This is to certify that the
thesis entitled

INTEGRATION OF POTATO PRODUCTION, DAIRY FORAGE AND MANURE MANAGEMENT SYSTEMS: NITROGEN DYNAMICS AND AGRONOMIC IMPLICATIONS

presented by

Timothy John Boring

has been accepted towards fulfillment
of the requirements for the

M.S. degree in Crop and Soil Sciences

Richard H Leep
Major Professor's Signature

December 16, 2005
Date

INTEGRATION OF POTATO PRODUCTION, DAIRY FORAGE AND MANURE MANAGEMENT SYSTEMS: NITROGEN DYNAMICS AND AGRONOMIC IMPLICATIONS

by

Timothy John Boring

A THESIS

Submitted to
Michigan State University
In partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

DEPARTMENT OF CROP AND SOIL SCIENCES

2005

ABSTRACT

INTEGRATION OF POTATO PRODUCTION, DAIRY FORAGE AND MANURE MANAGEMENT SYSTEMS: NITROGEN DYNAMICS AND AGRONOMIC IMPLICATIONS

by

Timothy John Boring

The integration of potato and livestock agronomic operations has been proposed as a means by which to improve overall system productivity and long-term sustainability. Two-year potato (*Solanum tuberosum* L.) rotations with alfalfa (*Medicago sativa* L.) and sorghum-sudangrass (*Sorghum bicolor* L. *x S. bicolor* L.) and 3-year potato rotations with 2-year stands of alfalfa and festulolium (*Festuca pratensis* Huds. *x Lolium perenne* L.) were compared to the regionally prevalent 2-year corn (*Zea mays* L.) - potato rotation. Liquid dairy manure was applied at 12,260 L ha^{-1} and evaluated against equivalent mineral fertilizer applications balanced on available nitrogen. Forage crop rotation and manure application increased soil N levels and potato petiole N throughout the growing season in 2003 and 2004. Crop rotation was a more determining factor of N levels in potato systems than manure application. Manure was more effective at increasing potato yield than crop rotations alone; the synergistic effect of manure amendment and crop rotation produced more significant increases in potato yields than either treatment alone. C_4 grasses corn and sudex increased potato yield more than C_3 grass festulolium or legume alfalfa. Manure application did not affect tuber scab disease in 2002 or 2003, but did increase scab in 2004. Festulolium yields increased with manure application in 2003, but not in 2004. Additions of high quality forage rotations and manure amendment can improve N synchrony with potato N demand resulting in increased potato yields.

ACKNOWLEDGEMENTS

Thank you to Dr. Richard Leep and Dr. Doo-Hong Min, my advisors, for giving me the opportunity to work with them on this project. A special thank you to Dr. Sieglinde Snapp for her innumerable contributions and to Dr. Roy Black for his guidance in the economic aspects of this project.

I would also like to extent thanks to all those who contributed to the field aspects of this research. The farm managers at the Montcalm Potato Research Farm, Dick Crawford, and at the Agronomy Farm, Brian Graff and Tom Galacka, have gone to great lengths to help whenever and wherever they were able. Thank you to Gary Zehr, Keith Dysinger, Bill Widdecombe, John Boyse, Lee Siler and Kitty O'Neil who provided time, resources and knowledge. Also, special thanks to Tim Dietz, who has gone above and beyond with his contributions of time and expertise.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: Literature Review and Introduction

Nitrogen Dynamics

Nitrogen in Potato Production

Nitrogen management has been shown to be one of the most critical functions of production efficiency in potato (*Solanum tuberosum* L.) cropping systems (Stark et al., 1993). In sandy soils, N is typically the most limiting factor for tuber growth (Errebhi et al., 1998). Nitrogen deficiencies have been shown to create management problems including increased weed competition; enhanced susceptibility to diseases such as early die complex; and limited production capability through reduced tuber size, tuber initiates, and marketable tuber yields (Roberts et al., 1982; Rosen, 1991; Lang et al., 1999).

Surveys of Washington state potato producers have indicated that growers frequently apply N at levels in excess of recommended levels in the belief that higher fertilization rates prevent or overcome management and environmental challenges such as sub-optimal irrigation and N fertilization timing, disease pressure, and excess precipitation (Lang and Stevens, 1997). However, excess N levels have been shown to be as detrimental to production efficiency as deficient N levels. Excess N may cause a variety of negative physiological effects on potatoes, including delayed tuber growth, bulking, and maturity; decreased specific gravity; and ultimately reduced yields (Ojala et al., 1990; Griffin and Hestermann, 1991). High N levels, both prior to and during tuber initiation and bulking result in an over-production of vegetative growth that delays tuber maturity (Allen and Scott, 1980; Ojala et al., 1990). Increased post-harvest tuber bruising and reduced storability have also been found to result from excess N fertilization (Ojala et al., 1990; Baritelle et al., 2000). Internal defects such as brown center and hollow heart become more frequent with excess N fertilization (McCann and Stark, 1989).

Further complicating N management, N losses due to leaching and subsequent groundwater contamination are a concern both economically and environmentally for Michigan potato producers. Potatoes have shallow rooting systems compared to other crops, resulting in lower effective rooting volumes from which N may be extracted (Stark et al., 1993). 90% of potato roots are found in the upper 30 cm of the soil. Nitrogen that moves below this level becomes largely unrecoverable by potatoes (Lesczynski and Tanner, 1976). The high propensity for N leaching on sandy soils (Vitosh and Silva, 1996) and small rooting volume for N recovery results in the leaching of nitrate from excess N applications (Rourke, 1985). In a proposal for a national nitrate leaching index assessment, Shaffer and Delgado (2002) stated that shallow rooted vegetable crops, manure application, and course textured sandy soils combine to pose a 'very high potential for nitrate leaching vulnerability.' The impacts of N leaching extend beyond the individual producer economic implications of decreased fertilizer efficiency. Nitrate leaching is receiving increasingly greater attention as a source of non-point source pollution by the non-agricultural community. Michigan's Natural Resources and Environmental Protection Act, Act 451 of 1994, regulates quantities and/or concentrations of nutrient releases that violate established water quality standards (State of Michigan Legislature, 1994). As part of the Michigan Right to Farm Act, Act 93 of 1981, a set of statewide standard and acceptable management practices were established in order to provide agricultural operations with a framework by which to comply with environmental legislation (State of Michigan Legislature, 1981). Compliance with these standards, Michigan's Generally Accepted Agricultural and Management Practices (GAAMPs) (MDA, 2005a), is voluntary and provides protection from public and private litigation regarding agricultural management. GAAMP standards are based upon scientific principles developed by, among others, university researchers. GAAMPs have been developed for a number of agriculture practices with the greatest potential environmental impacts, including nutrient utilization.

The potential for economic losses and environmental pollution associated with N mismanagement has generated a recognized need for effective N management strategies in the Montcalm potato producing region (Joern and Vitosh, 1995). This need is amplified as historically traditional production practices including animal manure amendment and diverse crop rotation use in potato systems have begun to receive renewed interest by regional producers. Mineral N fertilizers emerged and gained widespread use following World War II, supplanting manure amendment and crop rotation as the predominate agronomic sources of plant N. Research on N management followed this shift from non-mineral to mineral N fertilizers, though results from researchers including Lang and Stevens (1997) demonstrate that 70 years of research on the behavior of mineral N fertilizer sources has been insufficient to develop consistently accurate and accepted nutrient recommendations. Nitrogen contributions from animal manures and crop residues have received less research attention than mineral fertilizers and as a result, considerable confusion and mismanagement of these N sources is common.

Nitrogen Behavior

Nitrogen under agronomic conditions exists in both organic and inorganic forms. Commercially prepared fertilizers do not contain carbon and are classified as mineral, or inorganic, N sources. The N found in manures and crop residues exists in conjunction with carbon, and is therefore an organic material. Plant N uptake is typically limited to nitrate or exchangeable ammonium N forms. Both inorganic and organic N forms must undergo conversions from the compounds in which they were applied to the soil to plant available N forms for crop utilization. Mineral transformation, or the conversion of one inorganic compound to another inorganic compound, is regulated by bacteria occurring in the soil (Lewandowski, 2000). These transformations are not normally limiting in the soil and do not receive an extensive research focus. The process of conversion from organic N forms to inorganic N forms is called mineralization, which is regulated by microorganisms. The rate at which microorganisms mineralization N forms is a complex process that is not fully scientifically understood. A number of internal and external factors such as soil temperature and C/N ratio control microorganism activity, and therefore N mineralization. Despite extensive research on the subject, the mineralization of N continues to be largely unpredictable because of weather patterns including temperature and precipitation.

Nitrogen mineralization has been shown to be predominantly a function of source material quality and quantity (van der Krift et al., 2001). Carbon/N ratio has been found to be the most widely accepted measure of source material quality (Quemada and Cabrera, 1995; Vigil and Kissel, 1991; Norman et al., 1990; Ford et al., 1989), though other constituents including lignin (Quemada and Cabrera, 1995; Bruulsemann and Christie, 1987; Vigil and Kissel, 1991) and structural carbohydrate (Wagger et al., 1998; Ranells and Wagger, 1992) have been linked to N mineralization rates. Allison (1973) found that a C/N ratio of 25 or above leads to N immobilization, or a net loss of plant available N in the soil. The microorganisms responsible for converting non-mineral N forms to mineral N forms are dependent on C and N for their existence. The addition of either element to the soil system invokes micro consumption of the other. Nitrogen is typically the limiting factor because of larger amounts of C in most residues and inherently larger C stocks in the soil. If large quantities of residues or manure are added to the soil, microbe populations grow in response to introduced C, with a corresponding increase in N consumption. If N is not supplied in sufficient quantities along with C inputs, existing soil N is used by soil microbes. This microbial N consumption reduces soil N concentrations available for plant uptake. While not lost from the system, this N is nonetheless not readily available, and thus 'immobilized'. Aulakh et al. (1991) observed this effect of N immobilization in work with hairy vetch (*Vicia villosa* Roth), soybean (*Glycine max* L.), corn (*Zea mays* L.), and wheat (*Triticum aestivum* L.) residues with C/N ratios of 8, 43, 39, and 82 respectively. These residues were incorporated and surface applied at a rate of 2.5 g kg^{-1}. Hairy vetch was found to release sufficient amounts of mineral N to meet early season crop needs while the other residues immobilized applied N for several weeks.

Nitrogen "priming effects" have frequently been observed with N amendments. Priming was originally observed by Löhnis (1926) while examining green manure decomposition effects on legumes. The effects and mechanisms of priming have become better understood and more accurately defined since Löhnis's studies. Kuzyakov et al. (2000), reviewing mechanisms of priming effects, found that many priming definitions excluded non-plant interactions or only addressed mineralization acceleration. The authors ultimately proposed the definition that "priming effects are strong short-term changes in the turnover of soil organic matter caused by comparatively moderate treatments of the soil." However, the admission was also made that a complete understanding of the mechanisms driving priming effects continues to elude researchers.

The incorporation of fresh organic materials has been found to stimulate soil organic matter (SOM) mineralization. Wu et al. (1993) measured significant priming effects with ryegrass amendment to a soil. Manure amendments have been shown to increase microbial biomass, N mineralization, and enzyme activities (Kandler and Eder, 1993; Ma et al., 1999). Curless and Kelling (2003) measured potato petiole NO_3-N response to liquid dairy manure and conventional mineral fertilizers balanced by available N estimates and found that manure increased yields beyond those attributable to N inputs. Webb et al. (1997) noted increased mineralization rates from manure amendment in potato systems. However, mineralization has been shown to be more than just a response from increased microbial activity. Amendments of glucose, a more readily available microbial energy source than the polymerized structures found in manure or plant material, have not been shown to appreciably increase mineralization (Shen and Bartha, 1997). Fontaine et al. (2003), in a review of priming effects, concluded that mineralization is not a function of energy available to soil microbes. Rather, fresh organic matter (FOM) and existing SOM are decomposed by separate microbial populations, k-strategists and r-strategists. K-strategists are an ever-present population, feeding on the nearly limitless existing SOM supply. In contrast, r-strategists feed exclusively on FOM and are completely dependent on FOM supplies for subsistence. Amendments of FOM allow for r-strategist activity and growth; substrate exhaustion results in death or dormancy. The specificity of r-strategists activity is seen as an explanation for the observations of unchanging SOM decomposition following FOM amendments. From these assessments of mineralization dynamics, the authors proposed two potential mechanisms of priming. First, enzymes produced to decompose FOM by r-strategists may be partly effective in degrading SOM. This mechanism relies upon biochemical similarities in FOM and SOM, thus the more chemically diverse the FOM, the greater the likelihood that produced enzymes will degrade both organic matter substrates. The second possible mechanism calls for utilization of both FOM and SOM by k-strategists, stimulating greater SOM decomposition rates. The progression of this mechanism is largely regulated by prevalence and competition from r-strategists. Both of these mechanisms indicate manure amendment, with its chemically and biologically diverse composition, would be particularly stimulating in the N mineralization processes.

Additions of manures and crop residues are also important for building overall soil fertility. Hart et al. (1986) observed that priming effects increased in soils with high C and N concentrations. Mineralization rates as a whole have been found to be significantly influenced by existing soil N levels. 60-90% of mineralized N during a season may originate from a pool of existing, stabilized N, with the remainder of mineralized N contributed from recently preceding crop residues (Matus and Rodriguez, 1994). Increases to soil fertility require multiple years of management before results become discernable. Paul and Beauchamp (1993) observed that repeated manure application and legume crop rotation increased soil fertility, leading to greater N priming and mineralization rates. Ma et al. (1999) found corn yield responses to cattle manure amendment only after several years of annual application. Legumes especially have been found to build long-term soil fertility levels by increasing organic N reserves (Frye et al., 1985; Harris and Hestermann, 1990; Janzen et al., 1990; Ladd et al., 1981). However, residual ^{15}N research has shown that little fertilizer or legume N is taken up by a wheat crop two years after initial application (Ladd and Amato, 1986). Harris (1993) indicated that the true value of legume N inputs may be from contributions to N mineralization through conservation and cycling of soil N rather than short or long term direct N supply.

Environmental conditions such as temperature and precipitation influence N mineralization (Goncalves and Carlyle, 1994; Vigil et al., 2002). Increasing spring temperature, moisture availability, and crop residues increase N mineralization (Weinert et al., 2002). Ma et al. (1999) observed increased N mineralization in 1995 with 40 mm greater precipitation and 2° C warmer temperatures compared to 1996. While no strong correlations could be drawn between N mineralization and precipitation, a significant positive linear correlation (r^2=0.5, P>0.05) was found with temperature. Westermann and Crothers (1980) measured N mineralization with buried polyethylene bags and found that while moderate temperature fluctuations did not influence mineralization, overall higher temperatures increased mineralization. Both Ma et al. (1999) and Ruffo and

Bollero (2003) determined that soil moisture was the limiting factor in decomposition-day accumulation in non-irrigated conditions. Webb et al. (1997) found that low winter rainfall inhibits N mineralization. Wyland et al. (1995) did not observe consistent increases to soil N mineralization until irrigation was applied 20 days following crop residue plowdown.

Rotation Crop Effects on Nitrogen Dynamics

The potential impacts of lost soil N due to spring NO_3-N leaching has often drawn greater attention by both researchers and producers than N losses during other periods of the growing season. However, fall and winter NO_3-N losses have frequently been observed in potato production (Mitchell et al., 2001). Overwintering crops have been shown to reduce these N losses through the uptake and storage of N for subsequent crop utilization and by the reduction of water percolation that may carry NO_3-N through the soil profile (Weinert et al., 2002).

Kristensen and Thorup-Kristensen (2004) found root depth, more so than above ground biomass, to be a strong indicator of crop effectiveness in recovering leachable NO_3-N. Deep rooted crops have the ability to improve overall N use efficiency by recovering deep soil N that would otherwise be lost from the system. Lesczynski and Tanner (1976) determined that 90% of potato roots occur in the upper 30 cm of the soil profile; N leached below this level becomes largely inaccessible for potato uptake. Pan et al. (1998) used rhizotron computerized imaging to track potato root development through the season, finding root elongation occurred through tuber initiation and early tuber bulking, but declined thereafter. Total root depth was observed at 60 cm 4-6 weeks after planting. Similar potato rooting depths were observed by Ashley et al. (1997). These shallow rooting depths result in a number of rotation crops to having greater access to soil N than potato crops. Ashley et al. (1997) measured the effective rooting depths, or depth at which crops extract the majority of their consumed water, for a number of crops in Idaho potato production. While actual rooting depth may be greater, these depths indicate the soil volume in which the majority of plant nutrients are drawn.

Table 1.1. Depth of effective crop rooting zone for several crops in Idaho potato production.

Crop	Maturity	Depth (cm)
Alfalfa	new stand	30 - 45
	established stand	120
Cool season grass	new stand	15 - 45
	established stand	45 - 120
Potato		45 - 60
Corn		105
Winter cereal (rye)	Haun 4-7 stage	30 - 60

-reproduced from Ashley et al, 1997

Other researchers have obtained similar rooting depth results measuring crop root function. Alfalfa (*Medicago sativa* L.) recovery of injected ^{15}N at 120 cm was measured at 40% (Huang et al., 1996). Ashley et al. (1997) found that both alfalfa and cool season grass roots extend deeper with multiple year production. Corn roots were detected at 75 cm in Minnesota and Indiana (Nickel et al., 1995; Kuchenbuch and Barber, 1987). Crop characteristics other than rooting depth have been observed to impact N recovery abilities. Shipley et al. (1992) found forage grasses were better able to conserve residual fertilizer N than forage legumes. Longer and more frequent root hairs result in surface area and root volume several times that of legumes, giving grasses a strong competitive advantage in water and nutrient uptake (Evans, 1977).

In addition to recovered residual soil N, legume crops have the potential to contribute N through biological N fixation. Plant uptake of existing soil residual N or amended N, however, will be used to fulfill growth requirements before N fixation is utilized as a N source (Cherney and Duxbury, 1994; Lamb et al., 1995). Mohr et al. (1998) noted that alfalfa gradually releases N into the soil profile at a rate of up to 10% of that removed through harvest. This slow N release has the potential of adding to the overall soil N pool. Total N recovery from legume sources has been observed to exceed that provided through inorganic fertilizer sources (Janzen et al., 1990). While per unit N recovery of fertilizer N is often greater than that of legume N due to a greater initial availability, total uptake from legume N sources is often greater due to increased long-term availability (Ladd and Amato, 1986). These greater overall soil N supplies have been attributed to legume stimulation of larger microbial populations (Bolton et al., 1985; Harris, 1993).

Nitrogen Leaching

Course textured soils common in potato production are particularly prone to N leaching. Negatively charged N compounds, specifically NO_3-N, do not bind to negatively charged soil particles and are susceptible to leaching losses. Excessive irrigation (Middleton et al., 1975) and high volume rainfall events of at least 2 cm move NO_3-N out of the potato rooting zone (Cameron et al., 1978; Bundy et al., 1986). Cameron et al. (1978) obtained soil samples at 10 cm intervals up to 75 cm at six points during the growing season, providing detailed imagery of NO_3-N movement through the soil profile. Above average rains during late May and early June of 1975 moved NO_3-N below 20 cm, but there was no observed loss below 75 cm. Nitrate-N losses were also observed during the spring of 1976, correlated with several high rainfall events. Greater NO_3-N losses were attributed to fall leaching, but spring leaching had greater impacts of seasonal N plant availability.

Nitrogen from legume sources, largely as NH_4-N, has been shown to be less initially available in the soil and thus more resistant to leaching loss (USDA, 1980; Smith et al., 1987; Magdoff, 1991). Ammonia, as a positively charged compound, must be first mineralized into NO_3-N before it is susceptible to leaching. Harris (1993) found that the addition of legumes to potato cropping systems decreased leaching losses at the Rodale plots in Pennsylvania. The addition of N through animal manures, however, has been shown to be particularly susceptible to NO_3-N leaching. Nitrogen in manure exists in a variety of forms, primarily R-NH_2-N and NH_4-N, while to lesser extents NH_4-N, NO_2-N, and NO_3-N (Schmitt, 2002). Organic compounds and ammonium are largely immobile upon application, but rapid mineralization of these compounds join with initially present NO_3-N to pose a leaching risk. Manure application increased NO_3-N leaching compared to legume crop rotations systems or fertilizer based systems at Rodale (Harris, 1993). Bagayoko et al. (1992) associated precipitation and temperature with manure NO_3-N losses in the soil profile with two spring and one fall soil sampling events at 30 cm intervals to a depth of 150 cm. Rainfall during May and June of 1988 was measured at 83 and 26 cm compared to 22 and 105 cm during the same period of 1989. Average temperatures were 3 to 5° C lower in 1989 than 1988. Greater NO_3-N concentrations were measured at 150 cm depths for manure treatments during both spring sampling periods in each year. Greater total NO_3-N was seen in 1988 at this depth, indicating greater NO_3-N movement with higher mean spring temperatures and greater early season precipitation. Drinkwater et al. (1998), in comparisons of conventional, manure, and legume N fertility cropping systems over five years, found that while legume NO_3-N leaching losses tended to be lowest among the three systems, both legume and manure systems cumulative NO_3-N leaching over five years performed similarly compared to conventional fertilizer applications.

Measuring Nitrogen Availability

Several researchers have explored the use of ion exchange resin membranes as a means by which to monitor in-season N availability. Plant Root Simulator (PRS) ion exchange probes (Western Ag Innovations, Saskattoon, Canada) have been successfully used for measuring N availability from crop residue and manure mineralization (Adderley et al., 1998; Qian and Schoenau, 2002; Johnson et al., 2005). PRS probes are buried in the soil, providing an *in situ* measure of nutrient supply rates by continuously adsorbing ionic species on a charged membrane surface (Schoenau et al, 1993). These probes are encapsulated in a plastic sheath to assist with probe insertion and removal in field conditions. PRS probes provide an integrated measure of supply rates as they are subjected to all factors affecting nutrient supplies, including free ion activity, buffer capacity, mineralization, immobilization and others (Sulewski et al., 2002). This exposure to competing sinks, while important in providing a complete image of nutrient dynamics, is also subject to site variability. Non-representative competition, specifically from root proximity, will skew nutrient uptake and fail to provide an accurate assessment of nutrient availability. For this reason, root exclusion cylinders are often used to ensure competition free measurements (Sulewski et al., 2002).

Long-term burials (two weeks) have been shown to provide more detailed dynamics of nutrient supplies than short-term burials (one hour) as they allow for ion diffusion from greater distances, cation exchange, and uptake of slow release nutrients made available through mineralization and dissolution (Qian and Schoenau, 1997). Long-term burials provide an integrated assessment of initial soil conditions and gradual nutrient availability; together this information closely represents actual nutrient supply rates.

Probes measure nutrient supply rates per unit surface area per time (eg. ug N/10cm^{-2}/2 weeks) that are not comparable to typical nutrient availability indices used in conventional soil tests, such as ppm (Hangs et al., 2002). This difficulty in matching PRS probe data with conventional soil measurements initially relegated use of PRS probes to that of a soil science research tool (Hangs et al., 2002). To an extent, the lack of widespread use of PRS probes in many areas of the United States and Canada precluded acceptance of this tool as a common soil testing technique. However, though the establishment of a commercial laboratory, Western Ag Innovations Inc. (Saskatoon, Saskatchewan), providing grower consultation and accessible laboratory analysis of PRS probes, recognition of this methodology as a practical soil testing technique has evolved to a point of acceptance in the potato production industry.

PRS probes have been specifically used in research scenarios to measure differences in manure and fertilizer fertility treatments. Qian and Schoenau (1999) applied liquid swine manure and urea mineral fertilizer to canola (*Brassica napus* L.) plots, measuring soil N supply rates and canola N uptake to determine the effect on N availability and assess the relationship between measured N availability and actual plant N uptake. Manure amended soils were found to be less effective at supplying available N than N balanced fertilizer urea treatments, largely due to incomplete manure N mineralization. Strong r^2 correlation coefficients ranging from .79 to .96 were observed between measured soil N availability and plant N uptake. The authors concluded that PRS probes may serve as an effective tool by which to evaluate amendment effects on available N. Crop residue mineralization has been measured by several researchers using PRS probes. Adderley et al. (1998) observed mineralization differences in pea and lentil residues over a period of 56 days. Increased N availability measured by PRS probes was found to positively correspond with harvested wheat yields.

PRS probes have been demonstrated to be of comparable quality to other ion exchange resin technologies. Johnson et al. (2005) examined the abilities of two ion exchange resins, PRS probes and Unibest resin capsules (Unibest Inc., Bozeman, MT), for measuring soil nutrient availability compared to KCl extraction NH_4^+ and NO_3^- soil tests under varying temperature and moisture conditions. While soil tests and Unibest capsules were able to detect soil mineral N responses to both temperature and moisture, PRS probes were only able to detect moisture changes. However, PRS probes were shown to more accurately approximate temporal patterns in soil N mineralization than other tests.

Plant tissue analysis has evolved as a complementary means to soil measurement by which at assess soil N concentrations. Petiole sampling is the most accepted plant tissue measurement for determining the N status of potato crops (Westcott et al., 1993). The level of NO_3-N observed in the petiole is a reflection of the balance between uptake and transport of soil N-NO_3 to the leaves and the relocation of that N to the tubers (Westcott et al., 1991). In-season monitoring of petiole N samples has been widely adopted by Michigan potato growers in an effort to improve N efficiency by matching fertilizer applications with periods of greatest crop demand (Snapp et al., 2001). Petiole NO_3-N has been found to be highly correlated with fertilizer N application rates (r^2 0.68- 0.94) and yield potential (r^2 0.88 - 0.99) across a variety of potato cultivars (Waterer, 1996). However, a lack of information exists on how amendments such as crop residues and manures provide N availability (Snapp and Fortuna, 2003), and growers have been reluctant to credit these inputs as reliable sources of N (Snapp et al., 2001). Monitoring the concentrations of petiole NO_3-N through the season allows for an understanding of how plants respond to N availability from a variety of sources.

Sufficient N supplies are crucial in achieving maximum potato yields. While excessive N levels have been shown to cause a variety of developmental and physiological symptoms such as delayed tuber maturity, lower quality, and reduced yield (Griffin and Hesterman, 1991; Ojala et al., 1990), insufficient N supplies can be equally problematic.

Nitrogen is important during early growth in order to produce sufficient above ground biomass that will supply the photosynthetic energy and N reserves necessary for later tuber development. High rates of N encourage vegetative development over tuber development, delaying the period of maximum canopy N (Millard and MacKerron, 1986). This effect is desired, to an extent, in order to build a sufficient pool of above ground resources to produce maximum tuber yields.

Nitrogen utilized in tuber production originates from either existing N storage pools in petioles or may be absorbed from the soil, transported to leaves as NO_3, reduced, and translocated immediately as organic N to the tubers (Robinson and Millard, 1987). However, N used in tuber growth is drawn predominantly from existing plant capital N rather than recently absorbed soil N. Potatoes accumulate NO_3-N in petioles during the early vegetative growth stages (Millard and MacKerron, 1986). As tubers initiate and bulk, NO_3-N in the petioles is used to meet tuber N demands. During periods of rapid, short-term tuber growth, roots do not have the N absorption capacity to match petiole NO_3-N depletion (Millard and MacKerron, 1986). This makes adequate stores of petiole NO_3-N essential for sustained tuber production. Petiole NO_3-N concentrations are typically greatest early in the season, prior to tuber N demands (Roberts et al., 1989). Rapid decreases to petiole NO_3-N occur mid-season as tuber N demands increases, tapering off late in the season as N uptake and demand slows. While roots have the capacity for N uptake late into the growing season (Millard et al., 1989), rates of N uptake decrease throughout the season (Millard and MacKerron, 1986) and tuber N demands often outpace root supply abilities. When root N uptake becomes unable to match tuber N needs, petiole N pools are diverted to fulfill tuber demands. Millard and MacKerron (1986) observed maximum canopy N concentrations at 54 days after emergence, followed by a steady decrease in N levels throughout the season. Nitrogen fertilizer application, however, has been shown to influence root N uptake. Millard et al. (1989) found low rates of N fertilizer application resulted in earlier root N uptake decline than higher fertilizer applications.

Consistent petiole sampling methodology is crucial for effectively monitoring N concentrations. Sampling protocols call for the measurement of the third fully developed petiole on a stem. The sampling of this established, but relatively young tissue, is based on several morphological characteristics of potato N movement. Young growth located in the top of the canopy acts as a greater sink of root absorbed N than older growth located lower in the canopy (Robinson and Millard, 1987). Additionally, late season tuber N demands led to the senescence and abscission of lowermost canopy leaves (Millard and MacKerron, 1986). Sampling of lower canopy leaves is apt to provide an unrepresentative portrait of N concentrations.

Potato and Forage Agronomy

Forage Rotation Effects on Potatoes

Several studies have examined the effects of alfalfa crop rotation on potato yields in Michigan. Wheeler (1946) initiated a study in 1934 at the Lake City Experiment Station in Lake City, MI, 115 km north of the Montcalm Potato Research Farm in Entrican, MI. Alfalfa in a three-year stand, sweetclover (*Melilotus indica* L.) in a two-year stand, and corn as a one-year crop was rotated with potatoes in large 0.33 ha plots, using continuous potatoes as a check. Rye (*Secale celeale* L.) was seeding into the corn as an over wintering cover crop during summer cultivation. Rotations were replicated such that each year of a rotation was represented in the first growing season, allowing for comparisons between one, two, and three year alfalfa stands, and one and two years of sweetclover stands. Through ten seasons, results indicated that higher yields of potatoes could be achieved when alfalfa or sweetclover preceding potatoes rather than either corn or continuous potatoes. On average, U.S. No. 1 potatoes in alfalfa and sweetclover rotations out-yielded continuous potatoes by 46% and 23%, respectively. During the same period, corn rotation reduced yields by 6% compared to continuous potatoes. The length of the alfalfa stand prior to potatoes had an influence on potato yield as well. One year of alfalfa increased yield by 20%, two years by 40%, and three years by 130%. Control over potato scab was found to be greatest with alfalfa and corn rotation compared to continuous potatoes or sweetclover. Scab levels, reported as the percent U.S. No. 1 potatoes free from scab, averaged 84% in alfalfa rotation, 87% in corn, 43% in sweetclover, and 70% in continuous potatoes. While high levels of scab in sweetclover rotations were noted to be unexpectedly high, no explanation was provided that might offer insight for possible causes. Overall, Wheeler was able to conclude that long stands of alfalfa improved both the quantity and quality of potato yields over those possible with rotation of other legumes or a corn.

In 1987, six two-year potato rotations were established at the Montcalm Potato Research Farm in Entrican, MI, and at the Kellogg Biological Station in Hickory Corners, MI (Griffin, 1990). Rotation crops of corn, alfalfa, red clover (*Trifolium pretense* L.), birdsfoot trefoil (*Lotus corniculatus* L.), hairy vetch, and sweetclover were managed, with the exception of corn, as both hay and cover crops. Hay management called for the harvest and removal of above-ground vegetation in accordance with typical hay production techniques on a three-cut management schedule, while cover crops were not harvested during the seeding year. Potatoes followed corn and legume production in 1988 and were not amended with mineral N fertilizers. A marked response in vegetative potato growth following legumes was attributed to legume nitrogen contributions. At both sites, potato vine N concentration, dry matter yield, and N yield were found to be greater in legume crop rotations than corn rotations, while vine DM and N yields were greater for cover crops than hay crops. However, no yield differences were detected among crop rotations. This lack of yield boost was attributed to poor synchronization of legume N mineralization with crop N demand and the possibility of other limiting factors besides N.

Cool season grasses, such as Redtop (*Agrostis alba* L.), have also been researched in potato rotations. A field study begun in 1951 at the Rhode Island Agricultural

Experiment Station compared three potato rotations: continuous potatoes, redtop-redtop-potatoes, and red clover-red clover-potatoes (Odland and Sheehan, 1957). An identical redtop-redtop-potato rotation that had been under management for 18 years was also integrated into the experiment. Over the five years of the study, the 23-year stand of redtop out yielded continuous potatoes by 20%, while 5-year stands of redtop and red clover increased potato yield by 11% and 13%, respectively. Higher specific gravities were also measured in the long-term redtop rotation. The higher yields with redtop rotation were attributed to increases in soil organic matter levels from multiple years of grass production.

Carter et al. (2003) established a series of 2-year potato rotations in 1985 in Prince Edward Island utilizing Italian ryegrass (*Lolium multiflorum* Lam.), barley (*Hordeum vulgare* L.) plus Italian ryegrass, red clover, and barley. Biomass from these crops was harvested and returned to the plots as a soil amendment. Italian ryegrass grown alone produced the highest above-ground and below-ground biomass yields. These greater biomass contributions respective to other rotation crops resulted in the maintenance of soil organic matter levels, while barley and red clover rotations contributed to SOM declines. Tuber yields for nine years are presented in Table 1.2.

Table 1.2. Total tuber yields for potato in 2-year potato rotations over 9 years on a fine sandy loam Podzol in Prince Edward Island.

Rotation crop	Yield Mg ha^{-1}
Italian ryegrass	34.8 ab
Barley + Italian ryegrass	35.0 a
Red clover	31.1 c
Barley	33.5 b
LSD (0.05)	0.90

-reproduced from Carter et al., 2003

The authors cited improved potato yield performance with ryegrass rotations to improved soil fertility and structural properties associated with the greater organic matter contributions. The incorporation of wide C/N ratio barley straw, in contrast to narrow C/N ratio forage residue, contributed to N limiting conditions.

The effects of 2-year and 3-year crop rotation on potato yield and disease have been studied in a long-term field laboratory in Prince Edward Island, Canada (Carter and Sanderson, 2001). Established in 1994, a 2-year rotation of spring barley and potatoes was compared to a 3-year rotation of spring barley, red clover, and potatoes. Additionally, a tillage treatment of minimal till and conventional till was examined. Within two years, Rhizoctonia levels increased in the 2-year rotation and continued to become more severe over the next four years compared to the 3-year rotation. These disease impacts resulted in yield reductions in the 2-year rotation within four years. Off-sized tuber production increased in this rotation, further reducing tuber quality. The ability of the 3-year rotation to resist disease infection was largely attributed to increased microbe competition brought about from the addition of organic amendments.

Based upon the disease reduction observations seen by Carter and Sanderson (2001) in extended rotations, Peters et al. (2003) initiated a study to examine a wider array of disease pressures at this site beginning in 1999. They found stolon canker and black scurf levels were reduced in the 3-year compared to the 2-year rotation. They also found an interaction between rotation length and tillage, determining that 3-year rotations in minimum tillage resulted in a reduction of all potato diseases caused by *R. solani*, *H. solani*, and *Fusarium* spp. A series of greenhouse experiments were established in conjunction with this study to determine if the reduction of potato diseases in longer rotations involved transferable soil data. Potatoes were planted and grown in a greenhouse with soil obtained from the two rotation schemes. Inoculum of *Phytophthora erythroseptica* Pethybr., a casual agent of potato pink rot, was obtained from stored potatoes exhibiting symptoms of pink rot and applied to the experimental potatoes. After sixty days of growth, plants growing in soil managed under a 3-year rotation were significantly taller, less diseased, and produced higher plant biomass than plants grown in soil from a 2-year rotation. A second laboratory experiment was conducted to determine natural resistance of potato tubers grown under different management schemes. Clean, healthy tubers were obtained from field plots, inoculated with *P. erythroseptica*, and stored for two weeks under high humidity conditions. Tubers originating from 3-year rotations were found to have lower incidence and severity of pink rot than tubers grown in 2-year rotations. Peters et al. (2003) and Carter and Sanderson (2001) both concluded that 3-year rotations held the potential to reduce the incidence and severity of soil-borne disease.

Manure Effects on Potatoes

A long-term fertility study was initiated in 1948 in Prince Edward Island, Canada, to examine the effects of mineral fertilizer and manure on potato yields (Black and Cairns, 1958). Potatoes were grown in a 4-year rotation with oats (*Avena sativa* L.), clover (*Trifolium x.*), and a two-year stand of clover-timothy *(Phleum pretense* L.) hay in a 3 x 3 x 3 factorial fertilizer study. Combinations of N, P, and K were broadcast applied at a low (50-59-70 kg ha^{-1}), medium (101-89-140 kg ha^{-1}), and high (151-118-209 kg ha^{-1}) rate to potatoes. These applications were the only fertilizer amendments in the four-year rotation. Barnyard manure was fall applied to the clover-timothy hay crop following its second year of production at 9.7 t ha^{-1}, for a one year out of four amendment. No other information was provided as to the source or content of the manure.

Black and Cirnes (1958) reported their results from the first eight years of research as averages of each complete four-year rotation cycle. Tuber yields with manure amendment were found to be significant at the P = 0.01 level after four and eight years, with yield increases after eight years greater than those seen after four. Black and White (1973) reported on an additional three rotation cycles as the experiment was continued for twelve years following the initial 1958 report, for a total summary of twenty years of field research. Beginning in 1960, the low fertilizer rate was increased so as to provide the highest fertility levels at 202-148-279 kg ha^{-1}. Findings from the next three rotation cycles corroborated with trends previously established, with manure amendment continuing to increase marketable tuber yields at any fertilizer level. Some credit to increased yields was given to higher levels of available nutrients provided through manure application. However, the primary effects were attributed to increased soil organic matter, better soil structure, greater water holding capacity, and an increased presence of exchange sites for holding nutrients in the soil. Furthermore, it was noted that applications of manure did not increase scab levels, in contrast to expectations.

In order to determine the effects of manure on verticillium wilt and scab, a field experiment was initiated in Alliston, Ontario, a chief potato producing region in Canada (Conn and Lazarovits, 1999). Wood based chicken (66 t ha^{-1}), liquid swine (100 t ha^{-1}), and solid manure (55 hL ha^{-1}) was incorporated in the spring of the study's onset before potato planting at two commercial potato farms. No information was provided as to the previous cropping histories of these sites. Nitrogen fertilizer was applied after the manure amendment to equilibrate fertility across treatments. No manure was applied in years two or three of the experiment as the site was managed under common commercial production techniques. Verticillium wilt, microsclerotia (MS), and scab levels were monitored for three years following manure application. Verticillium wilt is caused by *Verticillium dahliae* Kleb., which in turns produces MS that are able to persist in soils for up to a decade. Microsclerotia initiate infections that lead to verticillium wilt. Increased initial soil pH resulted from chicken manure amendment, with a spike from pH 6.0 to 8.0 within two weeks. This increase was accompanied by an increase in ammonia levels, which the authors speculated may be involved in reducing populations of *S. scabies*. Soil pH levels returned to baseline levels within 21 weeks. Swine and cattle manure did not effect soil pH initially, but after 4 weeks, a decrease was seen from both. This decline may be attributed to the nitrification process. Potatoes treated with chicken manure showed an 80-96% reduction of verticillium wilt in the first year. This trend continued into the second year, but not the third. Swine manure in the first year reduced verticillium wilt by 62% at one site, but had no effect on the second. Cattle manure in year one reduced the level by 72% at the unaffected swine site, but had no effect on the first site. Chicken and swine manures both reduced scab levels in year one. Cattle manure had little or marginal reduction effects on scab. In the second and third years, swine manure was the only treatment that significantly lowered scab incidence. Cattle manure reduced scab levels slightly over the next two years at one site. Chicken manure caused increased scab levels in year three at one site. None of the manure amendments were found to increase tuber yields. However, the decrease in scab levels seen in some years resulted in higher numbers of marketable tubers.

A laboratory experiment was performed in association with this field study, using soils obtained from the two commercial potato operations, as well as soil from a research station with no history of potato production. Samples of three chicken manures, one liquid swine manure and one liquid dairy manure were used. After two weeks of application, chicken manure reduced MS levels by 25 and 90% for the two potato field soils and 10% for the research station soil. Swine and dairy manures reduced MS levels in one potato soil, but had no effect on the second. Ultimately, it was concluded from both field and laboratory studies that disease levels were only effectively reduced by manure amendment in the first year after application. The authors suggested that annual applications might be necessary in order for consistent MS reductions. Additionally, it was observed that in some cases, manure amendment resulted in increased levels of disease several years after application. While decreases to disease may be seen with manure application, neutral or increased effects are also possible; soil conditions, manure composition, and season of application all exerted influence on disease control.

A study in Limsden, Saskatchewan initiated in 1958 examined effects of a combination of forage crop rotation and manure amendment in long-term potato rotations (Emmond and Ledingham, 1972). Three rotations were compared: continuous potatoes, a 3-year rotation of potato followed by a 2-year stand of sweetclover hay, and a 6-year rotation of potato, potato, 4-year stand of alfalfa-crested wheatgrass (*Agropyron cristatum* L.) hay. Manure at 34 t ha^{-1} was applied once every three years. Emmond and Ledinham (1972) reported three years of results recorded from 1968 to 1970, ten years after the initial establishment of the experiment.

Table 1.3. Three year average total potato tuber yield in continuous, 2-year and 4-year crop rotations in Lumsden, Saskatchewan- 1968-1970.

Rotation crop	Yield Mg ha^{-1}
Continuous potatoes	32.76 c
2-year sweetclover	40.43 a
4-year alfalfa-wheatgrass	36.59 b
LSD (0.05)	2.93

-reproduced from Emmond and Ledingham, 1972

The yields of total and marketable tubers were significantly higher in the 3-year, followed by the 6-year and continuous potato rotation. High disease incidence was observed in continuous potatoes, mainly from verticillium wilt, black dot, and rhizoctonia. The 3-year rotation had the lowest incidence of disease over the three-year study, providing better control of verticillium wilt and other diseases than the 6-year rotation. The 3-year rotation had disease incidence rise only slightly over three years, while disease incidence increased steadily in the 6-year rotation. The 6-year rotation included potatoes in back to back years, and while the extended rotation of alfalfa-wheatgrass hay provided control of verticillium wilt in the first potato crop, the second crop suffered from high infection.

The authors speculated that alfalfa may act as an intermediary host for verticillium wilt producing fungi, though they could cite no previous occurrences of such an event in Saskatchewan. While rotations had a significant effect on disease levels, manure application was not found to impact disease severity.

Research specific to Michigan has also examined the effects of crop residue and manure amendments on potato scab in an experiment initiated in 1937 in East Lansing. (KenKnight, 1939). Blue grass and alfalfa crop resides were applied to potatoes at planting in furrow at a fresh weight of 44.7 Mg ha^{-1}, along with horse manure at 2.2 and 11.2 Mg ha^{-1} rates. These treatments were compared to control treatments receiving no plant or animal residue amendments. Both Blue grass and alfalfa crop residue treatments had greater surface scab area, 55.3% and 59.7%, respectively, than those found in control treatments at 38%. Scab incidence in the manure treatments at the low, 41.5%, and high, 37.8%, rates were found to be lower than those of the control, 45.3%. The author offered no insight or explanation of these results.

A secondary effect of manure application is an increased supply of non-limiting nutrients. Animal manure amendment in cropping systems functions essentially as well-balanced fertilizer. Typical inorganic mineral fertilizer applications provide formulations of N, P, and K in accordance with crop needs. Micronutrients are applied only on an as needed basis. The compositional formulation of animal manures is a fixed value that is difficult to tailor to crop needs. With most manure applications are balanced on a N or P need basis, other primary and secondary nutrients are often supplied at higher than normal rates. These changes to nutrient applications are important to consider when augmenting mineral fertilizer application with manure amendments.

Responses to P, K, and Ca have been frequently observed in potato production. However, response to these nutrients is typically only seen in soils initially testing low for these compounds. Rhue et al. (1986) found yield increases across a gradient of K fertilization levels ranging from 47 to 233 kg K ha^{-1} split between planting and sidedress applications in soils initially testing between 32 and 74 mg kg^{-1}. Westermann et al. (1994) observed similar responses when applying 112, 224, and 448 kg K ha^{-1} to soils with initially at 59-77 mg kg^{-1} K. Soils with higher initial soil nutrient levels have not been shown to respond to fertilizer applications. Locasicio et al. (1992) did not observe a yield response to K fertilization of 225 or 450 kg ha^{-1} in soils with high K concentrations. Panique et al. (1997) proposed 104 mg K kg^{-1} as a critical preplant soil test level at which K fertilization should be based. Yield responses to P have been similarly correlated with soil P concentrations. Locascio and Rhue (1990) observed yield response to a variety of P sources in soils initially ranging from 8 to 15 mg kg^{-1}. Phosphorus rates of 56 and 112 kg P_2O_5 ha^{-1} were not found to increase tuber yields in soils at 237 mg P kg^{-1} (Yuan et al., 1985).

Specific gravity has been shown to be affected by high nutrient rates. Panique et al. (1997) found decreasing specific gravity with increasing K rates of 93, 187, 280, and 373 kg K ha^{-1}. Westermann et al. (1994) observed highest specific gravity to be correlated with the lowest applied K rate (112 kg ha^{-1}).

Disease incidence, such as scab, has been found to be correlated with increased Ca levels. Davis et al. (1976) found a linear increase in scab infection with Ca applications. Suppression of scab was seen following P applications as free ion activities were altered.

Manure Effects on Forages

Manure application to forages has generated mixed results in terms of yield and quality. Daliparthy et al., (1994) applied both liquid dairy manure and conventional N mineral fertilizer at low (112 kg N ha^{-1}) and high (336 kg N ha^{-1}) rates in western Massachusetts to 1 and 2-year old alfalfa stands annually for two years. Dry matter production was not effected by manure or mineral fertilizer application in the first year. Alfalfa dry matter production was decreased with high manure application at one site in year two, attributed to low precipitation and delayed regrowth from application.

Liquid dairy manure effects on cool season grasses were researched by Griffin et al. (2002) in Maine in long-term 30-year grassland plots. The plots were predominated by Kentucky bluegrass (*Poa pratensis* L.), timothy, and couch (*Agropyron repens* L.), with smaller concentrations of cocksfoot (*Dactylis glomerata* L.), reed canarygrass (*Phalaris arundinacea* L.), white clover (*Trifolium repens* L.) and dandelion (*Taraxacum officinale* Weber). Four treatments were used to determine fertility effects: no fertilizer, N only, NKP, and liquid diary manure. All fertility treatments were balanced to equal rates of N, 84 kg N ha^{-1} for the first cutting and 56 kg N ha^{-1} for subsequent cuttings. Manure application rate was determined from the first year available N. The experiment was conducted over a six year period, with fertilizer applied two out of every three years.

Manure fertilization significantly increased DM grass yields compared to the control treatment; however, mineral fertilizer application was more effective in increasing DM yields. These differences were attributed to a lack of precision in estimating the amount of N mineralized from manure sources. Analysis of grass nutrient content indicated lower N concentrations in manure fertility treatments were not from improper estimation of available N, but rather a lack of synchrony between N availability and plant demand.

Forage quality of cool season grasses has been shown to increase with the application liquid dairy manure (Min et al., 2002). Stands of orchardgrass (*Dactylis glomerata* L.), reed canarygrass, alfalfa-orchardgrass and alfalfa-reed canary grass were treated with four rates of liquid dairy manure applied at 415, 690, 830, and 970 kg N ha^{-1}; mineral fertilizer at 225 kg N ha^{-1}; and an untreated control. In the first year manure was applied following the first cutting in June and following the third cutting in August. Mineral fertilizer was applied following the first cutting only. In the second year, manure application was increased from two to four applications: early spring prior to green-up and once following each of three cuttings. Applications rates were increased for manure to ~815, ~1230, 1590, and 2014 kg N ha^{-1}; and for mineral fertilizer to 560 kg N ha^{-1}.

Manure application was found to have no effect on acid detergent fiber or neutral detergent fiber. Crude protein (CP) was more variable, with variation between years, cuttings, and manure rates. Higher rates of manure generally increased CP content in the first year. In later cuttings, high manure rates increased CP content above those found with low manure rates. This trend was also observed in the second year of the study.

Liquid dairy manure was shown to have positive effects on forage quality beyond those achievable with conventional mineral fertilizers alone.

Applications of N and K to forage crops at greater than recommended rates through manure amendment is a possible when manure rates are balanced based according to soil P. Nitrogen applications in particular have been examined for their effects on alfalfa production. Alfalfa's biological N fixation allows for self-sustaining N production. However, seedling alfalfa stands do not posses biological N fixation capabilities. Low levels of N fertilization have been observed to benefit the formation of functional nodules, thus increasing establishment year alfalfa yields (Hannaway and Sheler, 1993). These effects have not been reproduced in established alfalfa stands (Jenkins and Bottomley, 1984; Lamb et al., 1995). Rather, NO_3-N has been shown to decrease root hair formation and the number of infection threads in established stands, reducing the amount of nodules (Truchet and Dazzo, 1982). This effect infrequently leads to yield reductions as the indeterminate growth habit of alfalfa nodules result in their regrowth with a retune to lower soil NO_3-N concentrations (Becana and Sprent, 1987).

Potassium responses in forage crops have been observed by several researchers. Increased K fertilization has been shown to increase dry matter yields in ryegrass stands (Keady and O'Kiely, 1998). Fertilization at 120, 180, and 240 kg K ha^{-1} increased dry matter yields over that of 0 and 60 kg K ha^{-1} rates. Fertilizer applications did not affect *in vitro* dry matter digestibility, crude protein, or modified acid detergent fiber.

Markus and Battle (1965) observed significant alfalfa yield responses with K fertilization over a period of nine years and twenty-six harvest events. Rates of 0, 47, and 93 kg ha^{-1} were progressively significant from one another, while rates of 187, 280, and 373 kg K ha^{-1}, were all statistically similar and returned the highest yields.

Background and Rational for Integration

The Montcalm county region in west-central Michigan is a state leader in dairy, wheat, forage, vegetable, and potato production (USDA, 2002a). The area's proximity to major markets such as Grand Rapids, Detroit, and Chicago facilitated the county's development from a from a small-scale general agriculture region in the late 1800's to a regional supplier of high-end dairy and vegetable products following World War II. The Montcalm county region has generally followed the productionist model that characterizes much of the nation's current agricultural landscape. Production efficiency drives an increasingly intensified archetype, often down-playing the implications of clashing cultural, social, economic, and environmental functions brought about by this focused narrow minded system (Hinrichs and Welsh, 2003). Mounting pressures on potato production from outside forces including urbanization, rising land prices, and increasing input costs have resulted in decreased soil quality and increased pest pressure brought about by a dependence on short, non-diverse rotations. Dairy production in the Montcalm area, like that of in many locations of the country, has seen average herd size and production per cow increase. Industry consolidation has reduced the number of dairy farms by 70% nationally since 1969 (McBride, 1997). The long-term sustainability and environmental ramifications of these systems has been called into question with an increasing awareness of potentially negative local, regional, and global consequences associated with agricultural industrialization (Matson et al., 1997).

In an attempt to minimize fixed costs and improve overall efficiency, many dairy farms have increased herd numbers to a point where their associated land bases can no long provide sufficient feed production or manure disposal sites. The separation of animal populations from feed sources disrupts the cyclical nature of animal feed inputs and manure outputs (Bannon and Klausnet, 1996; Lanyon and Thompson, 1996). A shift in dairy feed production from on-site, diverse rations to combination of on-site roughage production and off-site importation of high energy and protein grains and supplements has been able to compensate for the shift in head to acre ratios, but manure disposal and environmental protection issues have only recently been addressed. Emerging federal regulations from the Environmental Protection Agency in revisions to the Clean Water Act mandated changes as to how large farms, or confined animal feeding operations (CAFOs), deal with manure management (EPA, 2003). "Permit Regulations and Effluent Guidelines for Concentrated Animal Feeding Operations (CAFOs)" defined farms as CAFOs if they exceed a certain number of animals or meet certain other criteria dealing with how the animals or their waste comes into contact with surface water. Farms may also be designed as CAFOs if a permitting authority from the National Pollutant Discharge Elimination System inspects the operation and determines the farm is a significant contributor of pollutants to surface water. Any farm over 700 mature dairy cows is automatically classified a large CAFO. A farm with between 200 and 699 animals becomes a medium CAFO if so designated or has manure in some sort of contact with surface water. Any size farm can be designated a CAFO by the EPA. While many dairy farms in Montcalm county are small enough to avoid automatic CAFO classification, larger operations are required to submit to the manure management policies set forth by the EPA.

The EPA issued its final revision of "Managing Manure Guidance for Concentrated Animal Feeding Operations (CAFOs)" in December of 2004 (EPA, 2004). This document provides NPDES permitting authorities, permittees, and technical service providers guidance on how to implement the 2003 Clean Water Act revisions regarding CAFOs. These regulations developed by the EPA, along with Michigan GAAMPs specifically targeting manure management (MDA, 2005b), include both mandatory and voluntary regulations. Among these regulations, specific management of manure for nutrient loading is covered in great detail. As farms grow in size, the ratio of feed producing land base to animals often decreases as more feed is imported from off-farm sources. However, the increasing amount of manure must be spread on this constant or shrinking land base. As a result, nutrient excesses, particularly phosphorus, can build up with over application of manure. The CAFO and GAAMP regulations seek to monitor and control these nutrient excesses, and will ultimately require the certification of manure management plans. Realistic, long-term manure management strategies will be required to comply with these regulations. Complying with the EPA regulations will require many CAFOs to spread their manure over a larger land base than they are currently utilizing, and most will need to move their manure to off-farm sites (Ribaudo et al. 2003).

The deterioration of soil properties involved in intensive potato production has been attributed to a reduction in soil biological activity through lower organic material inputs compared to conditions found under pasture or natural vegetation (Saini and Grant, 1980). Increasing organic material contributions is crucial to mitigating and reversing yield declines. More effective rotation crops and carbon-based soil amendments hold potential for realistic, achievable system improvement. Michigan potato agronomic systems have been improved with forage crop rotation and manure amendment in both pre-modern agriculture (KenKnight, 1941; Wheeler, 1946; Doll and Thurlow, 1965) and in current intensive management systems (Griffin and Hestermann, 1991; Snapp et al., 2005). The re-integration of dairy and potato farm operations is seen as a viable substitute to the current segregated agricultural landscape; a substitute that by lengthening crop rotations and widening input distribution, will have an improved overall efficiency of the integrated agronomic systems.

Potato- dairy agronomic integration potential draws credibility from previously successful implementation. Potato and dairy producers in Maine have demonstrated mutual benefit from an integrated cropping system (Merrill, 2001). Farmers facing moderate to severe production stresses are more inclined to incorporate practices such as lengthened crop rotations and unfamiliar crops compared to farmers not facing servere production challenges (Corselius et al., 2003). The dairy industry, in contrast to other livestock industries, generally remains characterized by small level owner-operator producers with managerial and decision making control. These operations have been shown to be more open to conversion to more sustainable production techniques. However, recent trends in national dairy production indicate large-scale commercialization of the dairy industry in imminent (Jackson-Smith and Buttel, 1996). The integration of farming functions often necessitates a decline in individual control. The addition of new crops and amendments accompanies new constraints and logistical factors associated with their use. The degree to which integration is successful is a function of its ability to meet individual system requirements and conform to particular situations. While operations in Maine have neared total functional integration, the mere incorporation of manure amendment programs in potato production may evoke yield, and thus economic responses.

Integration of Montcalm county potato and dairy farms is seen as a method by which to alleviate individual system challenges. Potato farms are in need of soil enhancing rotation crops and carbon based soil amendments. Dairy farms need to expand their manure application land base and secure off-site feed production. By effectively executing land swaps, the constraints of one system become the benefits of the other. The proposed potato – dairy integration calls for the management of forages as a rotation crop with potatoes and the application of manure on potato soil. Forage crops needed for diary feed provide a viable rotation crop for potatoes. Spreading manure over a wider land base, including potatoes, serves to address concerns of excess nutrient loading while enhancing organic matter on chronically organic matter-short potato fields. Dairy farms benefit from this arrangement by obtaining a needed resource, quality forage, while disposing of an unneeded resource, manure. Integration represents a better allocation of resources to increase productivity and farm income while meeting the publics concerns and regulations pertaining to the environment.

One of the more challenging aspects to the integration of animal and potato systems is defining the viewpoints from each producer. Defining specific viewpoints is critical as each producer has needs and requirements specific to their operation. In order to integrate farming systems, management practices on one farm will be shifted to the other farm. The extent to which those operations take place depends upon the individual farm. For instance, a dairy farm will concentrate on forage production; potatoes will be utilized in a rotation, but forages remain the focus crop. Likewise, forage production emphasis on a potato farm is limited to a secondary rotation crop with the primary focus on potato production. Manure application functions in a similar manner. Manure to a dairy farm is a byproduct first and beneficial amendment second. The spreading of manure is a necessary, ongoing practice. Manure to a potato operation is solely a beneficial amendment and application is an occasional event only to be used to enhance soil characteristics.

This experiment adopts a potato grower viewpoint in terms of the focus on cropping systems and manure utilization. Forage production and manure application are not necessary practices, but are used only for the enhancement of potato production. Stands of perennial forages typically remain productive for multiple years with high establishment costs prohibiting frequent rotation. However, the focus on high value potato production relegates forages production to secondary concern and mitigates any establishment costs. A mix of 2-year and 3-year cropping rotations were used in this study to examine the need to keep potato production occurring at a relatively high frequency in order to maintain system profitability.

Cropping Systems

A set of five cropping systems were used to evaluate the effects of rotation and manure on potatoes production. Corn is a common rotation crop with potatoes in central Michigan and was used in this study as the standard defender system. This rotation was included in the study twice, staggered by year, in order to provide a baseline of potato production each year. Three forage crops were used to access rotation impacts. Alfalfa, a predominate legume for dairy feed production, was included as a 1 and 2-year crop. Festulolium (*Festuca pratensis* Huds. *x Lolium perenne* L.), a cool season perennial C_3 grass was also evaluated as a 1 and 2-year crop. Sorghum-sudangrass (Sudex) (*Sorghum bicolor* L. *x Sorghum bicolor* L.), a warm season C_4 grass, was evaluated as a 1-year crop. Alfalfa and festulolium were managed as harvest crops, with all biomass harvested in accordance with typical forage management schemes. Sudex was managed as a cover crop, with all biomass chopped and returned to the soil surface.

Corn – potato

A potato and corn rotation was included as the standard defender system. This rotation system is the predominant cropping system in Michigan potato production. Corn provides a modest financial return and requires fewer management resources than potatoes. However, the system is relatively inflexible with major field operations of corn planting and harvesting conflicting with potato planting and harvest.

Potato – alfalfa

Alfalfa, with over 420,000 hectares, is the primary legume dairy feed in Michigan (USDA NASS, 2002b). While other rotation legumes such as red clover, hairy vetch, and sweetclover have been researched in rotation with potatoes, the value and importance of alfalfa as a feed source necessitates its inclusion in this study. Legumes such as alfalfa can contribute significant soil nitrogen for following crops. Additionally, the taproot characteristic of alfalfa allows it to obtain sources of water and nutrients not typically assessable to other crops.

Potato – festulolium

Festulolium is a hybrid of meadow fescue (*Festuca pratensis* Huds.) and either Italian ryegrass (*Lolium multiflorum* Lam.) or perennial ryegrass *(Lolium perenne* L.). Duo, utilized in this experiment, has tetraploid perennial ryegrass lineage. Commercial varieties of Festulolium, including Duo, have been breed to exhibit fescues more developed root system, winter hardiness, midsummer growth, and drought tolerance; at the same time exhibiting the rapid establishment and forage quality of ryegrass (Thomas and Humphreys, 1991). Cool season grasses are characterized by their fibrous roots systems, compared to the taproots of alfalfa and corn. Festulolium variety trials in East Lansing, Michigan produced an average yield of 10.01 Mg ha^{-1} over three years in non-irrigated conditions (Leep and Dietz, 2004). Grass hays have also been shown to have higher acid detergent fiber (ADF) and neutral detergent fiber (NDF) than alfalfa hays (von Keyserlingk et al., 1996).

Potato – sudex

Sorghum-sugangrass hybrids are high biomass producing crops that require less intensive management than other forage crops. High yields can be achieved with low fertilizer inputs and infrequent mowing operations. Sudex is used extensively as a cover crop following potatoes in southern portions of the United States for its ability to reduce soil compaction, improve soil tilth, and reduce weeds (Jansson and Lecrone, 1991). Sudex has been proposed as a viable summer cover crop in vegetable production with its potential to suppress weeds, production of high levels of biomass, and ability to function as an emergency hay crop (McKinney et al., 2004). Sudex, a C_4 grass as opposed to C_3 crops such as alfalfa and festulolium, posses an additional CO_2 pathway that increases photosynthetic efficiency. C_4 crops have higher water use efficiency and achieve optimum growth at higher temperatures than C_3 plants.

Objectives

Ultimately, this experiment is conducted with the goal of establishing potato – livestock integration as a feasible endeavor in the central Michigan region. This study focuses on the agronomic aspects of the proposed integrated system. Economic and environmental aspects of these systems, while critical in the larger context, are beyond the scope of this experiment and are only briefly covered. Rather emphasis is placed on the agronomic effects of proposed integration upon soil fertility and crop yield. The impact of crop rotation and manure amendment on soil quality, specifically nitrogen dynamics, are important aspects of improved potato systems. Without demonstrable improvements to current yields, adoption of alternative cropping systems or amendments will be difficult to regardless of other benefits.

Nitrogen dynamics in potato production continue to be one of the greatest challenges facing potato growers. The ability to increase available soil N and absorbed potato petiole NO_3-N with manure amendment or forage rotation, while applying equal or less mineral fertilizers would be of significant value to producers. Equally important to increasing these N levels is the ability to provide consistent N concentrations through the season. The use of organic N compounds hold potential for more even N availability throughout the growing season. The following hypotheses aim to prove these benefits:

1. Nitrogen fertilization regimes including liquid dairy manure amendment preceding potato crop production will increase the amount and seasonal

distribution of soil N and petiole NO_3-N compared to conventional mineral N fertilizer regimes alone.

2. Potato rotations including forages will improve the amount and seasonal distribution of soil N and petiole NO_3-N compared to conventional potato – corn rotations. Benefits of forage crop production on N dynamics will increase with forage stand length.
3. Potato system N dynamics will benefit from antagonistic effects of forage rotation and manure amendment to a greater extent than either factor alone.

Manure amendment holds the potential not only the decrease reliance on mineral fertilizers, but also to increase the quantity and quality to forage and potato yields. Likewise, forage crop rotation with potato production is expected not only to increase potato yields, but also add external benefits beyond those currently found in the conventional corn – potato rotation. The following hypotheses are established as means by which to evaluate the effectiveness of these alternative inputs:

1. A minimum 3-year forage rotation is required to induce potato yield increases; 2-year forage rotation will not be sufficient to improve potato yields in an intensively managed potato-corn rotation.
2. The combination of forage rotation and liquid diary manure application will result in higher potato yield than either amendment individually.

3. Forage yield will be improved by the amendment of liquid diary manure to conventional inorganic fertilizers regimes compared to forage fertilization regimes solely supplied by inorganic fertilizers.

Literature Cited

Adderley, D. R., J. J. Schoenau, and F. A. Holm. 1998. Availability of soil nitrogen released from pea and lentil residue to subsequent cereal crops under reduced tillage. *In:* Proceedings of the 1998 Soil and Crops Workshop. University of Saskatchewan, Saskatoon, Saskatchewan. pp. 339-344.

Allen, E. J., and R. K. Scott. 1980. An analysis of the potato crop. Journal of Agricultural Science, Cambridge. 94:583-606.

Allison, F. E. 1973. Soil organic matter and its role in crop production. Elsevier Scientific Publishing Co., New York, New York.

Ashley, R. O., W. H. Neibling, and B. A. King. 1997. Irrigation scheduling- using water-use tables. University of Idaho Cooperative Extension Service Bulletin CIS 1039. Moscow, Idaho.

Aulakh, M. S., J. W. Doran, D. T. Walters, A. R. Mosier, and D. D. Francis. 1991. Crop residue type and placement effects on denitrification and mineralization. Soil Science Society of America. 55:1020-1025.

Bannon C.D. and S. Klausner. 1996. Land requirements for the land application of the animal manure. Animal Agriculture and the Environment: Nutrients, Pathogens, and Community Relations. *In:* Proceedings from the Animal Agriculture and the Environment North American Conference, Rochester, New York, December 11–13. Northeast Regional Agricultural Engineering Service, Ithaca, New York. pp. 194–204.

Bagayoko, M., S. C. Mason, and R. J. Sabata. 1992. Effects of previous cropping systems on soil nitrogen and grain sorghum yield. Agronomy Journal. 84:862-868.

Baritelle, A. L., G. M. Hyde, and R. E. Thornton. 2000. Influence of early-season nitrogen application patter on impact sensitivity: I. Russet Burbank potato tubers. Postharvest Biology and Technology. 19:273-277.

Becana, M., and J. L. Sprent. 1987. Nitrogen fixation and nitrate reduction in the root nodules of legumes. Physiologia plantarum. 70:757-765.

Black, W. N., and R. R. Cairns. 1958. The effect of varying levels of nitrogen, phosphorus and potassium and manure on the yield and starch content of potatoes. Canadian Journal of Soil Science. 38:1-7.

Black, W. N., and R. P. White. 1973. Effects of nitrogen, phosphorus, potassium, and manure factorially applied to potatoes in a long-term study. Canadian Journal of Soil Science. 53:205-211.

Bolton, H., Jr., L. F. Elliot, R. I. Papendick, and D. F. Bezdicek. 1985. Soil microbial biomass and selected soil enzyme activities: Effect of fertilization and cropping practices. Soil Biology and Biochemistry. 17:297-302.

Bruulsema, T. W., and B. R. Christie. 1987. Nitrogen contribution to succeeding corn from alfalfa and red clover. Agronomy Journal. 79:96-100.

Bundy, L. G., and R. P. Wolkowski, G. G. Weis. 1986. Nitrogen source evaluation for potato production in irrigated sandy soils. American Potato Journal. 63:385-397.

Cameron, D. R., R. De Jong, and C. Chang. 1978. Nitrogen inputs and losses in tobacco, bean, potato fields in a sandy loam watershed. Journal of Environmental Quality. 7:545-550.

Carter, M.R., H. T. Kunelius, J. B. Sanderson, J. Kimpinski, H. W. Platt, and M. A. Bolinder. 2003. Productivity parameters and soil health dynamics under long-term 2-year potato rotations in Atlantic Canada. Soil & Tillage Research. 72:153-168.

Carter, M.R., and J. B. Sanderson. 2001. Influence of conservation tillage and rotation length on potato productivity, tuber disease and soil quality parameters on a fine sandy loam in eastern Canada. Soil & Tillage Research. 63:1-13.

Cherney, J. H., and J. M. Duxbury. 1994. Inorganic nitrogen supply and symbiotic dinitrogen fixation in alfalfa. Journal of Plant Nutrition. 17:2053–2067.

Conn, K.L., and G. Lazarovits. 1999. Impact of animal manures on verticillium wilt, potato scab, and soil microbial populations. Canadian Journal of Plant Pathology. 21:81-92 .

Corselius, K. L., S. R. Simmons, and C.B. Flora. 2003. Farms perspectives on cropping systems diversification in northwestern Minnesota. Agriculture and Human Values. 20:371-383.

Curless, M.A., and K. A. Kelling. 2003. Preliminary estimates of nitrogen availability from liquid dairy manure to potato. HortTechnology 13:593-597.

Daliparthy, J., S. J. Herbert, and P. L. M. Veneman. 1994. Dairy manure applications to alfalfa: Crop response, soil nitrate, and nitrate in soil water. Agronomy Journal. 86:927-933.

Davis, J. R., R. E. McDole, and R. H. Callihan. 1976. Fertilizer effects on common scab of potato and the relation of calcium and phosphate-phosphorus. Phytopathology. 66:1236-1241.

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

Doll, E. C., and D. L. Thurlow. 1965. Soil management and fertilization for potatoes grown on mineral soils. Michigan State College Agriculture Experiment Station Research Report 31:1-6. East Lansing, Michigan.

Errebhi, M., C. J. Rosen, S. C. Gupta, and D. E. Birong. 1998. Potato yield response and nitrate leaching as influenced by nitrogen management. Agronomy Journal. 90:10-15.

Emmond, G.S., and R. J. Ledingham. 1972. Effects of crop rotation on some soil-borne pathogens of potato. Canadian Journal of Plant Science. 52:605-611.

EPA (Environmental Protection Agency). 2003. Producers' Compliance Guide for CAFOs- Revised Clean Water Act Regulations for Concentrated Animal Feeding Operations (CAFOs). EPA 821-R-03-010.

EPA (Environmental Protection Agency). 2004. Managing Manure Guidance for Concentrated Animal Feeding Operations (CAFOs). EPA 821-F-04-011.

Evans, P. S. 1977. Comparative root morphology of some pasture grasses and clovers. New Zealand Journal of Agricultural Research. 20:331-335.

Fontaine, S., G. Bardoux, D. Benest, B. Verdier, A. Mariotti, and L. Abbadie. 2004. Mechanisms of the priming effect in a Savanah soil amended with cellulose. Soil Science Society of America Journal. 68:125-131.

Ford, P. B., W. L. Hargrove, and C. L. Neely. 1989. Crop residue decomposition under conventional and no-tillage. *In:* Agronomy Abstracts. American Society of Agronomy, Madison, Wisconsin. p. 213

Frye, W. W., W. G. Smith, and R. J. Williams. 1985. Economics of winter cover crops as a source of nitrogen for no-till corn. Journal of Soil and Water Conservation. 40:246-258.

Goncalves, J. L. M., and J. C. Carlyle. 1994. Modeling the influence of moisture and temperature on net nitrogen mineralization in a forested sandy soil. Soil Biology and Biochemisty. 26:1557-1564.

Griffin, T. S. 1990. Legume-potato rotations: nitrogen management, economics, and pathogens. Ph.D. Thesis. Department of Crop and Soil Sciences, Michigan State University. East Lansing, Michigan.

Griffin T., E. Giberson, and M. Wiedenhoeft. 2002. Yield response of long-term mixed grassland swards and nutrient cycling under different nutrient sources and management regimes. Grass and Forage Science. 57:268-278.

Griffin, T. S., and O. B. Hestermann. 1991. Potato response to legume and fertilizer nitrogen sources. Agronomy Journal. 83:1004-1012.

Hangs, R., K Greer, C. Sulewski, and D. Hicks. 2002. Plant Root Simulator ™- Probes: An effective alternative for routine soil testing. *In*: Proceedings of the 2000 Soil and Crops Workshop. University of Saskatchewan, Saskatoon, Saskatchewan. pp. 120-130.

Hannaway, D. B., and P. E. Sculer. 1993. Nitrogen fertilization in alfalfa production. Journal of Production Agriculture. 6:80-85.

Harris, G. H. 1993. Nitrogen cycling in animal-, legume-, and fertilizer-based cropping systems. Ph. D. Thesis. Department of Crop and Soil Sciences, Michigan State University.

Harris, G. H., and O. B. Hestermann. 1990. Quantifying the nitrogen contribution from alfalfa to soil and two succeeding crops using nitrogen-15. Agronomy Journal. 82:129-134.

Hart, P. B. S, J. H. Rayner, and D. S. Jenkinson. 1986. Influence of pool substitution on the interpretation of fertilizer experiments with ^{15}N. Journal of Soil Science. 37:389-403.

Hinrichs, C. C., and R. Welsh. 2003. The effects of the industrialization of US livestock agriculture on promoting sustainable production practices. Agriculture and Human Values. 20:125-141.

Huang, Y., D. H. Ricker, and K. D. Kephart. 1996. Recovery of deep-point injected soil nitrogen-15 by switchgrass, alfalfa, ineffective alfalfa, and corn. Journal of Environmental Quality. 25:1394-1400.

Jackson-Smith, D. B., and F. H. Buttel. 1998. Explaining the uneven penetration of industrialization in the U.S. dairy sector. International Journal of Sociology of Agriculture and Food. 7:113-150.

Jansson, R.K., and S. H. Lecrone. 1991. Effects of summer cover crop management on wireworm (Coleoptera: Elateridae) abundance and damage to potato. Journal of Economic Entomology. 84:581-586.

Janzen, H. H., J. B. Bole, V. O. Biederbeck, and A. E. Slinkard. 1990. Fate of N applied as green manure or ammonium sulphate fertilizer to soil subsequently copped with spring wheat in three sites in Western Canada. Canadian Journal of Soil Science. 70:313-323.

Jenkins, M. B., and P. J. Bottomley. 1984. Seasonal response of uninoculated alfalfa to fertilizer N: soil N, nodule turnover, and symbiotic effectiveness of *Rhizobium meliloti*. Agronomy Journal. 76:959-963.

Joern, B. C., and M. L. Vitosh. 1995. Influence of applied nitrogen on potato part I: yield, quality and nitrogen uptake. American Potato Journal. 72:51-63.

Johnson, D. W., P. S. J., Verburg, and J. A. Aronone. 2005. Soil extraction, ion exchange resin, and ion exchange membrane measures of soil mineral nitrogen during incubation of a tallgrass prairie soil. Soil Science Society of America Journal. 69:260-265.

Kandler, E., and G. Eder. 1993. Effect of cattle slurry in grassland on microbial biomass and on activities of various enzymes. Biology and Fertility of Soils. 6:68-72.

Keady, T. W. J., and P. O. O'Kiely. 1998. An evaluation of potassium and nitrogen fertilization of grassland, and date of harvest, on fermentation, effluent production, dry-matter recovery and predicted feeding value of silage. Grass and Forage Science. 53:326-337.

KenKnight, G. 1941. Studies on soil actinomycetes in relation to potato scab and its control. Michigan State College Agriculture Experiment Station Technical Bulletin 178:1-48.

Kristensen, H. L., and K. Thorup-Kristensen. 2004. Root growth and nitrate uptake of three different catch crops in deep layer soils. Soil Science Society of America Journal. 529-537.

Kuchenbuch R. O., and S. A. Barber. 1987. Yearly variation of root distribution with depth in relation to nutrient uptake and corn yield. Communications in Soil Science and Plant Analysis. 18: 255-263.

Kuzyakov, Y., J. K. Freidel, and K. Stahr. 2000. Review of mechanisms and quantification of priming effects. Soil Biology and Biochemistry. 32:1485-1498.

Ladd, J. N, and M. Amato. 1986. The fate of nitrogen from legume and fertilizer sources in soil successively cropped with wheat under field conditions. Soil Biology and Biochemistry. 18:417-425.

Ladd, J. N., J. M. Oades, and M. Amato. 1981. Distribution and recovery of nitrogen from legume residues decomposing in soil sown to wheat in the field. Soil Biology and Biochemistry. 13:251-256.

Lamb, J. F. S., D. K. Barnes, M. P. Russelle, C. P. Vance, G. H. Heichel, and K. I. Henjum. 1995. Ineffectively and effectively nodulated alfalfas demonstrate biological nitrogen fixation continues with high nitrogen fertilization. Crop Science. 35:153-157.

Lang, N. S., and R. G. Stevens. 1997. Survey of central Washington fertilizer recommendations. *In:* Proceedings of the 36th Washington Potato Conference and Trade Show. February 4-6. 1997. Moses Lake, Washington.

Lang, N. S., R. G. Stevens, R. E. Thornton, W. L. Pan, and S. Victory. 1999. Irrigated potato nutrient management guide for central Washington. Washington State University Extension Bulletin #241.

Lanyon L.E. and Thompson P.B. 1996. Changing emphasis of farm production. Animal Agriculture and the Environment: Nutrients, Pathogens, and Community Relations. *In:* Proceedings from the Animal Agriculture and the Environment North American Conference. Rochester, New York. December 1–13, 1996. Northeast Regional Agricultural Engineering Service, Ithaca, New York. pp. 15-23.

Leep, R. H., and T. S. Dietz. 2004. Grass variety trials results 2004. Michigan State University Forage Information Systems. http://web1.msue.msu.edu/fis/research.htm

Lesczynski, D. B., and C. B. Tanner. 1976. Seasonal variation of root distribution of irrigated, field-grown Russet Burbank potatoes. American Potato Journal. 53:69-78.

Lewandoski, A. 2000. Soil biology and soil management. University of Minnesota Extension Service Bulletin BU-01403.

Locascio, S. J., J. A. Bartz, and D. P. Weingartner. 1992. Calcium and potassium fertilization of potatoes grown in north Florida. I. effects on potato yield and tissue Ca and K concentrations. American Potato Journal 69:95-104.

Locascio, S. J. and R. D. Rhue. 1990. Phosphorus and micronutrient sources for potato. American Potato Journal. 67:217-226.

Löhnis. F. 1926. Nitrogen availability of green manure. Soil Science. 22:253-290.

Ma, B. L., L. M. Dwyer, and E. G. Gregorich. 1999. Soil nitrogen amendment effects on seasonal nitrogen mineralization and nitrogen cycling in maize production. Agronomy Journal. 91:1003-1009.

Magdoff, F. 1991. Managing nitrogen for sustainable corn systems: Problems and possibilities. American Journal of Alternative Agriculture. 6:3-8.

Markus, D. K., and W. K. Battle. 1965. Soil and plant responses to long-term fertilization of alfalfa (*Medicago sativa* L.). Agronomy Journal. 57:613-616.

Matson, P. A., W. J. Parton, A. G. Power, and M. J. Swift. 1997. Agricultural intensification and ecosystem properties. Science. 277:504-508.

Matus, F. J., and J. Rodriguez. 1994. A simple model for estimating the contribution of nitrogen mineralization to the nitrogen supply of crops from a stabilized pool of soil organic matter and recent organic input. Plant and Soil. 162: 259-271.

McBride, W. D. 1997. Change in U. S. livestock production, 1969-92. Agricultural Economics Report No. AER754. United States Department of Agriculture Economic Research Service.

McCann, I. R., and J. C. Stark. 1989. Irrigation and nitrogen management effects on potato brown center and hollow heart. HortScience. 24:950-952.

McKinney, D. E., H. G. Creamer, M. G. Wagger, and J. R. Schulteis. 2004. A preliminary study of dual use cover crops: Sorghum Sudangrass as both hay and summer cover crop for no-till organic cabbage. 26^{th} Southern Conservation Tillage Conference. June 8-9, 2004. Raleigh, North Carolina.

Merrill, L. 2004. Maine farmers find sharing the land improves soil and increases yield. *In:* Berton., V. (Ed). The New American Farmer: Profiles of Agricultural Innovation. United States Department of Agriculture Sustainable Agriculture Research and Education, Beltsville, Maryland. pp. 56-58.

MDA (Michigan Department of Agriculture). 2005a. Generally Accepted Agricultural and Management Practices for Nutrient Utilization. Michigan Commission of Agriculture. Lansing, Michigan.

MDA (Michigan Department of Agriculture). 2005b. Generally Accepted Agricultural and Management Practices for Manure Utilization. Michigan Commission of Agriculture. Lansing, Michigan.

Middleton, J. E., S. Roberts, D. W. James, T. A. Cline, B. L. McNeal, and B. L. Carlile. 1975. Irrigation and fertilizer management for efficient crop production on a sandy soil. Washington State University College of Agriculture Research Center Bulletin 81.

Millard, P., D. and K. L. MacKerron. 1986. The effects of nitrogen application on growth and nitrogen distribution within the potato canopy. Annals of Applied Biology. 109:427-437.

Millard, P., D. Robinson, and L. A. Mackie-Dawson. 1989. Nitrogen partitioning within the potato (*Solanum tuberosum* L.) plant in relation to nitrogen supply. Annals of Botany. 63:289-296.

Min, D.H., L. R. Vough, and J. B. Reeves III. 2002. Dairy slurry effects on forage quality of orchardgrass, reed canarygrass and alfalfa-grass mixtures. Animal Feed Science and Technology. 95:143-157.

Mitchell, R., J. Webb, and R. Harrison. 2001. Crop residue can affect N leaching over at least two winters. European Journal of Agronomy. 15:17-19.

Mohr, R. M., H. H. Janzen, E. Bremer, and M. H. Entz. 1998. Fate of symbiotically-fixed $^{15}N_2$ as influenced by method of alfalfa termination. Soil Biology and Biochemistry. 30:1359-1367.

Nickel, S. E., R. K. Crookston, and M. P. Russelle. 1995. Root growth and distribution are affected by corn–soybean cropping sequence. Agronomy Journal. 87:895–902.

Norman, R. J., J. T. Gilmour, and B. R. Wells. 1990. Mineralization of nitrogen from nitrogen-15 labeled crop residues and utilization by rice. Soil Science Society of America Journal. 54:1351-1356.

Odland, T. E., and J. E. Sheehan. 1957. The effect of redtop and red clover on yields of following crops of potatoes. American Potato Journal. 34:282-284.

Ojala, J. C., J. C. Stark, and G. E. Kleinkopf. 1990. Influence of irrigation and nitrogen management on potato yield and quality. American Potato Journal. 67:29-43.

Pan, W. L, R. P. Bolton, E. J. Lundquist, and L. K. Hiller. 1998. Portable rhizotron and color scanner system for monitoring root development. Plant and Soil. 200:107-112.

Panique, R., K. A. Kelling, E. E. Schulte, D. E. Hero, W. R. Stevenson, and R. V. James. 1997. Potassium rate and source effects on potato yield, quality, and disease interaction. American Potato Journal. 74:379-398.

Paul, J. W., and E. G. Beauchamp. 1993. Nitrogen availability for corn in soils amended with urea, cattle slurry, and solid and composted manures. Canadian Journal of Soil Science. 73:253-266.

Peters, R.D., A. V. Sturz, M. R. Carter, and J. B. Sanderson. 2003. Developing disease-suppressive soils through crop rotation and tillage management practices. Soil & Tillage Research. 72:181-192.

Qian, P. J. and J. J. Schoenau. 1997. Recent developments in use of ion exchange membranes in agricultural and environmental research. Recent Research Developments in Soil Science. 1:43-54.

Qian, P., and J. J. Schoenau. 1999. Use of ion exchange membranes to assess soil N supply to canola as affected by addition of liquid swine manure and urea. Canadian Journal of Soil Science. 80:213-218.

Qian, P., J. and J. J. Schoenau. 2002. Availability of nitrogen in solid manure amendments with different C:N ratios. Canadian Journal of Soil Science. 82:219-225.

Quemada, M., and M. L. Cabrera. 1995. Carbon and nitrogen mineralized from leaves and stems of four cover crops. Soil Science Society of America Journal. 59:471-477.

Ranells, N. N., and M. G. Wagger. 1992. Nitrogen release from crimson clover in relation to plant growth stage and composition. Agronomy Journal. 84:424-430.

Rhue, R. D., D. R. Hensel, and G. Kidder. 1986. Effect of K fertilization on yield and leaf nutrient concentrations of potatoes grown on a sandy soil. American Potato Journal. 63:665-680.

Ribaudo, M., N. Gollehon, M. Aillery, J. Kaplan, R. Johansson, J. Agapoff, L. Christensen, V. Breneman, and M. Peters. 2003. Manure Management for Water Quality: Costs to Animal Feeding Operations of Applying Manure Nutrients to Land. Washington, DC: United States Department of Agriculture, ERS AER 824.

Roberts, S., H. H. Cheng, and F. O. Farrow. 1989. Nitrate concentration in potato petioles from periodic application of ^{15}N-labeled ammonium nitrate fertilizer. Agronomy Journal. 81:271-274.

Roberts. S., W. H. Weaver, and J. P. Phelps. 1982. Effect of rate and time of fertilization on nitrogen and yield of Russet Burbank potatoes under center pivot irrigation. American Potato Journal. 59:77-86.

Robinson, D., and P. Millard. 1987. Short-term uptake rates and partitioning of nitrogen in a potato crop. Journal of Experimental Botany. 38:551-557.

Rosen C. J. 1991. Potato fertilization on irrigated soils. Minnesota Extension Service. Bulletin AG-FO-3524-B.

Rourke, R. V. 1985. Soil solutions levels of nitrate nitrogen in a potato-buckwheat rotation. American Potato Journal. 62:1-8.

Ruffo, M. L., and G. A. Bollero. 2003. Modeling rye and hairy vetch residue decomposition as a function of degree-days and decomposition-days. Agronomy Journal. 95:900-907.

Saini, G.R., and W. J. Grant. 1980. Long-term effects on intensive cultivation on soil quality in the potato-growing areas of New Brunswick (Canada) and Maine (U.S.A.) Canadian Journal of Soil Science. 60:421-428.

Schoenau, J. J., P. Qian, and W. Z. Huang. 1993. Ion exchange resin strips as plant root simulators. *In:* Proceedings of the 1993 Soils and Crops Workshop. University of Saskatchewan, Saskatoon, Saskatchewan. pp. 392-400.

Schmitt, M. A. 2002. Manure management in Minnesota. University of Minnesota Extension Service. FO-03553.

Shaffer, M. J., and J. A. Delgado. 2002. Essentials of a national nitrate leaching index assessment tool. Journal of Soil and Water Conservation. 57:327-335.

Shen, J., and R. Bartha. 1997. Priming effect of glucose polymers in soil-based biodegradation tests. Soil Biology and Biochemistry. 29:1195-1198.

Shipley, P. R., J. J. Meisinger, and A. M. Decker. 1992. Conserving residual corn fertilizer nitrogen with winter cover crops. Agronomy Journal. 84:869-876.

Smith, M. S., W. W. Frye, and J. J. Varco. 1987. Legume winter cover crops. Advances in Soil Science. 7:95–139.

State of Michigan Legislature. 1981. Michigan Right to Farm Act. Act 93 on 1981. 286.471 - 286.474.

State of Michigan Legislature. 1994. Natural Resources and Environmental Protection Act. Act 451 of 1994. 324.101 - 324.90106.

Snapp S. S., Borden H., and D. D. Rohrbach. 2001. Improving nitrogen efficiency: Lessons from Malawi and Michigan. Second International Nitrogen Conference. The Scientific World. 1:42-48.

Snapp, S. S., and A. M. Fortuna. 2003. Predicting nitrogen availability in irrigated potato systems. HortTechnology. 13:598-604.

Snapp, S. S., K. O'Neil, B. Quackenbush, and E. Po. 2005. Improving productivity and soil quality in short term potato rotations- 2004 research and on-farm report. Departments of Horticulture and Crop and Soil Sciences, Michigan State University.

Stark, J. C., I. R. McCann, D. T. Westermann, B. Izadi, and T. A. Tindall. 1993. Potato response to split nitrogen timing with varying amounts of excessive irrigation. American Potato Journal 70:765-777.

Sulewski, C. A., K. J. Greer, J. J. Schoenau, and V. S. Baron. 2002. Factors affecting nutrient supply rate measurements with PRS^{TM} Probes. *In:* Proceedings of the 2002 Soils and Crops Workshop. University of Saskatchewan, Saskatoon, Saskatchewan. pp. 392-400.

Thomas H. and M. O. Humphreys. 1991. Progress and potential of interspecific hybrids of *Lolium* and *Festuca*. Journal of Agricultural Science. 117:1-8.

Truchet, G. L., and F. B. Dazzo. 1982. Morphogenesis of Lucerne root nodules incited by *Rhizobium meliloti* in the presence of combined nitrogen. Planta. 154:352-360.

Unibest Inc., 3535 Stucky Rd., Bozeman, Montana. 59718.

United State Department of Agriculture. 1980. Report and recommendations on organic farming. United States Government Printing Office, Washington, D. C.

United States Department of Agriculture, National Agriculture Statistics Service. 2002a. Census of Agriculture, Volume 1, Chapter 2. Michigan County Level Data. National Agriculture Statistics Service.

United States Department of Agriculture, National Agriculture Statistics Service. 2002b. Census of Agriculture, Volume 1, Chapter 2. United States State Level Data. National Agriculture Statistics Service.

van der Krift, T. A. J., P. Gioacchini, P. J. Kuikman, and F. Berendse. 2001. Effects of high and low fertility plant species on dead root decomposition and nitrogen mineralisation. Soil Biology and Biochemistry. 33:2115-2124.

von Keyserlingk, M. A. G, M. L. Swift, R. Puchala, and J. A. Shelford. 1996. Degradability characteristics of dry matter and crude protein of forages in ruminants. Animal Feed Science Technology. 57:291-311.

Vigil, M. F., B. Eghball, M. L. Cabrera, B. G. Jakubowski, and J. G. Davis. 2002. Accounting for season nitrogen mineralization: an overview. Journal of Soil and Water Conservation. 57:464-469.

Vigil, M. F., D. E. Kissel. 1991. Equations for estimating the amount of nitrogen mineralized from crop residues. Soil Science Society of America Journal. 55:757-761.

Vitosh, M. L., and G. H. Silva. 1996. Factors affecting potato petiole nitrate tests. Communications in Soil and Plant Analysis. 27:1137-1152.

Wagger, M. G., M. L. Cabrera, and N. N. Ranells. 1998. Nitrogen and carbon cycling in relation to cover crop residue quality. Journal of Soil and Water Conservation. 53:214-218.

Waterer, D. 1996. Petiole sap NO_3-N testing as a method for monitoring nitrogen nutrition of potato crops. Canadian Journal of Plant Science. 77:273-278.

Webb, J., R. Sylvester-Bradley, and F. M. Seeney. 1997. The effects of site and season on the fate of nitrogen residues from root crops grown in sandy soils. Journal of Agricultural Science. 128:445-460.

Weinert, T. L., W. L. Pan, M. R. Moneymaker, G. S. Santo, and R. G. Stevens. 2002. Nitrogen recycling by nonleguminous winter cover crops to reduce leaching in potato rotations. Agronomy Journal. 94:365-372.

Westcott, M. P., C. J. Rosen, and W. P. Inskepp. 1993. Direst measurement of petiole sap nitrate in potato to determine crop nitrogen status. Journal of Plant Nutrition. 16:515-521.

Westcott, M. P., V. R. Stewart, and R. E. Lund. 1991. Critical petiole nitrate levels in potato. Agronomy Journal. 83:844-850.

Westermann, D. T., and S. E. Crothers. 1980. Measuring soil nitrogen mineralization under field conditions. Agronomy Journal. 72:1009-1012.

Westermann, D. T., T. A. Tindall, D. W. James, and R. L. Hurst. 1994. Nitrogen and potassium fertilization of potatoes on yield and specific gravity. American Potato Journal. 71:417-431.

Western Ag Innovations, # 3-411 Downey Road, Saskatchewan, Saskatoon, Canada S7N 4L8.

Wheeler, E. J. 1946. The residual effect of crop rotations on potato yield and the presence of potato scab. Michigan State College Agriculture Experiment Station Quarterly Bulletin. 28:326-332.

Wu, J., P. C. Brookes, and D. S. Jenkinson. 1993. Formation and destruction of microbial biomass during the decomposition of glucose and ryegrass in soil. Soil Biology and Biochemistry. 25:1435-1441.

Wyland L.J., L. E.Jackson, and K. F. Schulbach. 1995. Soil–plant nitrogen dynamics following incorporation of a mature rye cover crop in a lettuce production system. Journal of Agricultural Science. 124:17-25.

Yuan, T. L., D. R. Hensel, R. S. Mansell, and R. D. Rhue. 1985. Yield and nutrient content of potato on a sandy Humaquept with high levels of accumulated Ca and P. Soil and Crop Science Society of Florid Proceedings. 44:68-71.

Chapter 2: Nitrogen Dynamics

Abstract

Effective N management strategies are needed for potato (*Solanum tuberosum* L.) production region in west central Michigan. Organic amendments and diverse crop rotations have been shown to increase potato yields, though a lack of reliable information on amendment and rotation impacts to overall system N dynamics present a barrier to widespread adoption of these management approaches. In order to better understand these influences on N, soil and plant N was measured during two seasons in potato rotations with and without liquid dairy manure amendment. Corn (*Zea mays* L.) preceded potatoes in both 2003 and 2004. Forage crops of one-year sudex (*Sorghum bicolor* L. *x S. bicolor* L.) and alfalfa (*Medicago sativa* L.) preceded potatoes in 2003, while two-year stands of festulolium (*Festuca pratensis* Huds. *x Lolium perenne* L.) and alfalfa preceded potatoes in 2004. Available soil N and plant absorbed NO_3-N as measured by PRS probes and potato petioles demonstrated similar trends within years. Crop rotation had greater impacts on N levels than manure application. Rotations with forage crops and manure amendment resulted in higher soil and plant N concentrations in 2003 than corn rotation or non-manure treatments. This trend was initially reversed in 2004, with corn rotation and non-manure treatments exhibiting higher N levels than forage rotations or manure treatment. Rotation and treatment differences were less significant in 2004 than in 2003. Additions of high quality crop rotations and manure amendment hold the potential to improve N synchrony with potato demand, though external variable including environmental conditions may play a significant role in N availability and plant uptake.

Introduction

Nitrogen management is one of the most important functions of production efficiency in potato cropping systems (Stark et al., 1993). In sandy soil potato production, N is typically the most limiting factor for tuber growth (Errebhi et al., 1998). Nitrogen deficiencies limit tuber size and marketable yield, allow weeds to compete, and enhance susceptibility to early die complex (Rosen, 1991; Lang et al., 1999). Low levels of N early in the season reduce the number of tuber initiates (Roberts et al., 1982), thereby limiting total potential yield. A recent survey of Washington potato producers indicated a belief that higher than recommended N levels are nesseary to avoid limiting conditions brought about by poor management or environmental conditions such as sub-optimal irrigation, N fertilizer application, disease pressure, and excess precipitation (Lang and Stevens, 1997). However, excess N has been shown to cause a variety of negative physiological effects on potatoes, including delayed tuber growth, bulking, and maturity; decreased specific gravity; and ultimately reduced yields (Ojala et al., 1990; Griffin and Hesterman, 1991; Belanger et al., 2002). High N levels, both prior to and during tuber initiation and bulking, result in an over-production of vegetative production, delaying tuber maturity (Allen and Scott, 1980; Ojala et al., 1990). Post-harvest management is also effected by excess N fertilization, increasing bruising and reducing storability (Ojala et al., 1990; Baritelle et al., 2000).

Further complicating N management, N losses due to leaching and subsequent groundwater contamination are a concern both economically and environmentally for

Michigan potato producers. Potatoes have shallow rooting systems compared to other crops, resulting in lower effective rooting volumes from which N may be extracted (Stark et al., 1993). 90% of potato roots are found in the upper 30 cm of the soil. Nitrogen that moves below this level becomes largely unrecoverable (Lesczynski and Tanner, 1976). The high propensity for N leaching on sandy soils (Vitosh and Silva, 1996) and small rooting volume for N recovery results in the leaching of nitrate from excess N applications (Rourke, 1985). In a proposal for a national nitrate leaching index assessment, Shaffer and Delgado (2002) stated that shallow rooted vegetable crops, manure application, and course textured sandy soils combine to pose a 'very high potential for nitrate leaching vulnerability.' The impacts of N leaching extend beyond the individual producer economic implications of decreased fertilizer efficiency. Nitrate leaching is receiving increasingly greater attention as a source of non-point source pollution by the non-agricultural community. Michigan's Natural Resources and Environmental Protection Act, Act 451 of 1994, regulates quantities and/or concentrations of nutrient release that violate established water quality standards (State of Michigan Legislature, 1994). As part of the Michigan Right to Farm Act, Act 93 of 1981, a set of statewide standard and acceptable management practices were established in order to provide agricultural operations with a framework by which to comply with environmental legislation (State of Michigan Legislature, 1981). Compliance with these standards, Michigan's Generally Accepted Agricultural and Management Practices (GAAMPs) (MDA, 2005), is voluntary and provides protection from public and private litigation regarding agricultural management. GAAMP standards are based upon scientific principles developed by, among others, university researchers. GAAMPs have been developed for a number of agriculture practices with the greatest potential environmental impacts, including nutrient utilization.

Utilization of alternative N sources for potato production, including legumes and animal manures, has been the subject of increasing interest among Michigan potato producers in recent years. Antidotal evidence of increased potato yields through the use organic soil amendments by various producers has prompted widespread interest in the diversification of conventional potato agronomic systems. Recent research efforts examining the effects of organic amendments on soil fertility properties have shown promising results. Perennial ryegrass (*Lolium multiflorum* L.) and red clover (*Trifolium pretense* L.) forages, managed as production hay crops, increased total C and N, light fraction C and N, microbial biomass, and microbial activity in potato rotations in Prince Edward Island, Canada (Angers et al., 1999). Increasing perennial forage frequency to at least 60% in potato rotations was found necessary in order to avoid soil degradation seen in more intensive forage and barley (*Hordeum vulgare* L.) rotations where potato frequency exceeded 50%. Grandy et al. (2002) found that cattle manure and legume green manure crop amendment increased organic matter, total C, and soil aggregation in Maine potato production. Griffin and Porter (2004) found that amendments of dairy manure increased total, particulate, and microbial biomass C and N compared to treatments not receiving manure. Webb et al. (1997) demonstrated greater soil N mineralization in potato crops amended with organic manures. Porter et al. (1999) found application of beef manure increased total tuber yields, in part due to increased nutrient availability from organic amendments. Griffin and Porter (2004) found amendments of manure to significantly increase total N pools.

Research in Michigan examining the use of organic amendments and crop rotations have considerable history. These studies, particularly the more dated, have typically focused on measurement of potato yields rather than the factors potentially influencing those yield increases. Wheeler (1946) found alfalfa rotations to increase potato yields over those possible with continuous potato production. Doll and Thurlow (1965) found alfalfa and bromegrass (*Bromus* L.) stands preceding potatoes increased potato yield compared to row crops.

Manure amendment and crop rotation have been shown through the literature to have credible positive effects on the N dynamics of potato agronomic systems. However, significant variability in potato yields can be seen in many of these experiments. While Snapp et al. (2005) found yield increases utilizing winter cover crops and low C/N ratio crop rotations in 2003, these same crops were associated with lower yields in 2004. Griffin and Hestermann (1991) found no yield increases when alfalfa preceded potatoes, attributing these results to poor synchronization between N mineralization and crop demand. A lack of consistent replicable responses to manure amendment or crop rotation is a common theme in the aforementioned experiments.

Variability in environment, soil composition, and management techniques all affect the rate and quantity of soil N mineralization (Vigil et al., 2002). Soil N levels available for plant growth are a function of system inputs such as N fertilizer application, crop residue contributions and system outputs including crop uptake and NO_3-N leaching (Tran and Grioux, 1991; Gasser et al., 2002). Much of the existing literature regarding N availability in potato production focuses on inorganic fertilizer applications (eg. Carter and Bosma, 1974; Timm et al., 1983; Webb et al., 2000) while a lack of information exists on how various organic N contributions interact with climate and soil conditions to supply N for crop uptake during the growing season (Snapp and Fortuna, 2003). Organic N from crop residue, amended animal manure, and residual fertilizer N contribute to the overall soil N pool, significantly impacting the N availability for future crops (Alexander, 1977; Campbell et al., 1991b). Accurate estimation of N release for plant uptake from organic sources is necessary for optimum fertilizer efficiency. With the knowledge of not only the quantity of organic N availability, but also the timing at which this N becomes available, inorganic fertilizer applications can be adjusted so as to avoid over-fertilization.

Effective methods by which to measure season N levels are necessary for accurate N management. Petiole NO_3-N sampling has become a widely accepted method for in-season N management in Michigan due to its reliability and feasible sampling protocol (Snapp et al., 2001; Vitosh et al., 2005). Potato petiole NO_3-N concentrations are a reflection of the balance between uptake and transport of soil NO_3-N to the canopy and the relocation of that N to the tubers (Westcott et al., 1991). A strong correlation between N inputs and potato yields have been seen though petiole NO_3-N concentrations (Gardner and Jones, 1975; Porter and Sisson, 1999).

Soil N measurement is another means by which to determine N status through the growing season. Ion exchange probes have been shown to be a reliable means to monitor in-season N availability. Plant Root Simulator (PRS) ion exchange probes (Western Ag Innovations, Saskatoon, Canada) are buried in the soil, providing an *in situ* measure of nutrient supply by continuously adsorbing ionic compounds on a charged membrane surface (Schoenau et al., 1993). PRS probes provide an integrated measure of supply rates as they are subjected to all factors affecting nutrient supplies, including free ion activities, buffer capacity, mineralization, and immobilization (Sulewski et al., 2002). This measure of N availability has been successfully demonstrated for measuring the N dynamics of manure and crop residue amendments in agronomic systems (Qian and Schoenau, 1997; Adderley et al., 1998; Qian and Schoenau, 2002).

PRS probes have shown to perform comparably to other ion exchange resin membranes. Johnson et al. (2005) examined the abilities of two ion exchange resins, PRS from Western Ag. Innovations and Unibest resin capsules (Unibest Inc., Bozeman, MT) for measuring soil nutrient availability compared to traditional NH_4^+ and NO_3^- soil tests under varying temperature and moisture conditions. While soil tests and Unibest capsules were able to detect soil mineral N responses to both temperature and moisture, PRS probes were only able to detect moisture changes. However, PRS probes were shown to more accurately approximate temporal patterns in soil N mineralization than other tests.

Qian and Schoenau (1999) were able to show strong correlations (r^2 0.79 to 0.96) between measured soil N availability and plant N uptake in manure and non-manure amended treatments, validating their assessment of PRS probe technology as an effective tool for measurement.

Crop residue quality and quantity have been shown to be the most important factors influencing N mineralization (van der Krift et al., 2001). A variety of compositional characteristics have been used to quantify residue decomposition, and thus nutrient mineralization and plant availability. Carbon/N ratio has evolved as the most widely accepted predictor of N mineralization (Norman et al., 1990; Aulakh et al., 1991; Vigil and Kissel, 1991; Quemada and Cabrera, 1995; Odhiambo and Bomke, 2001), though other quality constituents including lignin (Bruulsemann and Christie, 1987; Vigil and Kissel, 1991) and structural carbohydrate (Ranells and Wagger, 1992; Wagger et al., 1998) have been linked to N mineralization rates. These researchers have consistently proved an inverse relationship between C/N ratio and N mineralization. As a rule of thumb, a C/N ratio of 25:1 has been found to be the balancing point of N availability (Allison, 1973). At C/N ratios above 25:1, N immobilization and a temporary net loss of available soil N is expected to occur. Below this point, residues are generally expected to mineralize readily, providing rapidly available N. With the implication of C/N ratios on N availability, C/N is frequently used to imply the quality of the residue; high C/N residues are considered low quality and vise versa (Gil and Fick, 2001).

Manure amendments, like crop residue amendments, have been found to have significant in-season impacts on soil N dynamics. Composition analysis for prediction of N mineralization is often complicated by the heterogeneous nature of manure. Wilkerson et al. (1997) noted that dairy cows within the same herd, depending in diet and lactation period, can produce manure with variable compositions. Initial nutrient contributions of manure amendments are typically expressed as first-year availabilities, with liquid dairy manure N availability frequently cited in the neighborhood of 30% (Motavalli et al., 1989; Klausnet et al., 1994; Curless and Kelling, 2003). Manure amendment benefits, however, have often been found to extend beyond estimated nutrient availability. Increased microbial biomass, enzyme activity and N mineralization have been observed following manure application (Guenzi et al, 1978; Kandler and Eder, 1993; Kandler et al., 1994; Webb et al., 1997; Ma et al., 1999).

Objectives

Nitrogen dynamics in potato production continue to be one of the greatest challenges facing potato growers. The ability to increase available soil N and absorbed potato petiole NO_3-N with manure amendment or forage rotation, while applying equal or less mineral fertilizers would be of significant value to producers. Equally important to increasing these N levels is the ability to provide consistent N concentrations through the season. The use of organic N compounds hold potential for more even N availability throughout the growing season. The following hypotheses aim to prove these benefits:

1. Nitrogen fertilization regimes including liquid dairy manure amendment preceding potato crop production will increase the amount and seasonal distribution of soil N and petiole NO_3-N compared to conventional mineral N fertilizer regimes alone.
2. Potato rotations including forages will improve the amount and seasonal distribution of soil N and petiole NO_3-N compared to conventional potato – corn rotations. Benefits of forage crop production on N dynamics will increase with forage stand length.
3. Potato system N dynamics will benefit from antagonistic effects of forage rotation and manure amendment to a greater extent than either factor alone.

Materials and Methods

Experimental Design

This experiment was conducted at the Michigan State University Montcalm Potato Research farm, MI (43°21' N, 85°10' W) on a McBride sandy loam (coarse-loamy, mixed, frigid Alfic Fragiothods). Intensive potato rotations have dominated the farm for several decades. These rotations have degraded soil properties such as organic matter concentration to low levels. These conditions are expected to make changes in soil quality more apparent, exacerbating any potential yield shifts.

Table 2.1. 2002 initial soil characteristics at Montcalm Potato Research Farm.

		0-20 cm	SE	20-50 cm	SE
pH		6.59	0.04	6.59	0.05
CEC	cmol kg^{-1}	3.53	0.13	3.28	0.15
Phosphorus	mg kg^{-1}	154	5.16	101	5.85
Potassium	mg kg^{-1}	167	3.84	109	2.14
Magnesium	mg kg^{-1}	94	2.26	86	3.26
Calcium	mg kg^{-1}	391	12.49	373	22.47
Organic matter	%	1.10	0.06	1.07	0.04

SE- Standard Error

Treatments consisted of twelve systems, six rotation sequences with and without liquid dairy manure treatment. The experiment was arranged in a randomized complete block design replicated four times. The rotations included two corn-potato, two 2-year forage, and two 3-year forage treatments (Table 2.1). Corn as a rotation crop with potatoes is common cropping system in Michigan potato production and was included in this study as a defender system by which to gauge alternative cropping systems. Two defender crop rotations were staggered by annual entry point so that in each year both crops in the rotation were present. Alfalfa and festulolium rotations were managed as production forage systems, with all biomass removed from the plot at harvest. Sudex was managed as a green manure crop, with all biomass chopped and returned to the soil surface. Rye was planted as a winter cover crop each fall following potatoes in all rotations.

Two-year alfalfa and sudex rotations represent potato driven integration systems. Sudex production offers no benefit for livestock producers as a green manure crop.
One-year alfalfa stands are a move toward integration with livestock operations. Establishment year yields in alfalfa production provide livestock operations with modest feed supplies, though these limited production yields are below levels necessary for total farm feed production. Greater yields from multiple year stands are necessary for feed production on a reasonable landbase. High establishment costs of alfalfa also preclude short-term production intervals; establishment costs from alfalfa seedings are generally only recouped after several years of production. As such, one year alfalfa and sudex production are expected to have greater benefits to potato production than dairy systems. Three-year cropping systems of alfalfa and festulolium better suit the needs of integrated dairy farms than shorter one-year forage production. A second production year beyond establishment allows for production yields necessary to sustain dairy forage requirements. These systems place a greater emphasis on dairy production than shorter, 2-year potato driven systems.

Table 2.2. Crop rotation for 2002, 2003 and 2004 at Montcalm Potato Research Farm.

Rotation	2002	2003	2004
1	Corn	Potato	Corn
2	Potato	Corn	Potato
3	Alfalfa	Potato	Alfalfa
4	Sudex	Potato	Sudex
5	Festulolium	Festulolium	Potato
6	Alfalfa	Alfalfa	Potato

Table 2.3. Common, scientific, and cultivar names of species used in 2002, 2003 and 2004 at Montcalm Potato Research Farm.

Common name	Latin binomial	Cultivar
Potato	*Solanum tuberosum* L.	Snowden
Corn	*Zea mays* L.	Pioneer 36G12
Alfalfa	*Medicago sativa* L.	Pioneer 53Q60
Festulolium	*Festuca pratensis* Huds. *x* *Lolium perenne* L.	Duo
Sorghum/sudangrass	*Sorghum bicolor* L. *x* *S. bicolor* L.	Honeypot

Plots measuring 3.7 by 15.2 meters were oriented such that rows ran east to west with a gradual decreasing in elevation to the north. As a result of this slight hill, the north end of the range suffered from slower water drainage and subsequent flooding. The wet spring of 2004 resulted in a flooding event that prevented emergence of crops on the four northern-most plots and the subsequent abandonment of these plots.

Manure Amendment

Liquid dairy manure from a nearby 2,500 head operation with liquid pit manure storage was applied at 12,260 L ha^{-1}, a regionally common application rate. A pull-type liquid-manure applicator was used to inject manure to depth of 20 cm in the spring prior to planting in 2002. The applicator utilized a hydraulic cutter for even distribution of manure between four injection shanks. Sand bedding mixed with the manure resulted in a liquid density higher than that of what the transfer pump on the applicator could handle, necessitating the addition of water to increase the fluidity of the manure. Application rates were adjusted so that 12,260 L ha^{-1} of initial product was applied. A higher capacity, hydraulically powered pump was installed on the injector for amendment in 2003. With the presence of perennial forage crops in 2003 and 2004, manure was broadcast on the soil surface for all treatments. The distribution pattern in 2004 was refined so as to provide for more even surface coverage than that achieved in 2003. One day following manure broadcasting, primary tillage using a rototiller (Great Plains Mfg. Inc., Salina, KS) was performed on both manure and non-manure treatments. This tillage event served to incorporate surface applied manure within GAAMP regulations.

Table 2.4. Liquid dairy manure concentration characteristics in 2002, 2003 and 2004 at Montcalm Potato Research Farm.

		2002	2003	2004
Moisture	%	88.5	71.9	79.6
Solids	%	11.5	28.1	20.4
pH		7.06	7.28	7.10
Nitrogen, total	mg kg^{-1}	3256	4288	4586
Nitrogen, ammonium	mg kg^{-1}	1602	2412	2924
Nitrogen, organic	mg kg^{-1}	1654	1916	1664
Phosphorus	mg kg^{-1}	438	676	1932
Potassium	mg kg^{-1}	1970	2564	3822
OM by LOI	g kg^{-1}	332	810	589
Magnesium	mg kg^{-1}	1120	1760	1540
Calcium	mg kg^{-1}	3160	7440	410

reported on a dry weight basis
OM- organic matter
LOI- loss on ignition

Table 2.5. Total nitrogen applications for manure and conventional fertilizer treatments in 2002, 2003 and 2004 at Montcalm Potato Research Farm.

2002	Manure N Total kg ha^{-1}	Manure N Available kg ha^{-1}	Fertilizer N kg ha^{-1}	Total N Available kg ha^{-1}
Potato				
Manure	204	154	91	245
Conv.	-	-	224	224
Corn				
Manure	204	154	145	299
Conv.	-	-	207	207
Alfalfa				
Manure	204	154	-	154
Conv.	-	-	0	0
Fest.				
Manure	204	154	114	268
Conv.	-	-	171	171
Sudex				
Manure	204	154	84	238
Conv.	-	-	168	168
2003				
Potato				
Manure	319	219	91	310
Conv.	-	-	224	224
Corn				
Manure	319	219	145	364
Conv.	-	-	207	207
Alfalfa				
Manure	319	219	-	219
Conv.	-	-	0	0
Fest.				
Manure	319	219	114	333
Conv.	-	-	228	228
2004				
Potato				
Manure	326	238	91	329
Conv.	-	-	224	224
Corn				
Manure	326	238	145	383
Conv.	-	-	207	207
Alfalfa				
Manure	326	238	-	238
Conv.	-	-	0	0
Sudex				
Manure	326	238	84	322
Conv.	-	-	168	168

Potato Production

Potatoes were planted with a two-row potato planter (Lockwood Mfg., West Fargo, ND.) at a seed spacing of 22.5 cm in row and 91 cm between rows. Potatoes were hilled approximately five days prior to emergence. Weed control was achieved through standard chemical herbicide application and manual hoeing as needed. Fertilizer was applied in liquid form at planting and as broadcast granular for subsequent fertilizations. Wet conditions following the 2004 planting resulted in sporadic emergence and required replanting in spots in mid-May.

Forage Production

Forages were established with a John Deere (Deere & Company, Moline, IL) 2.4m drill followed by a Brillion Pulverizer (Brillion Farm Equipment, Brillion WI) equipped with rolling press wheels to ensure soil to seed contact . Alfalfa was drilled at 18.0 kg ha^{-1}, with festulolium and sudex drilled at 30.0 kg ha^{-1}. Plots were tilled with a rototiller (Great Plains, Mfg, Inc., Salina, KS) at manure incorporation and finished with a field cultivator (Kongskilde Industries, Bloomington, IL) prior to planting. Alfalfa and festulolium were cut twice in 2002, was cut twice. Alfalfa and festulolium produced four and five cuttings, respectively, in 2003. Alfalfa and sudex each were each harvested twice in 2004.

Corn Production

Corn was planted with a custom plot planter (ALMACO, Nevada, IA) to a population of 74,300 seeds ha^{-1}. Seed spacing was set 28 cm in row and 76 cm between rows. At emergence, plots were thinned if stands exceeded the desired population and spot replanted if needed. Weed removal was performed through chemical herbicide and mechanical cultivation for moderate weed pressure, and hand hoeing for light weed pressure.

Crop Fertility

Crop fertilization rates were based on Michigan State University Extension soil fertility publications (Vitosh, 1990; Christenson et al., 1992; Warncke et al., 1992; Snapp et al., 2002) and tailored to meet site conditions for potato (Dick Crawford, personal communication), corn (Keith Dysinger, personal communication), and forages (Rich Leep, personal communication) using MSU soil test laboratory recommendations.

Manure available nutrient contributions were calculated by plot for nitrogen, phosphorus and potassium. Any deviations in available manure nutrients from conventionally management treatments were corrected at the time of second fertilizer applications, with manure plots receiving higher or lower levels of fertilizer than that applied to conventional treatments. For potato, corn, sudex and festulolium, nitrogen was calculated as the primary balancing nutrient; in alfalfa, phosphorus was used to balance nutrients. Potatoes received a starter fertilizer applied at planting and subsequent applications at hilling and two and four weeks following emergence. Alfalfa, festulolium, and sudex received broadcast fertilizer at emergence and following the first cutting in coordination with anticipated rainfall events. In addition, festulolium was fertilized following cuttings 1 and 3 in 2002. Fertilizer was applied to corn at planting and at the V5 stage.

Table 2.6. Mineral fertilizer application in manure and conventional fertilizer treatments in 2002, 2003 and 2004 at Montcalm Potato Research Farm.

	Fertilizer			Manure		
	N	P	K	N	P	K
2002	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Potato	316	38	-	204	-	-
Corn	139	39	25	140	-	-
Alfalfa	-	204	612	-	146	437
Festulolium	171	-	-	114	-	-
Sudex	168	-	-	84	-	-
2003						
Potato	316	38	-	204	-	-
Corn	204	39	25	145	-	-
Alfalfa	-	204	612	-	146	437
Festulolium	228	-	-	114	-	-
2004						
Potato	316	38	-	204	-	-
Corn	204	39	25	145	-	-
Alfalfa	-	204	612	-	146	437
Sudex	168	-	-	84	-	-

Table 2.7. Fertilizer formulations utilized in experiment at Montcalm Potato Research Farm.

Crop	Timing	Formulation
Potato	starter	19-17-0
	sidedress	49-0-0
Corn	starter	19-19-19
	sidedress	28-0-0
Alfalfa		0-13-39
Festulolium		34-0-0
Sudex		34-0-0

Production Inputs

Pesticides were applied as needed throughout the growing season. Nematicide was applied over the entire range two years preceding the study's onset and again in the spring of 2003 to plots in which potatoes would be planted that season using a custom built injection system. Fungicides were applied during the season on weekly intervals beginning at a plant height of 15 to 20 cm and ended approximately two weeks prior to vinekill. A tractor-drawn sprayer was used for fungicide applications. Insecticides and herbicides were applied using a Hudson CO_2 backpack sprayer (H. D. Hudson Mfg. Co., Chicago, IL.).

Irrigation was provided as needed throughout the season, typically on a 7 to 9 day interval. Water was applied in 2002 via a solid set pipe system, using two lines with sprinklers set at 12 m intervals. For the 2003 and 2004 seasons, an overhead traveling system was utilized.

Soil Nitrogen Analysis

Plant Root Simulation (PRS) probes (Western Ag Innovations, Saskatoon, SK, Canada) were used to measure seasonal N availability during potato production in 2003 and 2004. PRS probes are comprised of ion exchange resin membranes encapsulated in a plastic sheath. These membranes measure 10 cm^2 and are charged with either Na^+ or HCO_3^- ions to adsorb NO_3^- or $NH4^+$, respectively. Probes were inserted in the same soil slots over the course of the season to minimize site variability. Probes were left in the soil for a period of two weeks. Upon removal at the end of the two week burial period, probes were removed from the soil and brushed in the field to remove large quantities of soil. Probes were then placed in a seal bags for transport to campus. In the lab, probes were rinsed with de-ionized water to remove any remaining soil. Probes are once again placed in sealed bags and shipped in a cooler to Western Ag Innovation laboratories in Saskatoon, Canada for analysis.

To determine NO_3 and NH_4, probes were eluted with a 0.5N HCl solution for one hour. The eluate was then used to determine nutrient concentrations using an automated colorimetry and inductively-coupled plasma spectrometer. Nutrient supply rate was calculated from the total volume of eluent and nutrient concentration, providing a measurement of mass of nutrient ion per unit ion-exchange surface area over the burial period (Hangs et al., 2002).

In furrow measurements were made in order to better determine total soil N availability rather residual N not absorbed by competing potato or weed roots. Root exclusion tubes were used throughout 2003 and 2004 to provide a root competition free estimate of N availability. During the second half of 2004, duplicate probes were inserted in-row in corn-potato rotations with exposure to competing roots to measure the influence of root competition.

In addition to in-season N measurement, end-of-season soil NO_3-N levels were measured following the 2004 production season. A Giddings hydraulic soil probe (Giddings Machine Company, Windsor, CO) was used to obtain three samples per plot, spilt at 0-8 inches and 8-20 inches. Soil was sealed in plastic bags, transported and stored at the Crop and Soils field lab.

Nitrate-N levels were determined by combining a 10 g moist soil sample with 50 ml of a 1N KCl solution. Containers were caped and shaken for 30 minutes at 180 rpm. Concluding the 30 minute shaking, samples were left to settle for 15 minutes. The supernatant was then filtered though funnels lined with Whatman #1 filter paper into vials and frozen. The Michigan State University Soil and Plant Nutrient Laboratory utilized a modified Griess-Ilosvay (Keeney and Nelson, 1982) cadmium reduction method to determine NO_3-N. Copperized cadmium reduces NO_3^- to NO_2^- under the principle that NO_2^- reacts with aromatic amines in acidic solution to give diazo salts. These salts couple with aromatic agents to form colored azo compounds that a spectrophotometer can use to determine color intensity (Geldermann and Beegle, 1998).

Potato Plant Nitrogen Analysis

Potato petioles were sampled with the maturation of the third petiole, 56 days after planting (DAP) in 2003 and 64 DAP in 2004. Samples were taken on an average of 10 day intervals. Samples were obtained mornings between 6 and 9 am, placed in cooled containers, and returned to campus. After a refrigeration period of several hours, petioles were shipped overnight to A&L Great Lake Laboratories (Fort Wayne, IN).

Statistical Analysis

Analysis of variance (ANOVA) was performed on PRS ion probe potato petiole and soil nitrates with Proc GLM (SAS Institute, 2004) using the Kenward-Roger method for determining degrees of freedom. When significant effects of treatment occurred, means were compared using Fischer's Least Significant Difference. Unless otherwise stated, differences were considered significant at an alpha level of 0.05

Environmental Conditions

Cool temperature predominated the two years during which nitrogen dynamics were examined in this experiment. 2003 was 1.0° C below 30-year temperature norms and 2004 was 0.4° C below normal. The months of March, April, and May in 2003 were -0.66°, -1.10°, and -1.89° C of normal temperatures, while those same months in 2004 were 2.4°, 0.6°, and -0.8° of normal. Rainfall in both 2003 and 2004 was below 30-year averages. While this experiment is supplemented by artificial irrigation, the system is operated only during periods of greatest tuber water demand in June, July and August. Early season soil moisture was totally dependent upon natural precipitation. Early season rainfall in 2003 was -2.97, -2.59, and 1.42 cm of normal for the months of March, April, and May. Rainfall was 2.82, -3.94, 13.46 cm of normal for this same period in 2004. While both growing seasons may be summarized overall cool and dry, the early season of 2003 was cool and dry compared to warm and wet in 2004.

Results and Discussion

2003 Nitrogen Dynamics

Soil nitrogen concentrations as measured by PRS probes at 76 and 90 days after planting (DAP) showed significantly higher levels of total N based upon crop rotation and manure amendment. Measurements after 90 DAP showed no differences between rotations or manure amendment. Alfalfa rotation and manure amendment provided the highest total N uptake at 76 DAP. While statistically similar to the alfalfa non-amended and corn amended systems, the alfalfa with manure system had significantly greater soil N availability than the corn with no manure system. This pattern was also seen at 90 DAP, though differences in rotations and manure amendment decreased. Overall, the alfalfa crop rotation with manure amendment provided the greatest concentrations of total N availability throughout the growing season.

Crop rotation and manure application both had significant treatment effects. Both alfalfa manure and non-manure treatments provided higher amounts of soil N than corn manure and non-manure treatments. Significance between cropping systems at the P= 0.05 level, however, was only found with the corn rotation treatment with no manure amendment. This system, with the widest C/N ratio residue and lack of manure organic N amendment, resulted in the lowest soil N concentrations. Treatment effects of rotation and manure on available soil N were only found early in the season. PRS probe measurements after 90 DAP until the end of the season indicated no rotation or manure treatment effects.

Initial sampling of petiole NO_3-N showed no differences due to crop rotation or manure amendment. A lack of initial petiole NO_3-N response to soil N fertility has previously been observed (Porter and Sission, 1991; Waterer, 1996). Petiole NO_3-N declined from 2 to 2.25% initially to between 1 and 1.5% for alfalfa and sudex rotations and 0.5 to 1.0% for corn rotations. Doll et al. (1971) found that petiole NO_3-N concentrations peak when plants are 4-6 weeks old, falling thereafter throughout the season. Earlier season petiole NO_3-N monitoring in 2004 indicated this peak may occur closer to 10 weeks, but declining NO_3-N concentrations following a peak occur regardless of seasonal timing. All petiole NO_3-N concentrations in 2003 followed this pattern, though not necessarily to the same degree.

Crop rotation and manure amendment both had significant treatment effects on petiole NO_3-N. Alfalfa and sudex rotations, regardless of manure application, provided statistically identical petiole NO_3-N concentrations throughout the growing season. In contrast, corn rotations provided consistently lower petiole NO_3-N following the initial sampling date 64 DAP. Effects of manure amendment were more apparent in corn rotations than in alfalfa or sudex rotations. Manure amendment did not increase overall petiole NO_3-N, but manure was able to sustain N petiole concentrations to a greater extent than non-manure treatment. Petiole NO_3-N concentrations were similar between manure and non-manure amendment treatments 81 DAP. While NO_3-N concentrations were lower in the non-amendment treatment at 92 DAP, the manure treatment had similar concentrations to those observed 81 DAP. At 102 DAP, manure treatment NO_3-N concentrations were similar to non-amendment treatment concentrations. This same

Figure 2.1. 2003 PRS probe 2-week NO_3 + NH_4 uptake.

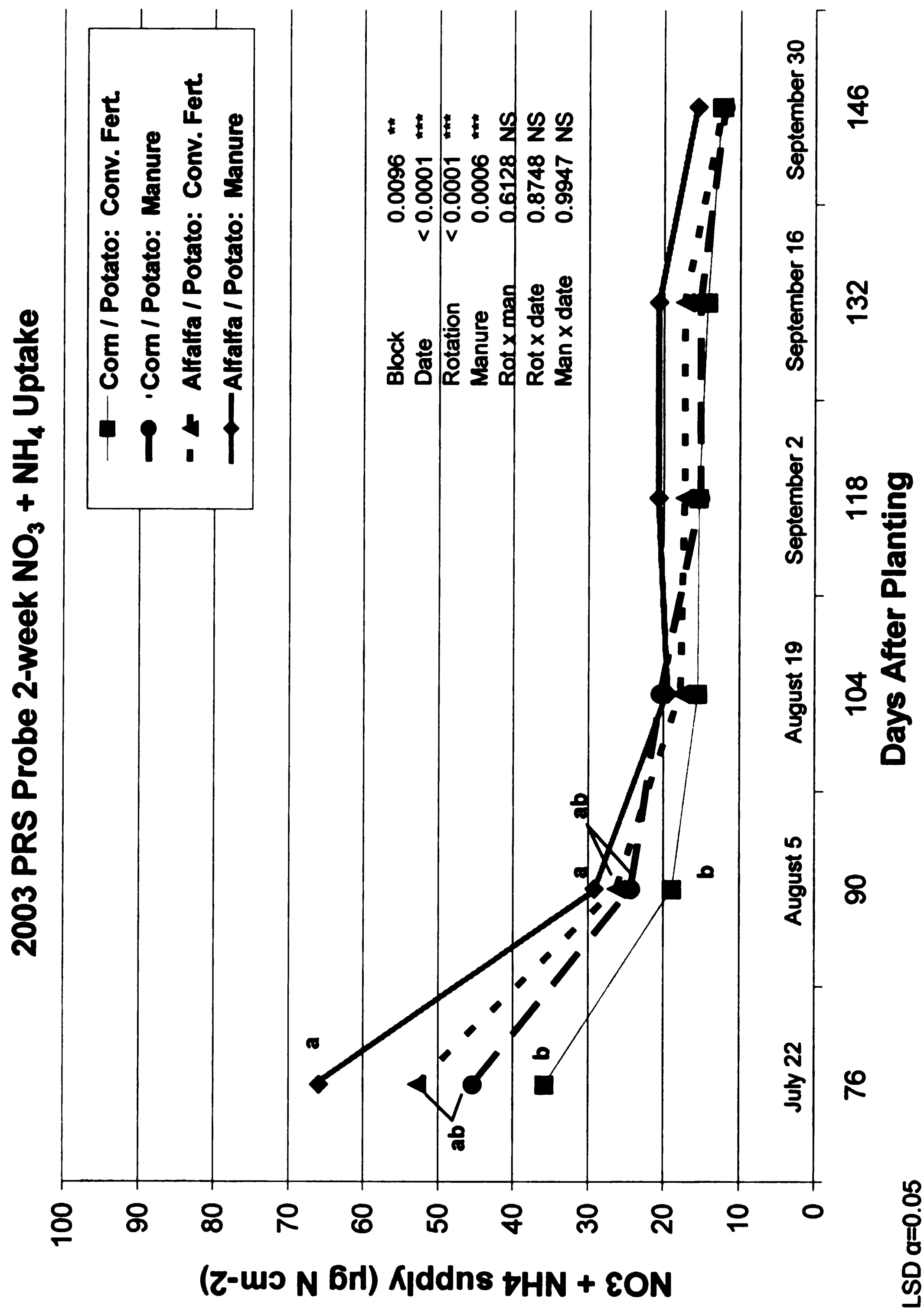
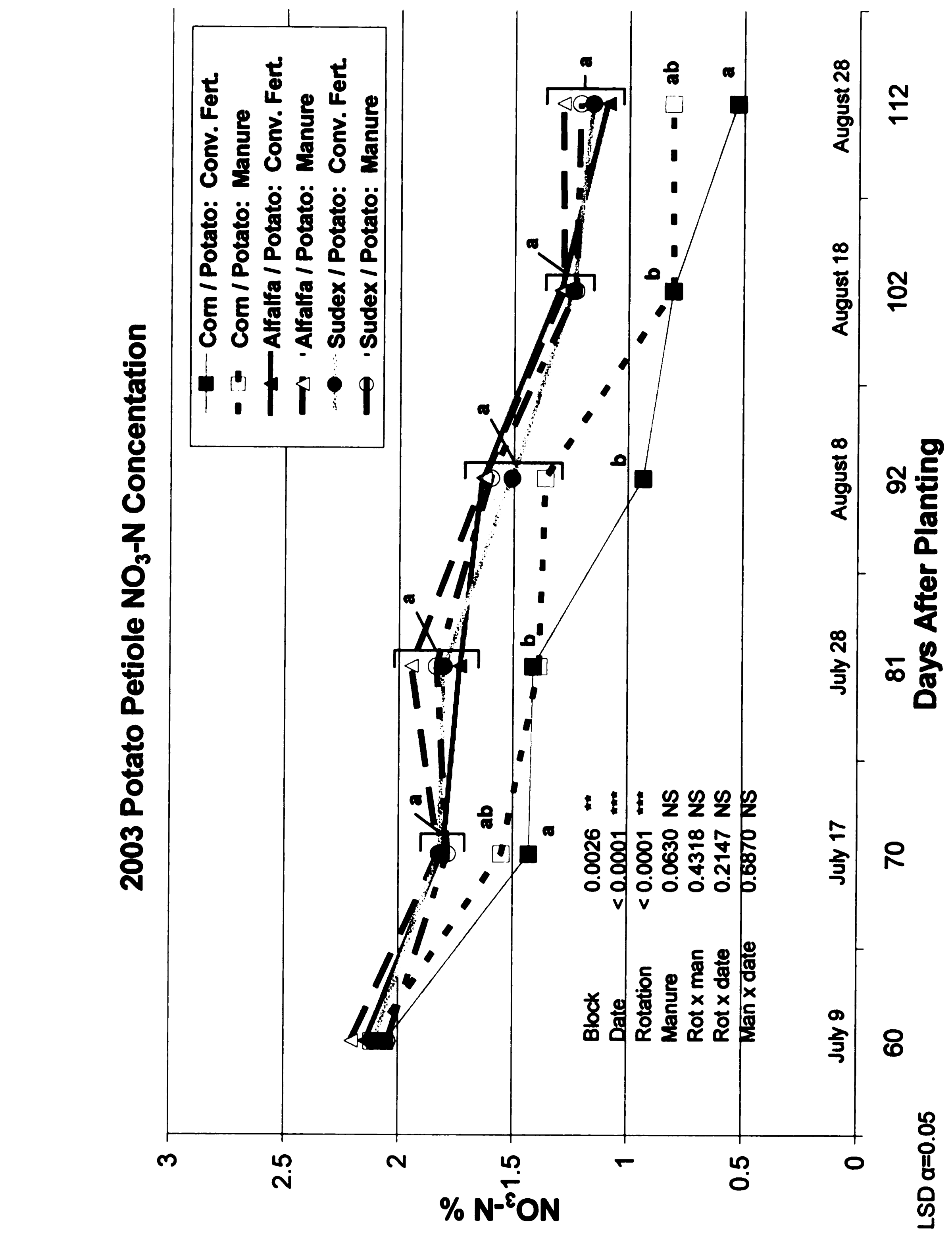


Figure 2.2. 2003 potato petiole NO_3-N concentration.



trend was repeated at 112 DAP. This trend of increased petiole NO_3-N concentration with manure application and the ability to sustain those higher levels indicates promise for manure application to increase soil fertility. These results are similar to other manure treatment studies. Webb et al. (1997), specifically in potato production, and Ma et al. (1999) have both previously observed increased soil N mineralization resulting from manure amendment at levels above those seen with equal nutrient application with mineral fertilization.

Crop rotation treatment effects as measured by PRS probes were expected with the widely dissimilar alfalfa and corn residues inputs. Allison (1973) found that residues with C/N ratios wider than 25:1 tend to immobilize soil N, with crop residue N only slowly becoming available for plant use. In contrast, residues with narrower C/N ratios are expected to immediately contribute available N. Both observed C/N ratios from forage quality determination (Table 2.9) and literature values (Table 2.10) suggest that if N mineralization were to proceed according to Allison's observations, plant available N early in the growing season would be greater from alfalfa rotation treatments than corn rotation treatment. These anticipated results are substantiated through both PRS probe observations and potato petiole measurements. Alfalfa crop rotation treatments significantly increased N concentrations compared to corn rotation treatments.

Table 2.8. Crop above and below-ground C/N ratios as complied from several authors.

	AG C:N	BG C:N
Corn (stover)	60:1 [1]	48:1 [2]
Sudex	47:1 [3]	
Alfalfa	18:1 [4]	21:1 [4]
Cool Season Grass *(Italian ryegrass)*	15:1 [4]	22:1 [4]

AG DM- above ground dry matter
BG DM- below ground dry matter
[1] Cowan, 2005
[2] Havlin et al., 1999
[3] Creamer and Baldwin, 2005
[4] Baron et al., 2001

Table 2.9. Observed C/N ratio* by treatment, cutting, and average in 2002, 2003 and 2004 at Montcalm Potato Research Farm.

	Cut 1	Cut 2	Cut 3	Cut 4	Cut 5	Av.
2002						
Alfalfa						13.8
Manure	17.3	10.7				
Conv.	16.2	10.9				
Sudex						26.7
Manure		25.0	29.4			
Conv.		25.8	26.4			
Festulolium						
Manure		17.6	14.0			14.7
Conv.		13.3	13.9			
2003						
Alfalfa						12.5
Manure	12.6	11.5	11.9	12.8		
Conv.	13.2	11.0	12.5	14.3		
Festulolium						17.1
Manure	22.6	13.8	13.4	14.5	17.8	
Conv.	26.0	17.3	14.2	12.8	18.5	
2004						
Alfalfa						13.4
Manure	13.6	13.2				
Conv.	14.5	12.4				
Sudex						36.2
Manure	31.6	33.2				
Conv.	37.7	42.4				

* Total nitrogen was determined through forage quality analysis using the Hach modified Kjeldahl procedure (Watkins et al., 1987), with crude protein estimated by multiplying total N by 6.25. Crop C concentrations were estimated at 45% (Campbell et al., 1991a) in order to determined C/N ratios.

Petiole NO_3-N concentrations in potatoes grown after alfalfa and sudex rotations treatments were statistically equivalent. These observations are in contradiction to general assumptions regarding sudex residues. Sudex, physiologically, is much more closely associated with corn than alfalfa. Both are C_4 grasses with similar structural design and growth characteristics. Their cited C/N ratios of 60:1 and 47:1, respectively (Table 2.9), suggest that their residues should impact similar effects on subsequent season N dynamics. However, sudex crop rotation effects on N uptake were more similar to the alfalfa rotation treatment than the corn rotation treatment. By managing sudex as a high production summer cover crop, high N fertilization and frequent cuttings likely contributed to lower residue C/N ratios that those expected had the crop received lower N inputs or reached greater maturity between harvests. Actual measured C/N ratios of sudex were much lower (25:1 - 30:1) (Table 2.10) than those measured by Creamer and Baldwin (2005) (Table 2.9). Sudex residue decomposition was also influenced by multiple harvest events during the summer of 2002, with all biomass production returned to the soil surface. The first cutting of sudex was exposed to decomposition for nine months prior to 2003 potato planting, resulting in an extended period for residue decomposition and subsequent N release. Alfalfa, as a production hay crop, had substantial portions of biomass removed during the season. Late season cuttings, common in high production hay crops, result in little overwintering biomass. Alfalfa residue contributions in the spring are comprised of limited above-ground spring regrowth and greater below ground root biomass. Literature values of below ground alfalfa biomass (Table 2.9) are similar to those observed by sudex residues in this experiment.

Environmental conditions, including temperature and soil moisture, play instrumental roles in N mineralization (Goncalves and Carlyle, 1994). 2003 was a cool and dry growing season, 1.0° C and 16.4 cm below 30-year temperature and precipitation averages between the period of March to October. August was the only month with above average temperatures, while May and July were slightly above average precipitation levels. The cool, dry season-long conditions would be expected to retard the microbial processes, effectively slowing mineralization and shifting N availability later into the season. Ma et al. (1999) observed lower than expected mineralization rates of manure during a dry, cool growing season in Ontario in 1996. Griffin and Hestermann (1991) observed that during drought conditions in 1988, dry conditions delayed legume N mineralization to such an extent that, while increases to plant N concentrations were observed, no overall tuber yield increases were seen with the forage crop rotation. Drought conditions existed throughout much of the Midwest in 1988, including the early spring period before planting. April, May, and June averaged 30% of normal rainfall for the period. The severe dry conditions during that spring likely slowed legume residue decomposition to a point where significant mineralization began only with irrigation in early June. The normal mineralization curve may have been shifted several weeks later in the growing season. The dry conditions observed in 2003 would also be expected to slow N release, though not to the extent of that observed in 1988.

2004 Nitrogen Dynamics

Nitrogen dynamics in 2004 demonstrated a very different trend that those in 2003. Whereas narrow C/N crop residues and manure amendment increased available soil N and potato petiole NO_3-N levels in 2003, wide C/N ratio residues and non-manured treatments increased soil and plant N in 2004. Initial PRS probe measurements showed soil N levels at 54 DAP to be greatest in the corn rotation without manure amendment, followed by the corn rotation with manure amendment and alfalfa rotation without manure amendment. This pattern was also observed at 68 DAP, though the alfalfa rotation with manure amendment replaced the corn rotation with manure amendment as the system with greatest soil N uptake. As in 2003, statistical differences between the four systems disappeared following the second burial period of the PRS probes. However, at 110 DAP, levels of significance were once again detectable. Following 68 DAP, a trend developed over the next two burial periods of decreasing soil N supply from the wide C/N, non-manure treatments. By 110 DAP, soil N concentrations were greatest in alfalfa rotation and manure amendment treatment; a pattern identical to that observed early in 2003.

Initial petiole NO_3-N measurements at 56 DAP did not act as an effective precursor for season N uptake trends. Alfalfa rotations with both manure and non-manure treatments and festulolium rotation with manure treatment contained the highest initial petiole NO_3-N. Alfalfa rotation without manure amendments continued to supply greater, though not statistically significant, amounts of petiole NO_3-N through the rest of the season compared to other systems. Alfalfa and festulolium rotations with manure amendment had low petiole NO_3-N over the remainder of the season. The corn rotation without

Figure 2.3. 2004 PRS probe 2-week $NO_3 + NH_4$ uptake.

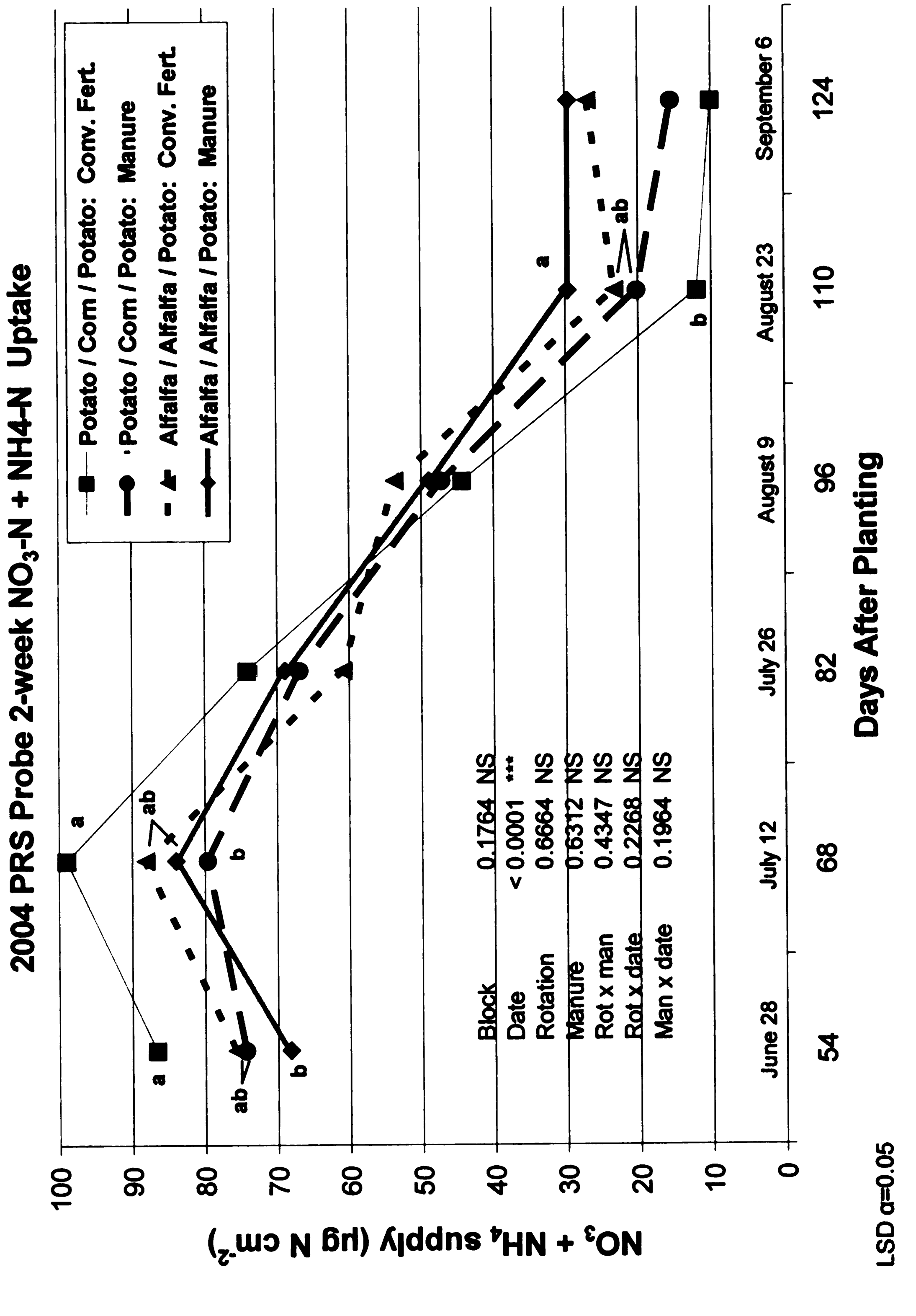


Figure 2.4. 2004 potato petiole NO3-N concentration.

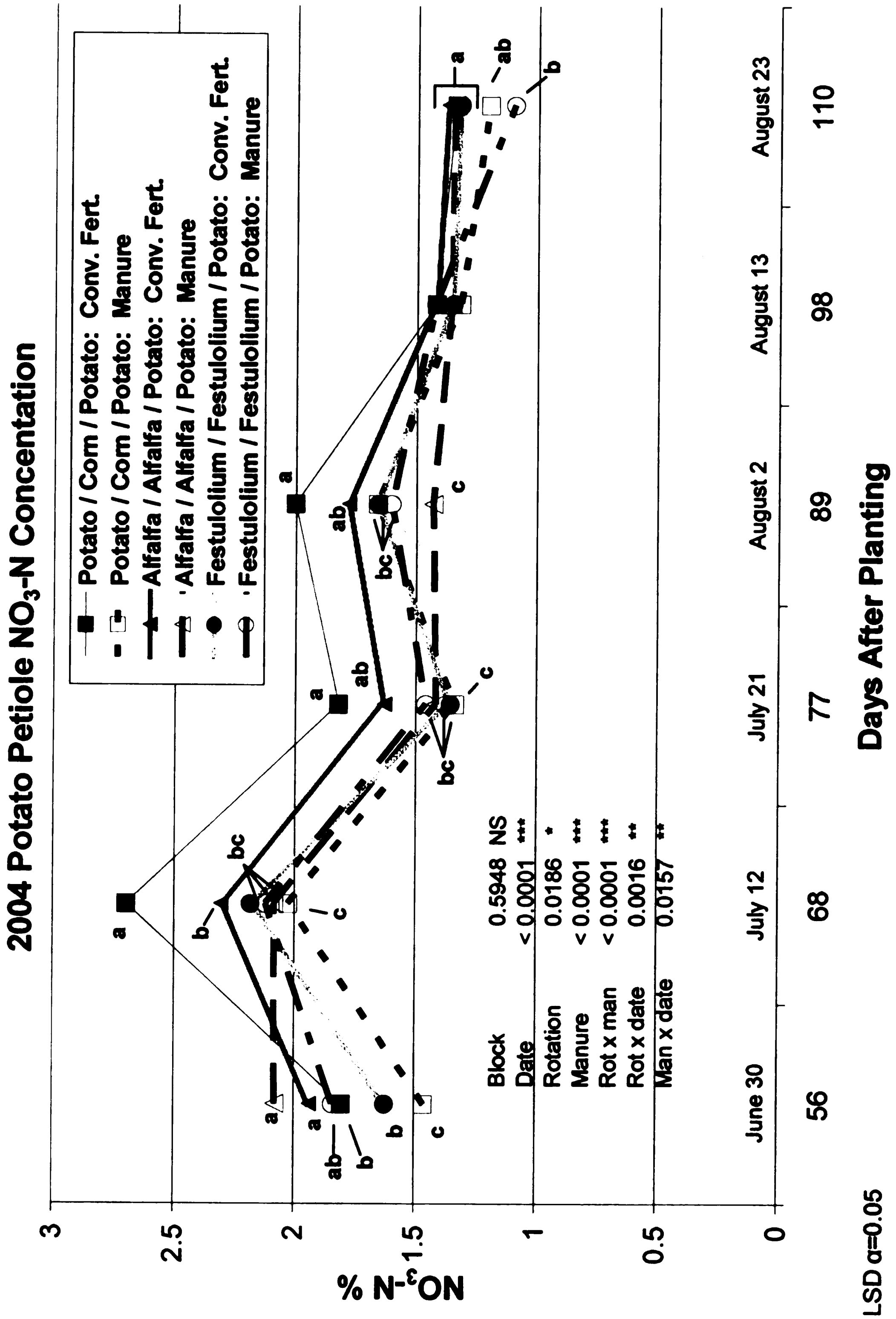
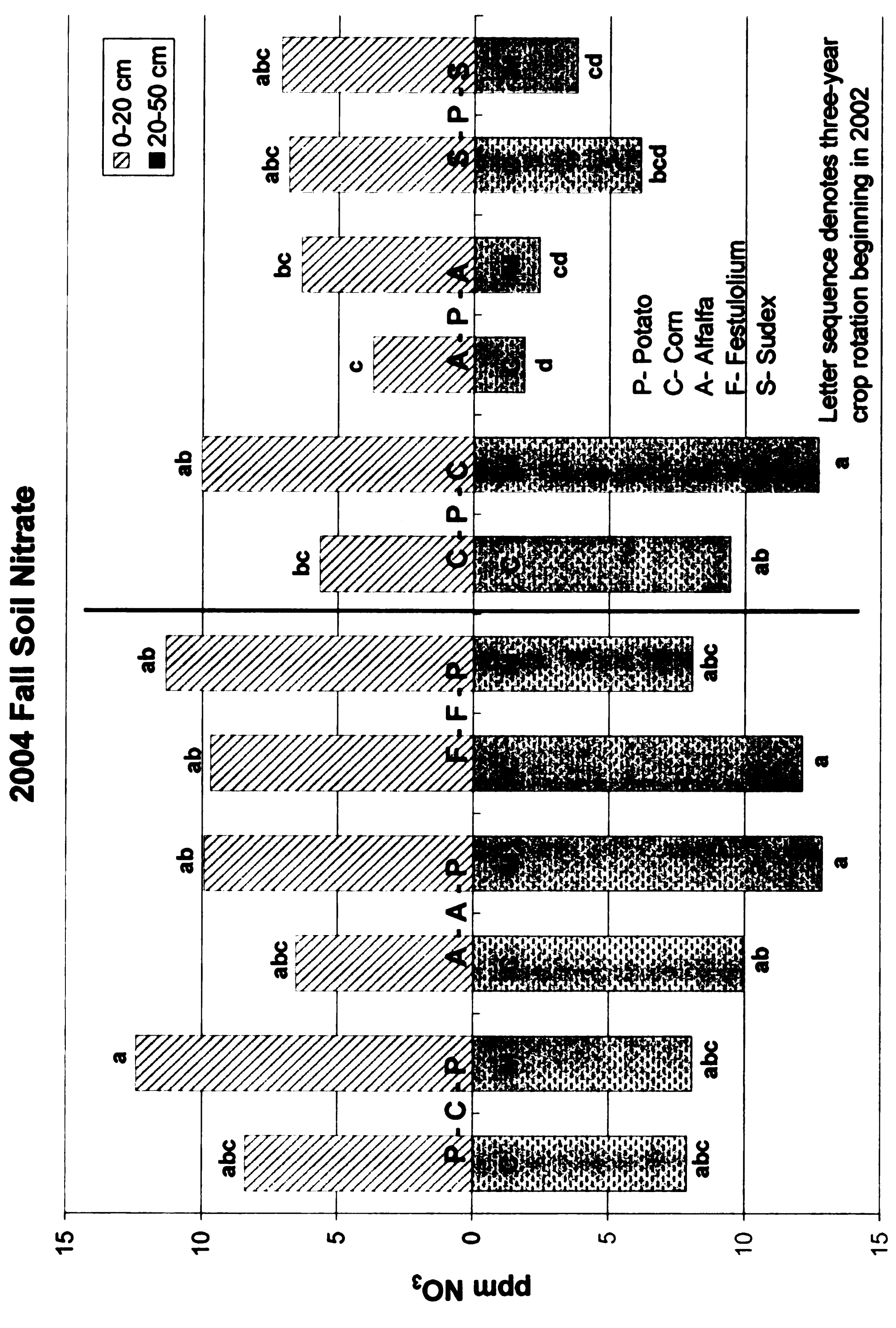


Figure 2.5. 2004 fall soil NO_3-N.



manure amendment emerged 68 DAP as the system with the highest petiole NO_3-N, remaining higher than other systems through 89 DAP. A small flush of petiole NO_3-N was observed at 89 DAP in all systems. While potato N uptake is generally considered to cease 70 to 80 days following emergence (Millard and MacKerron, 1986), Waterer (1996) measured increasing petiole NO_3-N as late as 88 DAP that could be correlated with increased tuber yields. No discernable differences in petiole NO_3-N concentrations between systems were observed at 98 or 110 DAP.

The observed soil and plant N levels in 2004 were in contrast to the expected mineralization characteristics of organic N sources. These predicted trends were, by and large, adhered to in 2003, though environmental conditions were suspected of subtly influencing mineralization. Climatic effects are theorized to have played a much larger role in 2004, likely explaining the observed N trends. While 2004 was, on a whole, a cool and dry season like that of 2003, early season environmental abnormalities significantly altered the N dynamics. Unseasonably warm temperatures in late March and mid April resulted in March and April temperatures 2.4° C and 0.6° C degrees above 30-year averages. Those warm conditions likely initiated considerable N mineralization of high quality alfalfa and festulolium residues. However, several significant rainfall events beginning in late April and continuing through late May likely resulted in high leaching losses of that early mineralized N. Rainfall events of over 2 cm have been shown to move NO_3-N out of the potato rooting zone (Cameron et al., 1978). Rainfall of 2.1 cm (April 25), 4.9 (May 8), 3.8 (May 9), 2.4 (May 14) 1.5 (May 21), and 3.7 (May 23) were among the events that contributed to a record 20.8 cm of precipitation during

May, 13.5 cm above long-term averages. These rainfall events followed manure application, perennial forage termination, primary tillage, and crop planting that was conducted between April 3 and April 6. Those rainfall events facilitated the conversion of organic N into leachable mineral N forms, with subsequent loss of available soil N for potato production. A large body of literature exists showing NO_3-N leaching losses can be exacerbated during periods of high precipitation following legume stand termination (Low and Armitage, 1970; Robbins and Carter, 1980; Adams and Pattison, 1985). Soil N availability measurements in 2004 indicated that manure treatments had lower N levels than non-manure treatments, particularly when coupled with alfalfa rotation. Rapid mineralization of organic N forms present in crop residues and animal manures to leachable inorganic compounds could be expected during the uncharacteristically warm conditions of early 2004. Harris (1993) noted in work conducted in 1989 at the Rodale Institute Research Center in east central Pennsylvania that leaching losses are potentially increased with the application of manure immediately after legume crop termination following heavy spring rainfall. Residual soil N existing following legume rotations was more susceptible to leaching than mineral fertilizer N.

The loss of mineralized N from forage crop and manure amendment sources dramatically altered the available soil N and potato petiole NO_3-N uptake during the 2004 season. Measurement of soil N availability and potato petiole NO_3-N concentrations in 2003 indicated greater soil N availability and plant N uptake from forage crop rotation and manure amendment. These effects would be expected to continue through the 2004 season, likely to a greater extent from longer forage stands and three years of annual manure amendments. Two-year forage stands of alfalfa and festulolium established in 2002 resulted in a three-year interval between potato crops in these rotations. Extended production intervals have been observed to increase potato yields, particularly when rotated with forage crops (Carter and Sanderson, 2001). Forage stands, particularly legumes with organic N contributions, have been cited as strong contributors to overall soil fertility levels (Frye et al., 1985; Harris and Hestermann, 1990; Janzen et al., 1990). Annual manure amendments have been shown to increase soil fertility much the same way (Paul and Beauchamp, 1993; Porter et al., 1999; Sanchez et al., 2001). The combination of perennial alfalfa and annual manure amendment would be expected to dramatically increase soil N pools (Paul and Beauchamp, 1993). However, the leaching events of early 2004 altered the expected N dynamics. Residue mineralization from narrow C/N crop residues and manure amendments resulted in a loss of those N contributions. The increased N mineralization potential following manure amendment (eg. Ma et al., 1999) acted to exacerbate this phenomenon.

Wide C/N ratio residues has been shown to mineralize N more slowly than narrower C/N residue crops (Bruulsema and Christie, 1987). However, the processes governing the N mineralization of crop residues are subject to a variety of factors, including environmental influences. Slower decomposing corn residues were able to retain more N during the high rainfall events in early 2004, releasing this N later in the season. These effects, however, were not shown to be consistent through the growing season, as changes in soil N availability was detected in the later stages of the 2004 growing season. Alfalfa and corn rotations with manure amendment provide increased available soil N in mid August, similar to that exhibited early in 2003 and similar to predicted mineralization patterns. Petiole NO_3-N concentrations increased slightly at 89 DAP. Though potato N uptake is assumed to negligible 70-80 days after emergence (Millard and MacKerron, 1986), Waterer (1996) observed petiole NO_3-N uptake at 88 DAP positively correlated with increased yields. These results might be best explained through increased soil microbial activity in treatments with greater diversity. Stimulation of soil N pools has been observed with alfalfa rotation and dairy manure treatment (Rasse et al., 1999; Masciandara et al., 2004). Despite the loss of available N sources early in the season, alfalfa and manure treatments provided improvement in season-long N availability. This observation raises concerns regarding N synchrony and possible detrimental effects of excessive N late in the season (Ojala et al., 1990; Griffin and Hestermann, 1991). However, the lack of response by petiole NO_3-N concentration to increased soil N levels indicates potatoes utilized little of this available N. Rather, this soil N may facilitate residue decomposition and additional N mineralization. The overwintering rye cover crop following potato production is expected to recover much of this residual N, recycling it for subsequent utilization the following year. Kristensen and Thorup-Kristenson (2004) showed an overwintering rye crop was able to uptake 90.5 kg N ha^{-1}.

Soil nitrate analysis conducted in the fall of 2004 at depths of 0-20cm and 20-50 cm measured residual soil N. Three of the six crop rotation treatments had been planted to potatoes in 2004 allowing feasible comparisons between two-year corn and three-year alfalfa and festulolium forage rotations. Despite a lack of significant rotation or manure treatment effect, manure application showed a trend toward increased soil N levels above non-manure treatments in the 0-20 cm depth. At the deeper 20-50 cm sampling depth, there were no differences between manure and non-manure treatments. However, manure treatment in alfalfa rotations and non-manure treatment in alfalfa and festulolium rotations showed greater soil N levels. Residual soil N at this depth following alfalfa or festulolium might be expected due to the deep rooting characteristics of these crops and the relatively shallow rooting depth of potatoes. Ashley et al. (1997) determined the depths which several crops are effective at utilizing water (Table 2.11). Established stands of both alfalfa and festulolium were found to have functional rooting at 120 cm depths, making deposition of N upon root decomposition likely. Potato roots at only 45 to 60 cm are unable to recover those sources of N. Residual soil N at depths up to 120 cm following potato production present leaching threats as there is no means by which to reincorporate this N back into production.

Table 2.10. Effective rooting depth of selected crops.

Crop	Maturity	Depth (cm)
Alfalfa	new stand	30 – 45
	established stand	120
Cool season grass	new stand	15 – 45
	established stand	45 – 120
Potato		45 – 60
Corn		105
Winter cereal (rye)	Haun 4-7 stage	30 - 60

-reproduced from Asheley et al., 1997

2003 vs. 2004 Nitrogen Dynamics

Total accumulated season soil and plant N concentrations were markedly higher in 2004 than 2003. Soil available N concentrations in 2003 initially ranged from 36 - 66 μg N cm^{-2} at 76 DAP, rapidly decreasing at 104 DAP to levels under 21 μg N cm^{-2} for the rest of the season. In 2004, soil N levels ranged from 68 - 87 5μg N cm^{-2} 54 DAP, increasing to 84 - 99 μg N cm^{-2} 68 DAP. Soil N level gradually decreased to 30 - 10 μg N cm^{-2} by the end of the season.

Similarly, petiole NO_3-N concentrations were lower in 2003 than 2004. Initial soil NO_3-N concentrations in 2003 ranged from 2 - 2.25%. End of season NO_3-N concentrations ranged from 1 - 1.5% for alfalfa and sudex rotations and 0.5 - 0.1% for corn rotations. Petiole NO_3-N concentration in 2004 was initially lower at 1.5 - 2.0 %, but did not drop though the season as drastically as the 2003 levels. At season end, petiole NO_3-N concentration was at 1.0 - 1.5%.

As noted previously, suppressed N mineralization has been observed in cool, dry environmental conditions such as those in 2003. However, a more likely explanation of these observations may be due to the increased overall N mineralization potentials from greater labile N pools. Kuzyakov et al. (2000) described this increase in N mineralization, or priming effect, as "strong short-term changes in the turnover of soil organic matter caused by comparatively moderate treatments of the soil." The addition of N to the soil stimulates soil microbial activity, resulting in greater overall available N than that applied from the amendment. This effect has been cited in both annual manure amendment and legume crop rotation (Paul and Beauchamp, 1993; Webb et al., 1997; Ma et al., 1999). Harris (1993) suggested that legume N input increases in soil N priming potentials may be of more value than legume contributions to either short or long-term direct N supplies.

Other researchers at this site observed effects of the environmental conditions of 2003 and 2004 as well. Snapp et al. (2005) observed increased potato yields in 2002 and 2003 with winter cover crops and high biomass production sweet corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) rotation crops. In 2004, these two management practices were associated with lower potato yields than systems including no winter cover crops or lower biomass production rotation crops. Highest yielding potato rotation utilized no winter cover crops. In systems with cover crops, rotations with a summer wheat or snap bean (*Phaseolus vulgaris* L.) crop followed by rye produced higher potato yields compared to a rotation with sweet corn or legume winter cover crops. These results suggest that grass crops may recover and recycle residue soil N more effectively than legumes. This conclusion is in agreement with research results of Shipley et al. (1992), where it was found that cereal rye and annual ryegrass recovered fall applied N better than hairy vetch, crimson clover, or native weeds. Additionally, wheat and snap beans residues should leave more residual N in the soil profile than sweet corn. Sweet corn and wheat C/N ratios are generally similar, but wheat residues with a mid-summer harvest date have greater exposure to favorable decomposition conditions prior to winter. Snap beans are expected to mineralize quickly because of their low C/N ratios. A key management variable was winter crop termination and primary tillage. Whereas overwintering crops in this study were terminated and incorporated prior to the high rainfall period of May, Snapp's overwintering crops were incorporated in late May. Actively growing perennial crops have been shown to reduce NO_3-N leaching losses (Henseler and Attoe, 1970; Long and Hall, 1987). However, the incorporation of high biomass winter cover crop residues into severally NO_3-N depleted soils may have resulted in initial N immobilization. Temporary immobilization of N from crop residues has often been observed (Aulakh et al., 1991; McKenney et al., 1995), which may lead to N supply poorly synchronized with potato N demand, as witnessed by Griffin and Hestermann (1991) at this site.

Furrow vs. Valley Placement of PRS Probes

Over the last three sampling periods of 2004, a duplicate set of PRS probes were placed in-row in order to determine the effect of placement on soil N measurement. PRS probes had been placed in furrow, within root exclusion cylinders for the main 2003 and 2004 experiments. Under this management scheme, total soil N availability was measured free of competing sinks. Placed in-row, probes measured soil N levels while competing with potato uptake.

Table 2.11. Location effects on soil N as measured by PRS probes.

	Aug 9	Aug 23	Sept 6
Hill			
Manure	46.80 a	19.83 a	18.73 a
Conv.	44.38 a	11.98 ab	10.33 b
Furrow			
Manure	41.87 a	15.17 ab	12.10 ab
Conv.	30.47 b	10.43 b	10.20 b
P- value			
Manure treatment	0.023	0.004	0.013
Location	0.005	0.086	0.074
Manure x location	0.108	0.359	0.084

Comparisons made by date

Furrow soil N, particularly in non-manure treatments, was consistently lower than those of in-row hill soil N.

Potential Improvements for Nitrogen dynamics

The results of this study suggest that the use of diverse crop rotations and animal manure amendments hold potential to improve N availability and uptake in potato production systems. However, these results also highlight the large influences environmental conditions can have on N dynamics. In order for any widespread reliance on organic N sources, effective means by which to mitigate uncontrollable environmental factors must be developed. Proactive management of organic inputs is currently unfeasible until long-term forecasting evolves to a point where seasonal climatic trends may be accurately predicted. Currently, management control is relegated to reactionary methods. More intensive management of crop residues and manure amendments may be able to fine-tune seasonal N dynamics, including N release and availability of organic materials. Shifts in manure amendment management are frequently more difficult than crop management adjustments. Aspects such as storage, incorporation, and application timing are controlled by on-farm logistics and environmental regulations that complicate management flexibility. Despite these challenges, a better understanding of factors influencing organic amendment N may allow for better N utilization.

The nutrient constituency variations of various crop residues have been explored in length in this study. As evidenced in this work and by others (eg. Aulakh et al., 1991; Vigil and Kissel, 1991), crop species can dramatically alter residue biochemical composition. High C/N ratios of corn residues release and mineralize N very differently than low C/N ratio alfalfa residues. Animal manures are inherently even more variable in composition than crops residues. Manure nutrient content is a function of animal type, animal age, feed ratio, and manure storage system. Animal species is a major influencing factor. Eghball et al. (2002) compared literature values of several animal species and found first year N availability ranging from 90% in swine and poultry manures to 32% in dairy manure, with second year N availability was similarly broad. Variability within species, and even with herds, also prevents consistent manure nutrient prediction. Wilkerson et al. (1997), in modeling estimated manure N excretions, emphasized the differences in manure compositions within a dairy herd with a range of lactating, non-lactating, growing, and replacement cattle.

The C/N ratio of manure has been shown to cause variations in N mineralization by up to 40% (Chadwick et al., 2000). Qian and Schoenau (2002) observed a negative correlation between cattle manure C/N ratio and N mineralization. They found that manure C/N ratios above 15:1 delayed initial N mineralization, a result corroborated by Beauchamp and Paul (1989). Van Kessel et al. (2000) examined the influence of manure components including residual feed stuffs, forage cell walls, simple N compounds, and nondietary metabolic components on N mineralization, determining that improving estimates of N mineralization requires research on both readily available N compounds and N immobilizing compounds. The demonstrated variability between not only different manure types, but also variability within a single manure source itself, makes management adjustments impacting N release very difficult.

While the modification of crop residue and manure characteristics to better meet crop demands though improved N synchrony has not been directly addressed, a limited amount of research has recorded the compositional shifts in manure from various management approaches. Powers and Van Horn (1998) demonstrated that dietary manipulation in dairy and swine production alters the nutrient composition of manure. Supplying limited amino acids, for example, allows for a reduction in total dietary protein needs, thereby reducing the excretion of N. Adjustments to N composition effects overall C/N ratios, with implications on N availability for crops following soil amendment. Manure handling and storage systems have been shown to significantly alter manure characteristics from initial excrement to field application. Schoenau et al. (2000) observed that solid dairy manure contains less inorganic N and is less immediately available compared to liquid dairy slurry. Stockpiling or aging manure lowers the C/N ratio, increasing the release of available N upon amendment (Qian and Schoenau, 2002). The use of manure handling techniques including composting, solid separation, anaerobic lagoons, and anaerobic digestion, in contrast to the more conventional liquid pit or solid pack, have also been shown to influence nutrient composition (Van Horn et al., 1994). The modification of manure handling prior to storage influences N concentrations as well; Muck and Richards (1983) found that nearly half of manure N from lactating dairy cows may be lost before manure reaches storage facilities.

The physical quality of crop residues impacts N mineralization as well. Residue particle size reduction through general tillage processes may be able to modify N dynamics. Vaughan and Evanylo (1998) demonstrated increased N release by mowing and disking crop residues. Greater residue particle surface area increases the soil micro-biota colonization area and influences the exchange of water, nutrients, and oxygen between the residue and soil (Swift et al., 1979). Particle size also controls the extent to which residue contacts clay and silt soil particles. Hassink (1997) found that these soil particles act to protect residues from microbial decomposition by occupying available surface area. Bending and Turner (1999) found that particle size effects on N mineralization were correlated with residue quality. Reducing the particle size of high-quality residues (Brussels sprout (*Brassica oleracea* L.), C/N of 15:1) promoted rapid microbial respiration and N mineralization. In contrast, particle size reduction of low quality residues (ryegrass (*Lolium perenne* L.) root, C/N of 38:1; wheat straw, C/N of 91:1) caused N immobilization and a delay in microbial respiration.

Timing of crop residue desiccation was shown in this research to have an impact on N availability. Sudex and corn residues are structurally and compositionally similar; their high C/N ratios typically result in slow N release. The early termination of sudex residues in the summer of 2002 led to much greater N release synchrony with potato demand in 2003 than corn residue termination in the fall of 2002. Sudex residues effected potato petiole NO_3-N more similarly to high-quality alfalfa residues than corn residues. Early termination of a low-quality reside may assist in synchronizing N availability. Phillips and Stopes (1995) demonstrated this effect as well, finding higher quality residues were more effective as N suppliers when followed immediately after incorporation with a crop. Effects from low-quality residues were greater when the following crop was delayed by a month. Wagger (1989) evaluated the effect of delayed crop termination and found that N mineralization rates could be slowed by allowing crop C/N ratios to increase with a two week delay in termination.

Residue placement has also been shown to alter short-term soil N mineralization. Crop residue incorporation, as opposed to surface placement, has been observed to initially depress N mineralization rates (Smith and Sharpley, 1990; Aulakh et al., 1991; Baggs et al., 2000). However, this N immobilization was frequently found to be positively correlated with C/N ratio. Smith and Sharpley (1990) observed greater N mineralization in the short-term (84 day) from higher quality residues, in the order of alfalfa > peanut (*Arachis hypogea* L.) > soybean (*Glycine max* L.) > oat (*Avena sativa* L.) ≥ sorghum (*Sorghum bicolor* L.) > wheat > corn. In addition to N mineralization effects, residue placement may affect early season soil temperature and moisture. Surface applied residues help conserve soil moisture that might otherwise be lost with residue incorporation. Early desiccation of winter crops through mechanical mowing was found by Vaughan and Evanylo (1998) to provide ample time for mineralization prior to corn planting while conserving soil moisture.

Despite a general understanding of the effects of termination timing, residue placement, and particle size modification, knowledge of when to implement management changes to fine-tune N releases is necessary. Currently, no reliable protocols exist on N dynamic modification.

Conclusion

Ultimately, the observed variation in N availability and uptake demonstrates the need for more accurate methods of predicting N dynamics in potato production. Crop rotation was found impact soil and plant N dynamics to a greater extent than manure amendment. Forages rotation and manure application improved overall potato N availability and uptake in 2003. This trend was reversed in 2004 when corn rotation and no manure amendment increased N availability and uptake. Environmental conditions, particularly above average temperatures early in April followed by record May precipitation, were cited as primary influences for these dissimilar N dynamics. The lack of response to forage crop and manure amendment N contributions in 2004 was in direct contrast to the commonly observed increasing yield response over time to reduced potato cropping frequency, diverse crop rotation, and annual manure amendment. When functioning as expected, forage crop rotations and manure amendments are capable of significantly increasing both soil available N and plant absorbed NO_3-N. However, as shown in this research, these effects are neither consistently reproducible nor always beneficial. More research is needed on the impact of N sources, particularly organic, on overall N dynamics under a range of field conditions. The ability to modify management effects in response to uncontrollable outside forces is a prerequisite for more intensive organic N source use.

Literature Cited

A & L Great Lakes Laboratories, 3505 Conestoga Drive, Fort Wayne, Indiana. 46808.

Adderley, D. R., J. J. Schoenau, and F. A. Holm. 1998. Availability of soil nitrogen released from pea and lentil residue to subsequent cereal crops under reduced tillage. *In:* Proceedings of the 1998 Soil and Crops Workshop. University of Saskatchewan, Saskatoon, Saskatchewan. pp. 339-344.

Adams, J. A., and J. M. Pattinson. 1985. Nitrate losses under a legume-based crop rotation in Central Canterbury, New Zealand. New Zealand Journal of Agriculture Research. 28:101-107.

Allison, F. E. 1973. Soil organic matter and its role in crop production. Elsevier Scientific Publishing Co., New York.

ALMACO, 99M Avenue, Nevada, Iowa. 50201.

Angers, D. A., L. M. Edwards, J. B. Sanderson, and N. Bissonnette. 1999. Soil organic matter quality and aggregate stability under eight potato cropping sequences in a fine sandy loam of Prince Edward Island. Canadian Journal of Soil Science. 79:411-417.

Allen, E. J., and R. K. Scott. 1980. An analysis of the potato crop. Journal of Agricultural Science. 94:583-606.

Allison, F. E. 1973. Soil organic matter and its role in crop production. Elsevier Scientific Publishing Co., New York, New York.

Alexander, M. 1977. Introduction to Soil Microbiology. John Wiley & Sons., New York. p. 472.

Ashley, R. O., W. H. Neibling, and B. A. King. 1997. Irrigation scheduling- using water-use tables. University of Idaho Cooperative Extension Service Bulletin CIS 1039.

Aulakh, M. S., J. W. Doran, D. T. Walters, A. R. Mosier, and D. D. Francis. 1991. Crop residue type and placement effects on denitrification and mineralization. Soil Science Society of America. 55:1020-1025.

Baggs, E. M., C. A. Watson, and R. M. Rees. 2000. The fate of nitrogen from incorporated cover crop and green manure residues. Nutrient Cycling in Agroecosystems. 56:153-163.

Baritelle, A. L., G. M. Hyde, and R. E. Thornton. 2000. Influence of early-season nitrogen application patter on impact sensitivity: I. Russet Burbank potato tubers. Postharvest Biology and Technology. 19:273-277.

Baron, V., D. Young, and C. Ullmann. 2001. Can pastures slow down global warming? Western Forage / Beef Group. May 2001. 5:3-6.

Belanger, G., J. R. Walsh, J. E. Richards, P. Milburn, and N. Ziadi. 2002. Nitrogen fertilization and irrigation affects tuber characteristics of two potato cultivates. American Journal of Potato Research. 79:269-279.

Bending, G. D., and M. K. Turner. 1999. Interaction of biochemical quality and partial size of crop residues and its effects on the microbial biomass and nitrogen dynamic following incorporation into soil. Biology and Fertility of Soils. 29:319-327.

Brillion Farm Equipment, 200 Park Ave, Brillion, Wisconsin. 541101.

Bruulsema, T. W., B. R. Christie. 1987. Nitrogen contribution to succeeding corn from alfalfa and red clover. Agronomy Journal. 79:96-100.

Cameron, D. R., R. De Jong, and C. Chang. 1978. Nitrogen inputs and losses in tobacco, bean, potato fields in a sandy loam watershed. Journal of Environmental Quality. 7:545-550.

Campbell, C. A., G. P. Lafond, A. J. Leyshon, R. P. Zentne, and H. H. Janzen. 1991a. Influence of fertilizer and straw baling on soil organic matter in a thin Black Chenozem in western Canada. Soil Biology and Biochemistry. 23:443-446.

Campbell, C. A., V. O. Biederbeck, R. P. Zentner, and G. P. Lafond. 1991b. Effect of crop rotations and cultural practices on soil organic matter, microbial biomass and respiration in a thin black Chernozem. Canadian Journal of Soil Science. 71:363-376.

Carter, M. R. and J. B. Sanderson. 2001. Influence of conservation tillage and rotation length on potato productivity, tuber disease, and soil quality parameters on a fine sandy loam in eastern Canada. Soil & Tillage Research. 63:1-13.

Carter, J. N, and S. M. Bosma. 1974. Effect of fertilizer and irrigation on nitrate-nitrogen and total nitrogen in potato tubers. Agronomy Journal. 66:263-266.

Chadwick, D. R., F. John, B. F. Pain, B. J. Chambers, and J. Williams. 2000. Plant uptake of nitrogen from the organic nitrogen fraction of animal manures: a laboratory experiment. Journal of Agricultural Science. 134:159-168.

Christenson, D. R., D. D. Warncke, M. L. Vitosh, L. W. Jacobs, and J. G. Dahl. 1992. Fertilizer recommendations for field crops in Michigan. Michigan State University Extension Bulletin E-550A.

Cowan, D. Building soil organic matter. *Referenced:* 10 January, 2005. Agri-Food Laboratories CCA.On www.agtest.com/articles/building.

Crawford, D. Farm Manager, Montcalm Potato Research Farm, Michigan State University. 4470 McBride Rd, Lakeview, Michigan. 48850.

Creamer, N. G., and K. R. Baldwin. 2005. An evaluation of summer cover crops for use in vegetable production systems in North Carolina. Southwest Florida Research & Education Center, University of Florida. http://www.imok.ufl.edu/LIV/groups/cultural/cover/ncvps.htm

Curless, M. A., and K. A. Kelling. 2003. Preliminary estimates of nitrogen availability from liquid dairy manure to potato. HortTechonolgy. 13:593-597.

Deere & Company World Headquarters. One John Deere Place, Moline, Illinois. 61265.

Doll, E. C., D. T. Christenson, and A. R. Wolcott. 1971. Potato yields as related to nitrate levels in petioles and soils. American Potato Journal. 48:105-112.

Doll, E. C., and D. L. Thurlow. 1965. Soil management and fertilization for potatoes grown on mineral soils. Michigan State College Agriculture Experiment Station Research Report. 31:1-6.

Dysinger, K. Corn Research Technician. Michigan State University, Department of Crop and Soil Science. Crop and Soil Science Teaching and Research Facility. 4450 Beaumont Rd., East Lansing, Michigan. 48824.

Eghball, B., B. J. Weinhold, J. E. Gilley, and R. A. Eigenberg. 2002. Mineralization of manure nutrients. Journal of Soil and Water Conservation. 57:470-473.

Errebhi, M., C. J. Rosen, S. C. Gupta, and D. E. Birong. 1998. Potato yield response and nitrate leaching as influenced by nitrogen management. Agronomy Journal. 90:10-15.

Frye, W. W., W. G. Smith, and R. J. Williams. 1985. Economics of winter cover crops as a source of nitrogen for no-till corn. Journal of Soil and Water Conservation. 40:246-258.

Gardner, B. R., and J. P. Jones. 1975. Petiole analysis and the nitrogen fertilization of Russet Burbank Potatoes. American Potato Journal. 52:195-200.

Gasser, M. O., M. R. Laverdiere, R. Lagace, and J. Caron. 2002. Impact of potato-cereal rotations and slurry applications on nitrate leaching and nitrogen balance in sandy soils. Canadian Journal of Soil Science. 82:469-479.

Gelderman, R. H., and D. Beegle. 1998. Nitrate- Nitrogen. *In:* Recommended Chemical Soil Test Procedures for the North Central Region. North Central Regional Research Publication No. 221. pp. 17-20.

Giddings Machine Company. 631 Technology Circle, Windsor, Colorado. 80550.

Gil, J. L., and W. H. Fick. 2001. Soil nitrogen mineralization in mixtures of eastern gamagrass with alfalfa and red clover. Agronomy Journal. 93:902-910.

Goncalves, J. L. M., and J. C. Carlyle. 1994. Modeling the influence of moisture and temperature on net nitrogen mineralization in a forested sandy soil. Soil Biology and Biochemisty. 26:1557-1564.

Grandy A. S., G. A. Porter, and M. S. Erich. 2002. Organic amendment and rotation crop effects on the recovery of soil organic matter and aggregation in potato cropping systems. Soil Science Society of America Journal. 66:1311-1319.

Great Plains Manufacturing Incorporated. 1525 E. North Street, Salina, Kansas. 67401.

Griffin, T. S., and O. B. Hestermann. 1991. Potato response to legume and fertilizer nitrogen sources. Agronomy Journal. 83:1004-1012.

Griffin, T. S., and G. A. Porter. 2004. Altering soil carbon and nitrogen stocks in intensively tilled two-year rotations. Biology and Fertility of Soils. 39:366-374.

Guenzi, W. D., W. E. Beard, F. S. Watanabe, S. R. Olsen, and L. K. Porter. 1978. Nitrification and denitrification in cattle manure-amended soil. Journal of Environmental Quality. 7:196-202.

H. D. Hudson Manufacturing Company. 500 N. Michigan Avenue, Chicago, Illinois. 60611.

Hangs, R., K Greer, C. Sulewski, and D. Hicks. 2002. Plant Root Simulator ™- Probes: An effective alternative for routine soil testing. *In*: Proceedings of the 2000 Soil and Crops Workshop. University of Saskatchewan, Saskatoon, Saskatchewan. pp. 120-130.

Harris, G. H. 1993. Nitrogen cycling in animal-, legume-, and fertilizer-based cropping systems. Ph.D. Thesis. Department of Crop and Soil Sciences, Michigan State University.

Harris, G. H., and O. B. Hestermann. 1990. Quantifying the nitrogen contribution from alfalfa to soil and two succeeding crops using nitrogen-15. Agronomy Journal. 82:129-134.

Hassink, J. 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant and Soil. 191:77-87.

Havlin, J. L., J. D. Beaton, S. L. Tisdale and W. L. Nelson. 1999. Soil fertility and fertilizers. 6th edition. Prentice Hall. Upper Saddle River, New Jersey.

Hensler, R. F., and O. J. Attoe. 1970. Rural sources of nitrate in water. *In:* V. L. Snoeyink (Ed.) Nitrate and water supply: source and control. Proceedings of the 12th

Sanitary Engineering Conference, Urbana, Illinois. University of Illinois. February 11-12, 1970. Urbana-Champaign, Illinois.

Janzen, H. H., J. B. Bole, V. O. Biederbeck, and A. E. Slinkard. 1990. Fate of N applied as green manure or ammonium sulphate fertilizer to soil subsequently cropped with spring wheat in three sites in Western Canada. Canadian Journal of Soil Science. 70:313-323.

Johnson, D. W., P. S. J., Verburg, and J. A. Aronone. 2005. Soil extraction, ion exchange resin, and ion exchange membrane measures of soil mineral nitrogen during incubation of a tallgrass prairie soil. Soil Science Society of America Journal. 69:260-265.

Kandler, E., and G. Eder. 1993. Effect of cattle slurry in grassland on microbial biomass and on activities of various enzymes. Biology and Fertility of Soils. 6:68-72.

Kandler, E., G. Eder, and M. Sobotik. 1994. Microbial biomass, N mineralization, and the activities of various enzymes in relations to nitrate leaching and root distribution in a slurry-amended grassland. Biology and Fertility of Soils. 18:7-12.

Keeney D. R. and D. W. Nelson. 1982. Nitrogen: Inorganic forms. *In:* Page, A. L. et al., (Ed.). Methods of Soil Analysis. Part 2, 2nd ed. Madison, Wisconsin: ASA and SSSA. pp. 643-698.

Kristensen, H. L., and K. Thorup-Kristensen. 2004. Root growth and nitrate uptake of three different catch crops in deep layer soils. Soil Science Society of America Journal. 529-537.

Klausner, S. D., and V. R. Kanneganti, D. R., Bouldin. 1994. An approach for estimating a decay series for organic nitrogen in animal manure. Agronomy Journal. 86:897-903.

Kongskilde Industries. Howard USA Inc., United States Distributors. 2439 South Main, Unit 2. Bloomington, Illinois. 61704.

Kuzyakov, Y., J. K. Freidel, and K. Stahr. 2000. Review of mechanisms and quantification of priming effects. Soil Biology and Biochemistry. 32:1485-1498.

Lang, N. S., and R. G. Stevens. 1997. Survey of central Washington fertilizer recommendations. *In:* Proceedings of the 36th Washington Potato Conference and Trade Show. February 4-6. 1997. Moses Lake, Washington.

Lang, N. S., R. G. Stevens, R. E. Thornton, W. L. Pan, and S. Victory. 1999. Irrigated potato nutrient management guide for central Washington. Washington State University Extension Bulletin #241.

Leep, R. Professor, Forage Crop Management. Michigan State University, Department of Crop and Soil Science, W. K. Kellogg Biological Station. 3700 Gull Lake Drive, Hickory Corners, Michigan 49060.

Lesczynski, D. B., and C. B. Tanner. 1976. Seasonal variation of root distribution of irrigated, field-grown Russet Burbank potatoes. American Potato Journal. 53:69-78.

Lockwood Manufacturing. 237 12th Street NW, West Fargo, North Dakota. 58078.

Long, S. P., and D. O. Hall. 1987. Nitrogen cycles in perspective. Nature. 329:584-585.

Low, A. J., and E. R. Armitage. 1970. The composition of leachate through cropped and uncropped soils in lysimeters to that of the rain. Plant Soil. 33:393-411.

Ma, B. L., L. M. Dwyer, and E. G. Gregorich. 1999. Soil nitrogen amendment effects on seasonal nitrogen mineralization and nitrogen cycling in maize production. Agronomy Journal. 91:1003-1009.

Masciandara, G., B. Ceccanti, S. Benedicto, H. C. Lee, and H. F. Cook. 2004. Enzyme activity and C and N pools in soil following application of mulches. Canadian Journal of Soil Science. 84:19-30.

McKenney, D. J., S. W. Wang, C. F. Drury, and W. I. Findlay. 1995. Denitrification, immobilization, and mineralization in nitrate limited and nonlimited residue-amended soil. Soil Science Society of America Journal. 59:118-124.

MDA (Michigan Department of Agriculture). 2005. Generally Accepted Agricultural and Management Practices. Michigan Commission of Agriculture. Lansing, Michigan.

Millard, P., D. and K. L. MacKerron. 1986. The effects of nitrogen application on growth and nitrogen distribution within the potato canopy. Annals of Applied Biology. 109:427-437.

Motavalli, P. P., K. A. Kelling, and J. C. Converse. 1989. First-year nutrient availability from injected dairy manure. Journal of Environmental Quality. 18:180-185.

Muck, R. E., and B. K. Richards. 1983. Losses of manorial nitrogen in free-stall barns. Agricultural Wastes. 10:205.

Norman, R. J., J. T. Gilmour, and B. R. Wells. 1990. Mineralization of nitrogen from nitrogen-15 labeled crop residues and utilization by rice. Soil Science Society of America Journal. 54:1351-1356.

Odhianbo, J. J. O., and A. A. Bomke. 2001. Grass and legume cover crop effects on dry matter and nitrogen accumulation. Agronomy Journal. 93:299-307.

Ojala, J. C., J. C. Stark, and G. E. Kleinkopf. 1990. Influence of irrigation and nitrogen management on potato yield and quality. American Potato Journal. 67:29-43.

Paul, J. W., and E. G. Beauchamp. 1993. Nitrogen availability for corn in soils amended with urea, cattle slurry, and solid and composted manures. Canadian Journal of Soil Science. 73:253-266.

Porter, G. A., G. B. Opena, W. B. Bradbury, J. C. McBurniw, and J. A. Sisson. 1999. Soil management and supplemental irrigation effects on potato: I. Soil properties, tuber yield, and quality. Agronomy Journal. 91:416-425.

Porter, G. A., and J. A. Sisson. 1991. Petiole nitrate content of Maine-grown Russet Burbank and Shepody potatoes in response to varying nitrogen rate. American Potato Journal. 68:493-505.

Powers, W., and H. H. Van Horn. 1998. Dietary manipulation to alter manure composition and odor. *In*: An International Conference on Odor, Water Quality, Nutrient Management and Socioeconomic Issues, Animal Production Systems and the Environment. July 19-22, 1998. Des Moines, Iowa.

Qian, P. J. and J. J. Schoenau. 1997. Recent developments in use of ion exchange membranes in agricultural and environmental research. Recent Research Developments in Soil Science. 1:43-54.

Qian, P. J., and J. J. Schornau. 1999. Use of ion exchange membranes to assess soil N supply as canola as affected by addition of liquid swine manure and urea. Canadian Journal of Soil Science. 80:213-218.

Qian, P., J. and J. J. Schoenau. 2002. Availability of nitrogen in solid manure amendments with different C:N ratios. Canadian Journal of Soil Science. 82:219-225.

Quemada, M., and M. L. Cabrera. 1995. Carbon and nitrogen mineralized from leaves and stems of four cover crops. Soil Science Society of America Journal. 59:471-477.

Rasse, D. P., A. J. M. Smucker, and O. Schebenbeger. 1999. Modifications of soil nitrogen pools in response to alfalfa root systems and shoot mulch. Agronomy Journal. 91:471-477.

Ranelles, N. N, and M. G. Wagger. 1992. Nitrogen release from crimson clover in relation to plant growth stage and composition. Agronomy Journal. 84:424-430.

Phillips, L. and C. Stopes. 1995. The impact of rotational practice on nitrate leaching losses in organic farming systems in the UK. Biological Agriculture and Horticulture. 11:123-134.

Roberts. S., W. H. Weaver, and J. P. Phelps. 1982. Effect of rate and time of fertilization on nitrogen and yield of Russet Burbank potatoes under center pivot irrigation. American Potato Journal. 59:77-86.

Robbins, C. W., and D. L. Carter. 1980. Nitrate-nitrogen leached below the root zone during and following alfalfa. Journal of Environmental Quality. 9:447-450.

Rosen C. J. 1991. Potato fertilization on irrigated soils. Minnesota Extension Service Bulletin AG-FO-3524-B.

Rourke, R. V. 1985. Soil solutions levels of nitrate nitrogen in a potato-buckwheat rotation. American Potato Journal. 62:1-8.

SAS Institute. 2004. Version 8.02. 100 SAS Campus Drive, Cary, North Carolina. 27513.

Sanchez, J. E., T. C. Willson, K. Kizilkaya, E. Parker, and R. R. Harwood. 2004. enhancing the mineralizable nitrogen pool though substrate diversity in long term cropping systems. Soil Science Society of America Journal. 65:1442-1447.

Schoenau, J. J., P. Qian, and W. Z. Huang. 1993. Ion exchange resin strips as plant root simulators. *In:* Proceedings of the 1993 Soils and Crops Workshop. University of Saskatchewan, Saskatoon, Saskatchewan. pp. 392-400.

Schoenau, J. J., P. Moolecki, P. Qian, G. Wen, and J. Charles. 2000. Nitrogen dynamics in manured Saskatchewan soils. *In*: Proceedings of the 2000 Soil and Crops Workshop. University of Saskatchewan, Saskatoon, Saskatchewan. pp. 265-273.

Shaffer, M. J., and J. A. Delgado. 2002. Essentials of a national nitrate leaching index assessment tool. Journal of Soil and Water Conservation. 57:327-335.

Shipley, P. R., J. J. Meisinger, and A. M. Decker. 1992. Conserving residual corn fertilizer nitrogen with winter cover crops. Agronomy Journal. 84:869-876.

Smith, S. J., and A. N. Sharpley. 1990. Soil nitrogen mineralization in the presence of surface and incorporated crop residues. Agronomy Journal. 82:112-116.

Snapp S. S., Borden H., and D. D. Rohrbach. 2001. Improving nitrogen efficiency: Lessons from Malawi and Michigan. Second International Nitrogen Conference The Scientific World. 1:42-48.

Snapp, S. S., D. Smucker, and M. Vitosh. 2002. Nitrogen management for Michigan potatoes. Michigan State University Extension Bulletin E-2779.

Snapp, S. S., and A. M. Fortuna. 2003. Predicting nitrogen availability in irrigated potato systems. HortTechnology. 13:598-604.

Snapp, S. S., K. O'Neil, B. Quackenbush, and E. Po. 2005. Improving productivity and soil quality in short term potato rotations- 2004 research and on-farm report. Departments of Horticulture and Crop and Soil Sciences, Michigan State University.

Stark, J. C., I. R. McCann, D. T. Westermann, B. Izadi, and T. A. Tindall. 1993. Potato response to split nitrogen timing with varying amounts of excessive irrigation. American Potato Journal 70:765-777.

State of Michigan Legislature. 1981. Michigan Right to Farm Act. Act 93 on 1981. 286.471 - 286.474.

State of Michigan Legislature. 1994. Natural Resources and Environmental Protection Act. Act 451 of 1994. 324.101 - 324.90106.

Sulewski, C. A., K. J. Greer, J. J. Schoenau, and V. S. Baron. 2002. Factors affecting nutrient supply rate measurements with PRS™ Probes. *In:* Proceedings of the 2002 Soils and Crops Workshop. University of Saskatchewan, Saskatoon, Saskatchewan. pp. 392-400.

Swift M. J., O. W. Heal, and J. M. Anderson. 1979. Decomposition in terrestrial ecosystems. Blackwell, Oxford.

Timm, H., J. C. Bishop, K. B. Tyler, M. Zahara, V. H. Schweers, and J. P. Guerard. 1983. Plant nutrient uptake and potato yield response to banded and broadcast nitrogen. American Potato Journal. 60:577-585.

Tran, T. S., and M. Giroux. 1991. Effects of N rates and harvest dates on the efficiency of ^{15}N- labeled fertilizer on early harvested potatoes (*Solanum tubersosum* L.). Canadian Journal of Soil Science. 71:519-532.

Unibest Inc., 3535 Stucky Rd., Bozeman, Montana. 59718.

van der Krift, T. A. J., P. Gioacchini, P. J. Kuikman, and F. Berendse. 2001. Effects of high and low fertility plant species on dead root decomposition and nitrogen mineralisation. Soil Biology and Biochemistry. 33:2115-2124.

Van Horn, H. H., A. C. Wilkie, W. J. Powers, and R. A. Nordstedt. 1994. Components of dairy manure management systems. Journal of Dairy Science. 77:2008-2030.

Van Kessel, J. S., J. B. Reeves III, and J. J. Mesinger. 2000. Nitrogen and carbon mineralization of potential manure components. Journal of Environmental Quality. 29:1669-1677.

Vaughan, J. D., and G. K. Evanylo. 1998. Corn response to cover crop species, spring desiccation time, and residue management. Agronomy Journal. 90:536-544.

Vigil, M. F., and D. E. Kissel. 1991. Equations for estimating the amount of nitrogen mineralized from crop residues. Soil Science Society of America Journal. 55:757-761.

Vigil, M. F., B. Eghball, M. L. Cabrera, B. G. Jakubowski, and J. G. Davis. 2002. Accounting for season nitrogen mineralization: an overview. Journal of Soil and Water Conservation. 57:464-469.

Vitosh, M. L. 1990. Best management practices for potatoes- potato fertilizer recommendations. Michigan State University Extension Bulletin E-2220.

Vitosh, M. L., and G. H. Silva. 1996. Factors affecting potato petiole nitrate tests. Communications in Soil and Plant Analysis. 27:1137-1152.

Vitosh, M. L., A. J. M. Smucker, E. A. Paul, R. R. Harwood, and J. T. Richie. Referenced March 23, 2005. Nitrogen stewardship practices to reduce nitrate leaching and sustain profitability in a irrigated potato system. Michigan State University Department of Crop and Soil Sciences and Montcalm Extension Service. Michigan State University. http://www.canr.msu.edu/fldcrp/nsp.htm.

Warncke, D. L., D. R. Christenson, L. W. Jacobs, M. L. Vitosh, and B. H. Zandstra. 1992. Fertilizer recommendation for vegetable crops in Michigan. Michigan State University Extension Bulletin E-550B.

Wagger, M. G. 1989. Time of desiccation effects on plant composition and subsequent nitrogen release from several winter annual cover crops. Agronomy Journal. 81:233-241.

Wagger, M. G., M. L. Cabrera, and N. M. Ranells. 1998. Nitrogen and carbon cycling in relation to cover crop residue quality. Journal of Soil and Water Conservation. 53:214-218.

Waterer, D. 1996. Petiole sap NO_3-N testing as a method for monitoring nitrogen nutrition of potato crops. Canadian Journal of Plant Science. 77:273-278.

Watkins, K. L., T. L. Veum, and G. F. Krause. 1987. Total nitrogen determination of various sample types: a comparison of the Hach, Kjeltec, and Kjeldahl methods. Journal of the Association of Official Analytical Chemistry. 70:410-412.

Webb, J., R. Sylvester-Bradley, and F. M. Seeney. 1997. The effects of site and season on the fate of nitrogen residues from root crops grown in sandy soils. Journal of Agricultural Science. 128:445-460.

Webb, J., R. Sylvester-Bradley, and F. M. Seeney. 2000. The fertiliser nitrogen requirement of cereals grown on sandy soils. Journal of the Science of Food and Agriculture. 80:236-274.

Westcott, M. P., V. R. Stewart, and R. E. Lund. 1991. Critical petiole nitrate levels in potato. Agronomy Journal. 83:844-850.

Western Ag Innovations, # 3-411 Downey Road, Saskatchewan, Saskatoon, Canada S7N 4L8.

Wheeler, E. J. 1946. The residual effect of crop rotations on potato yield and the presence of potato scab. Michigan State College Agriculture Experiment Station Quarterly Bulletin. 28:326-332.

Wilkerson, V. A., D. R. Mertens, and D. P. Casper. 1997. Prediction of excretion of manure and nitrogen by Holstein dairy cattle. Journal of Dairy Science. 80:3193-3204.

Appendix

Table 2.12. Temperature, precipitation and growing degree day monthly totals for March – October and season totals during 2002, 2003 and 2004 at Montcalm Research Farm.

		MARCH			APRIL			MAY			JUNE		
		Obs	Norm	Dev	Obs	Norm	Dev	Obs	Norm	Dev	Obs	Norm	Dev
2002	Temp.	-1.2	0.4	-1.6	7.6	8.1	-0.4	11.2	14.3	-3.1	20.3	19.5	0.8
	Prec.	5.36	6.43	-1.07	3.18	3.29	-0.11	10.57	7.32	3.25	8.92	8.71	0.20
	GDD 4.4	2	28	-26	130	135	-5	211	310	-99	856	821	34
	GDD 7.2	0	15	-15	93	82	12	137	228	-91	706	671	34
	GDD 10	0	28	-28	62	44	18	82	154	-72	556	522	34
	GDD MD	3	19	-16	85	85	0	125	195	-70	554	536	18
2003	Temp.	-0.2	0.4	-0.66	7.0	8.1	-1.10	12.4	14.3	-1.89	17.8	19.5	-2.4
	Prec.	3.45	6.43	-2.97	0.70	3.29	-2.59	8.74	7.32	1.42	4.70	8.71	-2.45
	GDD 4.4	34	28	6	122	135	-13	246	310	-64	721	821	-100
	GDD 7.2	14	15	-1	71	82	-10	160	228	-68	571	671	-100
	GDD 10	2	28	-26	37	44	-7	85	154	-68	421	522	-100
	GDD MD	26	19	7	89	85	4	130	195	-65	440	536	-96
2004	Temp.	2.8	0.4	2.4	8.6	8.1	0.6	13.5	14.3	-0.8	17.8	19.5	-1.7
	Prec.	9.25	6.43	2.82	4.42	8.36	-3.94	20.78	7.32	13.46	7.95	8.71	-0.76
	GDD 4.4	49	28	21	141	135	6	275	310	-36	400	456	-57
	GDD 7.2	24	15	8	85	82	4	197	228	-31	316	373	-57
	GDD 10	10	28	-18	50	44	6	124	154	-29	233	290	-57
	GDD MD	26	19	7	97	85	12	160	195	-35	246	298	-52

		JULY			AUGUST			SEPTEMBER			OCTOBER			SEASON		
		Obs	Norm	Dev	Obs	Norm	Dev	Obs	Norm	Dev	Obs	Norm	Dev	Obs	Norm	Dev
2002	Temp.	23.0	21.7	1.4	20.7	20.7	0.0	18.0	16.4	1.5	8.1	10.4	-2.4	13.5	13.9	-0.5
	Prec.	9.19	6.35	2.84	18.08	9.75	8.33	4.04	7.92	-3.89	7.11	6.96	0.15	66.5	56.7	9.72
	GDD 4.4	576	539	37	504	534	-30	405	365	40	118	197	-78	2802	2537	265
	GDD 7.2	490	453	37	418	423	-5	322	283	39	75	126	-51	2240	1979	261
	GDD 10	404	367	37	332	337	-5	239	202	37	42	72	-30	1715	1470	246
	GDD MD	393	359	34	330	335	-5	258	230	28	65	118	-53	1813	1640	174
2003	Temp.	20.8	21.7	-0.9	21.2	20.7	0.5	15.6	16.4	-0.9	8.9	10.4	-1.5	12.9	13.9	-1
	Prec.	6.60	6.35	0.25	6.60	9.75	-3.15	5.23	7.92	-2.69	4.32	6.96	-2.64	40.3	56.7	-16
	GDD 4.4	506	539	-34	519	534	-15	334	365	-31	142	197	-55	2624	2537	-421
	GDD 7.2	420	453	-34	433	423	10	251	283	-31	86	126	-41	2006	1979	-408
	GDD 10	333	367	-34	347	337	10	175	202	-27	46	72	-26	1447	1470	-378
	GDD MD	331	359	-28	344	335	9	201	230	-29	86	118	-32	1648	1640	-337
2004	Temp.	20.0	21.7	-1.7	17.9	20.7	-2.8	17.7	16.4	1.2	9.8	10.4	-0.6	13.5	13.9	-0.4
	Prec.	4.37	6.35	-1.98	5.05	9.75	-4.70	0.79	7.92	-7.14	7.59	6.96	0.63	46.5	61.8	-15
	GDD 4.4	481	539	-58	417	534	-117	397	365	31	167	197	-30	2326	2537	-381
	GDD 7.2	395	453	-58	330	423	-92	313	283	31	90	126	-36	1752	1979	-409
	GDD 10	309	367	-58	244	337	-92	230	202	28	36	72	-37	1236	1470	-421
	GDD MD	310	359	-49	261	335	-74	260	230	30	85	118	-33	1444	1640	-351

Temp = Mean temperature (°C)
Prec = Precipitation (cm)
GDD MD= Growing Degree Days calculated with 10°C and 30°c cutoffs
Obs = Totals observed
Norm = Normals calculated over 30 year period (1951-1980)
Dev = Deviation of observed from normal

Table 2.13. 2003 PRS ion exchange probe soil NO_3-N + NH_4-N 2-week uptake (μg N cm^{-2}).

	Days after planting (date)					
	76 (7-22)	90 (8-5)	104 (8-19)	118 (9-2)	132 (9-16)	146 (9-30)
Corn						
Manure	74 b	80 ab	67	47	20	15
Conv.	87 c	99 bc	74	44	12	10
Alfalfa						
Manure	68 ab	84 ab	69	49	30	30
Conv.	76 b	88 ab	61	54	23	27

LSD α=0.05

Table 2.14. 2004 PRS ion exchange probe soil NO_3-N + NH_4-N 2-week uptake (μg N cm^{-2}).

	Days after planting (date)					
	54 (6-28)	68 (7-12)	82 (7-26)	96 (8-9)	110 (8-23)	124 (9-6)
Corn						
Manure	45 ab	24 b	20	15	15 ab	12
Conv.	36 a	19 a	16	15	14 b	12
Alfalfa						
Manure	66 b	29 ab	19	21	21 a	16
Conv.	53 ab	26 ab	18	17	17 ab	12

LSD α=0.05

Table 2.15. 2003 potato petiole NO_3-N % by sampling date.

	Days after planting (date)					
	64 (7-9)	70 (7-17)	81 (7-28)	92 (8-8)	102 (8-18)	112 (8-28)
Corn						
Manure	2.12	1.55 ab	1.39 b	1.36 a	.81 b	.81 ab
Conv.	2.06	1.43 b	1.41 b	.98 b	.81 b	.53 b
Alfalfa						
Manure	2.21	1.83 a	1.95 a	1.63 a	1.28 a	1.29 a
Conv.	2.15	1.81 a	1.74 a	1.64 a	1.30 a	1.09 a
Sudex						
Manure	2.05	1.79 a	1.84 a	1.60 a	1.23 a	1.21 a
Conv.	2.11	1.82 a	1.80 a	1.51 a	1.24 a	1.16 a

LSD α=0.05

Table 2.16. 2004 potato petiole NO_3-N % by sampling date.

	Days after planting (date)					
	56 (6-30)	68 (7-12)	77 (7-21)	89 (8-2)	98 (8-13)	110 (8-23)
Corn						
Manure	1.46 bc	2.03 c	1.34 c	1.66 bc	1.32	1.20 a
Conv.	1.80 b	2.70 a	1.82 a	2.00 a	1.42	1.34 ab
Alfalfa						
Manure	2.08 a	2.09 bc	1.41 bc	1.43 c	1.36	1.34 a
Conv.	1.94 a	2.31 b	1.63 ab	1.78 b	1.41	1.37 a
Festulolium						
Manure	1.84 ab	2.12 bc	1.46 bc	1.60 bc	1.42	1.10 b
Conv.	1.62 b	2.18 bc	1.36 bc	1.66 bc	1.35	1.32 ab

LSD α=0.05

Table 2.17. 2004 fall soil % NO_3-N by sampling depth.

	Depth 0-20 cm	Std Dev	Depth 20- 50 cm	Std Dev
Corn / Potato	%		%	
Manure	1.82	0.71	2.31	0.37
Conv.	1.03	0.29	1.72	1.20
Potato / Corn				
Manure	2.26	1.20	1.47	0.80
Conv.	1.53	1.08	1.44	1.10
Sudex / Corn				
Manure	1.30	0.27	.68	0.42
Conv.	1.24	0.75	1.12	1.15
Alfalfa / Potato				
Manure	1.16	0.37	.44	0.23
Conv.	0.68	0.21	.34	0.09
Alfalfa / Alfalfa / Potato				
Manure	1.80	1.95	2.34	1.29
Conv.	1.19	0.48	1.82	1.11
Festulolium / Festulolium / Potato				
Manure	2.06	0.57	1.47	0.98
Conv.	1.76	1.09	2.21	0.98

LSD α=0.05

Chapter 3: Potato and Forage Agronomy

Abstract

Michigan dairy and potato producers posses system integration potential in the state's mid-central region. An understanding of the agronomic effects of integrated crop-livestock systems with manure transfers for potato (*Solanum tuberosum* L.) and forage production is essential in order to determine system viability. Forage crops as 1-year and 2-year stands were incorporated into potato rotations to determine effects on potato and forage yield and quality on a site historically predominated by intensive potato rotations. Two-year potato rotations with alfalfa (*Medicago sativa* L.) and sorghum-sudangrass (*Sorghum bicolor* L. *x S. bicolor* L.) and 3-year potato rotations with 2-year stands of alfalfa and festulolium (*Festuca pratensis* Huds. *x Lolium perenne*) L. were compared to the regionally common 2-year corn (*Zea mays* L.) - potato rotation. Liquid dairy manure was applied at 12,260 L ha^{-1} and evaluated against equivalent conventional mineral fertilizer applications balanced to available nitrogen. Manure was shown to be more effective at increasing potato yield than crop rotation alone. The combination of manure and crop rotation produced the most significant increases in potato yields. C_4 grass residues of corn and sudex were more effective as rotation crops than C_3 grass or legume residues of festulolium and alfalfa. Scab disease infection increased with manure application. Festulolium yields increased with manure application in 2003. The integration of forage crop rotation and manure amendment holds the potential to increase the potato yield and quality.

Introduction

Intensive cropping tends to deteriorate the physical condition of most soils, ultimately making them more difficult to manage and resulting in decreased crop yields (Saini and Grant, 1980). Rapid declines to soil organic matter and soil structure brought about by short, intensive potato production systems are common. At potato cropping frequencies of 33 to 50 percent, yields can be expected to decline at some point over the long term (Vos and van Loon, 1989). These trends are brought on primarily by reduced soil biological activity due to lower organic material inputs compared to soil under pasture or natural vegetation (Saini and Grant, 1980). The use of beneficial rotation crops and manure amendments has been shown to be key to mitigating and ultimately reversing these trends; increasing the quantity and quality potato yields.

Studies examining the effects of alfalfa, cool season grasses, and corn in potato rotations in Michigan have shown mixed results. In a 10-year study located at the Lake City Experiment Station in Lake City, Michigan, Wheeler (1946) found alfalfa rotation increased potato yields above corn rotation or continuous potatoes. Conversely, Griffin and Hesterman (1991) found alfalfa did not increase potato yields on the current experimental site in Entrican, Michigan. Elsewhere, studies in Rhode Island found 3-year redtop (*Agrostis alba* L.) - redtop - potato rotations outyielded 3-year red clover (*Trifolium pretense* L.) - red clover - potato rotations (Odland and Sheehan, 1957). Increasing the length of potato rotations utilizing legumes has been shown to influence increase potato yields. Carter and Sanderson (2001) found that a 3-year rotation of barley

(*Hordeum vulgare* L.) -red clover-potato increased potato yields above those seen in a 2-year rotation of barley-potato.

Manure amendment has been shown to increase potato yields above those possible with conventional mineral fertilizer alone. In a long-term study applying barnyard manure in addition to several rates of mineral fertilizers on 4-year potato rotations, manure amendment was found to consistently increase marketable tuber yield at any fertilizer rate (Black and Cairns, 1958; Black and White, 1973).

Liquid dairy manure effects on forages have been, as a body, inconclusive. Daliparthy et al. (1994) found no increase to alfalfa dry matter yields with manure and various mineral fertilizer applications. Similarly, Griffin et al. (2002) compared liquid dairy manure application to several mineral fertilizer regimes in cool season grasses, finding manure did not increases yields above those achieved with conventional fertilization. Cherney et al. (2002) found that four years of annual manure amendment increased cool season grass yield relative to conventional fertilization. These effects become more pronounced with time, even after annual application had ended. Greater responses to manure application have been observed in cool-season grasses compared to alfalfa (Min et al., 1999). Legume N fixation limits nutrient responses, but the high nutrient demands of perennial grass crops, particularly N (Bittman et al., 1999) makes cool-season grasses more responsive to manure application.

The existing literature indicates that the three main objectives of this research, to increase potato yield using forage crop rotation, to increase potato yield using manure amendment, and to increase rotation forage and corn yield using manure amendment are generally possible. Previous research, including studies conducted in Michigan and at this site, has shown that none of these goals have been found to be consistently reproducible, but a significant trend exists indicating a likelihood of success in any one particular attempt. The literature indicates that in the degraded potato production region of Montcalm county, forage crop rotation and liquid dairy manure amendment will have positive effects on potato production.

Objectives

The main focus of this experiment is to explore the agronomic implications of potato and livestock system integration. Manure amendment holds the potential not only the decrease reliance on mineral fertilizers, but also to increase the quantity and quality to forage and potato yields. Likewise, forage crop rotation with potato production is expected not only to increase potato yields, but also add external benefits beyond those currently found in the conventional corn – potato rotation. The following hypotheses are established as means by which to evaluate the effectiveness of these alternative inputs:

1. A minimum 3-year forage rotation is required to induce potato yield increases; 2-year forage rotation will not be sufficient to improve potato yields in an intensively managed potato-corn rotation.
2. The combination of forage rotation and liquid diary manure application will result in higher potato yield than either amendment individually.
3. Forage yield will be improved by the amendment of liquid diary manure to conventional inorganic fertilizers regimes compared to forage fertilization regimes solely supplied by inorganic fertilizers.

Materials and Methods

Experimental Design

This experiment was located at the Michigan State University Montcalm Potato Research farm, MI (43°21' N, 85°10' W) on a McBride sandy loam (coarse-loamy, mixed, frigid Alfic Fragiothods). Intensive potato rotations have dominated the farm for several decades. These rotations have degraded soil properties such as organic matter to low levels, making conditions ideal in terms of exacerbating yield improvements. These conditions are expected to make changes in soil quality more apparent, exacerbating any potential yield shifts.

Table 3.1. 2002 initial soil characteristics at Montcalm Potato Research Farm.

		0-20 cm	SE	20-50 cm	SE
pH		6.59	0.04	6.59	0.05
CEC	cmol kg^{-1}	3.53	0.13	3.28	0.15
Phosphorus	mg kg^{-1}	154	5.16	101	5.85
Potassium	mg kg^{-1}	167	3.84	109	2.14
Magnesium	mg kg^{-1}	94	2.26	86	3.26
Calcium	mg kg^{-1}	391	12.49	373	22.47
Organic matter	%	1.10	0.06	1.07	0.04

SE- Standard Error

Treatments consisted of twelve systems, six rotations with and without liquid dairy manure treatment. The experiment was arranged in a randomized complete block design replicated four times. The rotations included two corn-potato, two 2-year forage, and two 3-year forage treatments (Table 3.2). The use of two defender corn -potato rotations, staggered by year, allows for accurate comparisons to other potato rotations each year. Alfalfa and festulolium rotations were managed as production forage systems, with all biomass removed from the plot with each cutting. Sudex was managed as a green manure crop, with all biomass chopped and returned to the soil surface. Rye was planted as a winter cover crop each fall following potatoes.

Two-year alfalfa and sudex rotations represent potato driven integration systems. Sudex production offers no benefit for livestock producers as a green manure crop.
One-year alfalfa stands are a move toward integration with livestock operations. Establishment year yields in alfalfa production provide livestock operations with modest feed supplies, though these limited production yields are below levels necessary for total farm feed production. Greater yields from multiple year stands are necessary for feed production on a reasonable landbase. High establishment costs of alfalfa also preclude short-term production intervals; establishment costs from alfalfa seedings are generally only recouped after several years of production. As such, one year alfalfa and sudex production are expected to have greater benefits to potato production than dairy systems. Three-year cropping systems of alfalfa and festulolium better suit the needs of integrated dairy farms than shorter one-year forage production. A second production year beyond establishment allows for production yields necessary to sustain dairy forage requirements. These systems place a greater emphasis on dairy production than shorter, 2-year potato driven systems.

Table 3.2. Crop rotation for 2002, 2003 and 2004 at Montcalm Potato Research Farm.

Rotation	2002	2003	2004
1	Corn	Potato	Corn
2	Potato	Corn	Potato
3	Alfalfa	Potato	Alfalfa
4	Sudex	Potato	Sudex
5	Festulolium	Festulolium	Potato
6	Alfalfa	Alfalfa	Potato

Table 3.3. Common, scientific, and cultivar names of species used in 2002, 2003 and 2004 at Montcalm Potato Research Farm.

Common name	Latin binomial	Cultivar
Potato	*Solanum tuberosum* L.	Snowden
Corn	*Zea mays* L.	Pioneer 36G12
Alfalfa	*Medicago sativa* L.	Pioneer 53Q60
Festulolium	*Festuca pratensis* Huds. x *Lolium perenne* L.	Duo
Sorghum/sudangrass	*Sorghum bicolor* L. x *S. bicolor* L.	Honeypot

Plots of 3.7 measuring 15.2 meters were oriented such that rows ran east to west with a gradual decreasing in elevation to the north. As a result of this slight hill, the north end of the range suffered from slower water drainage and subsequent flooding. The wet spring of 2004 resulted in a flooding event that prevented emergence of crops on the four northern-most plots and the subsequent abandonment of these plots.

Manure Amendment

Liquid dairy manure from a nearby 2,500 head operation with liquid pit manure storage was applied at 12,260 L ha^{-1}, a regionally common application rate. A pull-type liquid-manure applicator was used to inject manure to depth of 20 cm in the spring prior to planting in 2002. The applicator utilized a hydraulic cutter for even distribution of manure between four injection shanks. Sand bedding mixed with the manure resulted in a liquid density higher than that of what the transfer pump on the applicator could handle, necessitating the addition of water to increase the fluidity of the manure. Application rates were adjusted so that 12,260 L ha^{-1} of initial product was applied. A higher capacity, hydraulically powered pump was installed on the injector for amendment in 2003. With the presence of perennial forage crops in 2003 and in 2004, manure was broadcast on the soil surface for all treatments. The distribution pattern in 2004 was refined so as to provide for more even surface coverage than that achieved in 2003. One day following manure broadcasting, primary tillage using a rototiller (Great Plains Mfg. Inc., Salina, KS) was performed on both manure and non-manure treatments. This tillage event served to incorporate surface applied manure within GAAMP regulations.

Table 3.4. Liquid dairy manure concentration characteristics in 2002, 2003 and 2004 at Montcalm Potato Research Farm.

		2002	2003	2004
Moisture	%	88.5	71.9	79.6
Solids	%	11.5	28.1	20.4
pH		7.06	7.28	7.10
Nitrogen, total	mg kg^{-1}	3256	4288	4586
Nitrogen, ammonium	mg kg^{-1}	1602	2412	2924
Nitrogen, organic	mg kg^{-1}	1654	1916	1664
Phosphorus	mg kg^{-1}	438	676	1932
Potassium	mg kg^{-1}	1970	2564	3822
OM by LOI	g kg^{-1}	332	810	589
Magnesium	mg kg^{-1}	1120	1760	1540
Calcium	mg kg^{-1}	3160	7440	410

reported on a dry weight basis
OM- organic matter
LOI- loss on ignition

Table 3.5. Total nitrogen applications for manure and conventional fertilizer treatments in 2002, 2003, and 2004 at Montcalm Potato Research Farm.

2002	Manure N Total kg ha^{-1}	Manure N Available Kg ha^{-1}	Fertilizer N kg ha^{-1}	Total N Available kg ha^{-1}
Potato				
Manure	204	154	91	245
Conv.	-	-	224	224
Corn				
Manure	204	154	145	299
Conv.	-	-	207	207
Alfalfa				
Manure	204	154	-	154
Conv.	-	-	0	0
Fest.				
Manure	204	154	114	268
Conv.	-	-	171	171
Sudex				
Manure	204	154	84	238
Conv.	-	-	168	168
2003				
Potato				
Manure	319	219	91	310
Conv.	-	-	224	224
Corn				
Manure	319	219	145	364
Conv.	-	-	207	207
Alfalfa				
Manure	319	219	-	219
Conv.	-	-	0	0
Fest.				
Manure	319	219	114	333
Conv.	-	-	228	228
2004				
Potato				
Manure	326	238	91	329
Conv.	-	-	224	224
Corn				
Manure	326	238	145	383
Conv.	-	-	207	207
Alfalfa				
Manure	326	238	-	238
Conv.	-	-	0	0
Sudex				
Manure	326	238	84	322
Conv.	-	-	168	168

Potato Production and Analysis

Potatoes were planted using a two-row potato planter (Lockwood Mfg., West Fargo, ND.) at a seed spacing of 22.5 cm in row and 91 cm between rows. Potatoes were hilled approximately five days prior to emergence. Weed control was achieved through standard chemical herbicide application and manual hoeing as needed. Fertilizer was applied in liquid form at planting and as broadcast granular for subsequent fertilizations. Wet conditions following the 2004 planting resulted in sporadic emergence and required replanting in spots in mid-May.

Potatoes were harvested using the center two of four rows for yield. In 2002 and 2003, a custom built self-propelled mechanical harvester was used to lift and bag the entire 15.2 m length of the two yield rows. Plant maturity variability resulting from late replanting necessitated by poor emergence required a more selective harvest method in 2004. A John Deere (Deere & Company, Moline, IL) one-row lifter was used to lay the two center yield rows on the ground. Two 1.5 m lengths were then collected for yield. Following harvest, regardless of harvest method, samples were graded and weighed for total yield, US#1, A, B, pickout, and oversize tubers. Specific gravity was measured from US#1 tubers from each plot. Internal defects were determined for hollow heart, internal brown spot, vascular disorder, black spot, and heat neurosis through random sampling of ten tubers. Scab was accessed through a visual rating on 0 (no scab) to 5 (high scab).

Forage Production and Analysis

Forages were established with a John Deere (Deere & Company, Moline, IL) 2.4m drill. Alfalfa was sown at 18.0 kg ha^{-1}, with festulolium and sudex drilled at 30.0 kg ha^{-1}. Plots were tilled with a rototiller (Great Plains, Mfg. Inc., Salina, KS) at manure incorporation and finished with a field cultivator (Kongskilde Industries, Bloomington, IL) prior to planting. A combination of adverse weather conditions, including eroding rains and soil crusting, along with possible herbicide carry-over, resulted in unacceptable alfalfa and festulolium initial stands in 2002. Atrazine application the previous year may have resulted in a carry-over effect, reducing germination of alfalfa. A subsequent reseeding of these crops also had poor stands, necessitating a third planting in early July. The late final planting date resulted in a shortened growing season for alfalfa and festulolium; only two cuttings were taken from each crop. Alfalfa and festulolium in the second year production during 2003 produced four and five cuttings, respectably. Alfalfa was drilled in 2004 with Brillion Pulverizer (Brillion Farm Equipment, Brillion, WI) equipped with rolling press wheels pulled behind the planter for improved soil to seed contact so as to avoid the emergence difficulties of 2002; two cuttings were harvested. Sudex in 2002 produced three cuttings and two cuttings in 2004.

A Carter flail harvester (Carter Manufacturing Co. Inc., Brookston, IN) was used to harvest a 0.91 by 6.1 m randomly selected representative subplot area at a cutting height of 8.9 cm from the soil surface. Care was taken to avoid sampling areas of poor emergence or higher than average weed pressure. Moisture content of harvested alfalfa was determined by measuring dry weight from a 500 g wet weight sample of the harvested alfalfa dried at 60 degrees C for 72 hours. This sample was retained for determination of forage quality. The dried sample was ground to pass through a 1mm screen using a Christy Mill (Christy-Turner Group, Ipswich, Suffolk, UK) with an attached, custom fabricated, cyclone separator.

Total nitrogen was determined by the Hach modified Kjeldahl procedure (Watkins et al., 1987), and crude protein was estimated by multiplying total N by 6.25. The Goering and Van Soest (1970) method was used for neutral detergent fiber (NDF) and acid detergent fiber (ADF) determination with the addition of 1 ml of alpha-amylase to the neutral detergent solution for the breakdown of starch. Dry matter (DM) content was determined by drying a 0.5 g sample in a ceramic crucible at 100°C for 12 hrs. The samples were then ignited in a muffle furnace at 500 degree C for 6 hrs to determine ash content.

Forage digestion protocol is directly proportional to particle characteristics. The size, shape, and integrity of forage particle effects the degree to which digestion will occur. To this end, the method by which forages are ground has bearing on overall digestion. The protocol for the Hach modified Kjeldahl method (Watkins et al., 1987) for crude protein and the Goering and Van Soest (1970) procedure for NDF and ADF were created using a hammer mill to reduce particle to 2 mm, followed by a deterioration mill reducing particle size to 1 mm. Samples for this experiment were ground using a deterioration mill to reduce particle size to 1 mm in a single milling event. The absence of a cutting mill in the grinding operation is likely to reduce overall particle length, and therefore size. A decrease in particle size will increase surface area of a given volume, increasing digestion. Forage digestions performed on one-pass deterioration ground sample may have digestions upwardly skewed; consideration to this fact should be made when comparing other experimental results.

Corn Production and Analysis

Corn was planted with a custom plot planter (ALMACO, Nevada, IA) to a population of 74,300 seed ha^{-1}. Seed spacing was 28 cm in row and 76 cm between rows. At emergence, plots were thinned if stands exceeded this population and spot replanted if needed. Weed removal was performed through chemical herbicide and mechanical cultivation for moderate weed pressure, and hand hoeing for light weed pressure. Corn yields and test weights were determined through mechanical harvesting with a Massey Ferguson 8XP combine (AGCO Corporation, Duluth, GA). The center two rows of the four row plot were measured for yield. Plots were trimmed to 12.2 m to minimize edge effects. Moisture content and field weight were measured by a GrainGage™, a HarvestMaster System™ (Juniper Systems, Inc., Logan, UT), mounted on the plot combine. Grain yield was reported at standard 15.5 percent moisture. Grain test weight was reported at harvest moisture.

Crop Fertility

Crop fertilization was developed from Michigan State University Extension soil fertility publications (Vitosh, 1990; Christenson et al., 1992; Warncke et al., 1992; Snapp et al., 2002) and tailored to meet site conditions for potato (Dick Crawford, personal communication), corn (Keith Dysinger, personal communication), and forages (Rich Leep, personal communication) based upon MSU soil test lab recommendations.

Manure available nutrient contributions were calculated by plot for nitrogen, phosphorus and potassium. Any deviations in available manure nutrients from conventionally management treatments were corrected at the time of second fertilizer applications, with manure plots receiving higher or lower levels of fertilizer than that applied to conventional treatments. For potato, corn, sudex and festulolium, nitrogen was calculated as the primary balancing nutrient; in alfalfa, phosphorus was used to balance nutrients. Potatoes received a starter fertilizer at planting and subsequent applications at hilling and two and four weeks following emergence. Alfalfa, festulolium, and sudex received broadcast fertilizer applied at emergence and following the first cutting in coordination with anticipated rainfall events. In addition, festulolium was fertilized following cuttings 1 and 3 in 2002. Fertilizer was applied to corn at planting and at the V5 stage.

Table 3.6. Mineral fertilizer application in manure and conventional fertilizer treatments in 2002, 2003 and 2004 at Montcalm Potato Research Farm.

	Fertilizer			Manure		
	N	P	K	N	P	K
2002	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Potato	316	17	-	204	-	-
Corn	139	17	21	140	-	-
Alfalfa	-	89	508	-	57	326
Festulolium	171	-	-	114	-	-
Sudex	168	-	-	84	-	-
2003						
Potato	316	17	-	204	-	-
Corn	204	17	21	145	-	-
Alfalfa	-	89	508	-	38	217
Festulolium	228	-	-	114	-	-
2004						
Potato	316	17	-	204	-	-
Corn	204	17	21	145	-	-
Alfalfa	-	89	508	-	41	234
Sudex	168	-	-	84	-	-

Table 3.7. Fertilizer formulations utilized in experiment at Montcalm Potato Research Farm.

Crop	Timing	Formulation
Potato	starter	19-17-0
	sidedress	49-0-0
Corn	starter	19-19-19
	sidedress	28-0-0
Alfalfa		0-13-39
Festulolium		34-0-0
Sudex		34-0-0

Table 3.8. Phosphorus and potassium inputs from manure and fertilizer in manure and conventional fertilizer treatments in 2002, 2003 and 2004 at Montcalm Potato Research Farm.

2002	Manure P kg ha^{-1}	Fertilizer P kg ha^{-1}	Total P kg ha^{-1}	Manure K kg ha^{-1}	Fertilizer K kg ha^{-1}	Total K kg ha^{-1}
Alfalfa						
Manure	32	57	89	144	326	470
Conv.	-	89	89	-	508	508
Festulolium						
Manure	32	0	32	144	0	144
Conv.	-	0	0	-	0	0
Sudex						
Manure	32	0	32	144	0	144
Conv.	-	0	0	-	0	0
2003						
Alfalfa						
Manure	51	38	89	190	217	407
Conv.	-	89	89	-	508	508
Festulolium						
Manure	51	0	51	190	0	190
Conv.	-	0	0	-	0	0
2004						
Alfalfa						
Manure	48	41	89	271	234	505
Conv.	-	89	89	-	508	508
Sudex						
Manure	48	0	48	271	0	271
Conv.	-	0	0	-	0	0

Production Inputs

Pesticides were applied as needed throughout the growing season. Nematicide was applied over the entire range two years preceding the study's onset and again in the spring of 2003 to plots in which potatoes would be planted that season using a custom built injection system. Fungicides were applied during the season on weekly intervals beginning at a plant height of 15 to 20 cm and ended approximately two weeks prior to vinekill. A tractor-drawn sprayer was used for fungicide applications. Insecticides and herbicides were applied using a Hudson CO_2 backpack sprayer (H. D. Hudson Mfg. Co., Chicago, IL.).

Irrigation was provided as needed throughout the season, typically on a 7 to 9 day interval. Water was applied in 2002 via a solid set pipe system, using two lines with sprinklers set at 12 m intervals. For the 2003 and 2004 seasons, an overhead traveling system was utilized.

Colorado Potato Beetle Control

This trial was located adjacent to ongoing Colorado Potato Beetle (CPB) research, conducted by the Michigan State University Entomology Department. In order to determine specific potato plant's biological pest control, potato plants in the trial receive no chemical or cultural pest control. The majority of potato plants in this trial are quickly decimated, forcing beetles into the surround area. In 2002, potato defoliation was complete in the adjoining CPB trial by early July. Despite chemical control with insecticides, near complete defoliation of this study occurred by mid-July. The subsequent potato yield was severally compromised. In early 2003, a 45 cm deep trench was dug between the Entomology study and the Potato Forage Integration study. The trench's sides were steeped and line with black plastic. The CPB inability to fly forces the insect to move across the ground. When a trench of this sort is encountered, the insects fall in and can't climb out. The combination of frequent irrigation flooding the trench and the black plastic tendency to become very hot in sunlight is effective in killing most of the beetles trapped in the trench. The use of a trench to impede beetle movement was used in 2004 as well.

Statistical Analysis

Analysis of variance (ANOVA) was performed on potato and forage yields and quality, with Proc GLM (SAS Institute, 2004) using the Kenward-Roger method for determining degrees of freedom. When significant effects of treatment occurred, means were compared using Fischer's Least Significant Difference. Proc Reg of SAS was used for regression analysis. Unless otherwise stated, differences were considered significant at an alpha level of 0.05. Scab data, complied though a visual rating system, was assessed for normality and found to be normal.

Environmental Conditions

Cool temperature predominated the two years during which nitrogen dynamics were examined in this experiment. 2003 was 1.0° C below 30-year temperature norms and 2004 was 0.4° C below normal. The months of March, April, and May in 2003 were -0.66°, -1.10°, and -1.89° C of normal temperatures, while those same months in 2004 were 2.4°, 0.6°, and -0.8° of normal. Rainfall in both 2003 and 2004 was below 30-year averages. While this experiment is supplemented by artificial irrigation, the system is operated only during periods of greatest tuber water demand in June, July and August. Early season soil moisture was totally dependent on upon natural precipitation. Early season rainfall in 2003 was -2.97, -2.59, and 1.42 cm of normal for the months of March, April, and May. Rainfall was 2.82, -3.94, 13.46 cm of normal for this same period in 2004. While both growing seasons may be summarized overall cool and dry, the early season of 2003 was cool and dry compared to warm and wet in 2004.

Results and Discussion

Corn Production

Corn grain yields were significantly higher for non-manure treatments in 2002, along with a trend toward higher test weight (Table 3.9). There were no differences between manure treatments for grain yields in 2003 or 2004, or test weights in 2003. However, test weight was significantly higher for the manure treatment in 2004.

Table 3.9. Corn yield and test weight- 2002, 2003, and 2004.

	Yield	Test Wt.
	Mg ha^{-1}	kg ha^{-1}
2002		
Manure	9.66 [b]	69.60 [a]
Conv.	10.82 [a]	71.29 [a]
LSD α=0.05	0.61	3.88
2003		
Manure	11.56 [a]	62.35 [a]
Conv.	11.43 [a]	62.19 [a]
LSD α=0.05	2.16	1.14
2004		
Manure	12.68 [a]	68.71 [a]
Conv.	12.42 [a]	67.71 [b]
LSD α=0.05	2.39	0.71

While manure application had a detrimental effect on corn yields and test weights in 2002, yields in manure amendment treatments were comparable to those receiving conventional fertilizer by 2004. This trend has been seen by others using liquid dairy manure on sandy soils. Jokela (1992) found that manure application had little effect on corn yields after one year of application, but manure amendment increasingly boosted corn yields in the second and third year of the study. Annual manure application effects becoming more discernable after several years of amendment might be expected in a degraded soil system, such as those often found in the Montcalm region.

Forage Production

Alfalfa

Alfalfa dry matter production and forage quality was not influenced by manure application in any of the three years. A lack of dry matter yield response from liquid dairy manure applications was previously demonstrated by Daliparthy et al. (1994) in Massachusetts. Neither low (112 kg N ha^{-1}) nor high (336 kg N ha^{-1}) rates of surface applied manure to existing alfalfa stands in June influenced yield. A similar lack of response to low and high mineral N fertilizer applications at equal rates in control treatments was observed. Other researchers have found contradictory evidence to these results. In studies in Wisconsin and Minnesota, Peters (1991) and Schmitt et al. (1993) both observed alfalfa dry matter responses to pre-plant liquid dairy manure amendment. These manure responses were greater than correspondently balanced mineral fertilizer applications. However, Schmitt et al. (1993) noted a lack of response to manure and fertilizer in one of the three study locations, citing high initial P and K soil test levels. Soil P and K concentrations were similarly high at this studies inception (Table 3.1). These results suggest that dry matter response may be regulated by limiting nutrient levels rather than possible soil microbial stimulation or soil conditions (Kelling and Schmitt, 2003).

Table 3.10. Alfalfa dry matter yield- 2002, 2003, and 2004.

2002	Yield Mg ha^{-1}		Yield Mg ha^{-1}
Total		Cut 1	
Manure	2.28 a	*Manure*	2.00 a
Conv.	2.53 a	*Conv.*	2.19 a
LSD α=0.05	1.16	*LSD α=0.05*	1.10
		Cut 2	
		Manure	.35 a
		Conv.	.28 a
		LSD α=0.05	1.99
2003			
Total		Cut 1	
Manure	9.59 a	*Manure*	4.59 a
Conv.	10.38 a	*Conv.*	5.19 a
LSD α=0.05	2.22	*LSD α=0.05*	1.37
		Cut 2	
		Manure	1.87 a
		Conv.	1.77 a
		LSD α=0.05	0.26
		Cut 3	
		Manure	1.66 a
		Conv.	1.65 a
		LSD α=0.05	0.32
		Cut 4	
		Manure	1.46 a
		Conv.	1.77 a
		LSD α=0.05	1.09
2004			
Total		Cut 1	
Manure	4.20 a	*Manure*	2.45 a
Conv.	4.26 a	*Conv.*	2.45 a
LSD α=0.05	1.92	*LSD α=0.05*	0.69
		Cut 2	
		Manure	1.76 a
		Conv.	1.81 a
		LSD α=0.05	1.28

Table 3.11. Alfalfa crude protein, acid detergent fiber and neutral detergent fiber- 2002, 2003, and 2004.

2002	CP g kg^{-1}	ADF g kg^{-1}	NDF g kg^{-1}
Cut 1			
Manure	159.28 a	272.48 a	406.40 a
Conv.	170.05 a	307.38 a	466.78 a
LSD α=0.05	21.5	47.99	75.20
Cut 2			
Manure	256.53 a	265.31 a	300.24 a
Conv.	252.81 a	267.80 a	365.11 a
LSD α=0.05	26.60	23.79	61.21
2003			
Cut 1			
Manure	218.13 a	304.58 a	412.03 a
Conv.	208.65 a	307.75 a	405.98 a
LSD α=0.05	33.67	57.50	66.89
Cut 2			
Manure	240.08 a	272.58 a	466.40 a
Conv.	249.30 a	257.25 a	398.65 a
LSD α=0.05	42.80	48.01	140.54
Cut 3			
Manure	231.03 a	265.30 a	434.38 a
Conv.	219.68 a	268.48 a	446.03 a
LSD α=0.05	25.84	27.73	39.26
Cut 4			
Manure	215.03 a	321.80 a	550.35 a
Conv.	192.83 a	317.75 a	533.65 a
LSD α=0.05	71.96	63.67	135.99
2004			
Cut 1			
Manure	201.98 a	258.48 a	439.55 a
Conv.	189.48 a	294.78 a	425.33 a
LSD α=0.05	68.77	58.25	45.73
Cut 2			
Manure	208.85 a	244.40 a	410.20 a
Conv.	221.73 a	223.70 a	367.35 a
LSD α=0.05	29.16	27.63	45.54

Dry matter yields were consistent between manure and non-manure treatments through the three years of the study, with one exception. Manure treatment yields, while not significant, were reduced in the first cutting of 2003. The effect may be attributed to delayed regrowth and smoothing following broadcast manure operations early in the 2003 season. Vehicular traffic and compaction problems associated with manure application have previously been cited as additional causes of yield reduction in manure amended plot research (Schmitt et al, 1993).

Festulolium

Festulolium yields were not affected by manure application in 2002. While conventional fertilizer treatments seemed to demonstrate a trend toward increased yields, no cutting event was found to significantly differed by fertility source. Manure treatment in 2003 increased overall dry matter production. Cuts one and three produced higher manure treatment yields and, while not significant, cut two showed a trend toward higher yields. The lack of yield response to manure application in 2002 may be attributed to a lack of available N. Nitrogen supplied by manure may not have mineralized during the growing season in sufficient quantities to match that supplied by conventional fertilizers, thereby reducing yields for the manure treatment. However, overall dry matter production in 2003 seemed to benefit from the previous season's manure application. Kaffka et al. (1996) noted a similar effect in multiple years of cool season grass production under manure application. Observed dry matter yields in the first year were similar, irrespective of manure or fertilizer N source. In year two, yields were higher in manure

Table 3.12. Festulolium dry matter yield- 2002 and 2003.

2002	Yield Mg ha^{-1}		Yield Mg ha^{-1}
Total		Cut 1	
Manure	2.86 a	*Manure*	1.94 a
Conv.	3.71 a	*Conv.*	2.33 a
LSD α=0.05	0.95	*LSD α=0.05*	1.16
		Cut 2	
		Manure	.92 a
		Conv.	1.38 a
		LSD α=0.05	0.63
2003			
Total		Cut 1	
Manure	12.59 a	*Manure*	3.68 a
Conv.	7.73 b	*Conv.*	.98 b
LSD α=0.05	2.71	*LSD α=0.05*	1.49
		Cut 2	
		Manure	1.78 a
		Conv.	1.11 a
		LSD α=0.05	1.01
		Cut 3	
		Manure	2.44 a
		Conv.	1.35 b
		LSD α=0.05	0.84
		Cut 4	
		Manure	1.66 a
		Conv.	1.66 a
		LSD α=0.05	1.71
		Cut 5	
		Manure	3.03 a
		Conv.	2.63 a
		LSD α=0.05	1.09

Table 3.13. Festulolium crude protein, acid detergent fiber, and neutral detergent fiber-2002 and 2003.

2002	CP g kg $^{-1}$	ADF g kg $^{-1}$	NDF g kg $^{-1}$
Cut 1			
Manure	156.58 b	287.85 a	559.38 a
Conv.	206.58 a	279.05 a	553.63 a
LSD α=0.05	30.10	48.95	79.36
Cut 2			
Manure	196.50 a	256.80 a	503.50 a
Conv.	197.40 a	292.38 a	556.30 a
LSD α=0.05	79.39	100.53	198.66
2003			
Cut 1			
Manure	121.43 a	251.65 a	479.40 a
Conv.	105.78 a	201.20 b	420.53 b
LSD α=0.05	4907	36.93	51.08
Cut 2			
Manure	198.75 a	293.15 a	549.85 b
Conv.	159.05 b	317.15 a	591.28 a
LSD α=0.05	29.49	51.00	25.83
Cut 3			
Manure	204.73 a	261.73 a	533.73 a
Conv.	194.25 a	253.45 a	454.88 a
LSD α=0.05	79.97	58.79	200.99
Cut 4			
Manure	190.08 a	290.55 a	529.45 a
Conv.	214.55 a	282.15 a	542.83 a
LSD α=0.05	56.94	19.24	19.53
Cut 5			
Manure	154.75 a	286.13 a	589.78 a
Conv.	148.93 a	307.28 a	608.15 a
LSD α=0.05	28.10	51.25	58.62

treatments, largely attributed to N contributions from the previous year. In a more long-term system, Cherney et al. (2002) found that annual dairy manure amendments improved cool season grass yields after two years of application compared to equivalent mineral fertilization rates. This trend continued for three years after manure amendment had ceased, evidently from the residual impacts of manure application.

Festulolium forage quality was only marginally affected by manure amendment. Four of seven harvest events between 2002 and 2003 experienced treatment effects for either CP, ADF, or NDF. Conventional mineral fertilizer resulted in higher CP levels for the first cutting of 2002. Manure increased CP in the second cutting of 2003. Manure also increased ADF and NDF levels in the first cutting of 2003. Manure application decreased NDF for the second cutting of 2003. VanWieringen et al. (2005) observed that perennial ryegrass and orchardgrass CP levels increased with liquid dairy manure application, with CP levels increasing as the season progressed. These effects were attributed to increasing N availability from manure mineralization. Min et al. (2002) also studied the effects of various rates liquid diary manure on orchardgrass and reed canarygrass. While manure application had no effect on ADF or NDF, CP was increased with manure. Increased festulolium CP compared to alfalfa following manure amendment is expected due to the alfalfa's ability to fix its own N. Cool season grasses are more responsive to manure application as they are wholly dependent upon external inputs for nitrogen supplies.

Adjustments in nutrient fertility between manure and non-manure resulted in greater P and K application in manure treatments (Table 3.8). While most fertilizer recommendations for hay crops are limited to N, dry matter yield responses have been observed from other nutrient applications, including K. Keady and O'Kiely (1998) demonstrated that applications of 120, 180, and 240 kg K ha^{-1} increased yields over that of 0 and 60 kg ha^{-1} rates. Fertilizer applications were not found to influence *in vitro* dry matter digestibility, crude protein, or modified acid detergent fiber.

Sudex

Sudex yields did not differ by manure amendment in 2002 or 2004. The depressed yields seen in 2002 were a result of late planting date. Sudex yield has been shown to be a function of nutrient amendment. Kilcer et al. (2002) in New York were able to demonstrate increased dry matter yields when N applications were split during the season. Fertilization with 168 and 224 kg N ha^{-1} split into two applications, one planting and the second following the first cutting significantly increased yields over single applications at planting. While no significant differences were observed between manure and non-manure treatments in 2002 or 2004, a trend toward increased dry matter yields with manure application was observed. Greater N availability over an extended period though N mineralization would be expected in these treatments. The clear advantage of lower N rates over a greater period of time demonstrated by Kilcer et al. (2002) offers one explanation for this observation.

Sudex fertilization for manure and non-manure treatments was, like festulolium, balanced on available N resulting in higher nutrient applications of P and K in manure treatments (Table 3.8). Previous research indicates that these increased fertility levels have little impact upon sudex dry matter production. Ketterings et al., (2005) studied brown mid-rib sudex across three K fertilization levels, 0, 92, and 184 kg K ha^{-1}, but did not observed a yield response.

Table 3.14. Sudex dry matter yield- 2002 and 2004.

2002	Yield Mg ha^{-1}		Yield Mg ha^{-1}
Total		Cut 1	
Manure	8.18 a	*Manure*	3.73 a
Conv.	7.37 a	*Conv.*	3.89 a
LSD α=0.05	1.94	*LSD α=0.05*	0.58
		Cut 2	
		Manure	2.48 a
		Conv.	3.17 a
		LSD α=0.05	1.39
		Cut 2	
		Manure	1.16 a
		Conv.	1.12 a
		LSD α=0.05	0.37
2004			
Total		Cut 1	
Manure	17.28 a	*Manure*	8.42 a
Conv.	14.48 a	*Conv.*	6.66 a
LSD α=0.05	7.09	*LSD α=0.05*	2.15
		Cut 2	
		Manure	8.87 a
		Conv.	7.82 a
		LSD α=0.05	5.93

Potato Production

Potato Yield Following Corn

The effects of year and manure treatment were not interacting for US #1 or total tuber yields in potato–corn rotations, so comparisons were made across years. Manure treatment increased both US #1 and total tuber yields over three years. However, these changes were not incremental, but rather occurred largely in 2004. Manure amendment had no effect on potato yield in 2002, and while a trend existed for higher US #1 and total yields with manure amendment in 2003, no significant yield effects were seen until 2004.

Table 3.15. Potato total and US#1 fresh weight tuber yield following corn rotation- 2002, 2003 and 2004.

	Total	US #1
2002	Mg ha^{-1}	Mg ha^{-1}
Manure.	15.31 c	11.12 c
Conv.	15.35 c	11.03 c
LSD α=0.05	8.72	9.90
2003		
Manure.	30.28 b	28.24 b
Conv.	24.51 b	22.36 b
LSD α=0.05	10.08	10.38
2004		
Manure.	39.57 a	36.09 a
Conv.	31.23 b	26.16 b
LSD α=0.05	8.27	9.18

Comparisons made between years

Potato Yield Following Forage

Manure treatment had no effect on potato yield following 1-year forages stands of alfalfa or sudex in 2003 or 2-year forage stands of alfalfa or festulolium in 2004.

Table 3.16. Potato total and US#1 fresh weight tuber yield following 1-year forage- 2003.

	Total	US #1
Alfalfa	Mg ha^{-1}	Mg ha^{-1}
Manure	30.87 a	28.82 a
Conv.	29.04 a	27.14 a
LSD α=0.05	5.12	5.39
Sudex		
Manure	33.24 a	31.41 a
Conv.	29.62 a	27.70 a
LSD α=0.05	11.28	11.80

Comparisons limited to crop

Table 3.17. Potato total and US#1 fresh weight tuber yield following 2-year forage- 2004.

	Total	US #1
Alfalfa	Mg ha^{-1}	Mg ha^{-1}
Manure	37.42 a	33.09 a
Conv.	35.20 a	31.01 a
LSD α=0.05	16.67	15.49
Festulolium		
Manure	36.16 a	32.83 a
Conv.	34.31 a	30.53 a
LSD α=0.05	4.77	6.14

Comparisons limited to crop

Defender System Improvement

The ultimate assessment of a cropping system rests in the potential improvement of the new system above that of the previous standard. In Montcalm county, a 2-year potato–corn rotation has become one of several prevalent cropping systems. Corn is a high biomass crop with demanding relatively low input and management requirements. For cropping system shifts to occur, new systems must demonstrate an improvement upon the previous system. The effectiveness of forage rotation crops and manure inputs to increase yields above those of the current corn-potato rotation with no manure inputs, or 'defender system' is measured through yield and disease comparisons. The percent yield increase above the defender system is determined by setting the potato-corn rotation with no manure inputs as the baseline level. This system is replicated twice in the experiment, staggered by year for potato comparisons each year. Statistical analysis determines significance of each system compared to the defender system. As each system is compared to that year's defender potato production, comparisons between years are not possible.

The effects of annual manure amendment were more dramatic in potato crop following corn. There was no significant difference in marketable tuber yield due to manure application in the first year of the study. Significant increases in US #1 yields were observed in 2004 from manure application with a 23.6% tuber yield that was significant at the P=0.1 level. However, the combined three years of manure application increased yields by 38.8 and 26.7% of US #1 and total tuber yields, respectively, that were significant at the P=0.05 level.

Table 3.18. Percent increase of alternative system total and US#1 fresh weight tuber yield above defender potato-corn rotation with no manure amendment- 2002, 2003, and 2004.

Year	Preceding Crop	Total	US #1
		%	%
2002	Corn		
	Manure	-0.3	0.8
2003	Corn		
	Manure	26.3	23.6 +
2004	Corn		
	Manure	38.8 *	26.7 *
2003	Sudex 1-yr		
	Manure	35.6 *	40.5 *
	Conv.	20.8	23.9
2003	Alfalfa 1-yr		
	Manure	26.0 +	28.9 +
	Conv.	18.5	21.4
2004	Alfalfa 2-yr		
	Manure	19.8 +	26.5 *
	Conv.	12.7	18.5
2004	Festulolium 2-yr		
	Manure	15.8	25.5 +
	Conv.	9.9	16.7

+ significant at P=0.10
* significant at P=0.05
Defender system = potato after corn with no manure amendments. Rotations compared to each season's defenders system, no comparisons possible between years

A 2-year crop rotation of potatoes and sudex was shown to produce the greatest yield increases above the defender system. Sudex with manure amendment produced 40.5 and 35.6% significant increases to US #1 and total tuber yields, respectively, in the second year of rotation. Yields of non-amendment treatments, while not a statistically significant, still improved yields above the defender system and were 20.8 and 23.9% higher for total and US #1 tubers compared to the defender system. These yield increases were the highest occurring from non-manure amendment systems. Alfalfa and festulolium in rotation with potatoes significantly increased tuber yields above that of the defender system, though not to the extent of sudex. One-year alfalfa increased yields by

26 and 28.9% for total and US #1 potatoes, both significant at the P=0.1 level. Two-year alfalfa was the most effective non-sudex forage crop at increasing yields with a 19.8% increase for total tubers, significant at P=0.1, while US #1 yields increased by 26.5%, significant at P=0.05. Two-years of festulolium resulted in the least effective rotation crop, with an insignificant 15.8% increase for total tubers and a 25.5% increase for US #1, significant at P=0.1.

Manure effects

Manure application in this study resulted in significant potato yield increases. No system produced a significant yield response above the standard defender system without the application of manure. This effect is in large part attributed to improved nitrogen availability throughout the season. Both manure and non-manure treatments received equal levels of available N. However, the manner in which N was supplied varied by treatment. Non-manured treatments received inorganic N as a liquid starter fertilizer and in two granular applications post-emergence. Manure treatments also received two granular inorganic fertilizer post-emergence applications, though no liquid starter fertilizer at planting. Rather, manure treatments relied solely on nutrients supplied by the pre-plant manure application for initial N fertility demands. Laboratory analysis of manure samples determined available N contributions from manure application, with N application rates increased as needed for manure treatments at the first post-emergence fertilizer application to equilibrate N rates.

Nitrogen supplied by manure contains fractions of immobile, organic N not in mineral fertilizers. These organic fractions are slow to decompose and are initially immobile in the soil, compared to the mobile, readily available inorganic N found in mineral fertilizers (Paul and Beauchamp, 1994). This immobile manure N mineralizes slowly throughout the season, providing N on a more continuous basis than inorganic N fertilizer applications. In addition to the differing availabilities of N fractions, manure application impacts N dynamics by enhancing existing soil N mineralization and reducing N loses through the stimulation of microbial biomass (Ma et al., 1999). Microorganisms mediate the mineralization of N from organic to inorganic forms. The application of manure increases microbial activity, in effect "priming" the system, increasing overall N mineralization through exponential microbial growth. While much of the N supplied by manure amendment is organic, and thus initially unavailable for plant uptake, the unavailability seems to be mitigated by the accompanying increase to N mineralization rates.

The effects of manure became more pronounced as the experiment progressed over the 3-year period. Manure N carries over from one year's application to the next, continually becoming available multiple seasons after application (Klausner et al., 1994; Sommerfeldt et al., 1988). Total levels of mineralized N following multiple years of manure amendment increase each year until an equilibrium is reached. The increasing effects of manure application on potato yields suggest such an equilibrium was not reached in the three years of the study. First year available organic N was estimated through laboratory analysis to be ~30%, with N fertilization levels balanced between manure treatments according to this first year availability. Paul and Beauchamp (1993) examined multiple year availability of N from liquid dairy manure in corn production and found that one year following amendment, 16.2% of the first year's N uptake could be recovered. However, three years after manure application, 27.3% of total applied N was recovered. Multi-year N availability from manure, in the case of 11.1% seen by Paul and Beauchamp (1993), is typically not included in fertilizer calculations, and results in more total N available in manure systems than non-manure systems. Curless and Kelling (2003) found that liquid dairy manure provided growth responses in potatoes above those seen with equal amounts of conventional fertilizer treatments. Their results suggest increases in multi-year nutrient availability from manure applications.

Multi-year nutrient availability from manure application is the most likely explanation for the significant yield increases of manure amendment in this experiment. Tuber yields were higher in response to manure application as the experiment progressed, suggesting a cumulative benefit. Potato yields in rotation with corn demonstrate this effect well. With potato yield measured each year in this system, the annual benefits of manure application are clear. The results of this experiment indicate that the greatest benefit of manure amendment may be realized only after several years of an annual amendment regime.

Crop Rotation Effects

Forage rotation crops, and their associated residue quantity and quality, significantly influenced potato yield. The 1-year sudex rotation significantly increased US #1 and total tuber yields compared to the 1-year alfalfa, 2-year alfalfa, and 2-year festulolium crop rotations. Potatoes following corn in 2004, after three years of manure amendment, and potatoes following 2-year alfalfa were the only other systems increasing US #1 yields at the P=0.05 level. The quality of crop residues has a large bearing on their overall impacts to the cropping system. C/N ratios are frequently used to predict the rate of residue decomposition, and thus N mineralization and plant availability (Wagger, 1989; Odhiambo and Bomke, 2001). These C/N ratios are used to imply the quality of the residue (Gil and Fick, 2001). Corn and sudex have high C/N ratios, and are thus termed "low quality" residues, as opposed to low C/N ratio, "high quality" residues of alfalfa and festulolium. The difference in these ratios is a function of the differing nature of each crop. Legumes, such as alfalfa, contain high levels of N due to symbiotic N fixation (Carpenter-Boggs et al., 2000). Festulolium, when managed in a high production, multiple cut system with high N inputs, builds significant N stocks. Corn and sudex, as C_4 grasses, contain more carbon than a C_3 grasses, such as festulolium, due to more efficient fixation of CO_2 (Al-Kaisi et al, 2004). These C/N ratios influence the mobilization of N in the soil. Carbon/N ratios narrower than 30:1 such as those of alfalfa and festulolium lead to net mobilization of N (Alexander, 1977), resulting in rapid N availability. Conversely, the broad C/N ratios of corn and sudex lead to net immobilization of N, with slow availability. Environmental conditions, including temperature and rainfall, influence N dynamics including residue decomposition and N leaching (Wagger, 1989). The spring of 2003 was much colder than normal and while below average in total rainfall, had several high volume precipitation events. 2004 was also cooler than normal with above average higher precipitation. These events may have contributed to lower than expected potato yield response to alfalfa and festulolium.

Honeycutt et al. (1996) determined that various legume and non-legume crops in rotation with potatoes had more of an influence on yield in dry years. The same rotations can produce different results in considerably more moisture-limiting conditions. The soil conditions at this site could have influenced N mineralization rates as well. Verbene et al. (1990) observed that crop residues decompose more rapidly in sandy soils than clay soils. Low quality residues in sandy soil, such as that in this experiment, will experience more rapid N mineralization than rates found in other soil types.

Residues in this experiment may be divided into two groups: those of the C_4 grasses corn and sudex, and those of the C_3 grass festulolium and the legume alfalfa. Festulolium and alfalfa are managed as production forage crops, subjected to multiple cutting events and removal of most aboveground biomass. Late season cutting provides only stubble and belowground biomass residues for incorporation prior to potato production. In contrast, corn and sudex provide above and below ground biomass residue contributions. Sudex is managed as a green manure cover crop, with all biomass retuned to the soil surface. Corn managed for grain production has significant biomass returned from stover. The C/N ratios of these two groups of residues differ dramatically. Corn stover and sudex have been found to have high aboveground C/N ratios of 67:1 (Burgess et al., 2002) and 47:1 (Creamer and Baldwin, 2005), respectively. Their belowground C/N ratios, however, are lower at approximately 48:1 (Havlin et al., 1999), and thus more readily mineralized. Alfalfa and festulolium have much lower aboveground C/N ratios, 18:1 and 15:1 respectively (Baron et al., 2001). However, the main residue contributions of these crops in a hay system are belowground, were C/N ratios are slightly higher at 21:1 and 22:1 (Baron et al., 2001).

Table 3.19. Crop above and below-ground C/N ratios as complied from several authors.

	AG C:N	BG C:N
Corn (stover)	60:1 [1]	48:1 [2]
Sudex	47:1 [3]	
Alfalfa	18:1 [4]	21:1 [4]
Cool Season Grass *(Italian ryegrass)*	15:1 [4]	22:1 [4]

AG DM- above ground dry matter
BG DM- below ground dry matter
[1] Cowan, 2005
[2] Havlin et al., 1999
[3] Creamer and Baldwin, 2005
[4] Baron et al., 2001
Italian ryegrass (*Lolium multiflorum* Lam.)

Corn and sudex residues, with above and belowground components, contain more diverse fractions than those of alfalfa and festulolium. The management of corn for grain leads to more diverse residues, with cob and husk residues in addition to the stem and leaf resides common to both corn and sudex (Burgess et al., 2002). Cobs and husks combine to comprise 29% of the total residue and have C/N ratios of 147:1 and 103:1, respectively. These high ratios lead to very little N mineralization, only 17.3% of total residues. Stems and leaves comprise 38% and 32%, respectably, of corn residues and 82.7% of mineralized N. Stem and leaf C/N ratios differ as well, at 80:1 and 42:1 respectively. This wide array of C/N ratios has a significant bearing on residue mineralization. Separate residue constituents mineralize at different rates, providing N availability over a wide period of time. Sudex residues consists of stem and leaf vegetative growth, with mowing events prior to seed production. While sudex stem and leaf residues differ in composition from those of corn, the same general trend of variable N mineralization from differing residues can be drawn. A heterogeneous collection of crop residues with differing N mineralization rates provides a more consistent supply of plant-available N over time than homogenous crop residues.

The difference in corn and sudex rotation impacts on potato yield is likely a function of these residue dynamics. Corn residues, on average, have greater C/N ratios than those of sudex. The broader average C/N ratio residue of corn will mineralize and become available over a longer period of time than the narrower C/N ratio residue of sudex. However, management of these crops in the field results in the opposite situation. Sudex is managed as a summer cover crop, with large amounts of crop residue returned to the soil surface with each mowing event. Even with a late first mowing in 2002, residues began to decompose July, eight months prior to potato planting. Corn residues were not applied to the soil surface until late in the fall preceding potato production. With the large impact of environmental conditions, including temperature, on N mineralization (Eghball et al, 2002; Wagger, 1989), sudex residues were able to mineralize to a much greater extent than corn residues. In addition to the greater time period for sudex residue mineralization, sudex residues mineralize at a faster rate than corn residues, particularly in non-soil incorporated conditions (Smith and Sharpley, 1990).

While sudex and corn rotations resulted in the greatest yield responses in potatoes tubers, alfalfa as a rotation crop also produced significant tuber yield increases. The mechanisms for this response must be independent of the slow residue N mineralization characteristic of sudex and corn. Alfalfa belowground contributions are the lowest of the four rotation crops in the experiment, leading to the assumption that yield responses must be induced more from residues quality than quantity. Through N fixation, alfalfa crowns and roots have been shown in Michigan to retain 115 kg N ha^{-1} after two years of growth (Rasse et al. 1999). The presence of these additional levels of N are not indicative of tuber yield response, as seen both by the lack of response in the non-manure amendment system and from the experiments of Griffin and Hesterman (1991) at this site in 1988 and 1989. While they observed increased potato vine DM and N content in alfalfa rotations, no yield responses were seen. They concluded that while N from soil incorporated legumes becomes available during the season, lack synchrony between that N availability and potato demand negates any yield increases from N. However, in the current experiment, the response of tuber yields to alfalfa rotation in a manure amended system suggest that the manure N mineralization priming effect releases otherwise unavailable N. The combination of alfalfa N and manure N have an antagonistic effect that results in N availability concurrent with potato N demand.

There was no significant yield response from potatoes associated with festulolium rotations. The belowground residue C/N ratio of festulolium favors rapid N mineralization and availability, and the total root biomass exceeds that of any other crop. However, root masses were observed to decompose slowly following their incorporation in 2004. While grass roots are efficient scavengers of N and accumulate significant amounts of the N in roots (Gasser et al., 2002), the observed presence of undecomposed roots at potato harvest indicates that N and OM release from these residues was unable to supply N to potatoes to the same extent of the other rotation crops. Gasser et al. (2002) suggested that perennial crops such as alfalfa and grass may only begin to decompose and release N after plant termination. If decomposition of alfalfa and festulolium residues began with tillage shortly before potato planting, it is unlikely that the N mineralization rate of festulolium would provide adequate available N during periods of greatest potato tuber demand. Wagger (1989) concluded that legume residues decompose quickly in the soil after incorporation, with increasing rates of decomposition up to four months following incorporation. Grass residues decomposed more slowly, with steady decomposition rates four months after incorporation.

Previous research has indicated that reside mineralization is linked to factors other than C/N ratio, including lignin, carbohydrate, and cellulose content (Herman, et al., 1977; Ranells and Wagger, 1996). Van Soest (1964) noted that lignin linkages differ between legumes and non-legumes, with linkages in non-legumes resulting in greater proportions of dry matter resistant to decomposition. In an attempt to characterize N mineralization using various residue characteristics, Vigil and Kissel (1991) found that lignin content is a second independent variable which can strengthen already robust equations based on C/N ratio. Although lignin and other crop residue components play a role in residue decomposition, direct comparisons between cellular constitute composition and C/N ratios have indicated that C/N ratios are more accurate predictors of residue mineralization (Janzen and Kucey, 1988).

Manure was shown in this study to have a more significant effect on tuber yield than crop rotation. This trend was also observed by Porter et al. (1999) in Maine potato production. Cattle manure and compost increased potato tuber yield more than oat (*Avena sativa*) and legume green manure rotations. These effects were attributed to increased nutrient availability, improved soil physical properties, and greater soil water holding capacity. The yield responses to manure may also be associated with N mineralization priming effects. With the equilibrated N fertilizer applications between manure and non-manure treatments, the only differences in fertility levels are attributed to multi-year N availability from manure and alfalfa. Increased fertility levels have been shown to increase N mineralization of aboveground, but not belowground residues (Soon and Arshad, 2002). Increased aboveground residue mineralization would explain tuber yield increases seen in corn and sudex rotations.

Shifts in commonly accepted agronomic practices may be necessary in order to fully utilize organic amendment benefits. Fall termination of perennial alfalfa and festulolium may hasten N mineralization in the following season, allowing for N availability to better match tuber demand. The adoption of a nondormant alfalfa is feasible for use as a single season crop. Groya and Sheaffer (1985) found comparable biomass and N production with a nondormant alfalfa compared to a dormant variety. A nondormant alfalfa terminated by winter conditions would decompose and mineralize more rapidly than a conventional, dormant variety, shifting the window of N availability earlier in the season for better utilization by potatoes.

The use of legume-grass binary mixtures have been identified as a means to modify C/N ratios, increasing N mineralization above that commonly found in grasses (Ranells and Wagger, 1996). While the authors reduced the mineralization rates typically associated with cereal grasses using crimson clover (*Trifolium incarnatum* L.) and hairy vetch (*Vicia villosa* Roth) legumes, the use of cool-season grass and alfalfa binary mixtures could modify C/N dynamics such that N availability more evenly matches potato tuber demands. A cool-season grass legume mixture would still retain the nutritive feed qualities necessary for dairy feed use in an integrated system.

Potato Scab

Table 3.20. Alternative system scab rating and increase from defender potato-corn rotation with no manure amendment- 2002, 2003, and 2004.

Year	Preceding Crop	Rating	Increase from defender
			%
2002	Corn		
	Manure	2.38	8.7
	Conv.	2.19	-
	LSD α=0.05	1.31	
2003	Corn		
	Manure	3.00	33.3
	Conv.	2.25	-
	LSD α=0.05	1.52	
2004	Corn		
	Manure	3.00	38.3
	Conv.	2.17	-
	LSD α=0.05	1.76	
2003	Sudex 1-yr		
	Manure	3.00	33.3
	Conv.	2.75	22.2
	LSD α=0.05	0.80	
2003	Alfalfa 1-yr		
	Manure	3.00	33.3
	Conv.	2.25	0
	LSD α=0.05	0.80	
2004	Alfalfa 2-yr		
	Manure	3.50 *	61.3 *
	Conv.	2.25	0
	LSD α=0.05	0.76	
2004	Festulolium 2-yr		
	Manure	2.50	15.2
	Conv.	2.38	9.7
	LSD α=0.05	2.38	

+ significant at P=0.10
* significant at P=0.05
Defender system = potato after corn with no manure amendments. Rotations compared to each season's defenders system, no comparisons possible between years

Manure application had greater influences on surface scab levels following alfalfa rotation compared to other crops rotations in this study. When potatoes followed corn, sudex, or festulolium in rotation, surface scab levels were not significantly increased by manure application. Alfalfa as a rotation crop increased surface scab levels, both as a 1-year rotation crop and as a 2-year rotation crop. Scab levels following 1-year of alfalfa did not differ statistically from those following 2-years of alfalfa, but demonstrated a slight trend toward less scab following 1-year alfalfa rotation.

When comparing scab levels of individual treatments against the non-manured corn-potato rotation defender system, increases to scab levels were only observed with manure amended 2-year alfalfa as a preceding crop. While no other rotation or treatment significantly increased scab levels, it is worthy noting that no forage crop was effective in reducing scab levels. Non-amended 1-year alfalfa was the only treatment not to increase overall scab levels. Forage crops, regardless of manure application, increased scab levels. The addition of manure amendments exacerbated this trend, increasing scab levels in all instances.

Scab incidence has been correlated with higher soil N in previous research (Lapwood and Dyson, 1966). High soil N levels were found to promote vegetative growth and delay tuber initiation, shifting the times at which tubers were most susceptible to scab infection. Manure application, particularly when annually applied, increases available N throughout the growing season. Similarly, alfalfa as a preceding crop contributes high levels of N to the soil (Rasse et al., 1999). Multiple years of alfalfa production may result in higher residual N contributions to potatoes than other rotation crops, delaying the tuber initiation in potatoes following alfalfa. This delay in tuber formation may provide a possible explanation for the increased levels of scab seen following 2-year alfalfa production.

While manure amendment does not add greater amounts of overall N to the system above that of mineral fertilizer, the organic and inorganic forms of N from these two sources do not necessarily behave the same over the course of the season. The organic N contributed by manure must be mineralized in order to be available to plants, whereas N supplied through commercial fertilizers is available at a faster rate. Alfalfa also contributes to the organic N pool with these effects compounded by N contributions to the system from N fixation. Nitrogen levels in both the 1-year and 2-year alfalfa rotations may be expected to be higher due to N fixation, with a 2-year stand adding more N than a 1-year stand. The combined effects on manure amendment and 2-year alfalfa rotation changed the soil N dynamics enough to significantly increase surface scab infection.

Scab infection has also been found to increase with application of Ca. The nutrient diverse composition of manure results in the application of sizable quantities of compounds not otherwise agronomically applied.

Table 3.21. Calcium applied through 12,260 L ha^{-1} liquid dairy manure amendment- 2002, 2003 and 2004.

	Total	1^{st} yr aval
	kg ha^{-1}	kg ha^{-1}
2002	232.6	127.9
2003	553.0	304.1
2004	277.3	156.1

Lambert and Manzer studied the effects of Ca application in potatoes with applications of 6.4 t ha^{-1} gypsum (17% Ca) and 4.5 t ha^{-1} dolomitic lime (24% Ca) measured against a control treatment at Preque Isle, Maine in 1989. These three fertilizer rates were then split between treatments with and without *Streptomyces scabies* inoculation. Inoculated treatments in both 1989 and 1990 for the control and gypsum applications ranged from 18 to 22% infection. Non-inoculated treatments had no infection. Dolomitic lime application resulted in 53% infection in 1989 and 80% infection in 1990 with inoculation. Non-inoculated treatments were 32% infected in 1990. Scab infection was found to be more correlated to soil pH modification from liming than Ca application. Davis et al. (1976) applied $Ca(NO_3)_2$ and $(NH_4)SO_4$ at 200 kg N ha^{-1}, S at 673 and 897 kg ha^{-1}, N-serve [2-chloro-6-(trichloromethyl)-pyride] at .6, 1,1, and 1.7 kg ha^{-1}, and PCNB (pentachloronitrobenzne) at 28 kg ha^{-1} in Blackfoot, Idaho. Triplie-super phosphate (P_2O_5) was applied to all plots at 168 kg ha^{-1}. Significant positive linear correlation (r= 0.56) was observed between Ca levels and tuber peeling and scab severity. The effects of Ca on scab severity were found to be mitigated by applications of phosphate, with Ca:phosphate-P ratios highly correlated to scab infection (r= 0.99). These studies suggest that while Ca applications may not have direct implications of scab infection, indirect effects may compound scab issues. However, with no mechanism to measure Ca soil or tuber concentrations, it is difficult to determine the effects of Ca in this experiment.

Goss (1936) examined the effects of long-term crop rotation, including alfalfa, upon the effects of scab in potatoes. One, two, three, and four year rotations with sugarbeets (*Beta vulgaris* L.), oats, corn, and alfalfa resulted in decreasing scab levels with increasing lengths of crop rotation and lengths of alfalfa stands preceding potatoes. Weinhold et al. (1964) found 3-year stands of alfalfa in rotation with potatoes decreased scab levels compared to 1-year barley, sugarbeet or cotton (*Gossypium hirsutum* L.) rotations.

Regional studies in Michigan have not found similar beneficial results from alfalfa rotation effects on potato scab. Wheeler (1946) found that alfalfa provided similar control of scab to that of corn rotations, though better than other legumes or grasses. Griffin and Hesterman (1991), at this site, found that alfalfa hay as a preceding crop to potatoes moderately increased scab levels compared to other legumes. Scab levels in alfalfa were similar to corn.

The reduction in potato scab levels seen following alfalfa in the literature validates the assumption that the observed scab increases following alfalfa are a result of altered N dynamics. Nitrogen mineralization is largely dependent on fluctuating environmental conditions. The likelihood exists that unusual weather conditions led to N levels in which scab initiation was abnormally favorable in 2003 and 2004. Lapwood and Dyson (1966) postulated such a theory to explain their observations when scab levels increased with increasing N levels.

Manure amendment has long been discouraged in potato production due to a belief that manure is a major cause of scab infection (Wheeler and Tucker, 1895; Stuart, 1937; Smith, 1968). Anecdotal accounts from farmers show both positive and negative potato disease effects from manure application, though the risk of increased disease pressure often prevents the use of manures (Conn and Lazarovits, 1999). The mechanisms by which animal manures effect scab levels are not well understood (Loria et al., 1997), with conflicting reports from research results showing no consistent evidence of scab increases from manure application. Goss (1936) found that manure increased scab levels within several different potato rotations. In studies conducted in East Lansing, Michigan, KenKnight (1941) found that applications of horse manure decreased potato scab levels. Conn and Lazarovits (1999) found that solid cattle manure had no effect on scab levels one year following application, while inducing slight decreases two and three years after amendment. They also examined poultry and liquid swine manure effects on scab, finding that swine manure reduced scab at one of two sites and poultry manure reducing scab at both sites. They postulated several theories for this occurrence, including manure changes to soil pH and stimulation of biological control. Swine and cattle manures were shown to temporarily decrease soil pH levels 4 weeks following amendment, reducing soil pH from about 6.0 to 5.5. Scab is found in soils with a pH ranging from 5.2 to 8.0 (Loria et al., 1997) with a positive correlation between increasing scab and increasing pH (Lambert and Manzer, 1991). Thus, a reduction of soil pH to 5.5 is likely to suppress most scab infection. The soil pH at MRF was measured as 6.59 at the study onset, making it unlikely that manure amendment would reduce pH level below that of scab tolerance. Potato production in Michigan is recommended on soils with a pH from 5.2 to 6.5, with a liming recommendation of 6.0 (Vitosh, 1990). Many Michigan potato soils may be able to have soil pH levels temporarily decreased with manure application, thereby reducing scab activity.

The few experiments in the literature that do report increases in scab infection with manure application offer no explanation for their findings. However, one explanation for the increased scab levels seen in this experiment may be linked to the same mechanisms that increased scab levels with alfalfa rotations. The excess N available throughout the season with manure amendment compared to conventional fertilization may push the window of tuber initiation later into the season, thereby shifting the period of highest tuber susceptibility later into the growing season for manure treatments compared to non-manure treatments.

Economic Aspects

System-wide integration shifts revolve wholly around their accompanying economic ramifications. The current agronomic systems in place are practiced because at some point, they provided benefits over the previous systems. Thus, the adoption of new systems, such as the integrated potato-dairy model suggested in this research, is dependent on demonstrable, tangible economic benefits. Potatoes and milk are two high value agricultural enterprises that under high intensity management systems often operate near their current maximum profit potentials. The agricultural landscape is dominated by low commodity prices, high land values, and high input costs. Profit margins are tight and economies of scale are commonly called into practice. However, serious questions arise as to the sustainability of this current model. There are no indications in the foreseeable future that commodity prices will raise or input costs lower. At some point, building larger and larger farming enterprises will no longer prove pragmatic. The need for a paradigm shift is essential for the way in which farming operations are conducted. However, enacting widespread reform throughout the agricultural community is only feasible when the risk of adoption is below a certain level. Research study results examining farmers facing moderate to severe production stresses find that these producers are more inclined to incorporate practices such as longer crop rotations and utilization of new crops than farmers not facing as severe of production challenges (Corselius et al., 2003). Integration utilization can only achieved if the economic implications are addressed. Accurate assessments of the costs of yearly potato and forage production are required to establish baselines by which to measure future decisions. Additionally, manure economics must be incorporated. Manure represents a unique challenge as the divergence viewpoints of its intrinsic worth as a waste product or potential fertilizer and soil conditioner result in different values to different players. The utilization of manure as nutrient source may hold particular promise as a mineral fertilizer substitute. Costs associated with agronomic production shifts from grain to forage production must be adsorbed by corresponding increases in production and return on investment. Above all, and often forgotten by producers, are the unrealized costs in gaining necessary proficiency in new management practices, shifts in required manpower, and other unforeseen barriers to economic viability associated with wide-spread agronomic change. Potato – livestock integration may hold legitimate economic promise for one set of producers while remaining an unfeasible enterprise for others. Extensive utilization of agronomic integration hinges on individual economic practicality.

Conclusion

This experiment shows that agronomic integration of dairy and potato operations offers a production increase potential for potato producers. US #1 tubers yields were found to be responsive to manure and crop rotation effects. Liquid dairy manure significantly increased tuber yields and slightly increased surface scab infection to a greater extent than crop rotation. No crop rotation induced significant increases to potato yields without manure amendment. There was a synergistic effect of crop rotation and manure application as crop rotation with manure application was shown to increase US #1 tuber yields most effectively in a 2-year rotation with sudex managed as a green manure, followed by grain corn in a 2-year rotation and a 2-year stand of alfalfa managed as a hay crop with crop biomass removed. One-year alfalfa and 2-year festulolium did not result in significant yield responses of potato tuber yields. Forage rotation crops managed for hay production in 1-year and 2-year stands were not as effective at increasing potato tuber yields or decreasing tuber scab infection as 2-year rotations with corn produced for grain or sudex managed as a green manure cover crop. The combination of manure application and C_4 grass crop rotation was the most effective at increasing tuber yields. Manure application increased festulolium yield, but did not increase alfalfa or sudex forage yields. No consistent forage quality effects could be drawn between manure treatments. Manure application decreased corn grain yield in 2002, but increased test weight in 2004. This study indicates that crop rotation and manure amendment holds the potential to increase potato yields.

Literature Cited

AGCO Corporation, 4205 River Green Parkway, Duluth, Georgia. 30096

Alexander, M. 1977. Introduction to Soil Microbiology. John Wiley & Sons., New York. p. 472.

Al-Kaisi, M. M., X. Yin, and M. A. Licht. 2005. Soil carbon and nitrogen changes as influenced by tillage and cropping systems in some Iowa soils. Agriculture, Ecosystems & Environment. 105:635-647.

ALMACO, 99M Avenue, Nevada, Iowa. 50201.

Baron, V., D. Young, and C. Ullmann. 2001. Can pastures slow down global warming? Western Forage / Beef Group. May 2001. 5:3-6.

Bittman, S., C. G. Kowalenko, D. E. Hunt, and O. Schmidt. 1999. Surface-banded and broadcast dairy manure effects on tall fescue yield and nitrogen uptake. Agronomy Journal. 91:826-833.

Black, W. N., and R. R. Cairns. 1958. The effect of varying levels of nitrogen, phosphorus and potassium and manure on the yield and starch content of potatoes. Canadian Journal of Soil Science. 38:1-7.

Black, W. N., and R. P. White. 1973. Effects of nitrogen, phosphorus, potassium, and manure factorially applied to potatoes in a long-term study. Canadian Journal of Soil Science. 53:205-211.

Brillion Farm Equipment, 200 Park Ave, Brillion Wisconsin. 541101

Burgess, M. S., and G. R. Mehuys, and C. A. Mardramootoo. 2002. Nitrogen dynamics of decomposing corn reside components under three tillage systems. Soil Science Society of America Journal. 66:1350-1358.

Carpenter-Boggs, L., J. L. Pikul Jr., M. F. Vigil, and W. E. Riedell. 2000. Soil nitrogen mineralization influenced by crop rotation and nitrogen fertilization. Soil Science Society of America. 64:2038-2045.

Carter, M.R., and J. B. Sanderson. 2001. Influence of conservation tillage and rotation length on potato productivity, tuber disease and soil quality parameters on a fine sandy loam in eastern Canada. Soil & Tillage Research. 63:1-13.

Carter Manufacturing, Incorporated., 896 E. Carter Court, Brookston, Indiana. 47923

Cherney, D. J. R., J. H. Cherney, and E. A. Mikhailova. 2002. Orchardgrass and tall fescue utilization of nitrogen from dairy manure and commercial fertilizer. Agronomy Journal. 94:405-412.

Christenson, D. R., D. D. Warncke, M. L. Vitosh, L. W. Jacobs, and J. G. Dahl. 1992. Fertilizer recommendations for field crops in Michigan. Michigan State University Extension Bulletin E-550A.

Christy-Turner Group, Knightsdale Road, Ipswich, Suffolk IP1 4LE. United Kingdom.

Conn, K.L., and G. Lazarovits. 1999. Impact of animal manures on verticillium wilt, potato scab, and soil microbial populations. Canadian Journal of Plant Pathology. 21:81-92.

Corselius, K. L., S. R. Simmons, and C. B. Flora. 2003. Farmers perspectives on cropping systems diversification in northwestern Minnesota. Agriculture and Human Values. 20:371-383.

Cowan, D. Building soil organic matter. *Referenced:* 10 January, 2005. Agri-Food Laboratories CCA.On www.agtest.com/articles/building.

Crawford, D. Farm Manager, Montcalm Potato Research Farm, Michigan State University. 4470 McBride Rd, Lakeview, Michigan. 48850.

Creamer, N. G., and K. R. Baldwin. 2005. An evaluation of summer cover crops for use in vegetable production systems in North Carolina. Southwest Florida Research & Education Center, University of Florida. http://www.imok.ufl.edu/LIV/groups/cultural/cover/ncvps.htm

Curless, M.A., and K. A. Kelling. 2003. Preliminary estimates of nitrogen availability from liquid dairy manure to potato. HortTechnology. 13:593-597.

Daliparthy, J., S. J. Herbert, and P. L. M. Veneman. 1994. Dairy manure applications to alfalfa: crop response, soil nitrate, and nitrate in soil water. Agronomy Journal. 86:927-933.

Davis, J. R., R. E. McDole, and R. H. Callihan. 1976. Fertilizer effects on common scab of potato and the relation of calcium and phosphate phosphorus. Phytopathology. 66:1236-1241.

Deere & Company World Headquarters. One John Deere Place, Moline, Illinois. 61265

Dysinger, K. Corn Research Technician. Michigan State University, Department of Crop and Soil Science. Crop and Soil Science Teaching and Research Facility. 4450 Beaumont Rd., East Lansing, Michigan. 48824.

Eghball, B., B. J. Weinhold, J. E. Gilley, and R. A. Eigenberg. 2002. Mineralization of manure nutrients. Journal of Soil and Water Conservation. 57:470-473.

Gasser, M. O., M. R. Laverdiere, R. Lagace, and J. Caron. 2002. Impact of potato-cereal rotations and slurry applications on nitrate leaching and nitrogen balance in sandy soils. Canadian Journal of Soil Science. 82:469-479.

Gil, J. L., and W. H. Fick. 2001. Soil nitrogen mineralization in mixtures of eastern gamagrass with alfalfa and red clover. Agronomy Journal. 93:902-910.

Goering, H. K., and P. J. Van Soest. 1970. Forage fiber analysis: apparatus, reagents, procedures, and some applications. USDA Agriculture Handbook 379. United States Government Printing Office, Washington D. C.

Goss, R. W. 1936. The effect of irrigated crop rotations upon potato scab. American Potato Journal. 13:91-96.

Great Plains Manufacturing Incorporated. 1525 E. North Street, Salina, Kansas. 67401

Griffin T., E. Giberson, and M. Wiedenhoeft. 2002. Yield response of long-term mixed grassland swards and nutrient cycling under different nutrient sources and management regimes. Grass and Forage Science. 57:268-278.

Griffin, T.S., and O. B. Hesterman. 1991. Potato response to legume and fertilizer nitrogen sources. Agronomy Journal. 83:1004-1012.

Groya, F. L., and C. C. Sheaffer. 1985. Nitrogen from forage legumes: harvest and tillage effects. Agronomy Journal. 77:105-109.

Havlin, J. L., J. D. Beaton, S. L. Tisdale and W. L. Nelson. 1999. Soil fertility and fertilizers. 6th edition. Prentice Hall. Upper Saddle River, New Jersey.

Herman, W. A., W. B. McGill, and J. F. Dormaar. 1977. Effect of initial chemical composition on decomposition of roots of three grass species. Canadian Journal of Soil Science. 57:202-215.

Honeycutt, C. W., W. M. Clapham, and S. S. Leach. 1996. Crop rotation and N fertilization effects on growth, yield, and disease incidence in potato. American Potato Journal. 73:45-61.

H. D. Hudson Manufacturing Company. 500 N. Michigan Avenue, Chicago, Illinois. 60611.

Janzen, H. H., and R. M. N. Kucey. 1988. C, N, and S mineralization of crop residues as influenced by crop species and nutrient regime. Plant and Soil. 106:35-41.

Jokela, W. E. 1992. Nitrogen fertilizer and dairy manure effects on corn yield and soil nitrate. Soil Science Society of America Journal. 56:148-154.

Juniper Systems, Incorporated. 1132 West 1700 North, Logan, Utah. 84321.
Kaffka, S. R., and V. R. Kanneganti. 1996. Orchardgrass response to different types, rates, and application patterns of dairy manure. Field Crops Research. 47:43-52.

Keady, T. W. J., and P. O. O'Kiely. 1998. An evaluation of potassium and nitrogen fertilization of grassland, and date of harvest, on fermentation, effluent production, dry-matter recovery and predicted feeding value of silage. Grass and Forage Science. 53:326-337.

Kelling, K. A., and M. A. Schmitt. 2003. Applying manure to alfalfa- pros, cons, and recommendation for three application strategies. North Central Regional Research Report 346. University of Wisconsin.

KenKnight, G. 1941. Studies on soil actinomycetes in relation to potato scab and its control. Michigan State College Agriculture Experiment Station Technical Bulletin 178:1-48.

Ketterings, Q. M., G. Godwin, J. H. Cherney, and T. F. Kilcer. 2005. Potassium management for brown midrib Sorghum x Sudangrass as a replacement for corn silage in the north-eastern USA. Journal of Agronomy and Crop Science. 191:41-46.

Kilcer, T., Q. M., Ketterings, T. Katsvairo, and J. C. Cherney. 2002. Nitrogen management for Sorghum Sudangrass: how to optimize N uptake efficiency? What's Cropping Up? 12:6-9.

Klausner, S.G., V. R. Kanneganti, and D. R. Bouldin. 1994. An approach for estimating a decay series for organic nitrogen in animal manures. Agronomy Journal. 88:897-903.

Kongskilde Industries. Howard USA Inc., United States Distributors. 2439 South Main, Unit 2. Bloomington, Illinois. 61704.

Lambert, D. H., and F. E. Manzer. 1991. Relationship of calcium to potato scab. Phytopathology. 81:632-636.

Lapwood, D. H., and P. W. Dyson. 1966. An effect of nitrogen on the formation of potato tubers and the incidence of common scab (*Streptomyces scabies*). Plant Pathology. 15:9-14.

Leep, R. Professor, Forage Crop Management. Michigan State University, Department of Crop and Soil Science, W. K. Kellogg Biological Station. 3700 Gull Lake Drive, Hickory Corners, Michigan 49060.

Lockwood Manufacturing. 237 12th Street NW, West Fargo, North Dakota. 58078.

Loria, R., R. A. Bukhalid, B. A. Frye, and R. R. King. 1997. Plant pathogenicity in the genus Steptomyces. Plant Disease. 81:836-846.

Ma, B. L., L. M. Dwyer, and E. G. Gregorich. 1999. Soil nitrogen amendment effects on seasonal nitrogen mineralization and nitrogen cycling in maize production. Agronomy Journal. 91:1003-1009.

Min, D.H., L. R. Vough, and J. B. Reeves III. 2002. Dairy slurry effects on forage quality of orchardgrass, reed canarygrass and alfalfa-grass mixtures. Animal Feed Science and Technology. 95:143-157.

Odland, T.E., and J. E. Sheehan. 1957. The effect of redtop and red clover on yields of following crops of potatoes. American Potato Journal. 34:282-284.

Odhiambo, J. J. O., and A. A. Bomke. 2001. Grass and legume cover crop effects on dry matter and nitrogen accumulation. Agronomy Journal. 93:299-307.

Paul, J. W., and E. G. Beauchamp. 1993. Nitrogen availability for corn in soils amended with urea, cattle slurry, and solid and composted manures. Canadian Journal of Soil Science. 73:253-266.

Peters, J. B. 1991. Comparison of manure as an organic fertilizer source and commercial fertilizer for establishment and production of alfalfa. *In:* Sustainable Agriculture Program Final Report. Wisconsin Department of Agriculture, Trade, and Consumer Protection. Madison, Wisconsin. p. 25.

Porter, G. A., G. B. Opena, W. B. Bradbury, J. C. McBurnie, and J. A. Sisson. 1999. Soil management and supplemental irrigation effects on potato: I. Soil properties, tuber yield, and quality. Agronomy Journal. 91:416-425.

Ranelles, N. N, and M. G. Wagger. 1992. Nitrogen release from crimson clover in relation to plant growth stage and composition. Agronomy Journal. 84:424-430.

Rasse, D. P., A. J. M. Smucker, and O. Schebenbeger. 1999. Modifications of soil nitrogen pools in response to alfalfa root systems and shoot mulch. Agronomy Journal. 91:471-477.

Saini, G.R., and Grant, W.J. 1980. Long-term effects on intensive cultivation on soil quality in the potato-growing areas of New Brunswick (Canada) and Maine (U.S.A.) Canadian Journal of Soil Science 60:421-428.

SAS Institute. 2004. Version 8.02. 100 SAS Campus Drive, Cary, North Carolina. 27513.

Schmitt, M. A., C. C. Sheaffer, and G. W. Randall. 1993. Preplant manure and commercial P and K fertilizer effects on alfalfa production. Journal of Production Agriculture. 6:385-390.

Smith, O. 1968. Potatoes: Production, Storing, Processing. The Avi Publishing Company, Incorporated. Westport, Connecticut. pp. 405-406.

Smith, S. J., and A. N. Sharpley. 1990. Soil nitrogen mineralization in the presence of surface and incorporated crop residues. Agronomy Journal. 82:112-116.

Snapp, S. S., D. Smucker, and M. Vitosh. 2002. Nitrogen management for Michigan potatoes. Michigan State University Extension Bulletin E-2779.

Sommerfeldt, T. G., C. Chang, and T. Entz. 1988. Long-term annual manure applications increase soil organic matter and nitrogen, and decrease carbon to nitrogen ratio. Soil Science Society of America Journal. 52:1668-1672.

Soon, Y. K., and M. A. Arshad. 2002. Comparison of the decomposition and N and P mineralization of canola, pea, and wheat residues. Biology and Fertility of Soils. 36:10-17.

Stuart, W. 1937. The Potato- Its Culture, Uses, History, and Classification. *In:* Davis K. C. (Ed). J. B. Lippincott Company, Chicago Illinois. pp. 30-31, 264-267.

Van Soest., P. J. 1964. Symposium on nutrition and forage and pastures: New chemical procedures for evaluating forages. Journal of Animal Science. 23:838.

VanWieringen, L. M., J. H. Harrison, T. Nennich, D. L. Davidson, L. Morgan, S. Chen, M. Bueler, and F. Hoisington. 2005. Manure management effects on grass production, nutritive content, and soil nitrogen for a grass silage-based dairy farm. Journal of Environmental Quality. 34:164-173.

Verbene, E. L., J. Hassink, P. de Willingen, J. J. Groot, J. A. Van Veen. 1990. Modeling organic matter dynamics in different soils. Netherlands Journal of Agriculture Science. 38:221-238.

Vigil, M. F., and D. E. Kissel. 1991. Equations for estimating the amount to nitrogen mineralized from crop residues. Soil Science Society of America. 55:757-761.

Vitosh, M. L. 1990. Best management practices for potatoes- potato fertilizer recommendations. Michigan State University Extension Bulletin E-2220.

Vos, J., C. D. van Loon. 1989. Effects of cropping frequency on potato production. *In:* Vos, J., van Loon, C.D., Bollen, G.J. (Eds.), Effects of Crop Rotation on Potato Production in the Temperate Zones. Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 1-24.

Wagger, M. G. 1989. Time of desiccation effects on plant composition and subsequent nitrogen release from several winter annual cover crops. Agronomy Journal. 81:233-241.

Watkins, K. L., T. L. Veum, and G. F. Krause. 1987. Total nitrogen determination of various sample types: a comparison of the Hach, Kjeltec, and Kjeldahl methods. Journal of the Association of Official Analytical Chemistry. 70:410-412.

Weinhold, A. R., J. W. Oswald, T. Bowman, J. Bishop, and D. Wright. 1964. Influence of green manures and crop rotation on common scab of potato. American Potato Journal 41:265-273.

Wheeler, E. J. 1946. The residual effect of crop rotations on potato yield and the presence of potato scab. Michigan State College Agriculture Experiment Station Quarterly Bulletin. 28:326-332.

Wheeler, H. J. and G. M. Tucker. 1895. Upon the effect of barnyard manure and various compounds of sodium, calcium, and nitrogen upon the development of potato scab. Rhode Island Agricultural Experiment Station Bulletin No. 33. 33:51-79.

Appendix

Table 3.22. Potato tuber disease infection ratings- 2002, 2003 and 2004.

2002	HH	VD	BC	IBS	HN
Corn					
Manure	0.625 a	2.25 a	0	0.125 a	0.25 a
Conv.	0.125 b	2.13 a	0	0.125 a	0.25 a
2003					
Corn					
Manure	4.0 ab	0.25 a	0.75 a	0 a	0
Conv.	4.75 a	0 a	0 b	0 a	0
Sudex					
Manure	2.5 ab	0.50 a	0.5 ab	0 a	0
Conv.	2.75 ab	0.25 a	0 b	0.25 a	0
Alfalfa 1-yr					
Manure	1.25 b	0 a	0 b	0.25 a	0
Conv.	3.25 ab	0.25 a	0.75 a	0.25 a	0
2004					
Corn					
Manure	0.125 ab	2.88 a	0 a	0	0
Conv.	0 b	2.63 a	0.75 a	0	0
Alfalfa 2-yr					
Manure	0 b	2.25 a	0 a	0	0
Conv.	0.125 ab	4.75 a	0.13 a	0	0
Festulolium 2-yr					
Manure	0.75 a	2.13 a	0.13 a	0	0
Conv.	0.38 ab	2.25 a	0.25 a	0	0

Comparisons made inner-year, comparisons between years not applicable

HH- Hollow heart
VD- Vascular disorder
BC- Brown center
IBS- Internal brown spot
HN- Heat neurosis

Potato disease is determined through internal analysis of 10 oversized or US#1 tubers.

Table 3.23. Potato tuber specific gravity- 2002, 2003, and 2004.

2002	gravity
Corn	
Manure	1.0663
Conv.	1.0655
2003	
Corn	
Manure	1.079
Conv.	1.059
Sudex	
Manure	1.078
Conv.	1.080
Alfalfa 1-yr	
Manure	1.075
Conv.	1.075
2004	
Corn	
Manure	1.075
Conv.	1.082
Alfalfa 2-yr	
Manure	1.075
Conv.	1.078
Festulolium 2-yr	
Manure	1.078
Conv.	1.082

No statistical differences observed within year or between manure treatments.

	P- value
Year	0.043
Rotation	0.321
Manure treatment	0.503
Rot x manure	0.847