late	Rye+Vetch	1759	b	210	602	b	147	1889	bc	172	1408		330
Pot-Wh/Clover	Late	Wheat	- - -		- - -	- - -		- - -	- - -		- - -	- - -		- - -
ANOVA F-test, p-value														
Source														
Cropping System			<.0001			0.034			<.0001			0.970		
Pot-Bare-Bean	Late	Bare	0		0	0		0	80	b	40	41		20
Bean-Bare-Potato	Early	Bare	300		197	- - -		- - -	869	a	134	- - -		- - -
ANOVA F-test, p-value														
Source														
Cropping System			0.0834						<.0001					

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.
- - - = no below-ground biomass sampled

Table 4.7. Effect of cropping system on yield of above- and below-ground cover crop biomass in spring 2006 at Entrican (16 May 2006) and Benton Harbor, MI (10 May 2006).

			Entrican, MI						Benton Harbor, MI			
Cropping System	Cover Crop Planting	Cover Crop	Total biomass, kg ha^{-1}			Shoot : Root Ratio			Total biomass, kg ha^{-1}		Shoot : Root Ratio	
			Mean		SE	Mean		SE	Mean	SE	Mean	SE
Bean-Rye-Potato	Early	Rye	- - -		- - -	- - -		- - -	- - -	- - -	- - -	- - -
Bean-RV-Potato	Early	Rye+Vetch	- - -		- - -	- - -		- - -	- - -	- - -	- - -	- - -
Wh/Clover-Potato	Early	Clover	5688	a	1368	0.43	b	0.20	3060	672	1.52	0.83
Pot-Rye-Bean	Late	Rye	3462	ab	397	1.46	b	0.31	3974	476	2.07	0.41
Pot-RV-Bean	Late	Rye+Vetch	2361	b	377	3.56	a	0.99	3287	506	1.45	0.18
Pot-Wh/Clover	Late	Wheat	- - -		- - -	- - -		- - -	- - -	- - -	- - -	- - -
ANOVA F-test, p-value												
Source												
Cropping System			0.060			0.01			0.446		0.570	
Pot-Bare-Bean	Late	Bare	0		0	- - -		- - -	162	87	3.34	1.11
Bean-Bare-Potato	Early	Bare	- - -		- - -	- - -		- - -	- - -	- - -	- - -	- - -
ANOVA F-test, p-value												
Source												
Cropping System			- - -		- - -	- - -		- - -	- - -	- - -	- - -	- - -

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.
- - - = no below-ground biomass sampled

Table 4.8. Effect of cropping system on NDF and ADL content in spring 2006 above-ground whole cover crop tissues at Entrican, MI (16 May 2006).

Cropping System	Cover Crop Planting	Cover Crop	NDF, %			ADL, %			ADL:NDF		
			Mean		SE	Mean		SE	Mean		SE
Bean-Bare-Potato	Early	Bare	52.8	bcd	0.1	6.7	a	0.8	0.128	a	0.016
Bean-Rye-Potato	Early	Rye	69.1	a	0.4	4.9	a	0.3	0.071	b	0.004
Bean-RV-Potato	Early	Rye+Vetch	59.2	b	1.5	6.1	a	0.9	0.106	a	0.018
Wh/Clover-Potato	Early	Clover	45.0	d	1.9	3.1	b	0.2	0.072	b	0.008
Pot-Bare-Bean	Late	Bare	- - -		- - -	- - -		- - -	- - -		- - -
Pot-Rye-Bean	Late	Rye	55.3	bc	0.4	3.0	b	0.2	0.055	b	0.004
Pot-RV-Bean	Late	Rye+Vetch	53.8	c	0.5	2.8	b	0.2	0.052	b	0.003
Pot-Wh/Clover	Late	Wheat	- - -		- - -	- - -		- - -	- - -		- - -
ANOVA F-test, p-value											
Source											
Cropping System			<.0001			<0.001			0.007		

a, b, c, d Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 4.9. Effect of cropping system on NDF and ADL content in spring 2006 above-ground whole cover crop tissues at Benton Harbor, MI (10 May 2006).

Cropping System	Cover Crop Planting	Cover Crop	NDF, %			ADL, %			ADL:NDF		
			Mean		SE	Mean		SE	Mean		SE
Bean-Bare-Potato	Early	Bare	42.6	d	1.4	6.9	ab	0.2	0.163	a	0.006
Bean-Rye-Potato	Early	Rye	68.2	a	0.8	4.5	cde	0.1	0.066	c	0.002
Bean-RV-Potato	Early	Rye+Vetch	58.7	b	1.2	6.0	abc	0.4	0.103	b	0.007
Wh/Clover-Potato	Early	Clover	49.4	c	3.7	8.0	a	0.9	0.159	a	0.010
Pot-Bare-Bean	Late	Bare	35.1	e	0.8	5.4	bcd	0.5	0.153	a	0.012
Pot-Rye-Bean	Late	Rye	60.6	b	0.7	3.4	e	0.1	0.055	c	0.001
Pot-RV-Bean	Late	Rye+Vetch	55.0	bc	0.7	3.7	de	0.2	0.066	c	0.002
Pot-Wh/Clover	Late	Wheat	- - -		- - -	- - -		- - -	- - -		- - -
ANOVA F-test, p-value											
Source											
Cropping System			<.0001			<.0001			<.0001		

a, b, c, d, e Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 4.10. Effect of cropping system on yield of NDF and ADL in spring 2006 above-ground whole plant tissue at Entrican (16 May 2006) and Benton Harbor, MI (10 May 2006).

			Entrican, MI						Benton Harbor, MI					
Cropping System	Cover Crop Planting	Cover Crop	NDF, kg ha^{-1}			ADL, kg ha^{-1}			NDF, kg ha^{-1}			ADL, kg ha^{-1}		
			Mean		SE	Mean		SE	Mean		SE	Mean		SE
Bean-Rye-Potato	Early	Rye	3060	a	535	212	b	40	3317	a	279	215	b	17
Bean-RV-Potato	Early	Rye+Vetch	3120	a	297	297	a	14	3526	a	274	350	a	23
Wh/Clover-Potato	Early	Clover	536	b	130	34	c	8	739	b	189	122	c	33
Pot-Rye-Bean	Late	Rye	1102	b	121	59	c	6	1533	b	88	85	c	5
Pot-RV-Bean	Late	Rye+Vetch	951	b	121	51	c	9	1046	b	82	70	c	6
Pot-Wh/Clover	Late	Wheat	- - -		- - -	- - -		- - -	- - -		- - -	- - -		- - -
ANOVA F-test, p-value														
Source														
Cropping System			<0.001			<.0001			<.0001			<.0001		
Pot-Bare-Bean	Late	Bare	0		0	0		0	28	b	11	5	b	2
Bean-Bare-Potato	Early	Bare	158		104	20		14	322	a	47	52	a	7
ANOVA F-test, p-value														
Source														
Cropping System			0.391			0.391			0.013			0.015		

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 4.11. Effect of cropping system on soil macroPOM-C during the 2006 growing season at Entrican, MI.

			mg macroPOM-C kg soil^{-1}								
Cropping System	Cover Crop Planting	Cover Crop	6/1/2006			8/7/2006			10/27/2006		
			Mean		SE	Mean		SE	Mean		SE
Bean-Bare-Potato	Early	Bare	47	c	24	130	b	61	80		25
Bean-Rye-Potato	Early	Rye	1971	a	322	99	b	49	46		19
Bean-RV-Potato	Early	Rye+Vetch	941	b	325	90	b	18	46		13
Wh/Clover-Potato	Early	Clover	810	b	484	190	b	28	175		80
Pot-Bare-Bean	Late	Bare	15	c	7	37	b	6	65		31
Pot-Rye-Bean	Late	Rye	636	bc	90	78	b	36	148		60
Pot-RV-Bean	Late	Rye+Vetch	379	bc	207	69	b	21	118		69
Pot-Wh/Clover	Late	Wheat	393	bc	261	469	a	132	202		100
ANOVA F-test, p-value											
Source											
Cropping System			<0.001			0.001			0.475		

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 4.12. Effect of cropping system on soil macroPOM-C during the 2006 growing season at Benton Harbor, MI.

			mg macroPOM-C kg soil^{-1}								
Cropping System	Cover Crop Planting	Cover Crop	5/26/2006			8/4/2006			10/26/2006		
			Mean		SE	Mean		SE	Mean		SE
Bean-Bare-Potato	Early	Bare	246	de	60	71	e	27	- - -		- - -
Bean-Rye-Potato	Early	Rye	2923	a	753	484	c	94	188	b	55
Bean-RV-Potato	Early	Rye+Vetch	2234	ab	624	544	b	97	115	b	46
Wh/Clover-Potato	Early	Clover	686	cde	392	291	cd	120	219	b	105
Pot-Bare-Bean	Late	Bare	127	e	87	172	d	66	112	b	27
Pot-Rye-Bean	Late	Rye	1931	abc	494	412	c	137	228	b	26
Pot-RV-Bean	Late	Rye+Vetch	1520	bcd	351	581	b	246	196	b	111
Pot-Wh/Clover	Late	Wheat	782	cde	61	807	a	176	519	a	81
ANOVA F-test, p-value											
Source											
Cropping System			0.002			<.0001			0.017		

a, b, c, d, e, Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD

Table 4.13. Effect of cropping system on soil macroPOM-N during the 2006 growing season at Entrican, MI.

			mg macroPOM-N kg soil^{-1}							
Cropping System	Cover Crop Planting	Cover Crop	6/1/2006			8/7/2006			10/27/2006	
			Mean		SE	Mean		SE	Mean	SE
Bean-Bare-Potato	Early	Bare	3.1	c	1.5	7.6	b	3.0	2.4	0.9
Bean-Rye-Potato	Early	Rye	49.1	a	9.0	4.8	b	2.1	1.9	0.7
Bean-RV-Potato	Early	Rye+Vetch	32.5	ab	10.0	5.7	b	0.8	2.3	0.7
Wh/Clover-Potato	Early	Clover	33.8	ab	19.0	8.4	b	2.5	10.3	5.3
Pot-Bare-Bean	Late	Bare	0.7	c	0.3	2.4	b	0.4	3.1	1.5
Pot-Rye-Bean	Late	Rye	17.6	bc	1.6	4.1	b	1.9	4.9	1.5
Pot-RV-Bean	Late	Rye+Vetch	8.8	c	3.6	3.5	b	1.3	4.0	2.3
Pot-Wh/Clover	Late	Wheat	17.7	bc	12.1	20.4	a	5.3	8.1	4.1
ANOVA F-test, p-value										
Source										
Cropping System			0.004			0.002			0.312	

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 4.14. Effect of cropping system on soil macroPOM-N during the 2006 growing season at Benton Harbor, MI.

			mg macroPOM-N kg soil^{-1}							
Cropping System	Cover Crop Planting	Cover Crop	5/26/2006			8/4/2006		10/26/2006		
			Mean		SE	Mean	SE	Mean		SE
Bean-Bare-Potato	Early	Bare	8.7	cd	2.3	4.4	1.7	- - -		- - -
Bean-Rye-Potato	Early	Rye	66.1	a	11.4	15.8	3.1	8.1	b	2.6
Bean-RV-Potato	Early	Rye+Vetch	64.5	a	23.6	17.3	3.3	6.4	b	2.6
Wh/Clover-Potato	Early	Clover	27.5	bcd	13.2	18.2	7.2	8.9	b	2.8
Pot-Bare-Bean	Late	Bare	4.3	d	2.9	8.3	3.5	2.9	b	0.8
Pot-Rye-Bean	Late	Rye	42.7	abc	5.6	15.1	4.8	10.2	b	1.5
Pot-RV-Bean	Late	Rye+Vetch	39.5	abc	10.1	20.3	9.4	4.9	b	2.1
Pot-Wh/Clover	Late	Wheat	45.6	ab	3.0	15.0	4.4	18.1	a	3.1
ANOVA F-test, p-value										
Source										
Cropping System			0.0084			0.397		0.011		

a, b, c, d Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

Table 4.15. Effect of cropping system on soil macroPOM-C:N during the 2006 growing season at Entrican, MI.

			macroPOM-C:N Ratio								
Cropping System	Cover Crop Planting	Cover Crop	6/1/2006			8/7/2006			10/27/2006		
			Mean		SE	Mean		SE	Mean		SE
Bean-Bare-Potato	Early	Bare	14.8	d	0.6	15.8	c	1.1	37.6	a	3.0
Bean-Rye-Potato	Early	Rye	40.8	a	2.1	18.7	bc	1.7	24.0	bcde	4.2
Bean-RV-Potato	Early	Rye+Vetch	28.4	bc	3.1	15.3	c	1.0	20.7	de	1.2
Wh/Clover-Potato	Early	Clover	22.7	cd	0.9	25.7	a	3.6	18.2	e	1.0
Pot-Bare-Bean	Late	Bare	21.1	cd	0.0	15.7	c	0.3	20.9	cde	0.0
Pot-Rye-Bean	Late	Rye	36.1	ab	3.4	19.3	bc	0.0	28.6	b	3.3
Pot-RV-Bean	Late	Rye+Vetch	35.9	ab	5.4	20.6	b	0.8	27.7	bc	2.2
Pot-Wh/Clover	Late	Wheat	23.2	c	0.6	22.8	ab	1.3	25.3	bcd	1.1
ANOVA F-test, p-value											
Source											
Cropping System			<.0001			0.001			<0.001		

a, b, c, d, e Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 4.16. Effect of cropping system on soil macroPOM-C:N during the 2006 growing season at Benton Harbor, MI.

			macroPOM-C:N Ratio								
Cropping System	Cover Crop Planting	Cover Crop	5/26/2006			8/4/2006			10/26/2006		
			Mean		SE	Mean		SE	Mean		SE
Bean-Bare-Potato	Early	Bare	28.7	cd	1.1	16.3	d	0.7	- - -		- - -
Bean-Rye-Potato	Early	Rye	41.9	ab	5.0	30.6	bc	0.6	23.8	bcd	0.9
Bean-RV-Potato	Early	Rye+Vetch	37.8	abc	4.6	32.5	b	2.0	18.0	d	0.0
Wh/Clover-Potato	Early	Clover	23.4	d	2.0	15.9	d	0.6	25.1	bcd	4.1
Pot-Bare-Bean	Late	Bare	29.6	bcd	0.0	21.5	cd	1.2	39.1	a	1.8
Pot-Rye-Bean	Late	Rye	46.1	a	9.5	27.1	bc	0.7	23.4	cd	2.9
Pot-RV-Bean	Late	Rye+Vetch	39.0	abc	1.9	29.5	bc	2.5	33.4	ab	5.5
Pot-Wh/Clover	Late	Wheat	17.2	d	1.2	59.8	a	8.5	29.9	abc	3.4
ANOVA F-test, p-value											
Source											
Cropping System			0.002			<.0001			0.005		

a, b, c, d Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 4.17. Effect of cropping system on soil POM-C during the 2006 growing season at Entrican, MI.

Cropping System	Cover Crop Planting	Cover Crop	mg POM-C kg soil^{-1} 6/1/2006 Mean		6/1/2006 SE	8/7/2006 Mean	8/7/2006 SE	10/27/2006 Mean	10/27/2006 SE	Overall Mean	Overall SE
Bean-Bare-Potato	Early	Bare	1161	c	58	1417	138	1395	140	1339	74
Bean-Rye-Potato	Early	Rye	2189	ab	341	2026	287	1773	272	1996	170
Bean-RV-Potato	Early	Rye+Vetch	1956	abc	202	2826	855	1745	192	1889	101
Wh/Clover-Potato	Early	Clover	2533	a	211	2360	158	2048	78	2338	103
Pot-Bare-Bean	Late	Bare	1801	abc	291	1799	240	2027	367	1875	169
Pot-Rye-Bean	Late	Rye	1403	bc	104	1332	168	1419	100	1385	71
Pot-RV-Bean	Late	Rye+Vetch	1354	bc	153	1328	127	1429	161	1370	82
Pot-Wh/Clover	Late	Wheat	1898	abc	210	2120	549	2037	271	2009	185
ANOVA F-test, p-value											
Source											
Cropping System			0.097			0.146		0.584		0.216	

a, b, c Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

Table 4.18. Effect of cropping system on soil POM-C during the 2006 growing season at Benton Harbor, MI.

Cropping System	Cover Crop Planting	Cover Crop	mg POM-C kg soil^{-1}									
			5/26/2006		8/4/2006			10/26/2006			Overall		
			Mean	SE	Mean		SE	Mean		SE	Mean		SE
Bean-Bare-Potato	Early	Bare	1940	224	1603	bc	61	1601	c	157	1715	bc	95
Bean-Rye-Potato	Early	Rye	1566	158	1730	bc	138	1607	c	135	1634	bc	81
Bean-RV-Potato	Early	Rye+Vetch	2253	468	1786	b	112	1557	c	120	1859	ab	158
Wh/Clover-Potato	Early	Clover	1958	167	1923	b	148	1825	bc	167	1902	ab	89
Pot-Bare-Bean	Late	Bare	1308	52	1336	c	95	1406	c	112	1347	c	49
Pot-Rye-Bean	Late	Rye	2053	103	1959	b	105	2144	ab	108	2045	ab	61
Pot-RV-Bean	Late	Rye+Vetch	1581	84	1775	b	75	1824	bc	161	1727	bc	66
Pot-Wh/Clover	Late	Wheat	2168	252	2482	a	269	2376	a	249	2330	a	144
ANOVA F-test, p-value													
Source													
Cropping System			0.198		0.002			0.013			0.019		

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 4.19. Effect of cropping system on soil POM-N during the 2006 growing season at Entrican, MI.

Cropping System	Cover Crop Planting	Cover Crop	mg POM-N kg soil^{-1}								
			6/1/2006			8/7/2006		10/27/2006		Overall	
			Mean		SE	Mean	SE	Mean	SE	Mean	SE
Bean-Bare-Potato	Early	Bare	69.2	b	4.3	86.5	7.4	90.6	13.3	83.3	5.8
Bean-Rye-Potato	Early	Rye	128.0	a	18.7	133.5	24.6	103.8	12.5	121.8	11.0
Bean-RV-Potato	Early	Rye+Vetch	104.8	ab	9.3	115.0	4.5	101.3	11.4	106.7	5.2
Wh/Clover-Potato	Early	Clover	149.0	a	14.2	144.3	7.8	125.0	4.0	140.7	6.1
Pot-Bare-Bean	Late	Bare	102.4	ab	14.9	96.1	12.5	117.8	19.7	105.4	9.0
Pot-Rye-Bean	Late	Rye	78.6	b	5.0	76.6	9.5	84.0	4.6	79.8	3.8
Pot-RV-Bean	Late	Rye+Vetch	75.6	b	6.3	67.8	3.9	83.1	6.0	75.5	3.3
Pot-Wh/Clover	Late	Wheat	111.8	ab	9.9	124.8	31.1	116.8	12.9	117.1	9.8
ANOVA F-test, p-value											
Source											
Cropping System			0.0431			0.314		0.639		0.133	

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 4.20. Effect of cropping system on soil POM-N during the 2006 growing season at Benton Harbor, MI.

			mg POM-N kg soil^{-1}											
Cropping System	Cover Crop Planting	Cover Crop	5/26/2006			8/4/2006			10/26/2006			Overall		
			Mean		SE	Mean		SE	Mean		SE	Mean		SE
Bean-Bare-Potato	Early	Bare	105.8	abc	6.8	97.9	cd	3.4	97.3	c	7.3	100.3	cd	3.4
Bean-Rye-Potato	Early	Rye	98.5	bc	11.3	108.9	bcd	9.8	102.0	bc	8.5	103.1	bcd	5.5
Bean-RV-Potato	Early	Rye+Vetch	132.8	ab	23.4	117.4	bc	7.2	106.3	bc	7.5	118.7	bc	8.0
Wh/Clover-Potato	Early	Clover	126.1	ab	9.4	133.3	ab	10.2	135.0	ab	16.4	131.5	ab	6.9
Pot-Bare-Bean	Late	Bare	79.6	c	5.2	84.5	d	7.9	88.6	c	6.3	84.0	d	3.7
Pot-Rye-Bean	Late	Rye	116.0	abc	5.8	118.5	bc	7.6	132.4	ab	5.5	122.0	bc	3.9
Pot-RV-Bean	Late	Rye+Vetch	99.5	bc	5.8	111.1	bcd	4.7	118.6	bc	9.6	109.8	bcd	4.2
Pot-Wh/Clover	Late	Wheat	142.1	a	17.4	159.0	a	22.4	158.8	a	15.7	152.8	a	10.1
ANOVA F-test, p-value														
Source														
Cropping System			0.038			0.004			0.004			0.004		

a, b, c, d Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 4.21. Effect of cropping system on soil POM-C:N during the 2006 growing season at Entrican, MI.

			POM-C:N								
Cropping System	Cover Crop Planting	Cover Crop	6/1/2006		8/7/2006			10/27/2006		Overall	
			Mean	SE	Mean		SE	Mean	SE	Mean	SE
Bean-Bare-Potato	Early	Bare	16.9	0.5	16.3	bc	0.3	16.0	0.7	16.4	0.3
Bean-Rye-Potato	Early	Rye	17.0	0.4	15.8	c	0.6	16.7	0.6	16.5	0.3
Bean-RV-Potato	Early	Rye+Vetch	18.6	0.5	15.6	c	1.6	17.3	0.9	17.7	0.4
Wh/Clover-Potato	Early	Clover	17.2	0.4	16.3	bc	0.4	16.4	0.4	16.6	0.2
Pot-Bare-Bean	Late	Bare	17.3	0.5	18.6	ab	0.4	16.9	0.9	17.6	0.4
Pot-Rye-Bean	Late	Rye	17.8	0.3	17.5	abc	0.5	16.8	0.4	17.4	0.3
Pot-RV-Bean	Late	Rye+Vetch	17.6	0.6	19.3	a	1.0	16.8	0.8	17.9	0.5
Pot-Wh/Clover	Late	Wheat	16.8	0.5	16.9	abc	0.4	17.2	0.8	17.0	0.3
ANOVA F-test, p-value											
Source											
Cropping System			0.610		0.048			0.822		0.427	

a, b, c Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

Table 4.22. Effect of cropping system on soil POM-C:N during the 2006 growing season at Benton Harbor, MI.

Cropping System	Cover Crop Planting	Cover Crop	POM-C:N 5/26/2006 Mean		SE	8/4/2006 Mean		SE	10/26/2006 Mean		SE	Overall Mean		SE
Bean-Bare-Potato	Early	Bare	18.3		1.7	16.4	ab	0.3	16.3	a	0.6	17.0	a	0.6
Bean-Rye-Potato	Early	Rye	16.2		0.4	16.0	ab	0.3	15.8	abc	0.4	16.0	abc	0.2
Bean-RV-Potato	Early	Rye+Vetch	16.6		0.5	15.2	bc	0.3	14.6	cd	0.1	15.4	cd	0.3
Wh/Clover-Potato	Early	Clover	15.5		0.3	14.4	c	0.2	13.9	d	0.6	14.6	d	0.3
Pot-Bare-Bean	Late	Bare	16.7		0.8	16.0	ab	0.4	15.8	abc	0.4	16.2	abc	0.3
Pot-Rye-Bean	Late	Rye	17.8		0.6	16.6	a	0.3	16.2	ab	0.3	16.9	ab	0.3
Pot-RV-Bean	Late	Rye+Vetch	15.9		0.2	16.0	ab	0.3	15.3	abc	0.3	15.7	bc	0.1
Pot-Wh/Clover	Late	Wheat	15.3		0.2	16.0	ab	0.8	14.9	bcd	0.4	15.4	cd	0.3
ANOVA F-test, p-value														
Source														
Cropping System			0.119			0.022			0.020			0.006		

a, b, c, d Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 4.23. Effect of cropping system on anion-exchange resin NO_3-N accumulation in soil during the 2006 growing season at Entrican, MI.

Cropping System	Cover Crop Planting	Cover Crop	μg NO_3-N cm^{-2} day^{-1} 8/10/2006		8/22/2006		8/31/2006		9/15/2006	
			Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bean-Bare-Potato	Early	Bare	8.63	1.61	5.80	0.73	4.94	1.00	0.47	0.10
Bean-Rye-Potato	Early	Rye	5.27	0.91	3.95	0.75	3.22	0.50	0.43	0.11
Bean-RV-Potato	Early	Rye+Vetch	5.23	0.96	3.76	0.48	2.93	0.31	0.37	0.08
Wh/Clover-Potato	Early	Clover	5.45	1.27	4.86	1.28	3.24	0.36	0.21	0.04
ANOVA F-test, p-value										
Source										
Cropping System			0.400		0.178		0.146		0.240	

Table 4.24. Effect of cropping system on anion-exchange resin NO3-N accumulation in soil during the 2006 growing season at Benton Harbor, MI.

Cropping System	Cover Crop Planting	Cover Crop	8/15/2006 ($\mu g\ NO_3\text{-}N\ cm^{-2}\ day^{-1}$)		8/25/2006		9/7/2006		
			Mean	SE	Mean	SE	Mean		SE
Bean-Bare-Potato	Early	Bare	1.50	0.32	1.29	0.38	0.35	ab	0.10
Bean-Rye-Potato	Early	Rye	2.08	0.54	0.78	0.12	0.24	b	0.04
Bean-RV-Potato	Early	Rye+Vetch	3.29	0.54	1.96	0.48	0.50	a	0.09
Wh/Clover-Potato	Early	Clover	2.84	0.72	1.75	0.64	0.42	ab	0.09
ANOVA F-test, p-value									
Source									
Cropping System			0.128		0.283		0.076		

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table 4.25. Effect of cropping system on fall residual soil inorganic N and nitrogen mineralization potential (NMP) at Entrican, MI (November 2006).

Cropping System	Cover Crop Planting	Cover Crop	Inorganic N (μg N g^{-1} soil) 0-20 cm Mean		0-20 cm SE	Inorganic N 20-51 cm Mean		20-51 cm SE	NMP[z] (μg N g^{-1} soil day^{-1}) 0-20 cm Mean		0-20 cm SE
Bean-Bare-Potato	Early	Bare	5.36	bc	0.55	6.24	a	0.79	0.22	ab	0.02
Bean-Rye-Potato	Early	Rye	6.04	ab	0.24	5.80	a	0.47	0.20	bc	0.01
Bean-RV-Potato	Early	Rye+Vetch	5.78	ab	0.37	5.25	ab	0.29	0.20	bc	0.01
Wh/Clover-Potato	Early	Clover	7.21	a	0.27	5.25	ab	0.58	0.24	a	0.01
Pot-Bare-Bean	Late	Bare	5.84	ab	0.15	5.34	ab	0.35	0.18	c	0.02
Pot-Rye-Bean	Late	Rye	5.33	bc	0.18	4.77	b	0.43	0.19	bc	0.00
Pot-RV-Bean	Late	Rye+Vetch	3.95	c	1.22	4.61	bc	0.38	0.20	bc	0.01
Pot-Wh/Clover	Late	Wheat	5.78	ab	0.26	3.71	c	0.18	0.22	ab	0.01
ANOVA F-test, p-value											
Source											
Cropping System			0.031			0.002			0.040		

a, b, c Values followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.
[z] NMP was determined aerobically over a 30-day incubation period.

Table 4.26. Effect of cropping system on fall 2006 residual soil inorganic N and nitrogen mineralization potential (NMP) at Benton Harbor, MI (November 2006).

			Inorganic N ($\mu g\ N\ g^{-1}$ soil)						NMP[z] ($\mu g\ N\ g^{-1}$ soil day^{-1})		
Cropping System	Cover Crop Planting	Cover Crop	0-20 cm			20-51 cm			0-20 cm		
			Mean		SE	Mean		SE	Mean		SE
Bean-Bare-Potato	Early	Bare	5.21	bcd	0.34	4.33	ab	0.09	0.08	b	0.03
Bean-Rye-Potato	Early	Rye	5.57	bc	0.31	4.54	ab	0.34	0.08	b	0.03
Bean-RV-Potato	Early	Rye+Vetch	5.95	ab	0.14	4.75	a	0.49	0.07	b	0.02
Wh/Clover-Potato	Early	Clover	6.40	a	0.27	4.55	a	0.35	0.08	b	0.01
Pot-Bare-Bean	Late	Bare	4.93	cd	0.15	2.89	c	0.25	0.09	ab	0.02
Pot-Rye-Bean	Late	Rye	4.82	d	0.38	3.00	c	0.28	0.10	a	0.03
Pot-RV-Bean	Late	Rye+Vetch	4.75	d	0.20	2.73	c	0.55	0.11	a	0.03
Pot-Wh/Clover	Late	Wheat	5.33	bcd	0.18	3.40	bc	0.61	0.11	a	0.02
ANOVA F-test, p-value											
Source											
Cropping System			0.0013			0.003			0.004		

a, b, c, d Values followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.
[z] NMP was determined aerobically over a 30-day incubation period.

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APPENDIX

Table A1.1. Effect of cover crop treatment and nitrogen fertility on total organic matter, NDF and ADL in above-ground rye tissues at 416 GDD.

	Rye OM % of DM			Rye NDF % of DM			Rye ADF % of DM			Rye ADL % of DM		
416 GDD only	Mean		SE	Mean		SE	Mean		SE	Mean		SE
Rye	93.9		0.2	41.4		0.3	19.9		0.1	1.4		0.0
Rye-Vetch	93.6		0.2	41.0		0.8	19.9		0.3	1.5		0.0
Vetch	---		---	---		---	---		---	---		---
Crop effect, p-value	*0.452*			*0.555*			*0.822*			*0.234*		
+0N	93.9		0.2	42.3	a	0.4	20.3	a	0.2	1.4	b	0.0
+30N	93.6		0.2	40.1	b	0.4	19.5	b	0.1	1.5	a	0.0
N effect, p-value	*0.309*			*0.001*			*0.007*			*0.813*		
Rye +0N	94.1		0.3	41.9	ab	0.4	20.0	a	0.2	1.3		0.0
Rye +30N	93.8		0.3	40.9	bc	0.2	19.8	ab	0.0	1.5		0.1
Rye+Vetch +0N	93.8		0.4	42.6	a	0.8	20.5	a	0.4	1.5		0.0
Rye+Vetch +30N	93.5		0.3	39.4	c	0.6	19.2	b	0.2	1.5		0.0
Vetch +0N	---		---	---		---	---		---	---		---
Vetch +30N	---		---	---		---	---		---	---		---
*Crop*N interaction, p-value*	*0.965*			*0.022*			*0.031*			*0.070*		

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.2. Effect of cover crop treatment and nitrogen fertility on total organic matter, NDF and ADL in above-ground rye tissues at 532 GDD.

	Rye OM % of DM			Rye NDF % of DM		Rye ADF % of DM		Rye ADL % of DM	
532 GDD only	Mean		SE	Mean	SE	Mean	SE	Mean	SE
Rye	94.6	b	0.3	65.2	0.6	36.9	0.5	4.2	0.2
Rye-Vetch	95.3	a	0.1	64.1	0.5	37.1	0.5	4.5	0.1
Vetch	---		---	---	---	---	---	---	---
Crop effect, p-value	*0.037*			*0.266*		*0.872*		*0.335*	
+0N	94.8		0.3	64.4	0.4	36.7	0.4	4.3	0.1
+30N	95.2		0.1	64.9	0.6	37.3	0.5	4.5	0.2
N effect, p-value	*0.227*			*0.465*		*0.365*		*0.161*	
Rye +0N	94.2	b	0.6	64.6	0.7	36.4	0.4	4.1	0.2
Rye +30N	95.0	ab	0.1	65.8	0.8	37.5	0.8	4.4	0.3
Rye+Vetch +0N	95.3	a	0.1	64.3	0.6	37.0	0.7	4.4	0.2
Rye+Vetch +30N	95.4	a	0.1	64.0	0.8	37.1	0.7	4.7	0.2
Vetch +0N	---		---	---	---	---	---	---	---
Vetch +30N	---		---	---	---	---	---	---	---
*Crop*N interaction, p-value*	*0.363*			*0.230*		*0.476*		*0.944*	

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.3. Effect of cover crop treatment and nitrogen fertility on total organic matter, NDF and ADL in above-ground rye tissues at 962 GDD.

	Rye OM % of DM			Rye NDF % of DM			Rye ADF % of DM			Rye ADL % of DM		
962 GDD only	Mean		SE	Mean		SE	Mean		SE	Mean		SE
Rye	96.0		0.1	69.4		0.5	41.9		0.4	6.4		0.2
Rye-Vetch	95.7		0.2	70.4		0.3	42.7		0.2	6.5		0.1
Vetch	---		---	---		---	---		---	---		---
Crop effect, p-value	*0.057*			*0.229*			*0.198*			*0.811*		
+0N	95.6	b	0.1	69.9		0.4	42.0	b	0.3	6.4		0.2
+30N	96.1	a	0.1	69.9		0.5	42.6	a	0.4	6.4		0.1
N effect, p-value	*0.002*			*0.910*			*0.041*			*0.961*		
Rye +0N	95.9	a	0.1	69.3		0.5	41.5	b	0.3	6.4		0.3
Rye +30N	96.1	a	0.1	69.5		0.9	42.2	ab	0.7	6.4		0.3
Rye+Vetch +0N	95.3	b	0.0	70.5		0.4	42.4	ab	0.2	6.5		0.2
Rye+Vetch +30N	96.2	a	0.2	70.3		0.4	42.9	a	0.3	6.4		0.1
Vetch +0N	---		---	---		---	---		---	---		---
Vetch +30N	---		---	---		---	---		---	---		---
*Crop*N interaction, p-value*	*0.011*			*0.511*			*0.676*			*0.821*		

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.4. Effect of cover crop treatment, nitrogen fertility and sample date on total organic matter, NDF and ADL in above-ground hairy vetch tissues at 416 GDD.

	Vetch OM % of DM			Vetch NDF % of DM		Vetch ADF % of DM		Vetch ADL % of DM	
416 GDD only	Mean		SE	Mean	SE	Mean	SE	Mean	SE
Rye	---		---	---	---	---	---	---	---
Rye-Vetch	90.7	a	0.7	33.5	1.0	21.5	0.4	4.4	0.1
Vetch	74.8	b	3.3	33.7	0.8	22.7	0.7	5.0	0.2
Crop effect, p-value	*<.0001*			*0.989*		*0.294*		*0.057*	
+0N	78.1	b	4.6	32.4	0.7	22.0	0.5	4.7	0.3
+30N	86.9	a	1.7	34.9	0.8	22.2	0.7	4.7	0.2
N effect, p-value	*<.0001*			*0.079*		*0.927*		*0.933*	
Rye +0N	---		---	---	---	---	---	---	---
Rye +30N	---		---	---	---	---	---	---	---
Rye+Vetch +0N	90.0	a	1.0	32.1	1.3	21.1	0.6	4.2	0.2
Rye+Vetch +30N	91.7	a	0.6	35.3	0.6	22.0	0.5	4.6	0.1
Vetch +0N	66.2	c	1.6	32.7	0.6	23.0	0.5	5.1	0.4
Vetch +30N	83.3	b	0.5	34.6	1.5	22.3	1.3	4.8	0.3
*Crop*N interaction, p-value*	*<0.001*			*0.625*		*0.415*		*0.389*	

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.5. Effect of cover crop treatment, nitrogen fertility and sample date on total organic matter, NDF and ADL in above-ground hairy vetch tissues at 532 GDD.

	Vetch OM % of DM			Vetch NDF % of DM			Vetch ADF % of DM			Vetch ADL % of DM		
532 GDD only	Mean		SE	Mean		SE	Mean		SE	Mean		SE
Rye	---		---	---		---	---		---	---		---
Rye-Vetch	92.1		0.3	39.6		0.4	27.9		0.5	6.4	b	0.2
Vetch	81.6		4.9	39.8		0.8	29.2		1.0	7.3	a	0.2
Crop effect, p-value	*0.055*			*0.660*			*0.131*			*0.021*		
+0N	89.8		1.3	40.4		0.6	29.9	a	0.7	7.2	a	0.2
+30N	83.9		5.3	39.0		0.5	27.2	b	0.6	6.4	b	0.3
N effect, p-value	*0.263*			*0.106*			*0.024*			*0.024*		
Rye +0N	---		---	---		---	---		---	---		---
Rye +30N	---		---	---		---	---		---	---		---
Rye+Vetch +0N	91.9		0.5	39.4		0.7	28.7	ab	0.8	6.8	ab	0.2
Rye+Vetch +30N	92.3		0.2	39.7		0.4	27.0	b	0.2	6.0	b	0.2
Vetch +0N	87.7		2.0	41.5		0.7	31.0	a	0.7	7.6	a	0.2
Vetch +30N	75.4		9.0	38.2		0.9	27.4	b	1.3	6.9	a	0.4
*Crop*N interaction, p-value*	*0.238*			*0.057*			*0.302*			*0.802*		

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.6. Effect of cover crop treatment, nitrogen fertility and sample date on total organic matter, NDF and ADL in above-ground hairy vetch tissues at 962 GDD.

	Vetch OM % of DM			Vetch NDF % of DM			Vetch ADF % of DM			Vetch ADL % of DM		
962 GDD only	Mean		SE	Mean		SE	Mean		SE	Mean		SE
Rye	---		---	---		---	---		---	---		---
Rye-Vetch	94.1	a	0.2	48.1		0.8	31.1		0.7	8.0		0.4
Vetch	92.5	b	0.5	48.4		1.9	34.7		1.7	8.8		0.6
Crop effect, p-value	*0.014*			*0.871*			*0.082*			*0.229*		
+0N	93.4		0.3	50.7	a	1.2	35.0	a	1.5	9.0	a	0.5
+30N	93.2		0.6	45.8	b	1.1	30.8	b	0.9	7.8	b	0.4
N effect, p-value	*0.773*			*0.002*			*0.005*			*0.048*		
Rye +0N	---		---	---		---	---		---	---		---
Rye +30N	---		---	---		---	---		---	---		---
Rye+Vetch +0N	93.7	a	0.3	48.9	ab	1.1	32.0	b	1.0	8.2	b	0.4
Rye+Vetch +30N	94.5	a	0.0	47.3	bc	1.1	30.2	b	0.7	7.8	b	0.6
Vetch +0N	93.0	ab	0.5	52.5	a	1.7	38.0	a	1.7	9.9	a	0.7
Vetch +30N	91.9	b	0.8	44.3	c	1.6	31.4	b	1.8	7.7	b	0.5
*Crop*N interaction, p-value*	*0.116*			*0.012*			*0.050*			*0.116*		

a, b, c, d Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.7. Effect of cover crop treatment and nitrogen fertility on above-ground whole plant tissue C and N for rye plants only at 416 GDD.

	Rye N % of DM			Rye N ($kg\ ha^{-1}$)			Rye C % of DM		Rye C ($kg\ ha^{-1}$)			Rye C:N		
416 GDD only	Mean		SE	Mean		SE	Mean	SE	Mean		SE	Mean		SE
Rye	1.93		0.10	26.5		2.3	43.4	1.4	587		44	22.9		1.2
Rye-Vetch	2.10		0.12	28.3		2.6	44.9	1.1	594		43	21.8		1.1
Vetch	---		---	---		---	---	---	---		---	---		---
Crop effect, p-value	*0.284*			*0.711*			*0.496*		*0.941*			*0.562*		
+0N	1.83	b	0.07	20.6	b	1.7	43.5	1.1	478	b	29	24.0	a	1.2
+30N	2.19	a	0.11	34.2	a	1.7	44.8	1.4	704	a	34	20.6	b	0.7
N effect, p-value	*0.022*			*<.0001*			*0.437*		*<.0001*			*0.024*		
Rye +0N	1.79	b	0.12	20.6	b	2.5	42.7	1.9	476	b	41	24.2	a	2.1
Rye +30N	2.06	ab	0.15	32.5	a	2.5	44.1	2.4	698	a	54	21.5	ab	1.0
Rye+Vetch +0N	1.87	b	0.07	20.7	b	2.5	44.3	1.4	479	b	44	23.9	ab	1.6
Rye+Vetch +30N	2.33	a	0.17	36.0	a	2.4	45.6	1.7	709	a	46	19.7	b	0.7
Vetch +0N	---		---	---		---	---	---	---		---	---		---
Vetch +30N	---		---	---		---	---	---	---		---	---		---
*Crop*N interaction, p-value*	*0.461*			*0.433*			*0.957*		*0.919*			*0.537*		

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.8. Effect of cover crop treatment and nitrogen fertility on above-ground whole plant tissue C and N for rye plants only at 532 GDD.

	Rye N % of DM			Rye N (kg ha^{-1})			Rye C % of DM			Rye C (kg ha^{-1})			Rye C:N		
532 GDD only	Mean		SE	Mean		SE	Mean		SE	Mean		SE	Mean		SE
Rye	1.35	a	0.06	40.9		3.8	50.9	a	1.1	1533		128	38.0	b	0.8
Rye-Vetch	1.11	b	0.03	41.5		3.8	46.3	b	0.6	1729		170	41.7	a	0.7
Vetch	---		---	---		---	---		---	---		---	---		---
Crop effect, p-value	*0.010*			*0.945*			*0.007*			*0.587*			*0.011*		
+0N	1.20		0.05	31.7	b	2.2	48.2		1.0	1241	b	89	40.3		0.8
+30N	1.26		0.08	50.7	a	3.5	49.0		1.4	1990	a	134	39.4		1.2
N effect, p-value	*0.452*			*<0.001*			*0.590*			*<0.001*			*0.514*		
Rye +0N	1.29	ab	0.04	31.8	bd	2.9	50.1	ab	1.3	1236	c	107	38.9	ab	0.5
Rye +30N	1.41	a	0.11	49.9	ac	5.5	51.7	a	1.9	1830	ab	183	37.1	b	1.5
Rye+Vetch +0N	1.12	b	0.05	31.5	cd	3.6	46.3	b	0.8	1248	bc	156	41.7	a	1.2
Rye+Vetch +30N	1.11	b	0.04	51.5	ab	4.7	46.4	b	0.9	2150	a	190	41.8	a	1.0
Vetch +0N	---		---	---		---	---		---	---		---	---		---
Vetch +30N	---		---	---		---	---		---	---		---	---		---
*Crop*N interaction, p-value*	*0.434*			*0.819*			*0.626*			*0.455*			*0.461*		

a, b, c, d Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.9. Effect of cover crop treatment and nitrogen fertility on above-ground whole plant tissue C and N for rye plants only at 962 GDD.

	Rye N % of DM			Rye N (kg ha^{-1})			Rye C % of DM		Rye C (kg ha^{-1})			Rye C:N		
962 GDD only	Mean		SE	Mean		SE	Mean	SE	Mean		SE	Mean		SE
Rye	0.72	b	0.01	38.5		3.0	46.5	0.3	2468		183	64.5	a	0.8
Rye-Vetch	0.85	a	0.05	39.4		5.5	49.1	0.9	2306		338	58.6	b	2.4
Vetch	---		---	---		---	---	---	---		---	---		---
Crop effect, p-value	*0.025*			*0.924*			*0.032*		*0.793*			*0.046*		
+0N	0.79		0.05	27.1	b	2.9	47.8	0.9	1641	b	157	61.5		2.6
+30N	0.78		0.03	50.8	a	3.5	47.8	0.8	3133	a	223	61.6		1.5
N effect, p-value	*0.865*			*<.0001*			*0.976*		*<.0001*			*0.965*		
Rye +0N	0.72		0.01	29.0	b	1.8	46.4	0.4	1877	bc	110	65.0		0.7
Rye +30N	0.73		0.02	48.0	a	2.9	46.6	0.6	3059	ab	176	63.9		1.5
Rye+Vetch +0N	0.87		0.08	25.2	b	5.6	49.1	1.4	1406	c	278	58.0		4.7
Rye+Vetch +30N	0.83		0.05	53.7	a	6.4	49.1	1.3	3207	a	425	59.3		2.0
Vetch +0N	---		---	---		---	---	---	---		---	---		---
Vetch +30N	---		---	---		---	---	---	---		---	---		---
*Crop*N interaction, p-value*	*0.673*			*0.302*			*0.940*		*0.269*			*0.710*		

a, b, c Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

Table A1.10. Effect of cover crop species and nitrogen fertility on above-ground plant tissue NDF and NDF-C and -N fractions for rye plants only at 416 GDD.

	Rye NDF-N % of NDF			Rye NDF-N (kg ha^{-1})			Rye NDF-C % of NDF		Rye NDF-C (kg ha^{-1})			Rye NDF C:N	
416 GDD only	Mean		SE	Mean		SE	Mean	SE	Mean		SE	Mean	SE
Rye	0.74		0.04	3.8		0.5	42.7	0.4	238		15	59.7	5.0
Rye-Vetch	0.76		0.03	4.2		0.4	42.5	0.6	233		18	59.3	3.0
Vetch	---		---	---		---	---	---	---		---	---	---
Crop effect, p-value	*0.914*			*0.751*			*0.782*		*0.849*			*0.947*	
+0N	0.68	b	0.02	3.2	b	0.2	42.9	0.3	201	b	15	64.6	3.6
+30N	0.82	a	0.04	4.8	a	0.5	42.4	0.6	268	a	13	54.4	3.8
N effect, p-value	*0.003*			*0.002*			*0.454*		*<0.001*			*0.072*	
Rye +0N	0.67	cd	0.04	3.1	bd	0.3	42.4	0.6	198	cd	16	66.2	7.1
Rye +30N	0.83	ab	0.07	4.6	ac	0.9	43.1	0.5	277	ab	17	53.3	6.3
Rye+Vetch +0N	0.70	bd	0.03	3.3	cd	0.4	43.3	0.1	206	bd	28	63.1	2.8
Rye+Vetch +30N	0.82	ac	0.05	5.0	ab	0.4	41.7	1.1	258	bc	21	55.5	5.1
Vetch +0N	---		---	---		---	---	---	---		---	---	---
Vetch +30N	---		---	---		---	---	---	---		---	---	---
*Crop*N interaction, p-value*	*0.682*			*0.743*			*0.087*		*0.423*			*0.591*	

a, b, c, d Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

Table A1.11. Effect of cover crop species and nitrogen fertility on above-ground plant tissue NDF and NDF-C and -N fractions for rye plants only at 532 GDD.

	Rye NDF-N % of NDF			Rye NDF-N (kg ha^{-1})			Rye NDF-C % of NDF		Rye NDF-C (kg ha^{-1})			Rye NDF C:N		
532 GDD only	Mean		SE	Mean		SE	Mean	SE	Mean		SE	Mean		SE
Rye	0.20		0.01	4.0		0.4	45.2	0.1	888		75	236	a	15
Rye-Vetch	0.24		0.02	5.8		0.8	45.3	0.1	1084		105	191	b	12
Vetch	---		---	---		---	---	---	---		---	---		---
Crop effect, p-value	*0.337*			*0.158*			*0.446*		*0.540*			*<.0001*		
+0N	0.20	b	0.02	3.3	b	0.4	45.2	0.1	750	b	56	236	a	16
+30N	0.24	a	0.01	6.5	a	0.6	45.3	0.1	1202	a	85	190	b	10
N effect, p-value	*0.021*			*<.0001*			*0.366*		*0.002*			*0.033*		
Rye +0N	0.19	ab	0.01	3.1	c	0.4	45.1	0.2	719	b	63	261	a	23
Rye +30N	0.21	ab	0.01	5.0	b	0.6	45.2	0.1	1057	ab	109	211	ab	9
Rye+Vetch +0N	0.21	b	0.03	3.5	bc	0.6	45.3	0.2	785	b	100	212	ab	16
Rye+Vetch +30N	0.27	a	0.01	8.0	a	0.8	45.4	0.1	1346	a	115	169	b	9
Vetch +0N	---		---	---		---	---	---	---		---	---		---
Vetch +30N	---		---	---		---	---	---	---		---	---		---
*Crop*N interaction, p-value*	*0.264*			*0.026*			*0.863*		*0.556*			*0.928*		

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.12. Effect of cover crop species and nitrogen fertility on above-ground plant tissue NDF and NDF-C and -N fractions for rye plants only at 962 GDD.

	Rye NDF-N % of NDF			Rye NDF-N (kg ha^{-1})			Rye NDF-C % of NDF		Rye NDF-C (kg ha^{-1})			Rye NDF C:N	
962 GDD only	Mean		SE	Mean		SE	Mean	SE	Mean		SE	Mean	SE
Rye	0.23		0.02	8.6		1.3	47.7	0.6	1767		142	233	19
Rye-Vetch	0.18		0.02	6.3		1.3	46.9	0.2	1588		239	235	11
Vetch	---		---	---		---	---	---	---		---	---	---
Crop effect, p-value	*0.482*			*0.475*			*0.338*		*0.619*			*0.914*	
+0N	0.18		0.01	4.5	b	0.6	47.1	0.3	1144	b	118	239	11
+30N	0.22		0.03	10.4	a	1.4	47.5	0.6	2183	a	156	228	19
N effect, p-value	*0.172*			*<0.001*			*0.397*		*<.0001*			*0.708*	
Rye +0N	0.18	b	0.01	5.1	bc	0.5	47.2	0.4	1322	bc	83	250	17
Rye +30N	0.27	a	0.04	12.1	a	1.8	48.3	1.1	2212	a	151	215	35
Rye+Vetch +0N	0.19	ab	0.02	3.9	c	1.1	47.0	0.4	940	c	217	227	15
Rye+Vetch +30N	0.18	ab	0.04	8.7	ab	2.1	46.8	0.4	2155	ab	285	242	17
Vetch +0N	---		---	---		---	---	---	---		---	---	---
Vetch +30N	---		---	---		---	---	---	---		---	---	---
*Crop*N interaction, p-value*	*0.098*			*0.454*			*0.203*		*0.422*			*0.391*	

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.13. Effect of cover crop species and nitrogen fertility on above-ground plant tissue NDS and NDS-C and -N fractions for rye plants only at 416 GDD.

	Rye NDS-N % of NDS			Rye NDS-N (kg ha^{-1})			Rye NDS-C % of NDS		Rye NDS-C (kg ha^{-1})			Rye NDS C:N	
416 GDD only	Mean		SE	Mean		SE	Mean	SE	Mean		SE	Mean	SE
Rye	2.8		0.2	22.3		1.9	43.9	2.3	350		29	16.3	1.1
Rye-Vetch	3.0		0.2	24.2		2.2	46.5	1.8	363		28	15.6	0.9
Vetch	---		---	---		---	---	---	---		---	---	---
Crop effect, p-value	*0.299*			*0.645*			*0.478*		*0.816*			*0.685*	
+0N	2.7		0.1	17.5	b	1.5	44.0	1.9	277	b	16	16.8	1.2
+30N	3.1		0.2	29.0	a	1.5	46.5	2.2	436	a	23	15.0	0.6
N effect, p-value	*0.055*			*<.0001*			*0.368*		*<.0001*			*0.148*	
Rye +0N	2.6	b	0.3	17.5	b	2.3	43.0	3.1	279	b	26	17.1	2.1
Rye +30N	2.9	ab	0.2	27.1	a	2.0	44.8	3.8	421	a	38	15.5	1.1
Rye+Vetch +0N	2.7	ab	0.1	17.4	b	2.1	45.0	2.5	275	b	20	16.6	1.6
Rye+Vetch +30N	3.3	a	0.2	30.9	a	2.0	48.1	2.7	451	a	28	14.5	0.4
Vetch +0N	---		---	---		---	---	---	---		---	---	---
Vetch +30N	---		---	---		---	---	---	---		---	---	---
*Crop*N interaction, p-value*	*0.482*			*0.283*			*0.813*		*0.521*			*0.820*	

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.14. Effect of cover crop species and nitrogen fertility on above-ground plant tissue NDS and NDS-C and -N fractions for rye plants only at 532 GDD.

	Rye NDS-N % of NDS			Rye NDS-N (kg ha^{-1})			Rye NDS-C % of NDS			Rye NDS-C (kg ha^{-1})			Rye NDS C:N	
532 GDD only	Mean		SE	Mean		SE	Mean		SE	Mean		SE	Mean	SE
Rye	3.5	a	0.2	36.9		3.4	61.7	a	3.4	645		57	17.5	0.4
Rye-Vetch	2.7	b	0.1	35.3		3.5	48.1	b	1.6	643		62	18.0	0.3
Vetch	---		---	---		---	---		---	---		---	---	---
Crop effect, p-value	*0.007*			*0.855*			*0.010*			*0.992*			*0.232*	
+0N	3.0		0.1	28.1	b	2.0	53.6		2.9	500	b	36	17.7	0.4
+30N	3.2		0.3	44.2	a	3.1	56.3		4.3	788	a	54	17.9	0.3
N effect, p-value	*0.480*			*<0.001*			*0.524*			*<0.001*			*0.739*	
Rye +0N	3.3	ab	0.1	28.8	cd	2.6	59.1	ab	3.7	517	bd	51	17.8	0.8
Rye +30N	3.7	a	0.4	44.9	ab	4.9	64.4	a	5.8	773	ac	81	17.3	0.4
Rye+Vetch +0N	2.7	bc	0.1	27.3	bd	3.2	48.0	b	2.3	483	cd	55	17.6	0.4
Rye+Vetch +30N	2.6	c	0.1	43.4	ac	4.0	48.2	b	2.6	804	ab	78	18.5	0.3
Vetch +0N	---		---	---		---	---		---	---		---	---	---
Vetch +30N	---		---	---		---	---		---	---		---	---	---
*Crop*N interaction, p-value*	*0.218*			*0.997*			*0.546*			*0.614*			*0.336*	

a, b, c   Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.15. Effect of cover crop species and nitrogen fertility on above-ground plant tissue NDS and NDS-C and -N fractions for rye plants only at 962 GDD.

	Rye NDS-N % of NDS			Rye NDS-N (kg ha^{-1})			Rye NDS-C % of NDS			Rye NDS-C (kg ha^{-1})			Rye NDS C:N	
962 GDD only	Mean		SE	Mean		SE	Mean		SE	Mean		SE	Mean	SE
Rye	1.9	b	0.1	29.9		2.2	43.8	b	1.5	701		44	23.7	0.8
Rye-Vetch	2.4	a	0.2	33.1		4.5	54.4	a	3.4	752		113	22.8	0.5
Vetch	---		---	---		---	---		---	---		---	---	---
Crop effect, p-value	*0.022*			*0.693*			*0.036*			*0.793*			*0.416*	
+0N	2.2		0.2	22.3	b	2.5	49.4		3.1	503	b	48	23.0	0.5
+30N	2.1		0.2	40.4	a	3.0	48.7		3.4	949	a	77	23.5	0.8
N effect, p-value	*0.721*			*<.0001*			*0.861*			*<.0001*			*0.587*	
Rye +0N	1.9	ab	0.0	23.8	c	1.4	44.8		0.9	554	c	27	23.7	0.6
Rye +30N	1.8	b	0.2	35.9	ab	2.9	42.8		3.0	847	ab	40	23.7	1.5
Rye+Vetch +0N	2.4	a	0.3	21.3	bc	4.6	54.1		5.4	451	bc	91	22.3	0.6
Rye+Vetch +30N	2.3	ab	0.2	45.0	a	5.0	54.7		4.8	1052	a	145	23.3	0.7
Vetch +0N	---		---	---		---	---		---	---		---	---	---
Vetch +30N	---		---	---		---	---		---	---		---	---	---
*Crop*N interaction, p-value*	*0.954*			*0.130*			*0.750*			*0.087*			*0.587*	

a, b, c, d Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.16. Effect of cover crop treatment and nitrogen fertility on above-ground whole plant tissue C and N for hairy vetch plants only at 416 GDD.

	Vetch N % of DM		Vetch N (kg ha^{-1})			Vetch C % of DM		Vetch C (kg ha^{-1})			Vetch C:N	
416 GDD only	Mean	SE	Mean		SE	Mean	SE	Mean		SE	Mean	SE
Rye	---	---	---		---	---	---	---		---	---	---
Rye-Vetch	4.05	0.22	5.6	b	1.3	45.5	1.8	62	b	14	11.3	0.3
Vetch	4.02	0.19	23.4	a	5.3	43.1	1.7	253	a	57	10.8	0.2
Crop effect, p-value	*0.908*		*0.019*			*0.430*		*0.020*			*0.176*	
+0N	4.08	0.12	24.5	a	5.0	44.6	1.4	267	a	54	10.9	0.1
+30N	3.99	0.26	4.4	b	1.1	44.0	2.1	48	b	12	11.2	0.4
N effect, p-value	*0.765*		*<.0001*			*0.797*		*<.0001*			*0.566*	
Rye +0N	---	---	---		---	---	---	---		---	---	---
Rye +30N	---	---	---		---	---	---	---		---	---	---
Rye+Vetch +0N	4.29	0.09	9.2	b	1.7	47.0	1.6	102	b	19	10.9	0.2
Rye+Vetch +30N	3.81	0.42	2.0	b	0.6	43.9	3.3	23	b	7	11.7	0.5
Vetch +0N	3.87	0.17	39.8	a	6.2	42.2	1.7	433	a	66	10.9	0.1
Vetch +30N	4.17	0.35	6.9	b	1.7	44.0	3.2	73	b	19	10.6	0.5
*Crop*N interaction, p-value*	*0.225*		*0.001*			*0.321*		*0.001*			*0.206*	

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.17. Effect of cover crop treatment and nitrogen fertility on above-ground whole plant tissue C and N for hairy vetch plants only at 532 GDD.

	Vetch N % of DM			Vetch N (kg ha^{-1})			Vetch C % of DM		Vetch C (kg ha^{-1})			Vetch C:N		
532 GDD only	Mean		SE	Mean		SE	Mean	SE	Mean		SE	Mean		SE
Rye	---		---	---		---	---	---	---		---	---		---
Rye-Vetch	2.90	b	0.10	11.9		3.1	41.0	1.8	168		44	14.2	a	0.5
Vetch	4.18	a	0.14	44.2		8.5	45.4	0.9	487		94	10.9	b	0.2
Crop effect, p-value	*0.001*			*0.055*			*0.108*		*0.094*			*0.002*		
+0N	3.51		0.27	43.1	a	8.6	42.7	2.0	505	a	91	12.4		0.6
+30N	3.57		0.27	13.0	b	3.8	43.8	1.2	150	b	42	12.7		0.8
N effect, p-value	*0.682*			*<0.001*			*0.596*		*<0.001*			*0.568*		
Rye +0N	---		---	---		---	---	---	---		---	---		---
Rye +30N	---		---	---		---	---	---	---		---	---		---
Rye+Vetch +0N	2.90	b	0.19	21.0	b	4.1	39.9	3.4	292	b	60	13.7		0.3
Rye+Vetch +30N	2.90	b	0.07	2.8	b	1.2	42.1	1.7	45	c	21	14.6		0.9
Vetch +0N	4.13	a	0.21	65.2	a	12.5	45.4	1.5	717	a	138	11.1		0.4
Vetch +30N	4.23	a	0.20	23.2	b	5.4	45.4	1.3	256	bc	64	10.8		0.3
*Crop*N interaction, p-value*	0.725			0.114			0.599		0.206			0.285		

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.18. Effect of cover crop treatment and nitrogen fertility on above-ground whole plant tissue C and N for hairy vetch plants only at 962 GDD.

	Vetch N % of DM			Vetch N (kg ha^{-1})			Vetch C % of DM			Vetch C (kg ha^{-1})		Vetch C:N	
962 GDD only	Mean		SE	Mean		SE	Mean		SE	Mean	SE	Mean	SE
Rye	---		---	---		---	---		---	---	---	---	---
Rye-Vetch	2.58		0.10	22.7	b	5.4	43.3		1.3	380	91	16.8	0.2
Vetch	2.83		0.13	78.2	a	9.7	45.8		1.0	1264	133	16.4	0.7
Crop effect, p-value	*0.143*			*0.019*			*0.236*			*0.058*		*0.267*	
+0N	2.61		0.09	51.5		7.5	44.4		1.1	914	124	17.1	0.5
+30N	2.81		0.14	49.4		13.1	44.6		1.4	752	192	16.0	0.4
N effect, p-value	*0.123*			*0.837*			*0.872*			*0.222*		*0.201*	
Rye +0N	---		---	---		---	---		---	---	---	---	---
Rye +30N	---		---	---		---	---		---	---	---	---	---
Rye+Vetch +0N	2.67	b	0.18	32.7	bc	9.3	44.6	ab	2.0	549	155	16.8	0.5
Rye+Vetch +30N	2.50	b	0.10	12.6	c	3.4	41.9	b	1.7	212	57	16.8	0.2
Vetch +0N	2.54	b	0.06	70.3	ab	7.1	44.3	ab	1.5	1239	108	17.5	1.0
Vetch +30N	3.12	a	0.13	86.2	a	18.2	47.3	a	1.0	1292	266	15.2	0.5
*Crop*N interaction, p-value*	*0.015*			*0.084*			*0.047*			*0.112*		*0.191*	

a, b, c Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

Table A1.19. Effect of cover crop species and nitrogen fertility on above-ground plant tissue NDF and NDF-C and -N fractions for hairy vetch plants only at 416 GDD.

	Vetch NDF-N % of NDF			Vetch NDF-N (kg ha^{-1})			Vetch NDF-C % of NDF			Vetch NDF-C (kg ha^{-1})			Vetch NDF C:N		
416 GDD only	Mean		SE	Mean		SE	Mean		SE	Mean		SE	Mean		SE
Rye	---		---	---		---	---		---	---		---	---		---
Rye-Vetch	1.58		0.21	0.6	b	0.1	43.4	a	0.5	21	b	4	30		4
Vetch	1.12		0.18	1.7	a	0.3	33.1	b	2.0	64	a	14	34		4
Crop effect, p-value	*0.228*			*0.012*			*0.002*			*0.017*			*0.686*		
+0N	1.08	b	0.21	1.6	a	0.3	36.8		2.7	67	a	13	38	a	3
+30N	1.62	a	0.15	0.7	b	0.1	39.2		2.2	17	b	4	25	b	2
N effect, p-value	*0.044*			*<0.001*			*0.229*			*<.0001*			*0.011*		
Rye +0N	---		---	---		---	---		---	---		---	---		---
Rye +30N	---		---	---		---	---		---	---		---	---		---
Rye+Vetch +0N	1.42	ab	0.34	0.8	b	0.1	43.3	a	0.7	29	b	5	35	ab	6
Rye+Vetch +30N	1.80	a	0.17	0.4	b	0.1	43.5	a	0.7	10	b	2	25	b	3
Vetch +0N	0.75	b	0.09	2.5	a	0.4	30.3	b	2.1	104	a	19	42	a	3
Vetch +30N	1.49	a	0.23	0.9	b	0.2	35.9	b	2.9	23	b	7	25	b	3
*Crop*N interaction, p-value*	*0.359*			*0.026*			*0.282*			*0.007*			*0.233*		

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.20. Effect of cover crop species and nitrogen fertility on above-ground plant tissue NDF and NDF-C and -N fractions for hairy vetch plants only at 532 GDD.

	Vetch NDF-N % of NDF		Vetch NDF-N (kg ha^{-1})			Vetch NDF-C % of NDF			Vetch NDF-C (kg ha^{-1})			Vetch NDF C:N	
532 GDD only	Mean	SE	Mean		SE	Mean		SE	Mean		SE	Mean	SE
Rye	---	---	---		---	---		---	---		---	---	---
Rye-Vetch	0.74	0.06	1.4		0.3	45.1	a	0.1	95	b	19	63	5
Vetch	0.54	0.04	2.2		0.5	39.3	b	2.0	179	a	38	75	5
Crop effect, p-value	*0.095*		*0.085*			*0.038*			*0.037*			*0.113*	
+0N	0.57	0.04	2.6	a	0.4	42.6		1.9	197	a	35	76	3
+30N	0.69	0.08	1.0	b	0.2	40.7		2.1	73	b	19	62	8
N effect, p-value	*0.260*		*0.004*			*0.306*			*0.004*			*0.378*	
Rye +0N	---	---	---		---	---		---	---		---	---	---
Rye +30N	---	---	---		---	---		---	---		---	---	---
Rye+Vetch +0N	0.65	0.04	1.8	b	0.3	45.2	a	0.2	125	b	21	70	5
Rye+Vetch +30N	0.91	0.06	0.7	b	0.2	45.1	a	0.1	36	b	10	50	3
Vetch +0N	0.50	0.04	3.3	a	0.7	40.0	ab	3.5	268	a	57	81	1
Vetch +30N	0.59	0.05	1.2	b	0.3	38.6	b	2.6	91	b	27	68	10
*Crop*N interaction, p-value*	*0.592*		*0.306*			*0.716*			*0.295*			*0.714*	

a, b Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

Table A1.21. Effect of cover crop species and nitrogen fertility on above-ground plant tissue NDF and NDF-C and -N fractions for hairy vetch plants only at 962 GDD.

	Vetch NDF-N % of NDF		Vetch NDF-N ($kg\ ha^{-1}$)			Vetch NDF-C % of NDF		Vetch NDF-C ($kg\ ha^{-1}$)			Vetch NDF C:N	
962 GDD only	Mean	SE	Mean		SE	Mean	SE	Mean		SE	Mean	SE
Rye	---	---	---		---	---	---	---		---	---	---
Rye-Vetch	0.72	0.04	2.8	b	0.6	46.6	0.3	192	b	44	66	4
Vetch	0.79	0.07	10.8	a	1.2	46.0	0.5	623	a	61	61	5
Crop effect, p-value	*0.817*		*0.002*			*0.390*		*0.005*			*0.535*	
+0N	0.77	0.07	8.5	a	1.4	46.5	0.3	494	a	68	64	6
+30N	0.74	0.04	5.2	b	1.3	46.0	0.5	329	b	80	63	4
N effect, p-value	*0.724*		*0.027*			*0.244*		*0.031*			*0.937*	
Rye +0N	---	---	---		---	---	---	---		---	---	---
Rye +30N	---	---	---		---	---	---	---		---	---	---
Rye+Vetch +0N	0.73	0.08	4.1	b	1.1	46.4	0.5	277	b	74	66	7
Rye+Vetch +30N	0.72	0.06	1.6	b	0.4	46.7	0.3	107	b	26	66	5
Vetch +0N	0.82	0.13	12.5	a	1.6	46.7	0.3	687	a	59	61	9
Vetch +30N	0.77	0.06	8.9	a	1.7	45.3	0.7	551	a	111	61	6
*Crop*N interaction, p-value*	*0.911*		*0.697*			*0.066*		*0.801*			*0.978*	

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.22. Effect of cover crop species and nitrogen fertility on above-ground plant tissue NDS and NDS-C and -N fractions for hairy vetch plants only at 416 GDD.

	Vetch NDS-N % of NDS		Vetch NDS-N (kg ha^{-1})		Vetch NDS-C % of NDS		Vetch NDS-C (kg ha^{-1})		Vetch NDS C:N	
416 GDD only	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Rye	---	---	---	---	---	---	---	---	---	---
Rye-Vetch	5.6	0.1	5.8 b	1.2	48.9	1.3	50 b	11	8.8	0.2
Vetch	5.5	0.2	21.7 a	5.0	47.9	2.7	189 a	43	8.7	0.4
Crop effect, p-value	*0.616*		*0.006*		*0.842*		*0.003*		*0.975*	
+0N	5.5	0.1	22.9 a	4.8	48.3	1.5	201 a	41	8.8	0.2
+30N	5.6	0.2	4.4 b	1.0	48.4	2.9	37 b	8	8.7	0.4
N effect, p-value	*0.873*		*<.0001*		*0.971*		*<.0001*		*0.792*	
Rye +0N	---	---	---	---	---	---	---	---	---	---
Rye +30N	---	---	---	---	---	---	---	---	---	---
Rye+Vetch +0N	5.6	0.1	8.4 b	1.6	48.8	2.2	73 b	14	8.7	0.3
Rye+Vetch +30N	5.5	0.1	2.2 b	0.5	49.1	1.7	20 b	5	8.9	0.1
Vetch +0N	5.4	0.2	37.4 a	5.9	47.9	2.4	329 a	48	8.9	0.2
Vetch +30N	5.6	0.4	6.0 b	1.5	47.9	5.2	50 b	13	8.6	0.7
*Crop*N interaction, p-value*	*0.690*		*0.001*		*0.971*		*0.001*		*0.552*	

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A1.23. Effect of cover crop species and nitrogen fertility on above-ground plant tissue NDS and NDS-C and -N fractions for hairy vetch plants only at 532 GDD.

	Vetch NDS-N % of NDS		Vetch NDS-N ($kg\ ha^{-1}$)		Vetch NDS-C % of NDS		Vetch NDS-C ($kg\ ha^{-1}$)		Vetch NDS C:N	
532 GDD only	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Rye	---	---	---	---	---	---	---	---	---	---
Rye-Vetch	4.2 b	0.2	14.4	3.2	39.0 b	3.5	129 b	31	9.2 a	0.7
Vetch	6.6 a	0.2	42.0	8.1	49.3 a	1.5	307 a	57	7.5 b	0.3
Crop effect, p-value	*0.001*		*0.184*		*<.0001*		*0.021*		*0.025*	
+0N	5.5	0.5	40.5 a	8.2	42.8	3.7	308 a	57	7.8	0.5
+30N	5.4	0.5	16.3 b	4.1	46.4	2.3	128 b	29	8.8	0.7
N effect, p-value	*0.271*		*<0.001*		*0.482*		*0.003*		*0.144*	
Rye +0N	---	---	---	---	---	---	---	---	---	---
Rye +30N	---	---	---	---	---	---	---	---	---	---
Rye+Vetch +0N	4.4 b	0.3	19.2 b	3.8	36.6 b	5.7	167 b	40	8.3 ab	0.7
Rye+Vetch +30N	4.0 b	0.1	4.8 b	1.2	42.2 b	3.5	53 b	17	10.5 a	1.0
Vetch +0N	6.7 a	0.4	61.9 a	11.8	49.1 ab	2.2	449 a	83	7.4 b	0.6
Vetch +30N	6.5 a	0.3	22.0 b	5.1	49.5 a	2.2	165 b	37	7.6 b	0.2
*Crop*N interaction, p-value*	*0.886*		*<.0001*		*0.804*		*0.185*		*0.219*	

a, b Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

Table A1.24. Effect of cover crop species and nitrogen fertility on above-ground plant tissue NDS and NDS-C and -N fractions for hairy vetch plants only at 962 GDD.

	Vetch NDS-N % of NDS		Vetch NDS-N (kg ha^{-1})		Vetch NDS-C % of NDS		Vetch NDS-C (kg ha^{-1})		Vetch NDS C:N	
962 GDD only	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Rye	---	---	---	---	---	---	---	---	---	---
Rye-Vetch	4.4	0.2	19.9 b	4.8	41.5	2.3	189 b	47	9.5	0.2
Vetch	4.7	0.2	67.2 a	8.4	45.4	2.2	641 a	79	9.7	0.4
Crop effect, p-value	*0.212*		*0.011*		*0.281*		*0.012*		*0.634*	
+0N	4.5	0.2	44.3	6.0	42.5	2.5	421	57	9.4	0.3
+30N	4.6	0.2	44.2	11.8	44.5	2.2	423	113	9.7	0.3
N effect, p-value	*0.690*		*0.962*		*0.511*		*0.929*		*0.671*	
Rye +0N	---	---	---	---	---	---	---	---	---	---
Rye +30N	---	---	---	---	---	---	---	---	---	---
Rye+Vetch +0N	4.5	0.3	28.6 bc	8.2	43.0	4.3	272 bc	81	9.4	0.4
Rye+Vetch +30N	4.2	0.2	11.1 c	3.1	40.0	2.1	105 c	31	9.6	0.4
Vetch +0N	4.4	0.1	58.2 ab	5.5	41.9	3.0	552 ab	49	9.5	0.6
Vetch +30N	5.0	0.3	77.3 a	16.6	48.9	2.4	741 a	157	9.9	0.6
*Crop*N interaction, p-value*	*0.094*		*0.045*		*0.131*		*0.037*		*0.867*	

a, b, c Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A2.1. Effect of cover crop and manure amendment on B-size potato tuber yield in 3 rotation cycles at Entrican and Benton Harbor, MI.

	B-size Tuber Yield, Mg ha⁻¹											
	Entrican, MI						Benton Harbor, MI					
	2003		2004		2005		2003		2004		2005	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bare	2.1	0.3	1.6 a	0.2	3.8	0.7	2.9	0.4	3.0	0.4	3.8	0.5
Rye	2.9	0.5	1.2 ab	0.2	2.9	0.3	2.0	0.3	2.0	0.3	2.3	0.3
Rye-Vetch	3.7	0.6	0.6 b	0.1	2.6	0.2	2.6	0.3	2.6	0.4	3.4	0.4
Crop effect, p	*0.174*		*0.042*		*0.307*		*0.282*		*0.107*		*0.081*	
No Manure	2.7	0.4	1.1	0.2	2.8 b	0.3	2.4	0.2	2.7	0.3	3.4	0.3
Manure	3.0	0.4	1.1	0.2	3.4 a	0.5	2.6	0.3	2.5	0.3	2.9	0.4
Manure effect, p	*0.614*		*0.945*		*0.046*		*0.364*		*0.640*		*0.206*	
Bare	2.1	0.4	1.6	0.4	2.8 b	0.6	3.2 a	0.3	3.2	0.7	4.6 a	0.6
Bare + M	2.1	0.5	1.5	0.2	5.2 a	1.2	2.6 ab	0.7	2.9	0.4	2.9 bc	0.6
Rye	2.5	0.5	1.0	0.3	2.6 b	0.4	1.7 b	0.3	1.9	0.4	2.7 bc	0.4
Rye + M	3.4	0.9	1.4	0.2	3.3 ab	0.5	2.3 ab	0.4	2.2	0.5	1.9 c	0.4
Rye-Vetch	3.8	0.8	0.7	0.2	3.0 ab	0.3	2.2 ab	0.2	2.9	0.4	2.9 bc	0.5
Rye-Vetch + M	3.5	0.9	0.4	0.2	2.2 b	0.3	3.0 ab	0.4	2.4	0.6	3.9 ab	0.6
*Crop*Manure interaction, p*	*0.675*		*0.260*		*0.001*		*0.060*		*0.708*		*0.022*	

a, b, c   Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A2.2a. Effect of cover crop and manure amendment on yield of snap bean pod dry matter in 3 rotation cycles at Entrican, MI.

	Snap Bean Pods, dry (Mg/ha)								
	Entrican, MI								
	2003			2004		2005			
	Mean		SE	Mean	SE	Mean	SE		
Bare	1.41	a	0.06	2.02	0.06	0.47	0.07		
Rye	1.38	a	0.07	2.11	0.05	0.53	0.07		
Rye-Vetch	1.16	b	0.06	2.13	0.06	0.57	0.04		
Crop effect, p	*0.040*			*0.698*		*0.764*			
No Manure	1.28		0.06	2.03	0.04	0.53	0.05		
Manure	1.35		0.05	2.14	0.05	0.53	0.04		
Manure effect, p	*0.151*			*0.063*		*0.917*			
Bare	1.34	ab	0.07	2.03	0.06	0.47	0.11		
Bare + M	1.47	ab	0.09	2.01	0.12	0.50	0.10		
Rye	1.50	a	0.11	2.01	0.09	0.55	0.12		
Rye + M	1.26	b	0.07	2.22	0.04	0.51	0.08		
Rye-Vetch	1.00	c	0.07	2.04	0.09	0.55	0.05		
Rye-Vetch + M	1.32	ab	0.07	2.21	0.09	0.59	0.06		
*Crop*Manure interaction, p*	*<0.001*			*0.245*		*0.794*			

a, b, c Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

Table A2.2b. Effect of cover crop and manure amendment on yield of snap bean pod dry matter in 3 rotation cycles at Benton Harbor, MI.

	Snap Bean Pods, dry (Mg/ha)								
	Benton Harbor, MI								
	2003		2004			2005			
	Mean	SE	Mean		SE	Mean	SE		
Bare	1.17	0.05	1.61		0.08	0.29	0.12		
Rye	1.11	0.04	1.68		0.06	0.30	0.06		
Rye-Vetch	1.09	0.04	1.70		0.05	0.38	0.08		
Crop effect, p	*0.357*		*0.433*			*0.884*			
No Manure	1.16	0.04	1.70		0.06	0.36	0.07		
Manure	1.09	0.03	1.63		0.05	0.29	0.07		
Manure effect, p	*0.172*		*0.400*			*0.443*			
Bare	1.22	0.07	1.78	a	0.12	0.39	0.19		
Bare + M	1.12	0.06	1.43	b	0.06	0.19	0.14		
Rye	1.14	0.06	1.72	a	0.13	0.36	0.07		
Rye + M	1.09	0.07	1.65	ab	0.05	0.24	0.10		
Rye-Vetch	1.12	0.05	1.59	ab	0.05	0.32	0.12		
Rye-Vetch + M	1.07	0.05	1.81	a	0.08	0.44	0.10		
*Crop*Manure interaction, p*	*0.854*		*0.009*			*0.291*			

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A2.3a. Effect of cover crop and manure amendment on yield of snap bean total above-ground dry biomass over 3 rotation cycles at Entrican, MI.

	Total Snap Bean biomass, dry (Mg/ha)								
	Entrican, MI								
	2003			2004			2005		
	Mean		SE	Mean		SE	Mean		SE
Bare	3.74		0.14	4.55		0.20	1.80		0.19
Rye	3.70		0.17	5.04		0.19	1.85		0.14
Rye-Vetch	3.17		0.18	4.92		0.21	1.95		0.13
Crop effect, p	*0.068*			*0.270*			*0.904*		
No Manure	3.34	b	0.14	4.45	b	0.12	1.75		0.13
Manure	3.73	a	0.14	5.22	a	0.17	1.98		0.10
Manure effect, p	*0.004*			*0.001*			*0.114*		
Bare	3.53	a	0.12	4.35		0.14	1.74		0.32
Bare + M	3.94	a	0.23	4.75		0.37	1.87		0.23
Rye	3.80	a	0.21	4.61		0.28	1.79		0.27
Rye + M	3.60	a	0.28	5.46		0.14	1.90		0.13
Rye-Vetch	2.69	b	0.17	4.39		0.20	1.73		0.14
Rye-Vetch + M	3.65	a	0.22	5.46		0.26	2.16		0.18
*Crop*Manure interaction, p*	*0.003*			*0.408*			*0.563*		

a, b Values within a column grouping followed by the same letter are not significantly different ($P \leq 0.05$) according to the LSD.

Table A2.3b. Effect of cover crop and manure amendment on yield of snap bean total above-ground dry biomass over 3 rotation cycles at Benton Harbor, MI.

	Total Snap Bean biomass, dry (Mg/ha)								
	Benton Harbor, MI								
	2003		2004			2005			
	Mean	SE	Mean		SE	Mean	SE		
Bare	2.95	0.12	3.02		0.16	1.66	0.30		
Rye	2.96	0.12	3.09		0.11	2.08	0.16		
Rye-Vetch	3.01	0.12	3.07		0.10	2.07	0.23		
Crop effect, p	*0.919*		*0.920*			*0.707*			
No Manure	3.05	0.10	3.16		0.11	1.94	0.20		
Manure	2.90	0.10	2.96		0.09	1.93	0.19		
Manure effect, p	*0.281*		*0.108*			*0.945*			
Bare	3.16	0.12	3.46	a	0.19	1.81	0.48		
Bare + M	2.74	0.19	2.59	d	0.12	1.51	0.39		
Rye	2.94	0.18	3.18	abd	0.22	2.22	0.21		
Rye + M	2.99	0.18	3.00	bcd	0.11	1.94	0.25		
Rye-Vetch	3.04	0.21	2.83	cd	0.08	1.80	0.34		
Rye-Vetch + M	2.97	0.13	3.30	ab	0.14	2.33	0.30		
*Crop*Manure interaction, p*	*0.355*		*<0.001*			*0.270*			

a, b, c, d Values within a column grouping followed by the same letter are not significantly different (P ≤ 0.05) according to the LSD.

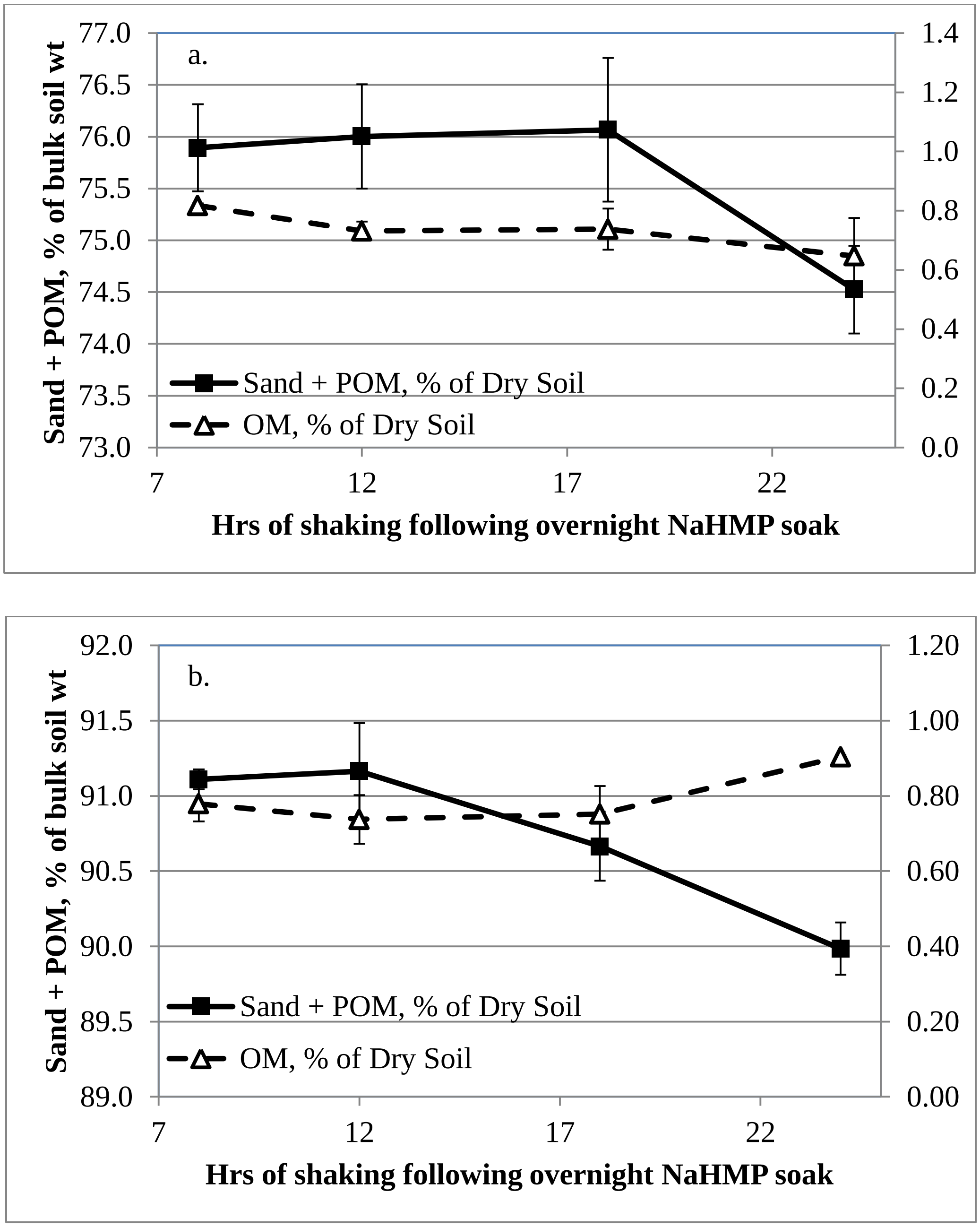


Figure A4.1. Effect of duration of dispersion and shaking time on POM recovery for a.) Entrican and b.) Benton Harbor soils. Duplicate 40 g soil samples in 100 ml of 5.0 g L^{-1} sodium hexametaphosphate solution were placed on a reciprocating shaker on POM recovery for 8 to 24 hours to determine optimal dispersion and shaking time.

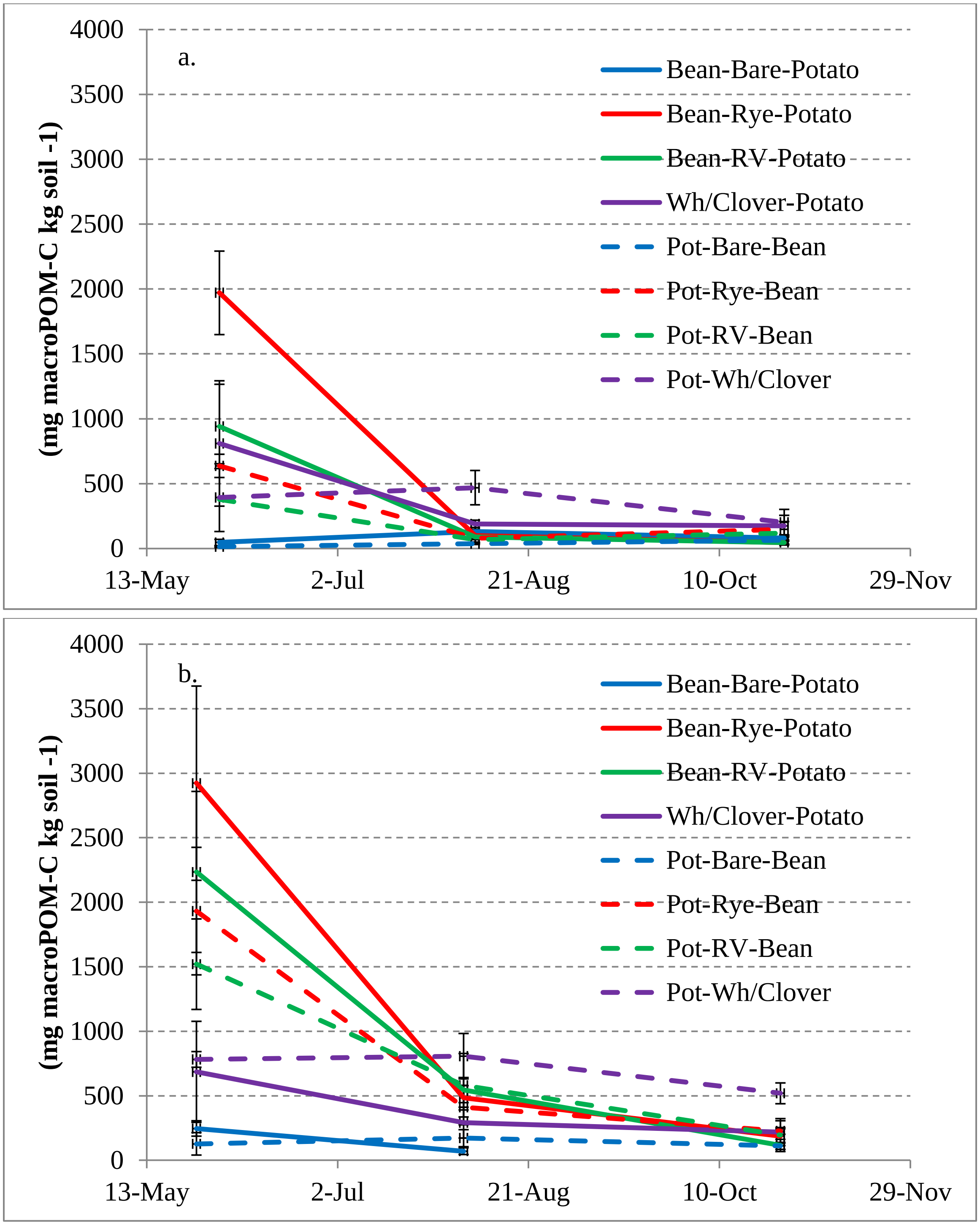


Figure A4.2. Macro-POM-C fraction in soil in Entrican, MI (a.) and Benton Harbor, MI (b.) from June to October 2006.

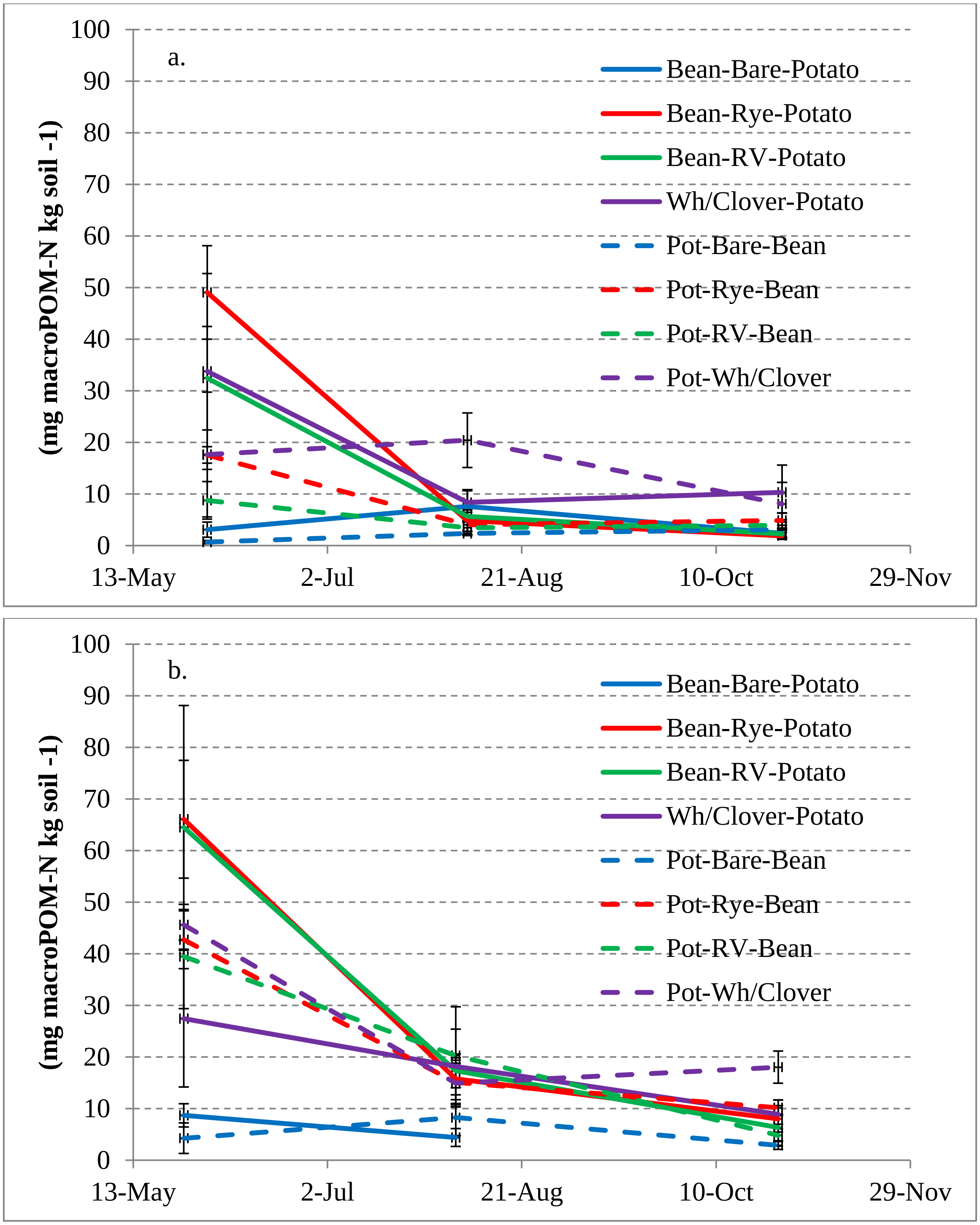


Figure A4.3. Macro-POM-N fraction in soil in Entrican, MI (a.) and Benton Harbor, MI (b.) from June to October 2006.

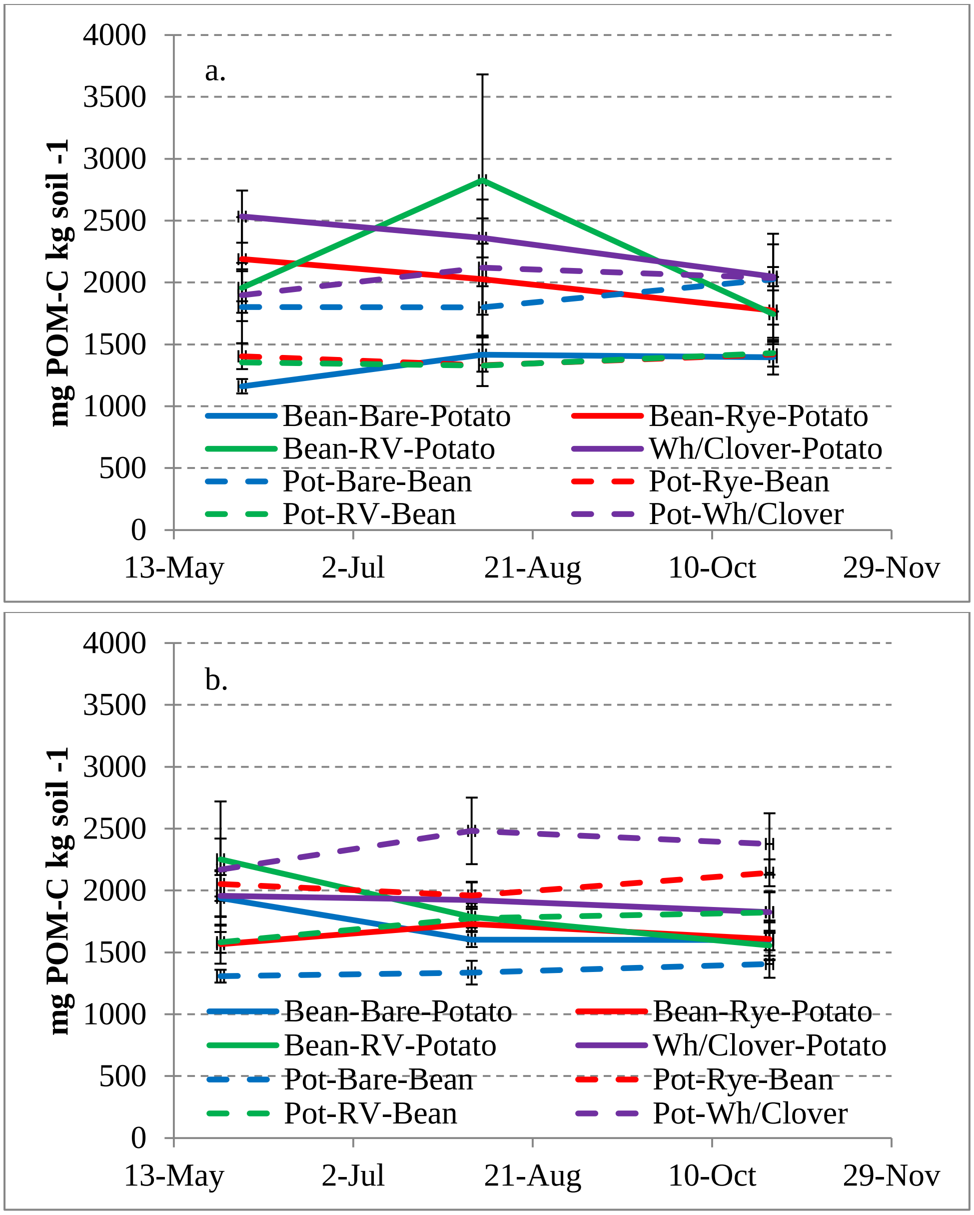


Figure A4.4. POM-C fraction in soil in Entrican, MI (a.) and Benton Harbor, MI (b.) from June to October 2006.

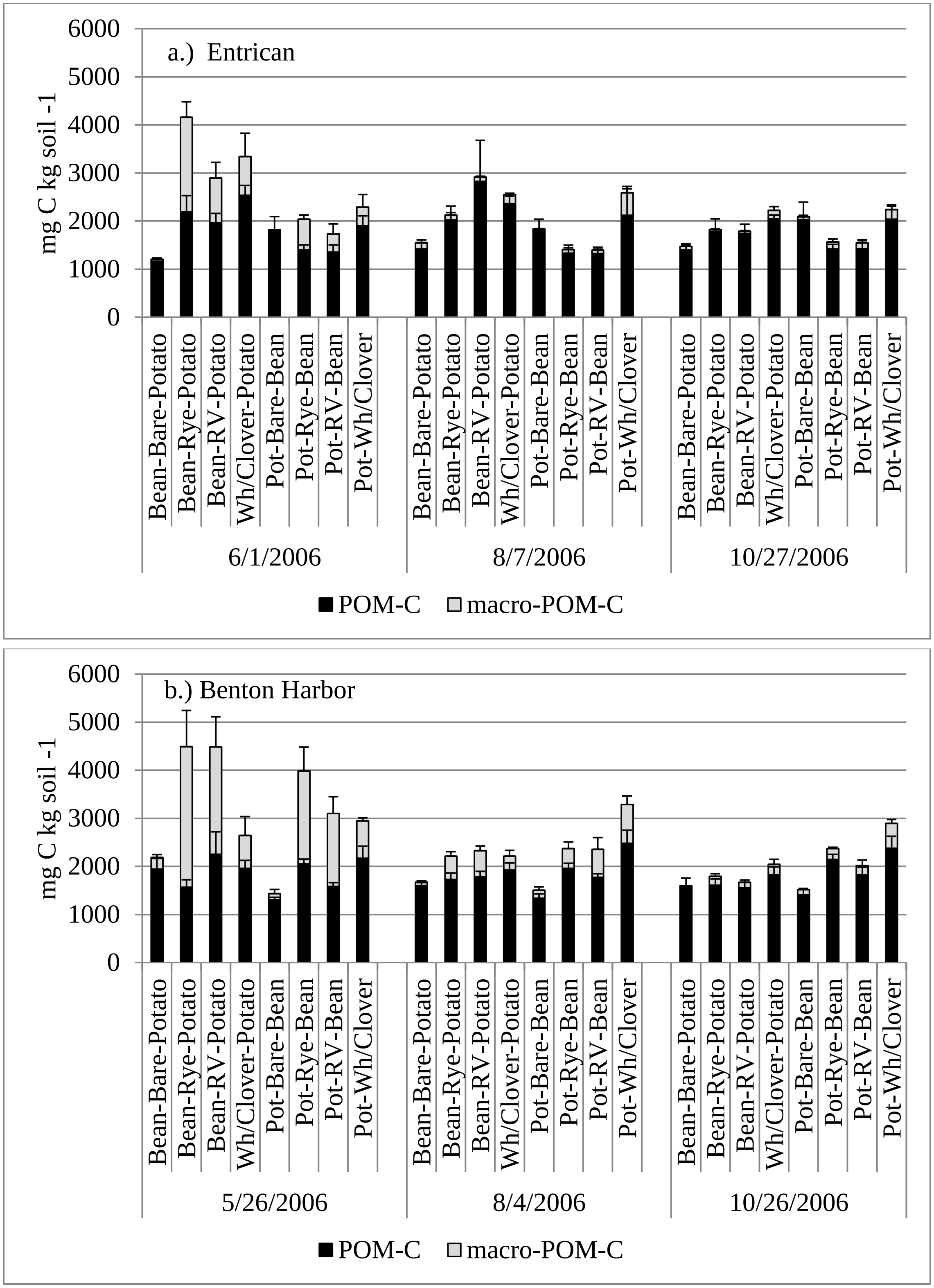


Figure A4.5. POM-C and macro-POM-C fractions in soil in Entrican, MI (a.) and Benton Harbor, MI (b.) from June to October 2006.

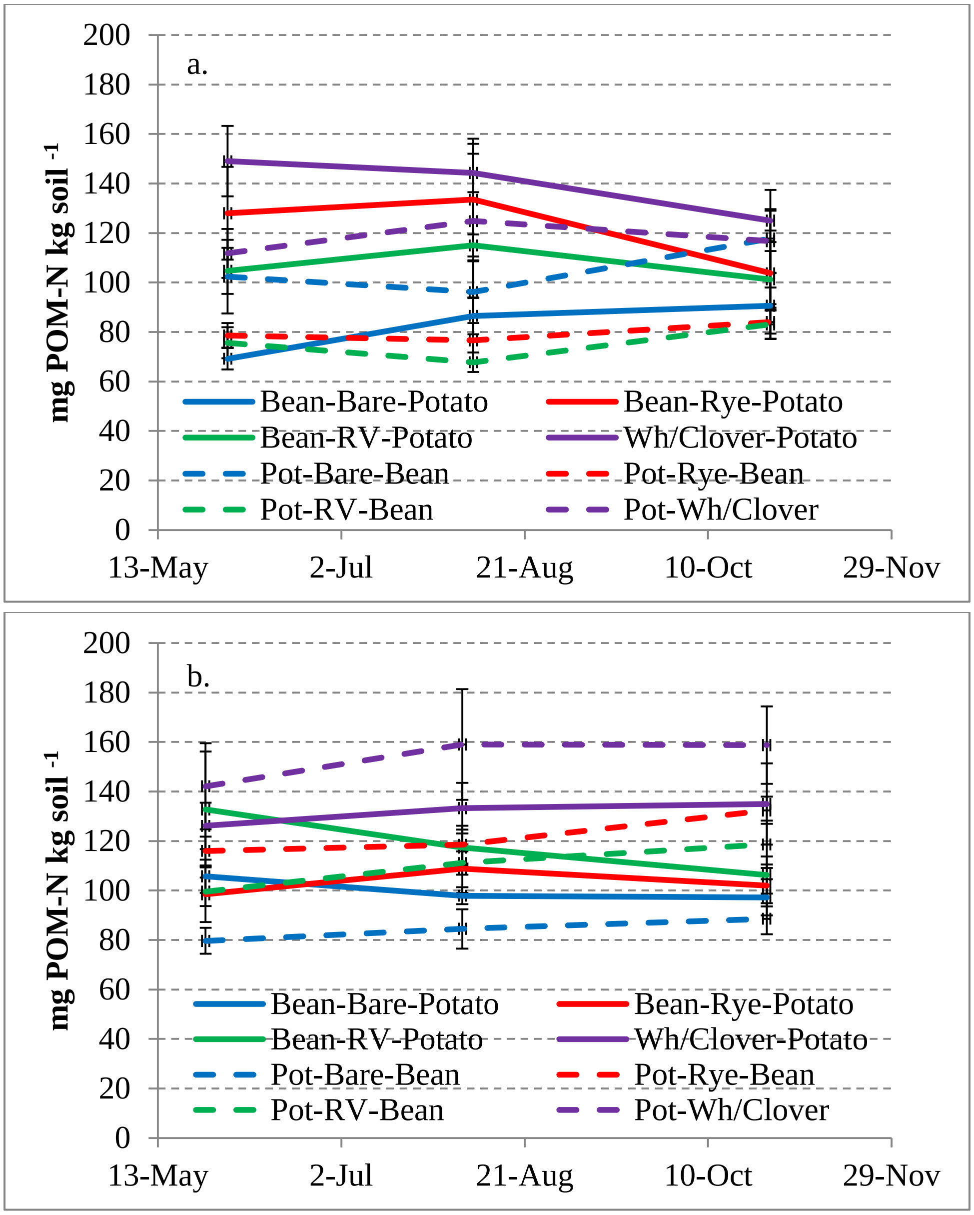


Figure A4.6. POM-N fraction in soil in Entrican, MI (a.) and Benton Harbor, MI (b.) from June to October 2006.

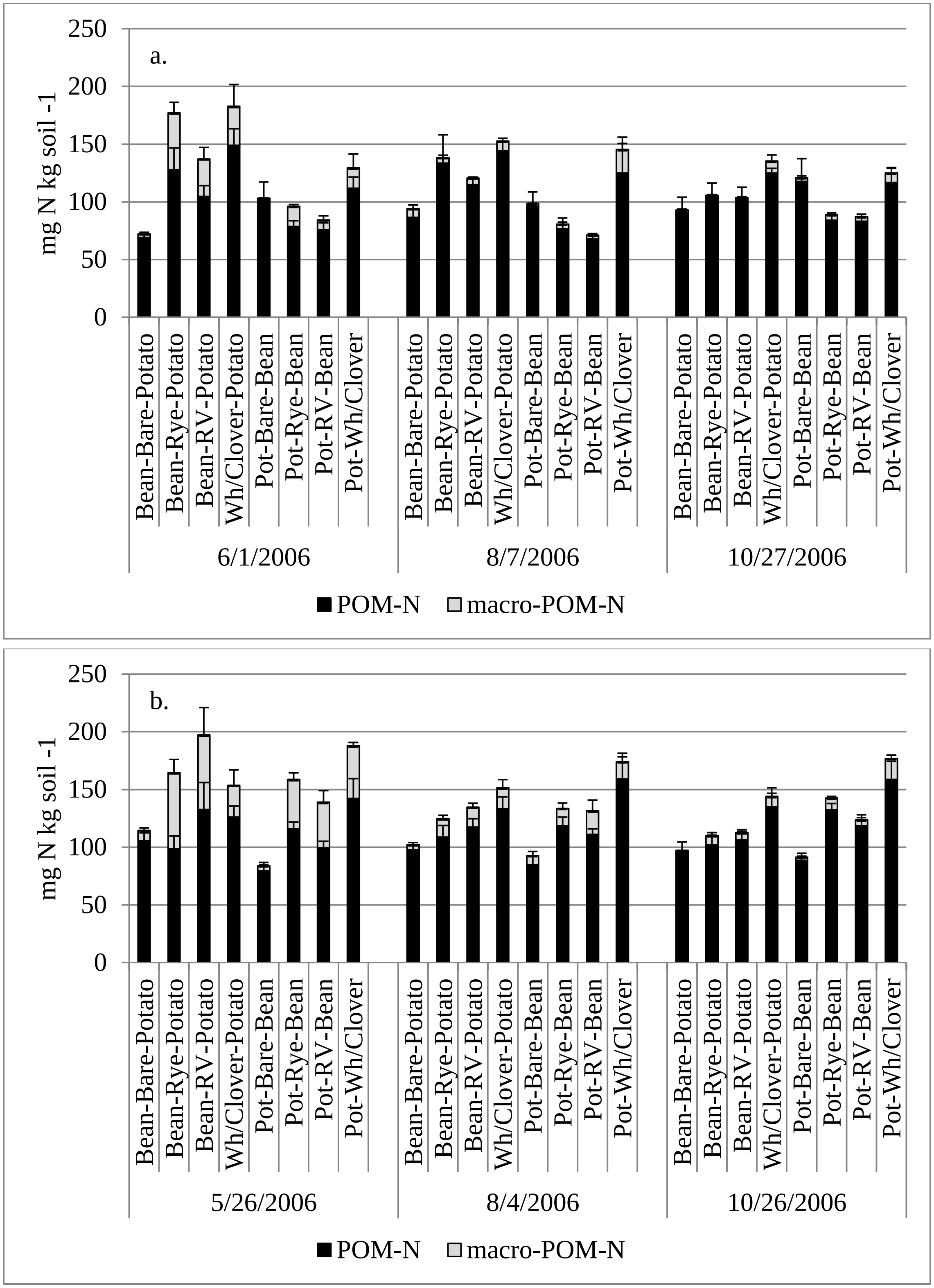


Figure A4.7. POM-N and macro-POM-N fractions in soil in Entrican, MI (a.) and Benton Harbor, MI (b.) from June to October 2006.

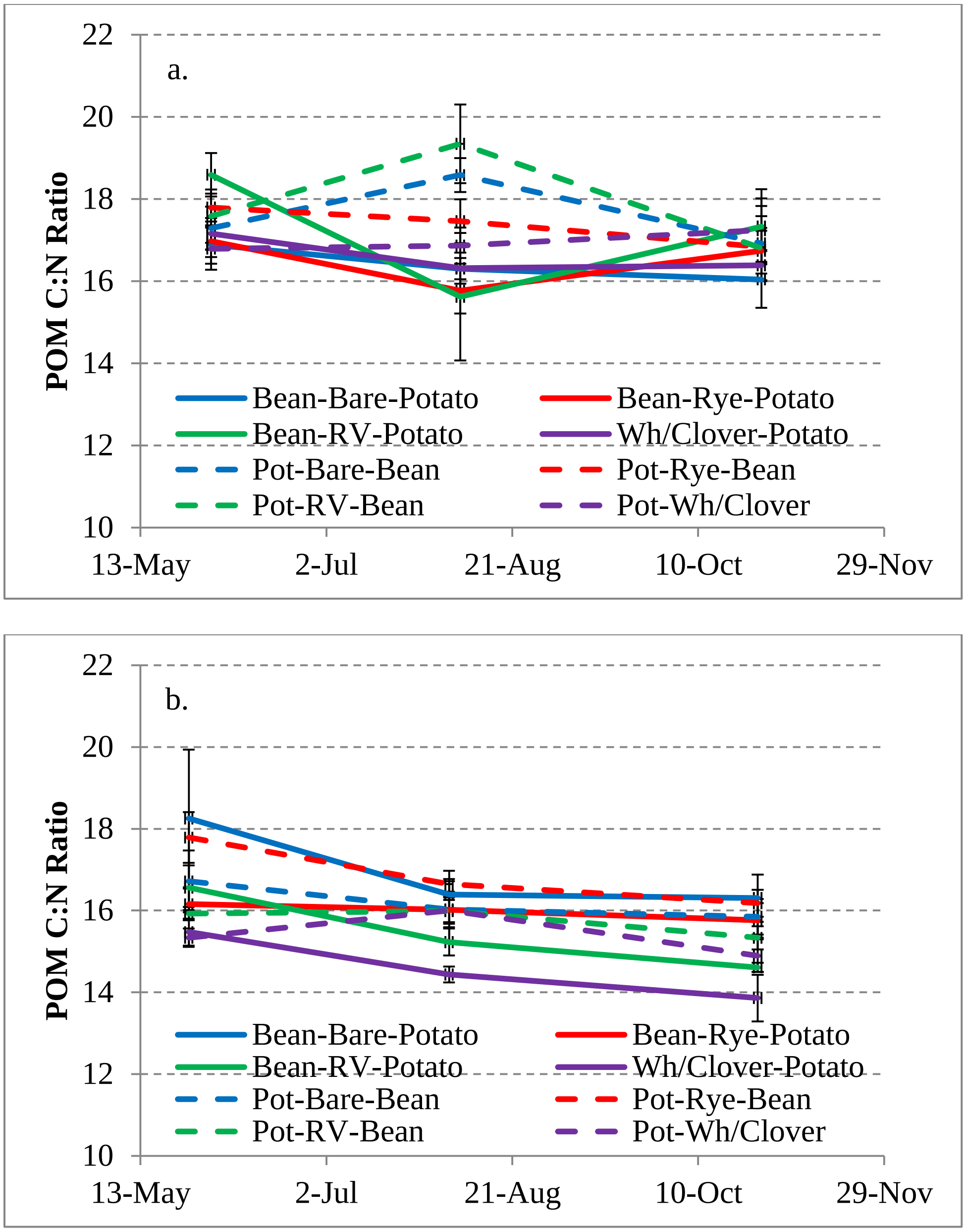


Figure A4.8. Soil POM C:N ratio at Entrican, MI (a.) and Benton Harbor, MI (b.) from June to October 2006.

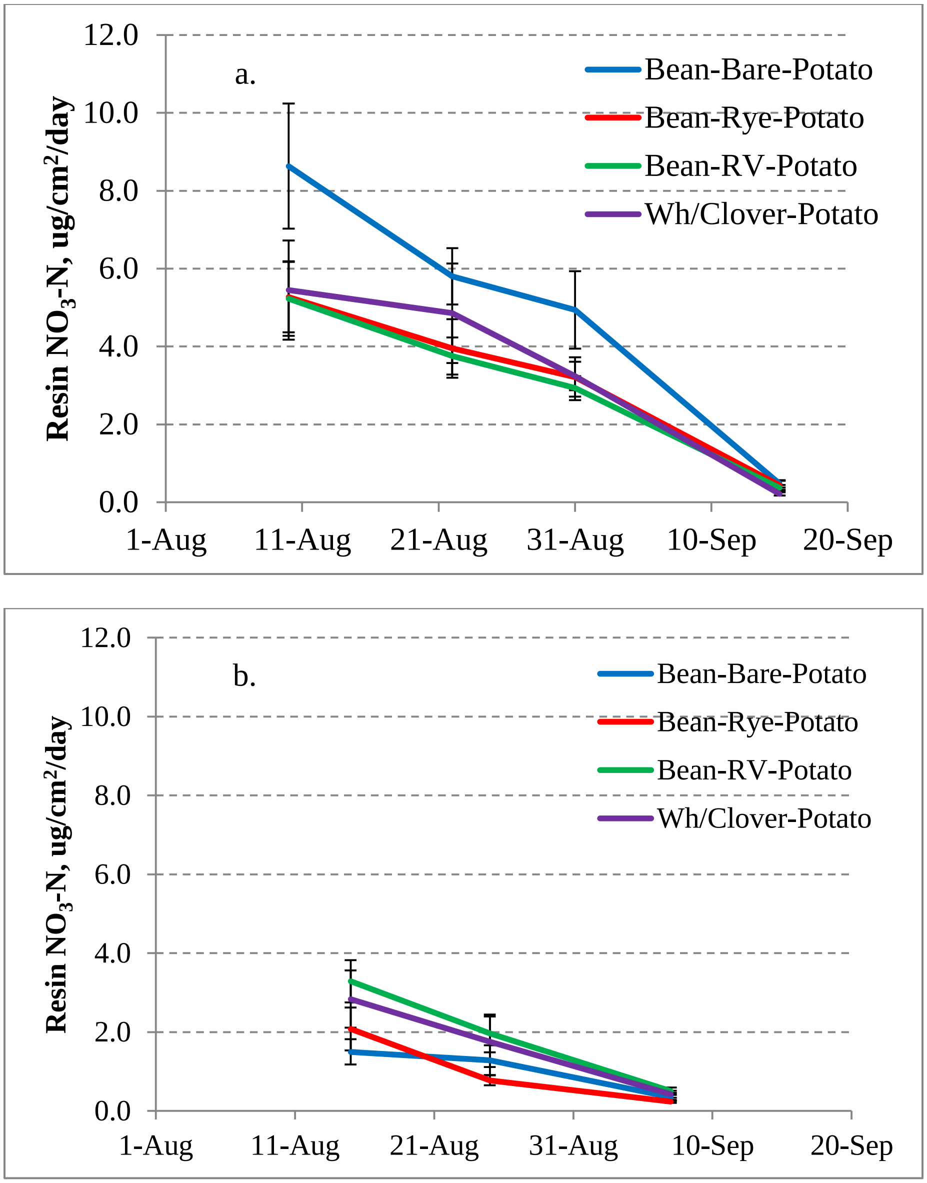
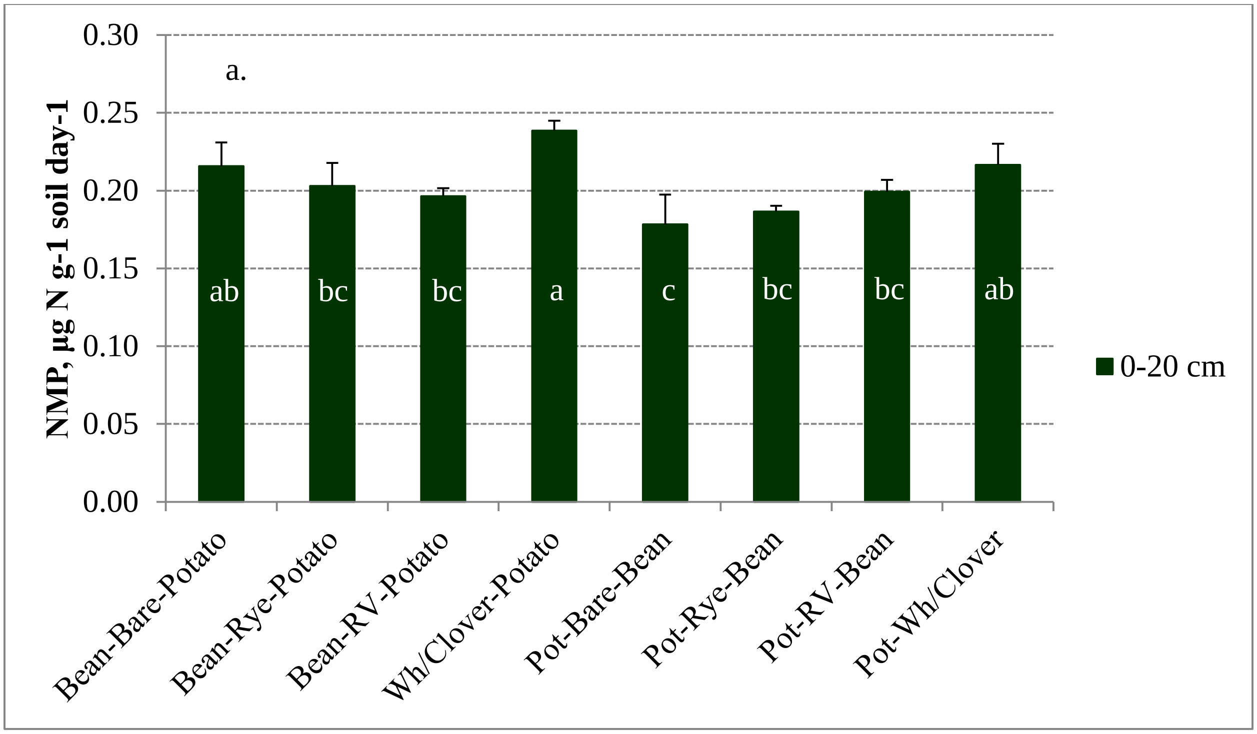


Figure A4.9. Soil NO_3-N availability at a 0-10cm depth, as measured with anion exchange resin, at Entrican, MI (a.) and Benton Harbor, MI (b.) from August to September 2006.



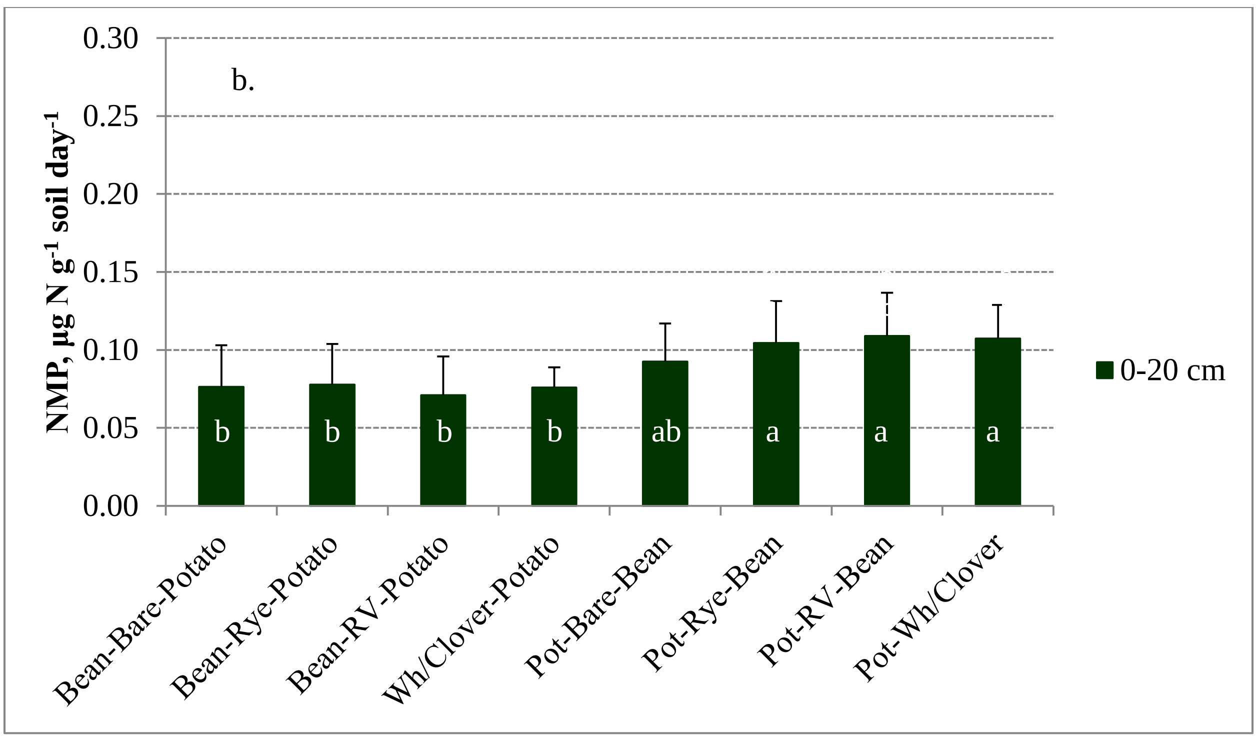


Figure A4.10. Effect of cropping system on November 2006 nitrogen mineralization potential (NMP) in the surface 20 cm of soil at Entrican, MI (a.) and Benton Harbor, MI (b.)