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Crop/Livestock Integration Effects on Soil Quality, Crop Production, and Soil Nitrogen Dynamics

Ellen B. Mallory

CROP/LIVESTOCK INTEGRATION EFFECTS ON SOIL QUALITY, CROP PRODUCTION, AND SOIL NITROGEN DYNAMICS

By

Ellen B. Mallory

B.A. Biology, Swarthmore College, 1987

M.S. University of Wisconsin, 1994

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Advisory Committee:

Timothy S. Griffin, Research Agronomist, USDA-ARS, Co-Advisor

M. Susan Erich, Professor of Soil Chemistry, Co-Advisor

Gregory A. Porter, Professor of Crop Management

David Bryan Dail, Assistant Professor of Soil Microbiology

Michel A. Cavigelli, Soil Scientist, USDA-ARS, Beltsville, MD

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Thesis Advisors: Dr. Timothy S. Griffin

Dr. M. Susan Erich

An Abstract of the Thesis Presented
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Regional integration of potato and dairy farms has developed in Maine through arrangements where manure, feed, and sometimes land, are exchanged between neighboring farms. The effects of integration on soil quality, crop production, nitrogen (N) cycling, and N loss were investigated in field and laboratory studies of contrasting amended (manure, compost, green manure, and supplemental fertilizer) and nonamended (fertilizer only) soil management systems within 2-year potato (*Solanum tuberosum* L.) rotations in the Maine Potato Cropping Systems Project (MPEP). Additionally, soil quality of 48 integrated and nonintegrated Maine potato and dairy farm fields was assessed. The MPEP's amended soil system enhanced soil quality and demonstrated aspects of increased resilience for crop production and N cycling. The amended system produced higher and more stable potato yields than the nonamended system by reducing the impact of adverse growing conditions. It also demonstrated the potential to buffer

excess N by retaining a greater proportion of net N inputs than the nonamended system. Possible mechanisms to explain increased N retention include better early-season synchrony between N release and crop uptake, as observed in *in situ* soil monitoring; carbon-enhanced immobilization of excess N, as observed in a laboratory study; increased recalcitrance of N sources; and physical protection. Nitrogen loss, in absolute terms, however, was higher in the amended system due to higher N inputs and a build-up of soil organic N. Soil amendment history had the largest impact on soil N mineralization capacity – fall nitrate levels were higher in the amended system in two of three years, and residual manure N contributed more N than predicted using the standard decay-series model – but it also reduced the availability of recently added N. As currently practiced in Maine, integrated potato systems appear to need greater increases in carbon inputs (preferably as sod crops and trap crops) and reductions in tillage to produce changes in soil carbon that can be detected at a landscape level. Future work should focus on finding balance points for soil organic matter content that enhance soil's crop production and N cycling functions while avoiding N excesses and loss.

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LIST OF ABBREVIATIONS

C, carbon

CEC, cation exchange capacity

CV, Coefficient of variation

DM, dry matter

IPM, integrated pest management

MPEP, Maine Potato Ecosystem Project

N, nitrogen

N_i, inorganic N

P, phosphorus

POM, particulate organic matter

SMB, soil microbial biomass

SOC, soil organic carbon

SOM, soil organic matter

Chapter 1

INTRODUCTION

1.1. Integrating Crop and Livestock Farming

Increasing industrialization of agriculture has decoupled crop and livestock production and encouraged individual farmers to specialize in one or the other (Naylor et al., 2005). Consequently, crop farmers rely on purchased inorganic fertilizers to meet crop nutrient needs, while livestock farmers import feed nutrients and often do not have enough land to avoid excessive applications of manure nutrients. Given these concurrent trends, it is not surprising that agriculture is the leading source of nitrogen (N) pollution in much of the United States, with fertilizer and manure accounting for up to 90% of point and nonpoint sources of N in agricultural watersheds (Pucket, 1994).

In Maine and elsewhere, an increasing number of farmers are establishing linkages between the nutrient cycles of neighboring crop and livestock operations, a process referred to as *integration*. In some cases, integration consists solely of excess dairy manure being applied to nearby potato (*Solanum tuberosum* L.) farm fields. In other cases, integration is more complex, with farmers sharing land between operations, expanding the potato rotation to include feed crops (e.g., silage corn (*Zea mays* L.) or barley (*Hordeum vulgare* L.) as forage or grain) for the dairy operation, and trading services such as tillage or spraying. This crop-livestock integration has many potential benefits. For instance, manure N, often in excess on a dairy farm, may replace a portion of the fertilizer needs of a neighboring potato farm. Hence, integration is viewed as a potential strategy to increase N use efficiency and reduce N losses to the environment at watershed or regional scales (Christensen, 2004; Naylor et al., 2005; Russelle et al., 2007; Schröder, 2005). These efficiencies, however, may go beyond input substitution.

Organic amendments, including animal manures, compost, and crops grown for soil improvement, create soil that is fundamentally different than nonamended soil. Repeated applications of organic amendments increase stocks of total and labile carbon (C) and N (Aoyama et al., 1999a; Cambardella and Elliott, 1992; Griffin and Porter, 2004; Sommerfeldt et al., 1988; Wander et al., 1994), enhance soil microbial biomass and activity (Fauci and Dick, 1994b; Gunapala and Scow, 1998; Houot and Chaussod, 1995; Witter et al., 1993), improve soil structure (Angers and Carter, 1996; Grandy et al., 2002), and increase water-holding capacity (Khaleel et al., 1981; Weil and Magdoff, 2004). All of these characteristics influence how a soil functions with regard to nutrient cycling, crop production, and environmental impact. This dissertation investigates how amended soil management systems alter soil characteristics and soil function, relative to nonamended systems.

The research for this thesis was conducted as part of the interdisciplinary project “Reintegrating Crop and Livestock Enterprises in Three Northern States,” an Initiative for Future Agricultural and Food System (IFAFS) project funded by USDA-CSREES that involved researchers, farmers, and educators from Maine, Michigan, and Iowa.

1.2. Soil Quality and Resilience

The concept of soil quality emerged to describe the functional capacity of soil, not only for crop production, but also for environmental quality, human health, and multiple uses (Karlen et al., 2004). Soil quality is necessarily a subjective term with varied definitions and interpretations (Schjønning et al., 2004). In this dissertation, the term soil quality is used according to the definition proposed by the Soil Science Society of America (SSSA) as, "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen et al., 1997). Soil quality includes both inherent properties (e.g., parent material and topography), and dynamic properties influenced by management (e.g., soil organic carbon (SOC) and compaction) (Carter, 2002; Karlen et al., 2004). In this dissertation, the soil quality term is used to refer to dynamic properties with regard to crop production and environmental quality.

The linkage between soil quality characteristics and soil productivity is well established. Numerous studies have demonstrated increased productivity associated with enhanced SOC, achieved by amending with organic materials (Barzegar et al., 2002; Christensen and Johnston, 1997; Hornick and Parr, 1987) or other means (Díaz-Zorita et al., 2002; Dick et al., 1997; Johnston, 1991). Additionally, predictive relationships have been found between crop yield and soil quality characteristics, such as total soil C (Alvarez et al., 2002), active soil C and macroaggregate stability (Stine and Weil, 2002), and total soil N (Stenberg, 1998). Productivity increases in SOC-enhanced soils have been attributed to improvements in soil structure, water-holding capacity (Johnston, 1991), and nutrient supply (Cassman, 1999; Díaz-Zorita et al., 1999).

There is also a perception that high-quality soils produce more stable yields by buffering environmental factors such as limited or excessive rainfall, pests, and diseases (Ellmer et al., 2000; Karlen et al., 2004; Romig et al., 1995). Thus, high-quality soils are considered to produce more robust growing environments because they are more resistant and resilient to external stresses (Karlen et al., 2004; Schjønning et al., 2004; Seybold et al., 1999). It has been shown that crops grown on soil that receives organic amendments and has enhanced soil quality characteristics have access to greater soil moisture (Liebig and Doran, 1999; Lotter et al., 2003) and are more resistant to weed (Gallandt et al., 1998a) and insect (Alyokhin et al., 2005) pressures. But direct evidence that amended systems reduce year-to-year variation in yields is lacking.

Chapter 2 of this dissertation investigates the influence of an amended soil management on soil quality characteristics, potato yield, and potato yield stability. Chapter 2 has been published previously (Mallory and Porter, 2007). This and three of the other studies comprising this dissertation were conducted as part of the Maine Potato Ecosystem Project (MPEP). A brief description of the MPEP is given in section 1.6.

1.3. Nitrogen Stabilization and Loss

The concept of soil resilience as a component of soil quality (Seybold et al., 1999) can be extended to nutrient dynamics with regard to soil's nutrient supplying and buffering functions. In this context, "resilience is imparted by a balance between nutrient mobilization for biological uptake and nutrient stabilization in the soil or other system components to avoid leaching or erosion loss" (p. 157, Tiessen et al., 1994). Amended soil management systems designed to improve soil quality may provide resilience regarding nitrogen dynamics by rejoining the biological links between C and N cycles and enhancing N stabilization in the soil (Drinkwater et al., 1998; Drinkwater and Snapp, 2007).

Two possible mechanisms may contribute to greater N stabilization in high-C systems: C-enhanced immobilization and physical protection. The major pathways of loss from cultivated soil (leaching, volatilization, and denitrification) all act on inorganic forms of N. Thus there is potential to reduce N loss by reducing high levels of inorganic N when crop demand is low. Immobilization of inorganic N to organic N by microbes is a major N stabilizing mechanism and is stimulated by readily available C. Research on untilled soils has illustrated this linkage. Barrett and Burke (2000) found a positive linear relationship between soil C concentration and gross rates of mineralization (slope = 0.595) and immobilization (slope = 0.934) in grassland soil, with greater influence on immobilization. Similarly, Hatch et al. (2000) detected a greater increase in N-immobilization in high- vs. low-C pasture soil 3 months after a one-time surface application of manure.

Physical protection of N as organic matter in soil microaggregates also is an important N stabilizing mechanism and is influenced by soil C (Six et al., 2002). Manure application has been shown to increase aggregate-protected N fourfold compared to a synthetic fertilizer treatment (Aoyama et al., 1999b).

The role of amended soil management systems in stabilizing N has been investigated in a limited number of medium-term cropping systems trials by comparing changes in soil total N with calculated N balances (inputs minus outputs). In two such studies, a greater proportion of N inputs was accounted for, either as harvested crop or soil storage, in manure- and legume-based systems compared with fertilizer-based systems, but the influence of increased soil C could not be confirmed in either study due to the inclusion of N-scavenging winter cover crops in only the organic systems (Drinkwater et al., 1998; Poudel et al., 2001). In Chapter 3, a similar N budgeting method is used to assess whether an amended soil management system reduced loss and enhanced soil stabilization of N relative to a nonamended system over an eight year period, where the soil management factor was not confounded with tillage or rotation factors. Carbon stabilization is also addressed.

1.4. Managing Nitrogen in Amended Systems

Soil management systems that rely on organic sources of nutrients and build soil quality represent a fundamentally different approach to nutrient management than fertilizer-based approaches (Drinkwater and Snapp, 2007). Whereas fertilizer-based systems focus on adding soluble, plant-available nutrients to meet crop needs for a single season, amended systems build stocks of mineralizable nutrients, or nutrient “capital” (van Noordwijk, 1999), and rely more on microbial and plant-mediated processes and the re-coupling of nutrient cycles. Both systems share a common goal of synchronizing nutrient availability, temporally and spatially, with plant uptake.

Managing N in amended soil management systems can be challenging, compared to fertilizer systems, because organic N sources must be mineralized to plant available inorganic forms (NO_3^- and NH_4^+). For instance, manure is a slower or more gradual source of plant-available N than fertilizer N (Langmeier et al., 2002; Ma et al., 1999). While this may result in increased synchrony with plant demand and reduce potential N leaching losses (Ma et al., 1999), it may also lead to potentially leachable end-of-season excesses of soil NO_3^- (Basso and Ritchie, 2005; Magdoff, 1991; Pang and Letey, 2000; Schröder, 2005). Additionally, standard manure application recommendations, which do not recognize N contributions after the third year following application, may underestimate the longer-term N-release potential of manure, leading to over application (Schröder, 2005; Whalen et al., 2001). Chapter 4 reports the results of an *in situ* field monitoring study that examines seasonal patterns of N availability relative to crop needs over three growing seasons in amended and nonamended soil treatments, and estimates the relative contribution of current and residual manure organic N.

In addition to the quantitative increase in the size of the soil organic N pool, repeated long-term application of organic amendments also brings about changes in soil characteristics that could affect N dynamics. Chapter 5 summarizes results from a laboratory investigation of the influence of soil amendment history on the mineralization and availability of recently added N substrates. This chapter has been published previously (Mallory and Griffin, 2007).

1.5. Potato-Dairy Integration and Soil Quality in Maine

Maintaining soil quality is difficult in potato cropping systems as they are typified by high levels of soil disturbance and low levels of crop residue return. That is why the relinking of C and nutrient cycles between potato and livestock farms through integration is seen as a promising strategy to assure soil quality and productivity in potato systems in Maine and elsewhere (Files and Smith, 2001; Stark and Porter, 2005). Chapter 6 addresses the question whether the adoption of integrated potato-dairy systems has produced changes in soil quality that are measurable on a landscape level across fields and farming operations. It reports results from an on-farm assessment of the soil quality status of 48 potato and dairy farm fields under various degrees of integration in Central Maine.

1.6. The Maine Potato Ecosystem Project

Four of the five studies in this dissertation were conducted as part of the MPEP. This interdisciplinary cropping systems trial is located in Presque Isle, Maine. Since its establishment in 1991, the MPEP has included a comparison of contrasting amended and nonamended soil management systems in the context of 2-year potato rotations. The amended soil system is representative of an integrated potato system. It was designed to rapidly improve soil quality through additions of organic amendments (manure, compost, and green manure) and was supplemented with inorganic fertilizer as needed to meet crop needs. The nonamended treatment, representative of a nonintegrated potato system, followed industry standards including inorganic fertilizers and red clover interseeded into the barley rotation crop. These soil management systems were in factorial combination with the other experimental factors (pest management systems and cultivars from 1991 to 1998 and rotation treatments from 1999 to 2006). This experimental design allows for the effects of soil management to be isolated from the other factors, which is not the case in most other cropping systems trials (Smolik et al., 1995; Stine and Weil, 2002).

The amended soil management system caused rapid changes in soil quality, with significantly greater organic matter content after only one season, and significantly greater water stable aggregates after only two (Gallandt et al., 1998b). After 8 years, differences in soil stocks of total and labile C and N between the soil management treatments for this trial were more dramatic than differences observed in similar medium-term cropping systems trials (Burger and Jackson, 2003; Harris et al., 1994; Langmeier et al., 2002; Poudel et al., 2001; Wander et al., 1994). The contrasting and highly divergent amended and nonamended soil management systems, along with the factorial arrangement of treatment factors, created an ideal opportunity to study the effects of amended soil management on soil quality, yield stability, and short- and long-term nitrogen dynamics.

Chapter 2

POTATO YIELD STABILITY UNDER CONTRASTING SOIL MANAGEMENT STRATEGIES

2.1. Chapter Abstract

Managing soil quality is recognized as a cornerstone of maintaining crop production potential. Here we show that soil management that improves soil quality characteristics can also reduce year-to-year variation in yields. Thirteen years of data from the Maine Potato Ecosystem Project were used to investigate the long-term effects of soil management, pest management, cultivar, and rotation in a factorial design on the yield and yield stability of potatoes grown in 2-year rotations. Potato yields in the amended soil system (manure, compost, green manure, and supplemental fertilizer) were up to 55% higher than yields in the contrasting nonamended soil system (synthetic fertilizer) in all but 1 year. Yield stability was also enhanced in the amended system compared with the nonamended system, as demonstrated by lower coefficients of variation (CV) of total and U.S. no. 1 potato tuber yield. Stability analysis indicated that yields in the amended system were less influenced by adverse growing conditions, particularly low rainfall. Total and U.S. no. 1 treatment yields in the poorest-yielding year were 63 and 59% of maximum yields, respectively, in the amended system, compared with 44 and 45% in the nonamended system. Yields and yield stability were also influenced by pest management system and cultivar but not by rotation. These results indicate that management practices that improve soil quality can enhance potato yield stability by reducing the impact of adverse growing conditions.

2.2. Introduction

Farmers emphasize yield potential when evaluating cropping systems but also consider the predictability, or stability, of those yields (Eghball et al., 1995; Varvel, 2000). Year-to-year variation in yields on a specific field is due primarily to weather-related environmental factors, pest and nutritional stresses, and management (Batchelor et al., 2002; Loomis and Conner, 1992; Smolik et al., 1995). A key question in designing cropping systems is whether management can buffer the effects of an unpredictable environment (Varvel, 2000).

Managing soil quality is fundamental to maintaining a soil's crop production potential (Christensen and Johnston, 1997). In fact, the term "soil quality" is commonly defined in terms of sustaining biological productivity as well as maintaining environmental quality and plant and animal health (Karlen et al., 1997). Evidence of the need to manage for soil quality comes from studies of degraded soils that exhibit reduced productivity even with high fertilizer inputs (Aref and Wander, 1998; Cassman, 1999; Parr and Hornick, 1992) and from studies in which increased productivity is associated with enhanced SOC, achieved by amending with organic materials (Barzegar et al., 2002; Christensen and Johnston, 1997; Hornick and Parr, 1987), growing a sod crop (Díaz-Zorita et al., 2002; Johnston, 1991), or reducing tillage (Díaz-Zorita et al., 2002; Dick et al., 1997). Others have found predictive relationships between yield and soil quality characteristics, such as total soil C (Alvarez et al., 2002), active soil C and macroaggregate stability (Stine and Weil, 2002), and total soil N (Stenberg, 1998). Productivity increases in SOC-enhanced soils have been attributed to improvements in soil structure, water-holding capacity (Johnston, 1991), and nutrient supply (Cassman, 1999; Díaz-Zorita et al., 1999).

There is also a perception that high-quality soils may produce more stable yields by buffering environmental factors such as limited or excessive rainfall, pests, and diseases (Ellmer et al., 2000; Romig et al., 1995). Crops grown on soil that receives organic amendments and has enhanced soil quality characteristics have been shown to have access to greater soil moisture (Liebig and Doran, 1999; Lotter et al., 2003) and are more resistant to weed (Gallandt et al., 1998a) and insect (Alyokhin et al., 2005) pressures. However, evidence is scarce that these amended systems reduce yield variation. One recent study comparing two organic systems with a conventional system found similar maize yields in years of adequate rainfall but higher yields in the organic systems in years of drought (Lotter et al., 2003). They attributed this difference to enhanced water-holding capacity of the organically managed soil. In contrast, analysis of two long-term experiments found no evidence that manure-amended systems, associated with improved soil quality, altered temporal yield variability (Aref and Wander, 1998; Eghball and Power, 1995). Additionally, in some organic systems that included soil amendments, greater variation in yield has been reported (Clark et al., 1999; Spiertz, 1989). Work in this area is insufficient to make broad generalizations. Few studies are of adequate duration to assess temporal yield variability (Varvel, 2000), and those with longer-term histories often compare entire cropping systems in an experimental design that makes it difficult to isolate soil management effects from other effects, such as tillage frequency and rotation (Smolik et al., 1995; Stine and Weil, 2002).

Potato may be particularly sensitive to weather-related variation in part because it has a shallower root system than other annual crops (Opena and Porter, 1999). Benoit and Grant (1980; 1985) noted that periods of water deficit or excess severely limited potato yields in northern Maine despite the fact that total rainfall amounts were generally sufficient. Compounding the sensitivity of potato to water stress is the fact that the water-supplying capacity of soil under potato production is often degraded. Potato production in Maine and northeastern Canada has resulted in lower SOC concentration and less structural stability (Saini and Grant, 1980) due to high levels of soil disturbance and low levels of crop residue returns (Angers and Carter, 1996; Grandy et al., 2002). Black and White (1973) noted an increase in potato yield with manure application, independent of applied fertilizer, which they attributed to increased organic matter, water-holding capacity, and cation exchange capacity (CEC). In Maine, the idea that degraded soils are limiting potato yields is supported by the observation that yields have remained relatively constant over the last 50 yr despite increasing inputs of pesticides and fertilizers (Economic Research Service, 2002; Westra and Boyle, 1991).

The Maine Potato Ecosystem Project (MPEP) was initiated in 1991 to investigate key factors limiting potato production. This cropping systems trial compared two contrasting soil management systems. The amended soil management system, designed to improve soil quality, received annual additions of organic amendments (manure and compost) supplemented by synthetic fertilizer. The nonamended soil management system used only synthetic fertilizers. These soil management systems were in factorial combination with the other experimental factors (pest management systems and cultivars from 1991 to 1998 and rotation treatments from 1999 to 2004) so the effects of soil management can be isolated from the effects of other factors. This aspect of the trial, and the fact that the soil treatments caused highly divergent soil characteristics, make the MPEP an ideal trial to investigate long-term effects of soil management. The objectives of this study were (i) to assess the impact of soil management on soil chemical and physical properties and (ii) to investigate the influence of soil management, pest management, cultivar, and rotation on yield and yield stability of potatoes grown in 2-yr rotations.

2.3. Materials and Methods

2.3.1. Site Description

The experiment was conducted from 1991 to 2004 at the Maine Agricultural and Forest Experiment Station's Aroostook Research Farm in Presque Isle, Maine, on a gravely, well drained, Caribou loam soil (fine-loamy, mixed, frigid Typic Haplorthods). The 5.9 ha used for the study had a long history of commercial and research potato production. Details of the establishment of the experiment are given in Porter (1996).

2.3.2. Cultural Practices and Treatments

The experiment consisted of 96 plots (14.6 by 41.0 m) in four replicate blocks and can be divided into two phases. During Phase 1 (1991–1998), treatments were arranged in a randomized, complete-block, split-plot design. Main-plot factors were one of three pest management systems: conventional, reduced input, and bio-intensive. Subplots were a fully factorial combination of two soil management systems (amended vs. nonamended), two potato cultivars ('Atlantic' vs. 'Superior'), and two rotation entry points (potato vs. rotation crop). Although pest treatments were randomly assigned to locations within blocks, and soil and cultivar treatments were randomly assigned to locations within main plots, entry points were assigned to alternating positions within the field in an effort to minimize the movement of insects.

The amended soil management system was designed to rapidly improve soil quality by adding organic amendments (raw beef manure and/or potato cull compost) and by rotating potato with a pea (*Pisum sativum* L. subsp. *sativum*)–oat (*Avena sativa* L.)–hairy vetch (*Vicia villosa* Roth) green manure crop. A secondary objective of this system was to reduce the need for fertilizer. Manure and compost were applied and incorporated before planting potatoes. These organic amendments were supplemented with fertilizer as needed to provide approximately the same nutrient levels as in the nonamended soil treatment. The nonamended soil management system followed industry standards, including rotating potato with barley interseeded with red clover (*Trifolium pratense* L.) and using recommended rates of inorganic fertilizers. Table 2.1 provides average annual application rates of manure, compost, and fertilizer and the estimated average annual availability of N, phosphorus (P), and potassium (K) for the two soil management systems. No micronutrient fertilizers were applied to either soil treatment. Complete descriptions of the pest and cultivar treatments and of the cultural methods are provided elsewhere (Gallandt et al., 1998b; Porter and McBurnie, 1996).

Table 2.1. Applications of amendments and fertilizer and estimated nitrogen (N), phosphorus (P), and potassium (K) availability from these sources during Phase 1 (1992–1998) and Phase 2 (1999–2004) of the Maine Potato Ecosystem Project.

	Average annual application rate					Total estimated average annual availability from current-year applications§		
	Amendments†		Fertilizer‡					
	Manure	Compost	N	P	K	N	P	K
	Mg ha^{-1} fresh wt.		—— kg ha^{-1} ——			——— kg ha^{-1} ———		
			Phase 1					
Amended								
Potato	45	22	84	25	58	179–203	150	239
Pea/oat/vetch	0	7¶	0	0	0	3	6	16
Nonamended								
Potato	0	0	191	59	169	191	59	169
Barley/red clover	0	0	72	0	0	72	0	0
			Phase 2#					
Amended								
Potato	67	0	78	0	19	152–186	90	135
Barley/red clover	45	0	0	0	0	57–73	64	92
Soybean	0	0	0	0	0	0	0	0
Nonamended								
Potato	0	0	190	59	221	190	59	221
Barley/red clover	0	0	73	0	0	73	0	0
Soybean	0	0	34	15	28	34	15	28

† Manure and compost had the following ranges of compositional factors, expressed in kg Mg^{-1} on a fresh weight basis. Manure: total solids, 219–418; total N, 4.0–7.0; NH_4^+–N, 0.08–1.90; P, 0.82–2.63; and K, 0.61–4.45. Compost: total solids, 289–543; total N, 2.3–11.7; NH_4^+–N, 0.21–0.62; P, 0.65–3.12; and K, 1.28–4.05.

‡ Fertilizers were applied in the following forms and times to the following crops: barley, NH_4NO_3 at planting; potato, 10–10–10 at planting (a blend of diammonium phosphate, KCl, NH_4NO_3, and NH_4SO_4), urea ammonium nitrate sidedress, and KCl preplant; soybean, 10–10–10 at planting. In Phase II, amended potato received NH_4SO_4 instead of 10–10–10.

§ The range presented for nitrogen (N) represents uncertain availability of N from solid-bedded manure and compost. The lower value was based on a conservative availability estimate of 50% of applied NH_4^+–N and 25% of applied organic N from manure (Klausner, 1983). The upper range uses less conservative values of 100 and 30%, respectively. Compost N availability was estimated at 50% of applied NH_4^+–N and 10% of applied organic N. The availabilities of N from fertilizer and of P and K from manure, compost, and fertilizer were assumed to be 100% of the applied amounts. The availability of N from the pea/oat/vetch green manure was not included due to uncertainty but was probably about 30 kg N ha^{-1}.

¶ Compost was applied to the pea/oat/vetch rotation crop in 1991, 1992, and 1993 at rates of 13, 22, and 22 Mg ha^{-1}, respectively.

Potato was grown every other year in Phase 2, as in Phase 1, but in a 2-yr rotation of potato-barley/red clover or a 4-yr rotation of potato-barley/red clover-potato-soybean.

The objectives of the project shifted in 1999 to include an investigation of crop diversity effects (Phase 2). The conventional and reduced input pest management plots were redistributed among three crop rotations: standard (potato–barley/red clover), intensive (potato–soybean [*Glycine max* (L.) Merr.]–potato–barley/red clover), and integrated (potato–soybean–barley/alfalfa [*Medicago sativa* L.]/timothy [*Phleum pratense* L.]–forage). These rotations were managed using conventional integrated pest management (IPM) and one potato cultivar (‘Atlantic’). The bio-intensive pest management plots were assigned to the integrated rotation only, with “biorational” IPM pest management (Alyokhin et al., 2005). The changes in the study for Phase 2 created two fully factorial experiments. Experiment 1 included crop rotation and soil management factors and was managed under conventional IPM. Experiment 2 compared pest management and soil management factors within the context of the integrated crop rotation. The two experiments shared the set of plots that were in the integrated rotation and managed with conventional IPM. For consistency with Phase 1, the only 1999–2004 results presented in this paper are those from the standard and intensive rotations of Experiment 1, in which potato was grown every other year.

Plot assignments for the soil management (and entry point) treatments remained constant from 1991 to 2004, giving the plots a continuous 14-yr history of amended or nonamended soil systems. During Phase 2, beef manure was applied before potato and barley crops (Table 2.1). No compost was applied, and amended system soybeans received no manure or fertilizer.

2.3.3. Soil Analyses

Cation exchange capacity, pH, and mineral nutrient content were determined from soil samples taken each fall after crop harvest. Ten soil cores were collected to a 15-cm depth from each plot, bulked, and mixed thoroughly. A subsample was dried, sieved through 2-mm screen, and submitted to the University of Maine Soil Testing Laboratory for pH and CEC analysis using standard methods (Hoskins, 1997; Northeast Coordinating Committee on Soil Testing, 1995). A modified Morgan procedure was used for phosphorus and cation extraction (Northeast Coordinating Committee on Soil Testing, 1995). Soil organic matter and water-stable aggregate content were determined from samples taken each spring before the application of organic amendments. Ten soil cores were collected from a 15-cm depth, air-dried, sieved through a 6.4-mm screen, bulked, and mixed thoroughly. Duplicate subsamples were analyzed for readily oxidizable SOC using the Walkley–Black method (Nelson and Sommers, 1996). A separate set of duplicate subsamples was analyzed for water-stable soil aggregate content according to the methods described by Porter and McBurnie (1996). Soil moisture content was estimated as part of the procedure to monitor soil mineral N content at biweekly intervals throughout the growing season. Ten soil cores were taken to a 20-cm depth and bulked. A 50-g subsample was sieved through a 2-mm screen, weighed wet, dried at 105°C for 24 h, and weighed again.

2.3.4. Yield and Tuber Quality

Potato crop yields were determined from the four center rows of each plot. Tubers were lifted with a two-row potato digger and collected by hand, and the yield of the entire four rows was weighed in the field. Any decaying tubers were weighed separately. Two

22.7-kg subsamples were collected from each plot and graded for tuber size and external defects. U.S. no. 1 yields were calculated as the yield of tubers between 4.8 cm and 10.2 cm in diameter, excluding decayed, sunburned, misshapen, scabby, or growth cracked tubers.

2.3.5. Statistical Analyses

Significant treatment effects and interactions on the selected soil characteristics were identified using ANOVA. The normality of total and U.S. no. 1 tuber yield data was tested using Kolmogorov-Smirnov tests ($p < 0.01$; SYSTAT v.11, 2004). Repeated-measures ANOVA was used to determine the significance of rotation cycle, treatment, rotation cycle by treatment, and treatment interaction effects on total and U.S. no. 1 tuber yields for each phase of the experiment. There were three rotation cycles for each entry point in both phases, corresponding to years 1993/1994, 1995/1996, and 1997/1998 for Phase 1 and 1999/2000, 2001/2002, and 2003/2004 for Phase 2. The first rotation cycle in Phase 1, 1991/1992, was not included because the treatment structure of the experiment was substantially altered after the 1991 season.

Yield stability was assessed by two methods. In the first, the CV of total and U.S. no. 1 yields over time was calculated for each plot within each phase of the experiment (Clark et al., 1999; Spiertz, 1989). The CVs were subjected to ANOVA to determine significant treatment effects and interactions. The second assessment of variability was stability analysis (Guertal et al., 1994; Raun et al., 1993), in which total and U.S. no. 1 yield for each soil management treatment was regressed on the annual mean yield of both treatments combined, designated the "environment mean yield." The environment mean yield reflects the overall growing conditions for each year, which includes temperature, rainfall, pest pressure, and effectiveness of pest and crop management. Regressing treatment yields on the environment mean yield allows one to evaluate the relative response of the treatments under the range of growing conditions that occurred, thereby providing a way to investigate significant year-by-treatment interactions that commonly appear in repeated-measures analyses of long-term trials (Raun et al., 1993). Data from the two phases of the experiment were combined for stability analysis because there were no significant interactions between the soil management treatment and other treatments (pest management, variety, and rotation) on total yield, U.S. no. 1 yield, and the CV of those yields during both phases. A subset of the plots were used that were consistent between Phases 1 and 2 in having potato grown every other year during both phases (this excluded the bio-intensive/biorational IPM plots) and in being planted to 'Atlantic' (this excluded the plots that were planted to 'Superior' in Phase 1). Data for the soil treatments were then averaged by replicate over the two remaining pest treatments in Phase 1 and the two rotation treatments in Phase 2.

The relationship between tuber yield and rainfall was explored to investigate the hypothesis that lower sensitivity to fluctuations in rainfall was a possible mechanism for enhancing yield stability. Using the subset of data used for stability analysis, tuber yield was regressed on rainfall amount (May–September, May–August, and June–August) and evenness (using Shannon diversity index [Bronikowski and Webb, 1996]). The residuals of the regression of yield on June–August rainfall (i.e., the variation in yield that was not explained by June–August rainfall) were regressed on the environment mean yield. The purpose of this second stability analysis, with the effect of rainfall removed, was to investigate the importance of rainfall as a driver of treatment differences in the original stability analysis. The regression lines for the soil treatments from stability analyses and from regressions of yield on rainfall were compared using the extra sums of squares procedure (Motulsky and Christopoulos, 2004). This procedure uses an *F* test to determine if there is a statistically significant difference between the error sum of squares for a model fitting treatments separately (sums of squares are added) and a model fitting all the data at once. We used a *p* value of 0.05 to indicate whether the model with separate fits provided a significant reduction in the error sums of squares, indicating that the treatment regression lines were significantly different.

2.4. Results and Discussion

2.4.1. Soil Characteristics

The amended soil management system substantially increased soil organic C, pH, CEC, and total water-stable aggregates (Table 2.2). Soil organic C in the amended soil was significantly greater than in the nonamended soil after only one season, and water-stable aggregates were significantly greater than in the nonamended soil after two seasons (Gallandt et al., 1998b). Soil organic C was 50% higher in the amended plots by the end of Phase 1 (1998) and 63% higher 5 yr into Phase 2 (2004). This is one of the largest increases in soil organic C among experiments investigating the effects of organic amendment on soil characteristics and crop performance (Clark et al., 1998; Fraser et al., 1988; Poudel et al., 2002; Wander et al., 1994). Consistent with these similar experiments, particulate organic matter carbon was disproportionately enhanced in the amended system, doubling by the end of Phase 1 (Griffin and Porter, 2004). Higher CEC and water-stable aggregate values in the amended system reflect the increase in soil organic C. The amended system substantially increased soil test P due to much greater rates of P inputs than in the nonamended system (Table 2.1). Modified Morgan P in the amended soil in 1998 and 2003 was above the level considered excessive according to Maine nutrient planning guidelines (45 kg ha^{-1}), although it was below the action level for row crops grown on land that is not classified as highly erodable or located in a most at-risk watershed (USDA-NRCS, 2004). In practice, manure application rates should be adjusted to avoid excessive P accumulation in the soil and potential loss to the environment (Sharpley et al., 2001).

Table 2.2. Selected chemical and physical properties of the amended (+) and nonamended (–) soil before initiation (1991) and 1 yr later (1992), at the end of Phase 1 (1998), and 5 yr into Phase 2 (2003) of the Maine Potato Ecosystem Project.

	Organic carbon†		Total water-stable aggregates†		pH		Cation exchange capacity		Modified Morgan P	
Year	+	–	+	–	+	–	+	–	+	–
	g kg^{-1}		%				meq 100 g^{-1}		kg ha^{-1}	
1991	15.7	15.5 ns ‡	25.6	25.7 ns	5.3	5.3 ns	5.3	5.3 ns	29.9	30.5 ns
1992	17.7	15.6 ***	25.8	25.1 ns	5.5	5.4 ns	5.1	4.9 ns	29.9	29.7 ns
1998	27.0	18.0 ***	30.6	19.7 ***	6.2	5.9 ***	10.7	8.2 ***	49.8	32.9 ***
2003	32.1	19.7 ***	36.9	26.4 **	6.3	5.7 ***	10.9	7.9 ***	66.9	36.8 ***

† Dry weight basis.

‡ ns, not significant.

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

2.4.2. Yields and Yield Variation

The amended soil management system produced total and U.S. no. 1 potato yields equal to or greater than those in the nonamended soil in all years but 1996 (Fig. 2.1). Repeated-measures ANOVA revealed significant rotation-cycle by soil system interactions for total and U.S. no. 1 yield (Table 2.3). Yield gains in the amended system, when statistically significant, were 4 to 54% for total yield and 8 to 36% for U.S. no. 1 yield. Foliar macronutrient concentrations in the amended system were lower or equal to those in the nonamended system in all years (Alyokhin and Atlihan, 2005; Porter and McBurnie, 1996) and were always in the sufficiency range for potato (Westermann, 1993). This suggests that yield enhancement in the amended system was not related to the supply of macronutrients. However, boron availability could have contributed to the difference in yields. Leaf tissue boron levels in the amended system (20–32 mg kg^{-1}) were in the sufficiency range, whereas they were in the marginal range for the nonamended system (10–22 mg kg^{-1}), with values of >20 mg kg^{-1} considered sufficient and 10 to 20 mg kg^{-1} considered marginal (Westermann, 1993). The yield results are consistent with many other trials that have demonstrated the ability of systems relying primarily on organic sources of fertility to produce crop yields comparable to those of synthetic fertilizer-based systems (Eghball et al., 1995; Johnston, 1991; Poudel et al., 2002; Stanhill, 1990). These results are also in agreement with others who have found that potato production can be limited by soil quality (Black and White, 1973; Porter et al., 1999).

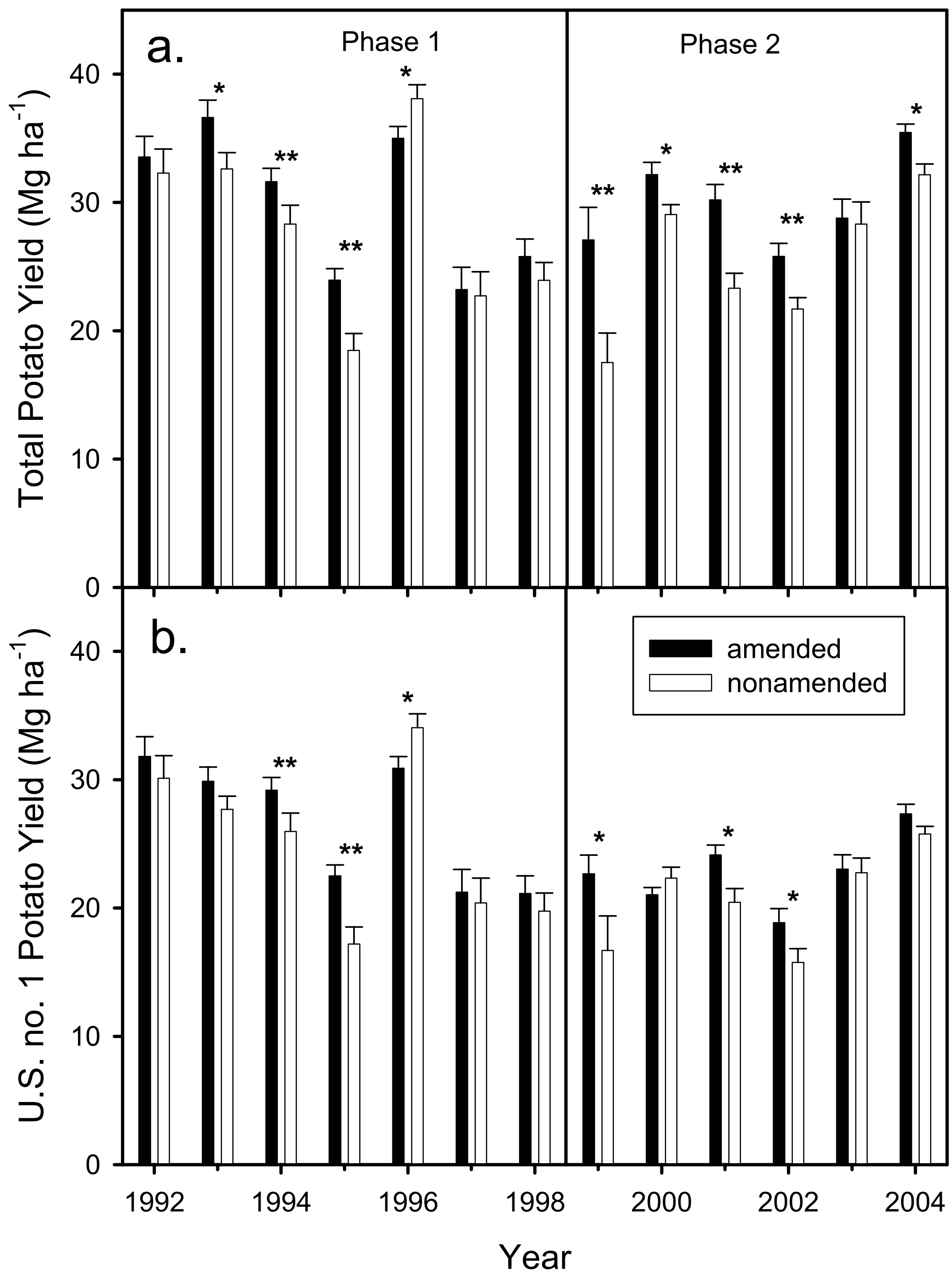

Figure 2.1. Annual mean yields of (a) total and (b) U.S. no. 1 potatoes in the amended and nonamended soil treatments in Phase 1 (n = 24) and Phase 2 (n = 8) of the Maine Potato Ecosystem Project. Error bars correspond to 1 SE. Significant differences between the treatments in any given year are indicated with * $p < 0.05$ and ** $p < 0.01$.

Table 2.3. Repeated-measures ANOVA of total and U.S. no. 1 potato tuber yield of the Maine Potato Ecosystem Project.

Sources of variation	df	Mean square: Total yield	Mean square: U.S. no. 1 yield
		Phase 1	
Cycle (C)†	2	135,974 ***	117,132 ***
C×Rep	6	2,400 **	1,576 ns
C×Pest (P)	4	2,400 ns ‡	56 ns
Error (a)	12	1,058	1,237
C×Soil (S)	2	3,896 ***	1,664 ns
C×Cultivar (V)	2	23,070 ***	33,207 ***
C×Entry point (EP)	2	198,710 ***	115,135 ***
C×P×EP	4	2,515 *	2,613 **
C×S×EP	2	13,130 ***	13,645 ***
C×V×EP	2	1,624 ns	3,120 *
Other interactions		ns	ns
Error (b)	126	734	733
		Phase 2	
C	2	24,969 ***	17,572 ***
C×Rep	6	1,882 ns	1,632 *
C×S	2	3,578 *	976 ns
C×Rotation	2	1,855 ns	1,329 ns
C×EP	2	21,898 ***	13,452 ***
C×S×EP	2	3,474 *	3,207 *
Other interactions		ns	ns
Error	42	937	684

† The “cycle” term refers to three rotation cycles for each entry point in Phase 1 and 2, which correspond to years 1993/1994, 1995/1996, and 1997/1998 for Phase 1 and 1999/2000, 2001/2002, and 2003/2004 for Phase 2.
*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
‡ ns, not significant.

Temporal variation in annual potato yield was high (Fig. 2.1) and loosely followed annual rainfall patterns (Table 2.4). However, year-to-year variation was significantly reduced in the amended soil system for both yield classes and during both phases of the study (Tables 2.5 and 2.6). This finding contradicts results from two long-term trials in which repeated manure application enhanced crop yields compared with unmanured treatments but failed to reduce year-to-year variation in those yields (Aref and Wander, 1998; Eghball et al., 1995). It is possible that the discrepancies in soil physical and chemical characteristics between contrasting soil treatments were not as great in these studies as in the MPEP. Neither study reported soil characteristics for the treatments or time period reported. Additionally, the crops tested (maize, oats, and hay) may not be as sensitive to sources of temporal variation as potato.

Table 2.4. Monthly rainfall amounts at Aroostook Research Farm, Presque Isle, Maine, 1992–2004.

	Monthly rainfall					Totals	
Year	May	June	July	Aug	Sept	May - Aug	May - Sept
1992	38	107	93	128	52	330	419
1993	83	141	51	76	131	267	483
1994	115	118	81	32	92	231	437
1995	58	39	61	61	56	161	276
1996	101	93	130	65	101	288	491
1997	138	62	74	113	64	249	451
1998	94	83	140	63	78	286	458
1999	37	104	64	114	239	283	558
2000	116	63	65	77	35	205	356
2001	50	58	83	46	114	186	351
2002	91	55	160	38	102	253	446
2003	66	94	117	85	42	295	404
2004	54	83	114	91	68	287	408

Table 2.5. Analysis of variance of year-to-year variation, expressed as the CV, in total and U.S. no. 1 potato tuber yield during Phase 1 (1992–1998) and Phase 2 (1999–2004) of the Maine Potato Ecosystem Project.

	CV of total yield		CV of U.S. no. 1 yield	
Sources of variation	df	Mean square	df	Mean square
		Phase 1		
Rep	3	299 ns †	3	200 ns
Pest	2	534 *	2	821 ns
Error (a)	6	76	6	200
Soil	1	444 *	1	482 *
Cultivar	1	4459 ***	1	6707 ***
Entry point	1	3172 ***	1	434 *
Interactions		ns		ns
Error (b)	62		61	
		Phase 2		
Rep	3	148 ns	3	335 **
Soil	1	697 **	1	759 **
Rotation	1	3 ns	1	1 ns
Entry point	1	144 ns	1	130 ns
Interactions		ns		ns
Error	21		21	

† ns, not significant.
*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Table 2.6. Effect of soil management, pest management, and cultivar on the CV of total and U.S. no. 1 potato tuber yield during Phase 1 (1992–1998) and Phase 2 (1999–2004) of the Maine Potato Ecosystem Project.

Treatments	CV of total yield	CV of U.S. no. 1 yield
	Phase 1	
Soil management		
Amended soil	24.5 b†	23.9 b
Nonamended soil	28.8 a	28.4 a
Pest management		
Conventional	23.7 b	21.7 a
Reduced input	24.8 b	25.0 a
Bio-intensive	31.4 a	31.8 a
Cultivar		
‘Atlantic’	19.8 b	17.7 b
‘Superior’	33.5 a	34.7 a
	Phase 2	
Soil management		
Amended soil	15.5 b	16.0 b
Nonamended soil	24.8 a	25.7 a
Rotation		
Potato-barley	19.9 a	20.7 a
Potato-barley-potato-soybean	20.5 a	21.0 a

† Treatment means within columns and treatment factors that are followed by different letters are significantly different based on Fisher-protected LSDs ($p < 0.05$).

Pest and cultivar (Phase 1) affected the CV for yields, whereas rotation (Phase 2) did not (Tables 2.5 and 2.6). ‘Superior’ showed considerably more variation in yield than ‘Atlantic’ (CVs for ‘Superior’ were 33.5 and 34.7% compared with CVs for ‘Atlantic’ of 19.8 and 17.7% for total and U.S. no. 1 yield, respectively) presumably because ‘Superior’ matures earlier and is more susceptible to heat stress, water stress, and early dying than ‘Atlantic’. Mean CVs for total and U.S. no. 1 yield were higher in the bio-intensive pest management system (31.4 and 31.8%, respectively) than in the pesticide-based systems (23.7 and 21.7%, respectively, for conventional and 24.8 and 25.0%, respectively, for reduced input). Pest and cultivar effects are discussed in more detail elsewhere (Gallandt et al., 1998b).

2.4.3. Yield Stability

Regression of treatment yield on the environment mean yield was significant in all cases (Fig. 2.2), and extra sums of squares analysis distinguished between the responses of the two soil management treatments for total and U.S. no. 1 yield. The amended system produced more stable yields over the range of growing conditions occurring in this study. Total and U.S. no. 1 treatment yields in the poorest-yielding year were 63 to 59% of maximum yields, respectively, in the amended system compared with 45 and 46% in the nonamended system. Yields were most divergent between the soil management systems at the lowest environment mean (i.e., poorest growing conditions) and converged as growing conditions improved, suggesting that the amended system buffered one or more yield-limiting factors.

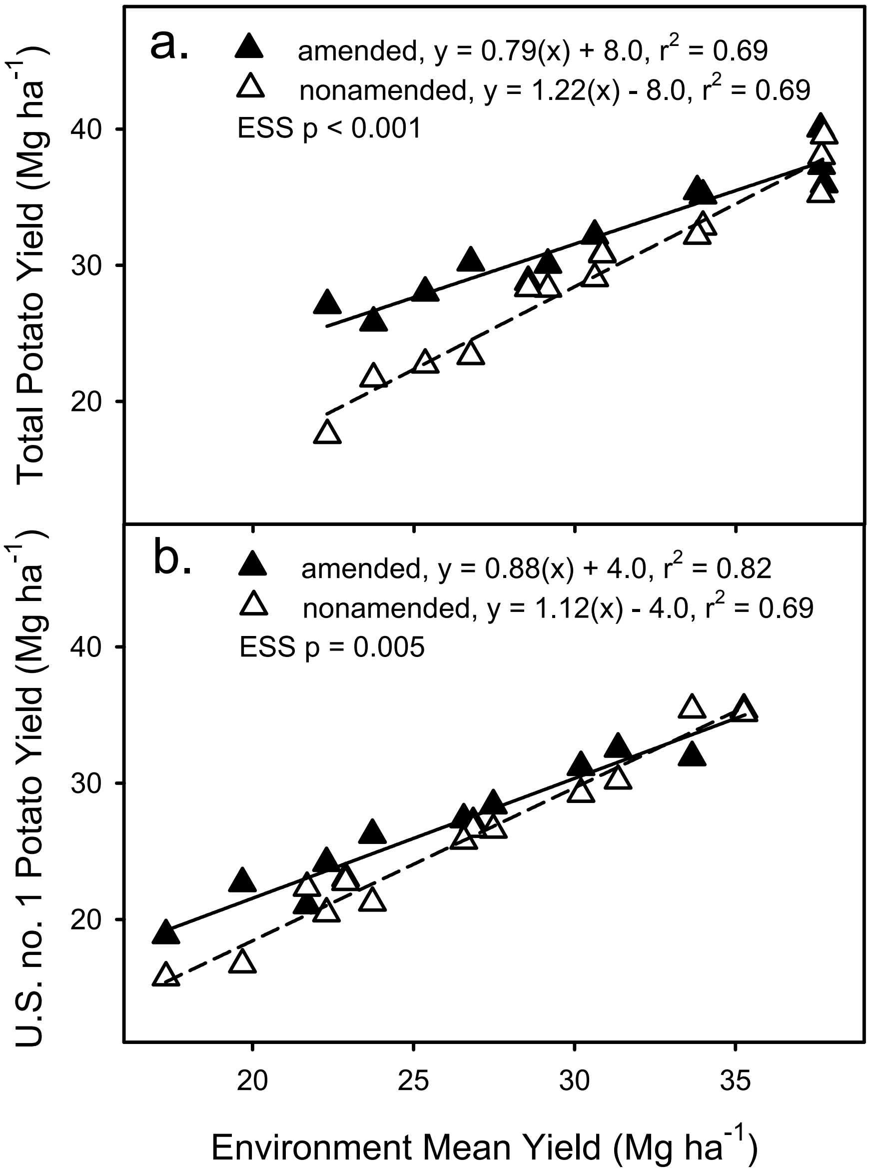

Figure 2.2. Linear regression of (a) total potato yield and (b) U.S. no. 1 potato yield on the environment mean yield for amended (filled triangle) and nonamended (open triangle) soil management treatments of the Maine Potato Ecosystem Project, 1992 to 2004. Individual data points are the mean of four replicates (n = 4). Probability values are from extra sums of squares (ESS) analysis comparing amended vs. nonamended soil regression lines (n = 52; 13 yr times four replicates).

Rainfall could be one such yield-limiting factor whose effects could be influenced by soil management. Variation in the amount and timing of rainfall is one of the primary causes of year-to-year variation in crop yields (Batchelor et al., 2002; Loomis and Conner, 1992; Runge and Hons, 1998). In this study, June–August rainfall produced the strongest linear relationship with total and U.S. no. 1 tuber yield (R^2 between 0.07 and 0.15) compared with other rainfall periods and rainfall evenness measures. Although the relationships between yield and the rainfall evenness measures used were weak, the distribution of rainfall was also important. For instance, June–August rainfall in 1999 was in the middle of the range (283 mm) but much of that rainfall came late in the season. In contrast, in 2002 most of the 253 mm of rain occurred early in the season, with little rainfall from mid-July through August during the critical tuber-bulking period. The poor distribution of rainfall in these years is reflected in relatively low yields. Additionally, other influences, such as insect pests, diseases, nutrient availability, and growing degree days, are important influences on yield and should be included in a subsequent study of the major determinants of yield in this trial. Here, our intention was to identify a likely source of year-to-year variation whose effects were influenced by soil management.

The amended treatment was less sensitive to changes in rainfall than the nonamended treatment, as indicated by the lower slopes and R^2 values (Fig. 2.3). Increased water-supply capacity is often associated with increased SOC (Barzegar et al., 2002; Liebig and Doran, 1999; Weil and Magdoff, 2004). Soil moisture, measured at biweekly intervals throughout the growing season, was almost always significantly higher in the amended versus the nonamended system. In the three representative years of soil moisture data presented in Fig. 2.4, soil moisture was 4 to 29% greater in the amended than in the nonamended plots.

The observation that the relationships between yields and rainfall paralleled those with the environment mean yield suggests that the different responses of the soil management systems to rainfall largely explain the difference in yield stability between the soil systems. Further evidence of this comes from the fact that when the residuals from regressing yield on rainfall were regressed against the environment mean, the soil management system effect was no longer significant (extra sums of squares p values were 0.181 and 0.504 for total and U.S. no.1 yields, respectively). In other words, removing the variation due to rainfall from the yields eliminated the difference in yield stability between the two soil management systems.

Lotter et al. (2003) recently reported increased drought tolerance of two organic cropping systems compared with a conventional system in Pennsylvania. In years of insufficient rainfall, the manure-based and legume-based organic systems, both of which had enhanced soil characteristics, produced higher yields of maize and soybean than a fertilizer-based system, but yields between the three systems were equal when rainfall was sufficient. Likewise, in the Argentine Pampa, wheat (*Triticum aestivum* L.) grain yields correlated with total soil C and soil water retention in years of rainfall deficit but correlated with total organic N and available P in higher rainfall years (Díaz-Zorita et al., 1999).

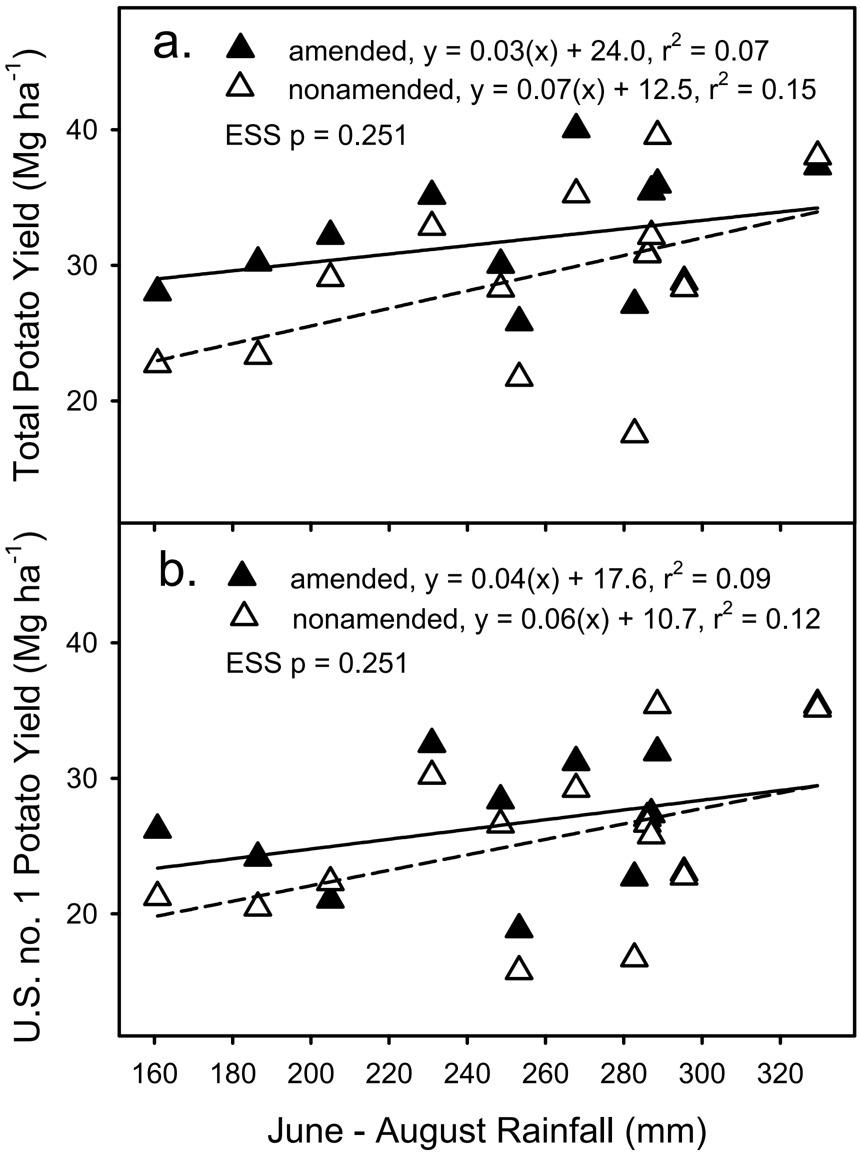

Figure 2.3. Linear regression of (a) total potato yield and (b) U.S. no. 1 potato yield on June through August rainfall for amended (filled triangle) and nonamended (open triangle) soil management treatments of the Maine Potato Ecosystem Project, 1992 to 2004. Individual data points are the mean of four replicates (n = 4). Probability values are from extra sums of squares (ESS) analysis comparing amended vs. nonamended soil regression lines (n = 52; 13 yr times four replicates).

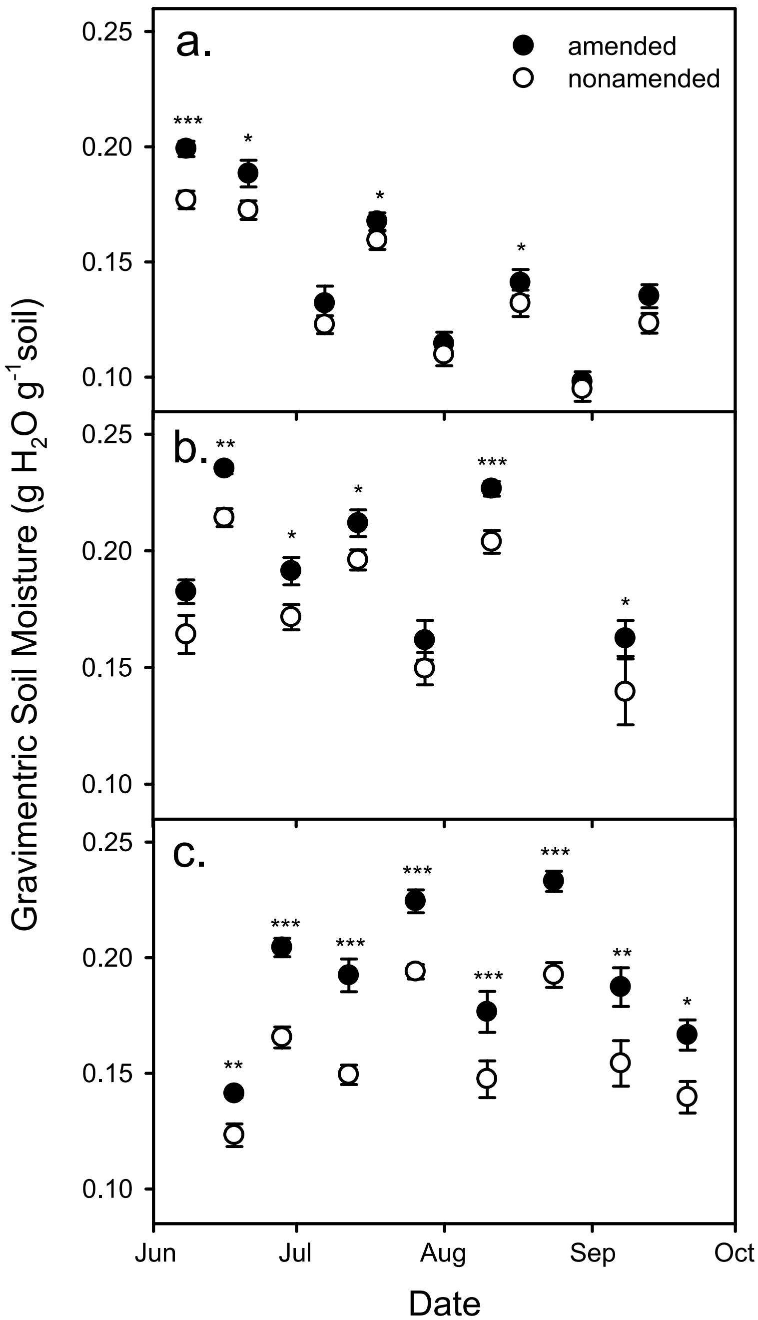

Figure 2.4. Gravimetric soil moisture in the amended and nonamended soil treatments (a) in the first year soil moisture was measured (1995), (b) at the end of Phase 1 (1998), and (c) 6 yr into Phase 2 (2004) of the Maine Potato Ecosystem Project (n = 8). Error bars correspond to 1 SE. Significant differences between the treatments in any given year are indicated with * $p < 0.05$, ** $p < 0.01$, and ***$p < 0.001$.

Buffering variable rainfall amounts may not be the only way in which an amended soil management system enhances crop yield stability. Results from the MPEP show that when weed biomass significantly affects yield, as occurred in the bio-intensive pest management treatments, both were reduced in the amended as compared with the nonamended system (Gallandt et al., 1998a). The authors proposed that the amended soil management system produced a more vigorous crop that was better able to compete with weeds than the nonamended soil system. Also in the MPEP, *in situ* densities of Colorado potato beetles [*Leptinotarsa decemlineata* (Say)] were lower in the amended system compared with the nonamended system (Alyokhin et al., 2005), as were reproduction and development of Colorado potato beetles caged on potato plants grown in the amended versus the nonamended soil (Alyokhin and Atlihan, 2005). Additionally, potato leaf mineral compositions in the two soil systems were highly discrepant and explained 40 to 57% of the variation in *in situ* Colorado potato beetle populations (Alyokhin et al., 2005). The authors proposed that, taken together, these results provide support for the mineral balance hypothesis (Phelan et al., 1996), which postulates that increased SOC and microbial activity associated with organically managed soils maintain a balanced nutrient profile in the plants that promotes good plant growth and resistance to herbivory. The relative importance of the amended soil management system's apparent abilities to modulate the effects of weed pressure, insect pest pressure, and variable rainfall on potato yields cannot be separated in this study.

In addition to enhancing soil physical and chemical characteristics considered favorable for crop production, the amended soil treatment exhibited an increase in soil test P (Table 2.2), raising concerns of environmental export. From this standpoint, levels of manure such as these might not be desirable, nor are they likely possible given a limited supply (Christensen and Johnston, 1997; Magdoff and Weil, 2004). However, if the enhancement of organic matter and its associated soil quality characteristics are primarily responsible for increasing yield stability, then the relationship between organic matter and yield stability should be maintained for other management strategies that improve or maintain soil quality, such as reduced tillage (Díaz-Zorita et al., 2002; Dick et al., 1997), rotations with sod crops (Johnston, 1991), or reducing amendment applications to maintenance levels (Grandy et al., 2002).

2.5. Conclusions

A soil management system designed to improve soil quality through the addition of organic amendments provided the optimal combination of enhancing potato yields and reducing the year-to-year variability of those yields. Potato production in the contrasting nonamended soil system was more susceptible to adverse growing conditions, particularly low rainfall, and seemed to be limited by poor soil quality. These results demonstrate that managing for soil quality with an amended soil management system can be a viable strategy to buffer the effects of an unpredictable growing environment and stabilize yield.

Chapter 3

STORAGE AND LOSS OF CARBON AND NITROGEN UNDER CONTRASTING SOIL MANAGEMENT STRATEGIES

3.1 Chapter Abstract

Soil management systems that retain a greater proportion of added C and N can play a key role in reducing the negative impact of agriculture on the environment. Soil retention of N appears to be related to soil C availability, thus systems that enhance soil C stocks may also reduce N loss. Carbon and N loss and retention were evaluated in contrasting amended (manure, compost, green manure, and supplemental fertilizer) and nonamended (synthetic fertilizer) soil management treatments in the Maine Potato Ecosystem Project from 1991 to 1998. Loss of C and N was greater in the amended system, which received three and two times more inputs of C and N, respectively, than the nonamended system. In relative terms, however, the amended system lost less, and retained more, C and N. Retention efficiencies for C and N were 43% and 88%, respectively, in the amended system compared with 14% and 71%, respectively, in the nonamended system. Greater retention efficiencies in the amended system are probably related, for C, to input quantity and quality, and, for N, input quality and higher soil C levels.

3.2. Introduction

Maintaining or improving soil stocks of C and N while minimizing their export to the environment are key goals of sustainable agriculture. Soil management systems that include organic amendments (animal manure, compost, and green manure) may play a role in meeting both goals. Studies comparing amended and nonamended soil systems have found a linear relationship between the quantity of C added to the soil and resulting soil C (Carter, 2002; Griffin and Porter, 2004). The composition, or quality, of added C also appears to play a role by influencing the retention of added C in the soil (Paustian et al., 1992). For instance, solid cattle manure, grass green manure, straw plus N fertilizer, and straw alone, applied annually for 35 years at equivalent C loading rates, altered soil C differently; C retention was 27, 12, 17, and 5% of applied C, respectively, for these treatments (Persson and Kirchmann, 1994). The authors attributed the higher retention of manure C to its composition, specifically its higher proportion of recalcitrant C. Drinkwater et al. (1998) used natural abundance $\delta^{13}C$ analysis to show that a legume-based system retained a greater proportion of C from the residue of C_3 plants versus C_4 plants. Using the same technique, Gregorich et al. (2001) also found increased retention of C in a legume-based versus a monoculture corn cropping system. Drinkwater et al. (1998) proposed that the lower C:N ratio and the diversity of inputs in the legume-based system resulted in better biological cycling and increased retention.

Soil N retention appears to be governed largely by soil C content, but clear evidence of this relationship in agricultural soil is lacking. In two studies, a greater proportion of N inputs was accounted for, either as harvested crop or soil storage, in manure- and legume-based systems compared with fertilizer-based systems, but the influence of increased soil C could not be confirmed in either study due to the inclusion of N-scavenging winter cover crops in only the organic systems (Drinkwater et al., 1998; Poudel et al., 2001). The linkage between N retention and C availability has been shown more definitively in non-cultivated soils. Barrett and Burke (2002) applied ^{15}N labeled fertilizer to a range of grassland soils from the Great Plains and found that soil C concentration explained up to 40% of the variation in total recovery of applied N one to three growing seasons after application. Similarly, Hatch et al. (2000) detected a greater increase in N immobilization in high- vs. low-C pasture soil three months after a one-time application of manure.

The Maine Potato Ecosystem Project has included a comparison of contrasting amended (manure, compost, and green manure) and nonamended soil management systems in the context of 2-year potato rotations since its establishment in 1991. The soil management factor was not confounded with tillage or rotation factors, as is often the case in cropping systems trials (Smolik et al., 1995), and produced soils of highly divergent C and N stocks. Changes in soil C and N from 1991 to 1998 were compared to C and N budgets to assess whether the amended soil management system reduced loss and enhanced soil retention of C and N relative to the nonamended system.

3.3. Materials and Methods

3.3.1. Site Description

The Maine Potato Ecosystem Project (MPEP) was established in 1991 at the Maine Agricultural and Forest Experiment Station's Aroostook Research Farm in Presque Isle, Maine. The 5.9 ha used for the study were on a gravely, well drained, Caribou loam soil (fine-loamy, mixed, frigid Typic Haplorthods) that had a long history of commercial and research potato production. Details of the establishment of the experiment are given in Porter (1996). Results from the first eight years of the project are reported here.

3.3.2. Cultural Practices and Treatments

The experiment consisted of 96 plots (14.6 by 41.0 m) in four replicate blocks. Potatoes were grown in 2-year rotations, typical for northern Maine. Treatments were arranged in a randomized, complete-block, split-plot design with four replications. Main-plot factors pest management systems (conventional, reduced input, and bio-intensive). Subplots were a fully factorial combination of two soil management systems (amended and nonamended), two potato cultivars ('Atlantic' and 'Superior'), and two rotation entry points (potato and rotation crop). The present study focuses on the amended vs. nonamended comparison although statistical results for cultivar and pest management system factors (excluding the biological treatment) are presented. To reduce sample numbers, only plots from the second entry point were analyzed.

The amended soil management system was designed to rapidly improve soil quality by adding organic amendments. These amendments were supplemented with small inputs of inorganic fertilizer as needed during the potato phase of the rotation to provide approximately the same level of plant-available nutrients as the nonamended soil management system. Beef manure and potato compost were applied annually from 1991 to 1993 and semi-annually (potato year only) from 1994 to 1998. The amended soil system also included a pea–oat–hairy vetch green manure as the rotation crop, except in 1991 when barley was grown as the rotation crop. The nonamended soil management system followed industry standards, including rotating potato with barley interseeded with red clover and using recommended rates of inorganic fertilizers. Complete descriptions of the pest and cultivar treatments and of the cultural methods are provided elsewhere (Gallandt et al., 1998b; Porter and McBurnie, 1996).

Tillage practices were identical for all treatments. Plots were moldboard plowed in the fall of 1990. In subsequent years plots were generally chisel plowed in the fall, tandem offset disked once or twice in the spring, and harrowed prior to planting potato or rotation crops. Potatoes were hilled once or twice.

3.3.3. Soil Sampling and Analyses

Ten soil cores were collected to a 23-cm depth from each plot, bulked, and mixed thoroughly each fall after crop harvest. A subsample was dried, sieved through a 2-mm screen, and stored in a cardboard box. In 2007, a 2-g subsample of archived soil was pulverized and submitted to the University of California-Davis Stable Isotope Facility for total C and N analysis by combustion. The total C measured likely represents organic C because the soil pH (5.3 to 6.2) and the length of time between lime application and sampling (applied in 1991 and 1992 but before 1991 soil sampling) suggest that inorganic C levels were negligible.

Bulk density was determined each year in May before primary tillage, and in July of 1997 and 1998, using the core method described by Blake and Hartge (1986). Metal rings were pounded into the soil using a cylindrical sleeve. The sample rings were removed, trimmed with a metal spatula, capped, dried at 105°C, and sieved to 2 mm to separate coarse fragments. Both fractions were weighed and bulk density estimates were corrected for coarse fragments.

3.3.4. C and N in Harvested Crop, Crop Residues, and Amendments

Potato crop yields were determined from the four center rows of each plot (3.7 x 41 m). Tubers were lifted with a two-row potato digger and collected by hand, and the yield of the entire four rows was weighed in the field. Tuber and haulm biomass yields were determined by removing eight randomly selected plants per plot just before vine desiccation (representing a 1.7 m^2 area). Plants were separated into tubers, stems, and leaves, and these fractions were washed, weighed, and subsampled. Subsamples were dried, reweighed for dry matter determination, ground, and submitted to the University of Maine Analytical Laboratory for C and N determination.

Barley grain yields were determined by harvesting two 1.5-m swaths with a small-plot combine. Before combining, six 0.5-m^2 quadrat samples were collected to determine aboveground biomass production. Straw yields were determined by subtracting grain yields from above-ground biomass. Subsamples of grain and straw were dried, ground, and submitted to the University of Maine Analytical laboratory for C and N determination.

Green manure and red clover above-ground production was determined in October of each year by clipping biomass at soil level from six 0.5-m^2 quadrat samples per plot. Three of the quadrat samples were pooled to create a single aggregate yield sample. The remaining three quadrat samples were sorted to determine biomass of the individual crops and total weeds. A representative subsample of the aggregate green manure mixture was dried, ground, and submitted to the University of Maine Analytical Laboratory for C and N determination.

Manure and compost samples were submitted to the University of Maine Analytical Laboratory for moisture and nutrient analyses. Total C was measured starting in 1997.

The linear relationship between total C and N for manure samples from 1997 to 2005 was used to estimate manure C concentration in 1991 to 1996.

3.3.5. C and N Budget Calculation

Carbon and N input, output, and net input (balance) were estimated for each plot from 1991 to 1998 (Tables 3.1 and 3.2). Potato and barley yield data were available for all years, but at the time of writing, plant above-ground biomass and C and N concentration were available by plot for only 1997 and by soil management treatment for only 1991 to 1994. For other years, soil management treatment average values from 1991 to 1994 and 1997, as well as published values (Meisinger and Randall, 1991), were used. In the absence of measured values, plant tissue was assumed to be 40% C (Johnson et al., 2006). Legumes were assumed to have derived 58% of their N content from the atmosphere via dinitrogen fixation. This figure, determined in 2002 using the ^{15}N pool dilution method (Weaver and Danso, 1994) in a separate field experiment of red clover interseeded with barley (Mallory and Griffin, unpublished), was within the range published by Meisinger and Randall (Meisinger and Randall, 1991) for annual legumes grown in soil with 56-112 kg ha^{-1} available N. Root biomass input was estimated using published root:shoot ratios for the different plants (Bolinder et al., 1997; Bolinder et al., 1999; Buyanovsky and Wagner, 1986; Janzen et al., 2003; Johnson et al., 2006; Kolbe and Stephan-Beckmann, 1997; Marra, 1996; Opena and Porter, 1999; Vos and van der Putten, 2000). Rhizodeposition was not included due to the great uncertainty in these estimates (Johnson et al., 2006). Atmospheric deposition was estimated by year using published values of annual wet and dry N deposition for Caribou, Maine (National

Atmospheric Deposition Program, 2007) and Ashland, Maine (US Environmental Protection Agency, 2007).

Soil storage was calculated as the difference between 1991 and 1998 in soil C and N stocks, which were determined by converting measured soil C and N concentrations (g kg^{-1}) to an area basis (kg ha^{-1}) using bulk density measures. Bulk density varies with tillage, rainfall, and other temporal factors. Thus, it is preferable that bulk density samples be collected concurrently with soil C and N samples. This was not the case in the present study, as described previously. The measure of bulk density closest to the fall 1998 soil C and N sampling and with the least soil disturbance between them would have been in spring 1999, but bulk density was not taken that year. Instead, the average of May 1997 and May 2001 bulk densities were used (0.854 and 0.962 g cm^{-3} for amended and nonamended systems, respectively). Reliable estimates of bulk density in 1991 were not available for the selected plots used in this study. It was assumed, therefore, that the average estimate of spring 1998 bulk density for the nonamended system plots was representative of initial conditions in both the nonamended and amended system plots since soil C was similar for all three (Table 3.3).

Retention efficiency was calculated as the proportion of net C or N input that was found stored in the soil (i.e., soil storage divided by net input times 100).

Table 3.1. Carbon input, harvest output, and net C input in the amended and nonamended soil management systems of the Maine Potato Ecosystem Project, 1991 to 1998.

		Carbon (C) input							
Year	Crop†	Crop	Cover crop	Manure	Compost	Seed	Total	C harvest output	Net C input
		kg C ha^{-1}							
Amended									
1991	Barley/RC	1,044	404	0	632	51	2,131	442	1,688
1992	Potato	5,327	0	4,417	993	258	10,995	3,836	7,159
1993	POV	0	3,234	0	1,050	89	4,373	0	4,373
1994	Potato	4,703	0	3,842	1,425	235	10,205	3,387	6,819
1995	POV	0	3,234	0	0	72	3,306	0	3,306
1996	Potato	4,991	0	4,130	1,903	293	11,317	3,594	7,723
1997	POV	0	3,187	0	0	72	3,260	0	3,260
1998	Potato	3,764	0	3,891	1,904	339	9,899	2,710	7,188
Cumulative total		19,830	10,058	16,281	7,908	1408	55,485	13,970	41,515
Nonamended									
1991	Barley/RC	1,038	404	0	0	51	1,492	440	1,052
1992	Potato	5,279	0	0	0	258	5,537	3,802	1,735
1993	Barley/RC	2,849	404	0	0	51	3,303	1,207	2,096
1994	Potato	4,439	0	0	0	235	4,674	3,196	1,478
1995	Barley/RC	2,852	404	0	0	48	3,303	1,208	2,095
1996	Potato	5,595	0	0	0	293	5,887	4,029	1,859
1997	Barley/RC	2,760	405	0	0	56	3,220	1,301	1,919
1998	Potato	3,614	0	0	0	339	3,952	2,602	1,350
Cumulative total		28,425	1,616	0	0	1329	31,370	17,785	13,584

† RC, red clover interseeded cover crop; POV, Pea/oat/vetch green manure cover crop.

Table 3.2. Nitrogen input, harvest output, and net N input in the amended and nonamended soil management systems of the Maine Potato Ecosystem Project, 1991 to 1998.

Year	Crop†	Nitrogen (N) input							N harvest output	Net N input
		Manure	Compost	Fertilizer	Seed	N fixation	Atmosph. deposition	Total		
		kg N ha^{-1}								
Amended										
1991	Barley/RC	0	43	58	3	17	3	123	23	100
1992	Potato	315	67	110	10	0	3	505	153	352
1993	POV	0	71	0	11	70	3	156	0	156
1994	Potato	237	96	67	9	0	3	413	135	278
1995	POV	0	0	0	8	70	3	82	0	82
1996	Potato	276	110	71	12	0	3	471	144	327
1997	POV	0	0	0	8	71	3	82	0	82
1998	Potato	269	156	78	14	0	3	519	108	411
Cumulative Total		1098	543	383	76	228	24	2352	564	1788
Nonamended										
1991	Barley/RC	0	0	58	3	17	3	81	23	58
1992	Potato	0	0	171	10	0	3	185	152	33
1993	Barley/RC	0	0	85	3	17	3	108	63	44
1994	Potato	0	0	194	9	0	3	206	128	78
1995	Barley/RC	0	0	80	3	17	3	102	63	39
1996	Potato	0	0	207	12	0	3	222	161	61
1997	Barley/RC	0	0	74	3	17	3	97	66	31
1998	Potato	0	0	186	14	0	3	203	104	99
Cumulative total		0	0	1056	56	67	24	1203	761	442

† RC, red clover interseeded cover crop; POV, Pea/oat/vetch green manure cover crop.

Table 3.3. Soil total C and N concentration and stock in the amended and nonamended soil management systems of the Maine Potato Ecosystem Project, 1991 and 1998.

	n	Total C 1991	Total C 1998	Total C Stock 1991	Total C Stock 1998	Total N 1991	Total N 1998	Total N Stock 1991	Total N Stock 1998
		—— $g\ kg^{-1}$ ——		—— $kg\ ha^{-1}$ ——		—— $g\ kg^{-1}$ ——		—— $kg\ ha^{-1}$ ——	
Soil management system									
Amended	16	16.4	24.9 a†	35,910	53,522 a	1.52	2.29 a	3,333	4,912 a
Nonamended	16	15.9	16.6 b	34,517	36,392 b	1.51	1.66 b	3,322	3,626 b
					ANOVA (mean square)				
Sources of variation	df								
Year (Y)	1	341.71 ***		1477.7 *** ‡		3.1885 ***		13,848,000 ***	
YxRep	3	0.19 ns§		3.4 ns		0.0072 ns		69,287 ns	
YxPest	1	11.08 *		53.2 ns		0.0301 ns		141,931 ns	
Error (a)	3	0.96		8.27		0.0102		78,834	
YxSoil	1	221.98 ns		906.3 ***		1.4769 ***		5,893,440 ***	
YxCultivar	1	0.47 ns		1.9 ns		0.0001 ns		174 ns	
Interactions	4	ns		ns		ns		ns	
Error (b)	17	0.66		3.8		0.0055		25,771	

† Treatment means within columns followed by different letters are significantly different based on univariate ANOVAs.
*, *** Significant at 0.05, and 0.001 probability levels, respectively.
‡ Mean squares for soil C stock are in Mg ha^{-1}.
§ ns, not significant.

3.3.6. Statistical analysis

Repeated measures ANOVA was used to test the effects of year (1991 and 1998), soil management system, pest management system and cultivar on soil total C and N concentrations, and was followed by univariate ANOVA by year for significant year by treatment interactions.

3.4. Results and Discussion

3.4.1. C and N Input and Output

Total C inputs were 77% higher in the amended than in the nonamended soil system (Table 3.1). The amended system received 597 kg ha^{-1} yr^{-1}, or 50%, less C as crop residues (crop input – harvested crop), but 1055 kg ha^{-1} yr^{-1} more C as cover crop than the nonamended system. The amended system also received an average of 3024 kg C ha^{-1} yr^{-1} as manure and compost. Resulting net C inputs were three times higher in the amended system than the nonamended system.

Total N inputs were twice as high in the amended system as in the nonamended system (Table 3.2). The diverse sources of N amendments (manure, compost, and legume N fixation) together contributed 80% of the N to the amended system, with fertilizer, seed, and atmospheric deposition contributing the remainder. In the nonamended system, fertilizer N constituted 88% of total N inputs. Nitrogen outputs were 34% lower in the amended system than the nonamended system due to the inclusion of the non-harvested pea/oat/vetch green manure instead of barley in 1993, 1995, and 1997. The resulting net N inputs were four times higher in the amended system than the nonamended system.

3.4.2. Soil C and N Concentration

The high loading rates of organic amendments in the amended soil management system were intended to rapidly increase soil C and they did — soil total C concentration increased by 52% from 1991 to 1998, while it changed by only 4% in the nonamended soil management system over the same period (Table 3.3). Results were similar for total N concentration, with a 51% increase in the amended system and a 10% increase in the nonamended system from 1991 to 1998. The increases in soil C and N concentration in the amended system are large compared to changes observed in other cropping systems trials of similar duration most likely because organic amendment loading rates were lower in these other trials (Burger and Jackson, 2003; Fraser et al., 1988; Langmeier et al., 2002; Poudel et al., 2001) or growing conditions were more conducive to high C turnover (Clark et al., 1998). Increases in soil C and N concentration similar to those in the amended soil system have been observed in trials of much longer duration (Fauci and Dick, 1994a; Persson and Kirchmann, 1994). The amended soil management system also affected other soil characteristics. Soil bulk density was lower: 0.846 vs. 0.929 g cm^{-3} in 1997 ($p < 0.05$) and 0.863 vs. 0.994 g cm^{-3} in 2001 ($p < 0.001$) in the amended and nonamended systems, respectively. Additionally, soil pH, CEC, total water-stable aggregates, and soil test phosphorus were all higher in the amended system compared with the nonamended soil system after eight years (Mallory and Porter, 2007).

3.4.3. Calculating Soil Storage

In a similar C and N budget study, Persson and Kirchmann (1994) noted that soil C and N storage is underestimated if bulk density decreases over the study period, as typically happens when soil C increases with organic amendment (Khaleel et al., 1981;

Brady and Weil, 1996). This is because a decrease in the mass of soil (organic and inorganic) that is found in a fixed volume of soil without a concurrent decrease in soil organic matter indicates that some of the original inorganic soil mass is not accounted for in the later sample. Soil C and N stocks in the MPEP were adjusted to maintain a constant mass of inorganic soil, as in Persson and Kirchmann (1994). The mass of inorganic soil contained in the sample volume was calculated from bulk densities and soil C concentrations for 1991 and 1998, assuming that organic matter is 56% C. On average, the amended soil contained 0.07 g cm^{-3} less inorganic soil in 1998 than in 1991, equivalent to 3.3 cm of soil at the average 1998 bulk density (0.854 g cm^{-3}). The soil C and N associated with that mass of soil was added to the estimates of soil C and N stock. Soil C and N concentrations typically decrease with depth. In these plots, there were no data available for soil total C and N below 23 cm but water soluble C was 24% lower at 0 to 20 cm compared with 20 to 40 cm in the spring of 1993 (M.S. Erich, personal communication). Poudel et al. (2001) reported 22 to 29% lower total C concentration and 18 to 32% lower total N concentration at 15 to 30 cm compared with 0 to 15 cm depth. For the present study, we used a conservative estimate of 30% lower C and N concentration for the 23 to 26 cm soil.

3.4.4. Storage and Loss of Added C

The amended soil management system both stored nine times more and lost two times more C than the nonamended system from 1991 to 1998 (Tables 3.3 and 3.4). In relative terms, however, the amended system lost less and retained more C than the nonamended system. Soil C storage expressed as a percentage of net C inputs (i.e., retention) was 43% in the amended system compared with 14% in the nonamended system. These results were slightly sensitive to changes in the bulk density value used to convert soil C concentration into soil C stock. For example, when bulk density values from May and July 1998 were used, estimated retention rates were 50 and 49% for the amended system and 16 and 15% for the nonamended system, respectively. Although these estimates probably overestimate actual retention rates since they do not account for C inputs from rhizodeposition, they are representative of the relative difference between the two soil management systems, and as such indicate that the amended system was more efficient at storing C than the nonamended system.

Table 3.4. Net input, soil storage, loss, and retention of C and N in the amended and nonamended soil management systems in the Maine Potato Ecosystem Project, 1991 to 1998.

	Carbon		Nitrogen	
	Amended	Nonamended	Amended	Nonamended
Net input, kg ha^{-1}	41,515	13,584	1788	435
Soil storage, kg ha^{-1}	17,612	1,875	1579	305
Loss†, kg ha^{-1}	23,903	11,796	208	130
Retention‡, %	43	14	88	71

† Loss was calculated as net inputs minus soil storage.
‡ Retention was calculated as soil storage divided by net inputs.

Numerous studies comparing soil management systems with similar tillage regimes have shown a linear, but nonproportional, relationship between the level of C inputs and the resulting changes in soil C over time (Griffin and Porter, 2004; Parton et al., 1996; Paustian et al., 1992; Paustian et al., 1997). The nonproportional aspect of the relationship results from the x-intercept (the amount of C input needed to maintain steady state soil C) being greater than zero and suggests that C retention efficiency increases with C input level. This conclusion is congruent with conceptual and mathematical models of soil organic matter (SOM) dynamics (Carter, 2002; Grant et al., 2001; Sommerfeldt et al., 1988).

Carbon retention is also influenced by C input quality. In all of the above studies (Griffin and Porter, 2004; Parton et al., 1996; Paustian et al., 1992; Paustian et al., 1997), as in the MPEP, the amount of C added is confounded with its composition, or quality. For instance, the highest rates of C inputs were often achieved with applications of manure while the lower rates corresponded to treatments with crop residues alone. Paustian et al. (1992) found that materials with high lignin content (sawdust and farmyard manure) had greater C retention efficiencies than low-lignin materials (straw and green manure) when applied to soil at similar rates for 30 years, providing direct evidence of a residue-quality effect. Additionally, Drinkwater et al. (1998) observed higher retention of legume C than non-legume C, and proposed that the variety and lower C:N ratio of the inputs in systems containing legumes resulted in better biological cycling and increased retention compared with the conventional system. In the MPEP, the amended system received almost half of its C input as manure and compost, and had higher C inputs as legume green manure than the nonamended (Table 3.1). Carbon retention efficiency was probably influenced, therefore, by C input quality as well as quantity.

Possible differences between the treatments in rates of erosion should be mentioned as they can also affect C retention. No measurements of erosion losses were made in the MPEP plots, but soil high in C has been shown to be more resistant to wind and water erosion (Carter, 2002) and would therefore lose less C. Tillage, which stimulates soil C mineralization and thus also is influential in soil C storage (Paustian et al., 1997), was identical in the two soil management systems.

3.4.5. Storage and Loss of Added N

Results for N paralleled those for C — the amended soil management system demonstrated greater efficiency for storing excess N compared with the nonamended system (Table 3.4). As with C, N retention was probably influenced by the composition of N inputs (Paustian et al., 1992). Additionally, our results confirm that soil management system played a role in the higher N retention observed in organic (manure and legumes) systems compared to conventional systems by Drinkwater et al. (1998) and Poudel et al. (2001) and support the explanation that C is needed to retain N in the soil.

Two possible mechanisms to explain greater N retention in high-C systems are C-enhanced immobilization and physical protection. The major pathways of N loss from cultivated soil (leaching, volatilization, and denitrification) all act on inorganic forms of N. There is potential to reduce N loss by reducing high levels of inorganic N when crop demand is low. Immobilization of inorganic N to organic N by microbes is a major N retention mechanism and is stimulated by readily available C. In a recent laboratory study of the MPEP soil, C-enhanced immobilization was the most probable mechanism causing reduced soil NO_3^- levels in the amended soil relative to nonamended soil following the addition of fertilizer and manures (Mallory and Griffin, 2007). Physical protection of N as organic matter in soil microaggregates also is an important N retention mechanism and is influenced by soil C (Six et al., 2002). Manure application has been shown to increase aggregate-protected N fourfold compared to a synthetic fertilizer treatment (Aoyama et al., 1999b). Soil aggregate data from the MPEP support the idea that physical protection played a role in N retention. Total water stable aggregates increased by 19% in the amended soil system but decreased by 23% in the nonamended system from 1991 to 1998 (Mallory and Porter, 2007).

In spite of greater N retention rates, the amended soil management system also had more N loss, in absolute terms, than the nonamended system. A key strategy to reducing N loss is to optimize the synchrony between N availability and crop N demand (Christensen, 2004). Animal and green manures are considered slower or more gradual N sources than fertilizer because they must first be mineralized to plant available forms. This delay in availability may result in increased synchrony with plant demand early in the season (Ma et al., 1999), but continued mineralization after crop uptake ceases may lead to potentially leachable end-of-season excesses of soil NO_3^- (Magdoff, 1991; Schröder, 2005). High fall NO_3^- levels have been observed in manure-based systems relative to fertilizer-based systems (Jensen et al., 1999; Magdoff, 1991; Roth and Fox, 1990), underscoring the need to include N trap crops to prevent N loss from systems with high levels of soil organic N. Reducing amendment loading rates is another management option to reduce potential N loss. The rates used in the present study were designed to bring about rapid and dramatic increases in soil C for experimental purposes, but are not desirable from N loss and potential P loss standpoints. It may be possible to reduce amendment applications to maintenance levels and still maintain the higher N retention efficiencies associated with higher soil C levels, but this requires further research.

3.5. Conclusions

The amended soil management system was more efficient at retaining C and excess N than the nonamended system. The amended system received much higher inputs of C and N than the nonamended system, but also received the majority of its inputs as manure and compost, which are known to be more stable sources of C. The probable influence of C input quality and quantity on soil C storage has clear implications for developing strategies to increase soil C and improve attendant soil quality attributes in degraded soils. It may be of interest also for developing strategies to increase soil C sequestration in regard to climate change. In this case, a C budget analysis that includes the livestock production component of the amended system is needed to properly assess net gains in C storage relative to the nonamended system.

Our results support the concept that diversified soil management systems enhance biological linkages between C and N cycles and can reduce N loss (Drinkwater et al., 1998). The higher retention efficiency of N in the amended soil suggests that excess N was buffered via C-enhanced immobilization or protected from mineralization via aggregate formation. In light of the relatively high rate of N loss, in absolute terms, in the amended system, the importance of these possible N retention mechanisms should be investigated under lower amendment loading rates.

Chapter 4

SEASONAL NITROGEN AVAILABILITY FROM CURRENT AND PAST APPLICATIONS OF MANURE AND FERTILIZER

4.1 Chapter Abstract

Integrating crop and livestock production is increasingly viewed as a regional strategy to improve N efficiency and reduce N losses to the environment. Key to the proper management of manure N is predicting the rate and extent of manure N availability relative to crop needs. This includes recognizing the potential importance of N contributions from the accumulation of residual manure organic N that occurs with repeated applications. Nitrogen availability relative to crop needs was assessed in plots with 13–16 yr histories of contrasting manure- and fertilizer-based soil treatments in the Maine Potato Ecosystem Project. Soil and barley samples were collected every 7–14 days during 2003 to 2005, and once in 2006. In 2004 to 2006, samples also were collected from "zero-N" strips within the plots where normal applications of manure or fertilizer were withheld to estimate the proportion of available N that came from current versus previous manure applications. Barley dry matter, N content, and yield were equivalent between the two soil management systems. Temporal patterns of N availability in the manure-based system were more synchronous with crop needs early in the season compared with the fertilizer-based system, but potentially excessive after harvest. Apparent N recovery of the current years' application of manure organic N was less than predicted by a standard decay series. The relative contribution of residual manure N to total manure N uptake was more than predicted from the decay series,

providing support for a residual N effect from repeated manure applications. Standard manure recommendations may underestimate the N contribution from past applications.

4.2 Introduction

Crop and livestock production have been decoupled in industrial agricultural systems, with farmers encouraged to specialize in one or the other. Consequently, crop farmers rely on purchased inorganic fertilizers to meet crop nutrient needs, while livestock farmers import feed nutrients and often do not have enough land to avoid excessive applications of manure nutrients. As concerns about the negative impacts of agriculture on water quality continue to intensify, there is increasing interest in re-coupling or re-integrating crop and livestock farming (Naylor et al., 2005; Russelle et al., 2007). One aspect of integration, the use of manure as a N source for crop production, is seen as a way to increase N use efficiency and reduce N losses to the environment at a watershed or regional level (Christensen, 2004; Schröder, 2005).

The management of manure organic N can be challenging, compared to fertilizer N, because mineralization to plant available forms is necessary and robust estimates of the rate and extent of N mineralization from the organic pool remain elusive. In general, manure is considered a slower or more gradual source of plant-available N than fertilizer N (Langmeier et al., 2002; Ma et al., 1999). This may result in increased synchrony with plant demand and reduce potential N leaching losses (Ma et al., 1999), but may also lead to potentially leachable end-of-season excesses of soil NO_3^- (Magdoff, 1991; Schröder, 2005).

Decay series are commonly used to estimate the amount of N mineralized from the organic fraction of manure during the years after application (Ketterings et al., 2005;

Klausner and Bouldin, 1983). Decay series have been developed for specific manure types. A commonly used decay series for beef manure, 25-12-5 (Ketterings et al., 2005), predicts that 25% of manure organic N will be mineralized during the first year, 12% of the remaining manure organic N will be mineralized in the first year following application, and likewise 5% the second year after application. Mineralization during subsequent years is assumed to be negligible. Schröder (2005), however, has recently shown in a conceptual model that repeated applications of manure can lead to a residual N effect whereby the sum of many small contributions can constitute an important addition to overall N availability. The residual N effect can not be detected in short-term experiments such as those used to develop decay series, because soil organic N accumulation is small over the time frame of 1 to 3 growing seasons. Not accounting for the accumulation and subsequent mineralization of residual manure N can lead to over application of manure or fertilizer N (Schröder, 2005; Whalen et al., 2001).

The Maine Potato Ecosystem Project in Presque Isle, Maine established contrasting amended and nonamended soil management strategies in 1991 and so provided an ideal opportunity to examine *in situ* N dynamics in well-established manure- and fertilizer-based potato–barley production systems. The specific objectives were 1) to assess seasonal patterns of N availability in the two systems with particular regard to synchrony with crop demand and potentially leachable excesses, and 2) to estimate the relative contribution of current and residual manure organic N. The study was conducted during the barley phase of the rotation to minimize problems with soil N heterogeneity and to simplify plant sampling.

4.3 Materials and Methods

4.3.1 Site characteristics and field experiment

The study was conducted during 2003 to 2006 in the Maine Potato Ecosystem Project (MPEP), a large, interdisciplinary potato cropping systems experiment located in Presque Isle, Maine on a gravely, well-drained Caribou loam soil (fine-loamy, mixed, frigid, Typic Haplorthods). The MPEP has included a comparison of contrasting amended and nonamended soil management systems in the context of 2-yr potato rotations since its establishment in 1991. The amended soil management system relied largely on organic sources of nutrients. These were supplemented with small inputs of inorganic fertilizer as needed during the potato phase of the rotation to provide approximately the same nutrient levels as in the nonamended soil management system. Beef manure and potato compost were applied annually from 1991 to 1993 and semi-annually (potato year only) from 1994 to 1998. From 1999 to 2006, manure was applied to both potato and barley crops, but compost applications were discontinued. The amended soil system also included a pea–oat–hairy vetch green manure as the rotation crop until 1998, when it was changed to barley undersown with red clover. The nonamended soil management system followed industry standards, including inorganic fertilizers and a barley/red clover rotation crop. Table 4.1 provides average fertilizer and manure N, P, and K inputs to the amended and nonamended soil management systems from 2003 to 2006. Plot size was 14.6 m x 41.0 m.

During 2004 to 2006, zero-N subplots were established in the amended and nonamended plots in the barley phase of the rotation. The subplots were 2- to 3-m wide strips that were located about 1 m from one side of the plots and ran their full length (41 m). The application of either manure (amended system plots) or fertilizer (nonamended system plots) was withheld in the subplots.

The soil treatment factor was in factorial combination with other treatment factors (pest management and potato variety from 1991 to 1998, and rotation and pest management from 1999 to 2003) in a split plot design with four replicates. Further details about the establishment of the experiment, cultural methods, and the other treatment factors are provided elsewhere (Alyokhin et al., 2005; Gallandt et al., 1998b; Mallory and Porter, 2007; Porter, 1996; Porter and McBurnie, 1996).

Table 4.1. Average annual application rates of fertilizer nitrogen (N), phosphorus (P), and potassium (K), manure fresh weight, and manure nutrients from 2003 to 2006 in the Maine Potato Ecosystem Project.

	Fertilizer			Manure†				
	N	P	K	Fresh weight	Organic N	NH_4^+-N	P	K
	kg ha^{-1}			Mg ha^{-1}	kg ha^{-1}			
Amended								
Barley	0	0	0	45	177	14	56	147
Potato	78	0	0	67	266	21	83	220
Nonamended								
Barley	78	0	0	0	0	0	0	0
Potato	190	59	219	0	0	0	0	0

† Manure nutrient application rates are estimated based on analysis of the manure and do not take into account loss during storage and application.

4.3.2 Soil and plant analyses

Soil organic carbon was determined from samples taken each spring prior to the application of organic amendments. Ten soil cores were collected from a 15-cm depth, air-dried, sieved through a 6.4-mm screen, bulked, and mixed thoroughly. Duplicate subsamples were analyzed for readily-oxidizable SOC using the Walkley-Black method

(Nelson and Sommers, 1996). Total soil N was determined from samples collected for an incubation experiment in 2003 after barley harvest. Six individual soil cores were taken to a depth of 15 cm using an 8-cm diameter bulb corer. Soil was bulked by soil treatment, mixed gently, sieved to 2 mm. A 100-g sample of each soil was air-dried, from which 5 g was pulverized and analyzed in quadruplicate for total N concentration by combustion using a CE Instruments NA2500 Elemental Analyzer (ThermaQuest Italia S.p.A., Rodano, Italy). Bulk density was determined in the spring using the core method described by Blake and Hartge (1986). Metal rings were pounded into the soil using a cylindrical sleeve. The sample rings were removed, trimmed with a metal spatula, capped, dried at 105°C, and sieved to 2 mm to separate coarse fragments. Both fractions were weighed and bulk density estimates were corrected for coarse fragments.

Above-ground barley biomass was measured at 7 to 14 d intervals beginning 2 to 7 d after barley planting (May) and ending at physiological maturity (August). In 2006, barley samples were collected only at physiological maturity. Sampling occurred in about 2-m wide strips located 1 m from the plot edge. At four locations in each strip, barley plants were clipped 2 cm above the soil surface from 0.3 m of two adjacent rows. Samples from the four locations were bulked, representing a total sample area of 2.4 m of row. From 2004 to 2006, separate samples were collected in the same manner from the zero-N sub-plots. On successive sampling dates, sampling areas were spaced 0.5 m along the rows from the previous sampling area. Plant samples were dried at 60°C, weighed, and ground. A 5-g subsample was pulverized and analyzed for total N concentration by combustion using a CE Instruments NA2500 Elemental Analyzer (ThermaQuest Italia S.p.A., Rodano, Italy). Plant N uptake was estimated as the product of biomass and N concentration. Weed and red clover biomass and N uptake were not measured because visual assessments indicated that weed and red clover biomass were insignificant relative to barley biomass.

Soil sampling was conducted concurrently with barley sampling, and continued after barley harvest until the first killing frost (October). Two soil cores (2cm diameter) were taken to a depth of 20 cm in each of the four sample areas per plot, one within a row and one between rows. The eight cores per plot were bulked and mixed thoroughly. A 200-g subsample was sieved to 2 mm and stored at 4ºC for <24 h until inorganic N (N_i) and moisture determinations were made. A 3-g subsample of the soil (approximately 2.5 g dry weight equivalent) was placed in a 25 mL centrifuge tube with 25 mL of 2.0 *M* KCl, shaken for 1 h, and centrifuged (2700 x g for 10 min). The supernatant was filtered (0.45 µm) and analyzed for NH_4^+ and NO_3^- colorimetrically on a Lachat Autoanalyzer (Lachat Instruments, Mequon, WI). Inorganic N concentration was corrected for bulk density and expressed on an area basis. For moisture content, a 10-g subsample was weighed wet, dried at 105°C for 48 h, and weighed again.

Apparent N recovery (ANR) was calculated for manure and fertilizer using maximum barley N uptake average values for each treatment, adjusted to include root N uptake assuming a root/shoot ratio of 0.18 (Janzen et al., 2003; Johansson, 1992), and using Eq. [1]:

$$\text{(N uptake in main plot – N uptake in zero-N subplot) / N applied} \qquad [1]$$

Manure ANR was calculated for the organic N fraction by subtracting estimated available NH_4^+-N (50% of manure NH_4^+-N content (Klausner and Bouldin, 1983)) from the barley N uptake and from the manure N applied.

The contributions to barley N uptake from soil, new manure (current year), and residual manure (accumulated in the soil N pool) were estimated using two important assumptions. First, it was assumed that barley N uptake in the nonamended zero-N subplot was equivalent to the N contribution from soil in the amended manured treatment had it never received any manure. This assumption presupposes that there was no net accumulation or depletion of soil organic N in the nonamended soil over the course of the MPEP, and that there was minimal carryover of N from the previous potato crop year. Second, it was assumed that barley does not discriminate between the various sources of N_i. Given these assumptions, contributions to barley N uptake from the different sources were calculated from Eq. [2–4]:

$$\text{Soil} = \text{N uptake in nonamended zero-N subplot} \quad [2]$$

$$\text{Old manure} = \text{N uptake in amended zero-N subplot} - \text{Soil} \quad [3]$$

$$\text{New manure} = \text{N uptake in amended manured main plot} - \text{Old manure} \quad [4]$$

4.3.3 Statistical analysis

Repeated measures ANOVA was used to test the significance of sampling date, soil management system (amended vs. nonamended), nitrogen treatment (main plot vs. zero-N subplot), and treatment interactions on soil N_i, barley dry matter, and barley N uptake. Effects found significant in repeated measures ANOVA were then investigated further in univariate ANOVAs by sampling date. Univariate ANOVA also was used to test treatment effects on maximum barley N uptake.

4.4 Results and Discussion

4.4.1 Soil Characteristics

Stocks of SOC and soil total N were approximately 75% higher in the amended soil management system than the nonamended system. Soil organic C content averaged 31.4 and 18.0 g kg^{-1} in the amended and nonamended systems, respectively, from 2003 to 2006. Soil total N, measured in 2003, was 2.5 and 1.4 g kg^{-1} in the amended and nonamended systems, respectively. The amended system also influenced other soil characteristics, increasing soil pH, the proportion of total water stable aggregates, and CEC relative to the nonamended system (Mallory and Porter, 2007).

4.4.2 Soil Inorganic N

In the main plots (which received fertilizer or manure N as they had in the past), soil inorganic N (N_i) content was highest in the spring, after fertilizer or manure application and barley planting, and remained high for 2 to 4 wk until N uptake by the crop began (Fig. 4.1). In 2003 and 2005, decreases in soil N_i content in the main plots were large relative to the concomitant accumulations of barley N. This result suggests that N was lost from the system, possibly via denitrification or leaching below the sampling depth, and possibly below the root zone. The fertilizer-based system demonstrated greater potential for loss as spring soil N_i content was significantly higher in this system than in the manure-based, amended system in all years (Table 4.2 and Fig. 4.1). These results are congruent with previous findings that fertilizer is a more rapidly available source of plant available N than manure (Langmeier et al., 2002; Ma et al., 1999; Mallory and Griffin, 2007).

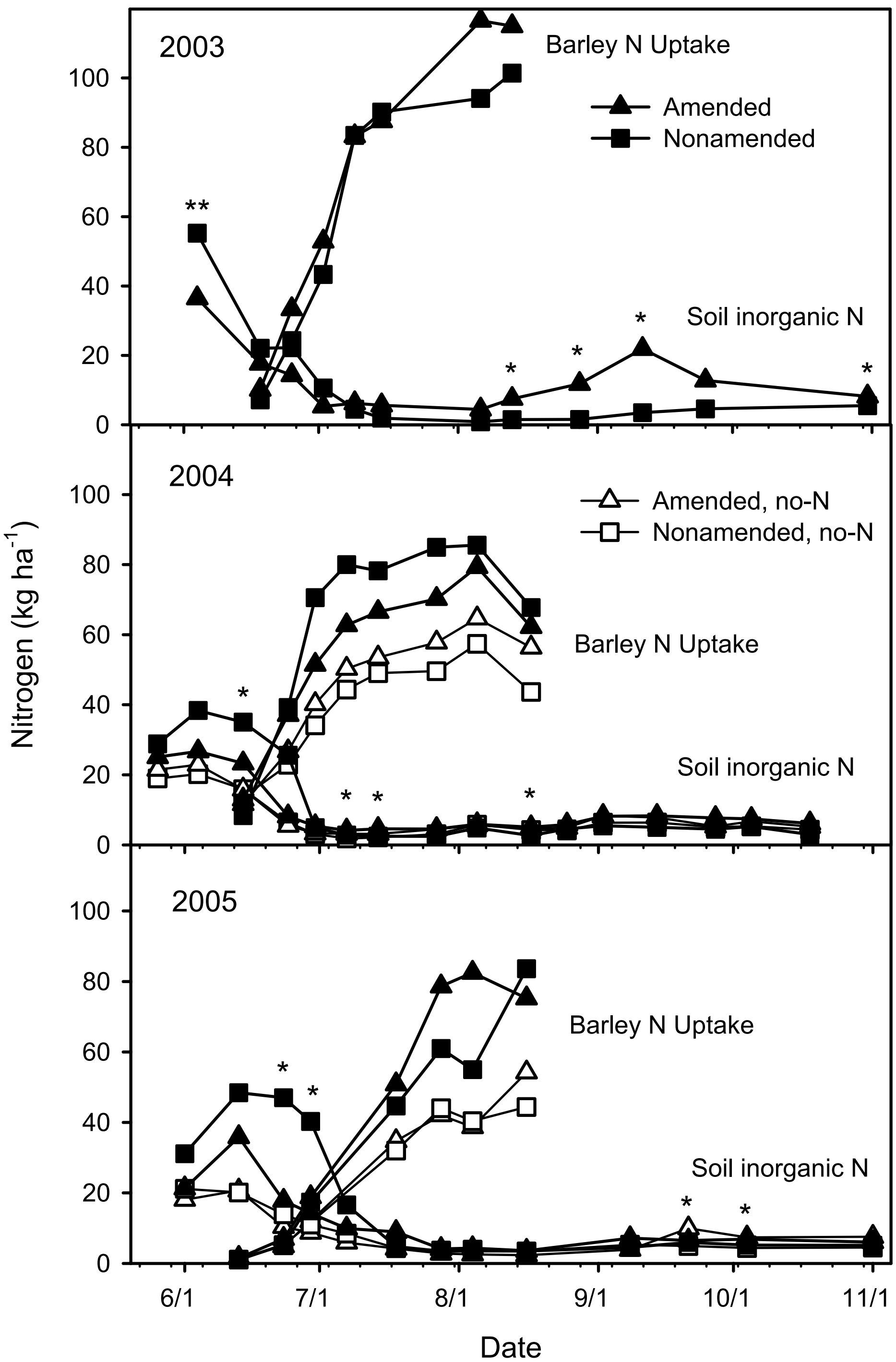

Figure 4.1. Soil inorganic N and barley N uptake over the growing season in 2003, 2004, and 2005 in the Maine Potato Ecosystem Project. *, Significant difference between soil management treatments at the 0.05 probability level.

Table 4.2. Probability values from repeated measures ANOVA of barley dry matter (DM), barley N content, and soil N content in 2003, 2004 and 2005 of the Maine Potato Ecosystem Project.

	2003					2004					2005				
	Barley			Soil		Barley			Soil		Barley			Soil	
Sources of variation	df	DM	N	df	N	df	DM	N	df	N	df	DM	N	df	N
Date (D)	7	<0.001	<0.001	12	<0.001	7	<0.001	<0.001	15	<0.001	6	<0.001	<0.001	12	<0.001
D×Rep	21	0.199	0.316	36	0.304	21	0.538	0.845	45	0.358	18	0.242	0.533	36	0.923
D×Soil (S)	7	0.245	0.831	12	<0.001	7	0.240	0.573	15	0.001	6	0.913	0.961	12	0.013
D×N†	-	-	-	-	-	7	0.000	0.017	15	0.000	6	0.001	0.006	12	0.214
D×S×N	-	-	-	-	-	7	0.907	0.446	15	0.033	6	0.325	0.369	12	0.940

† Nitrogen treatment (N vs. no N) was added in 2004 and 2005 as a subplot in the soil management treatment plots and the experiment was analyzed as a split plot design.

Spring soil N_i content in the subplots that received no fertilizer or manure (zero-N subplots) was significantly lower than in the fertilized and manured main plots (Table 4.2, Fig. 4.1). Soil N_i in the zero-N subplots originated from either early spring mineralization of the soil organic N pool or retention of soil N_i that remained after potato harvest. Surprisingly, there was no measurable difference in soil N_i in the zero-N subplots between the amended and nonamended soil in spite of the amended soil having approximately a 75% greater total soil N pool. This suggests that carryover of fall N_i could be an important contributor to early spring soil N_i. Zebarth et al. (2003) observed carryovers ranging from 22 to 63 kg N_i ha^{-1} (30 cm soil depth) in the spring following potato in eastern Canada.

After crop harvest, soil N_i remained low (< 10 kg ha^{-1}) in all treatments for the remainder of the season with one exception. In 2003, soil N_i in the amended soil management system began accumulating after crop harvest, presumably from the continued mineralization of the large organic N pool in this soil and of the recently added organic manure N. There was little rainfall during this period of accumulation (Fig. 4.2). The subsequent decline in soil N_i content coincided with significant rainfall events that probably leached the excess soil N_i below sampling depth. These results indicate that the lack of observable N_i accumulation in the amended soil in the other years could simply be due to more regular precipitation patterns (Fig. 4.2) and movement of soil N_i below the sampling depth rather than due to lower soil N mineralization rates. Others have observed high fall soil N_i levels in manure-based systems (Jensen et al., 1999; Magdoff, 1991; Roth and Fox, 1990) and stressed the importance of including trap crops to prevent N loss (Christensen, 2004).

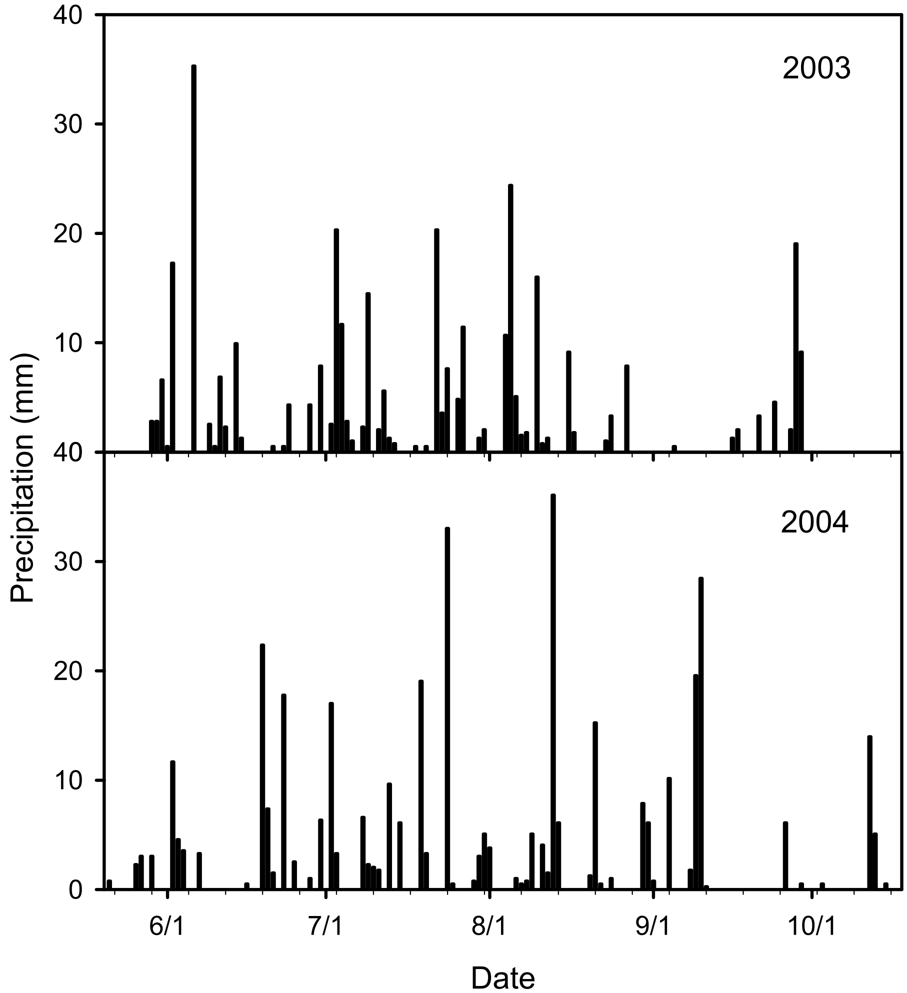

Figure 4.2. Daily precipitation in 2003 and 2004 in the Maine Potato Ecosystem Project.

4.4.3 Barley biomass and yield

Barley performed similarly in the amended soil management system as in the nonamended soil system. In spite of early season differences in plant N availability, barley dry matter accumulation was not significantly affected by soil management system (Table 4.2, Fig. 4.3). Barley grain yields also were not significantly affected by soil management and averaged 2368, 2483, and 1188 kg ha^{-1} in 2003, 2004, and 2005, respectively. These results suggest that barley was likely not N-limited in either soil system. Barley biomass was significantly lower in the zero-N subplots, but grain yield was not measured. Barley crop development and N uptake were slower in 2005 than in previous years due to poor initial seed germination and establishment of the crop. In 2004, there was a decrease in biomass at the last sampling date, presumably due to loss of leaves by the mature crop.

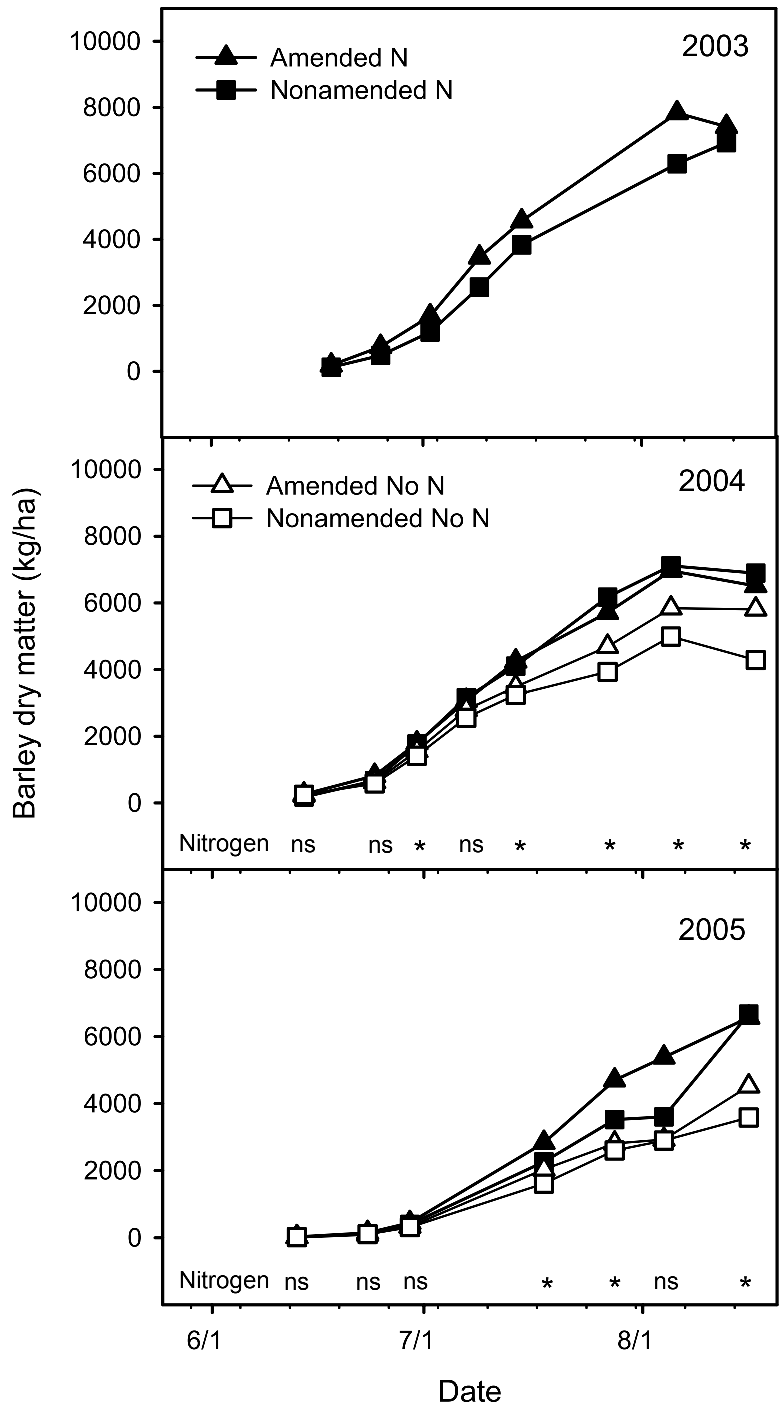

Figure 4.3. Barley biomass over the growing season in 2003, 2004, and 2005 in the Maine Potato Ecosystem Project. *, Significant difference between nitrogen treatments (with N and zero-N subplots) at the 0.05 probability level. There was no significant soil treatment effect.

4.4.4 Barley N Uptake

The maximum value of barley N uptake in the zero-N subplots represents cumulative plant available N supplied by the soil over the season. Soil N supply was not significantly different between the two soil management systems (Table 4.3). This result is surprising given that the amended soil had approximately 75% greater total N pool and, in a recent incubation study (Mallory and Griffin, 2007), demonstrated similarly higher mineralization potential. In 2006, soil N uptake was unusually low in both treatments due to plant disease.

Apparent N recovery (ANR) of the manure organic N applied in the amended soil management systems was 8, 11, and 9% in 2004, 2005, and 2006, respectively (Table 4.3). These values are only slightly lower than the 13% recovery by spring barley of sheep manure organic N reported by Jensen et al. (1999), yet they are considerably lower than the 25% estimated by a typical decay series for the plant availability of beef manure organic N during the year of application. Manure decay series typically have been developed based on experiments conducted with full-season corn (Klausner et al., 1994; Magdoff, 1978). Crops with shorter growing seasons, such as barley, can only capture a portion of this estimated plant available N because the remainder is mineralized after crop uptake has ceased. This highlights the need to adjust manure N credits for crops with shorter maturities and lower N uptake capacities than corn. Fertilizer ANR was 46 and 59% in 2004 and 2005, respectively, and is typical of fertilizer recovery values reported in the literature for barley (Glendining et al., 1997). Fertilizer ANR in 2006 was unusually low, again due to disease.

Table 4.3. Maximum barley N uptake in the amended and nonamended soil management system main plots and zero-N subplots, and calculated apparent N recover (ANR‡) of fertilizer N and manure organic N, from 2003 to 2006 of the Maine Potato Ecosystem Project.

	df	2003	2004	2005	2006
			kg ha^{-1}		
Amended					
Main plot		115	79.4	82.5	51.3
Zero-N subplot		-	64.7	54.2	34.3
(ANR)		-	(8%)	(11%)	(9%)
Nonamended					
Main plot		101	85.6	83.6	49.1
Zero-N subplot		-	57.4	44.4	32.0
(ANR)		-	(46%)	(59%)	(28%)
			ANOVA (p-values)		
Sources of variation					
Rep	3	0.748	0.220	0.478	0.009
Soil (S)	1	0.706	0.797	0.991	0.828
Error (a)	3				
Nitrogen (N)	1	-	0.049	0.023	0.007
S x N	1	-	0.199	0.813	0.634
Error (b)	5				
C.V. (%)		22.1	19.4	28.4	15.0

‡ Manure ANRs are for organic N. ANR for total manure N (organic plus NH_4^+-N) were 10, 17, and 11% in 2004, 2005, and 2006, respectively.

The relative contribution of residual manure N to barley N uptake was greater than predicted based on a standard decay series for solid beef manure (Table 4.4). The decay series predicted that 27 and 23% of total manure N contributions would be from residual manure N and that 73 and 77% would be from new manure (NH_4^+-N and organic N) in 2004 and 2005, respectively. In contrast, observed estimates of the relative contribution from residual manure were 33 and 26%, in these years. These higher than expected values may be evidence of a residual N effect (Schröder, 2005) brought about by 14 to 15 years of manure applications. These results should be interpreted cautiously for two reasons. First, estimates of the relative contributions of new and residual manure were sensitive to small changes in barley N uptake for the different treatments. Second, these estimates are based on the assumption that barley N uptake in the nonamended zero-N subplots was equivalent to the indigenous soil N contribution in the amended manured treatment had it never received any manure. While there has been little change in the organic N content of the nonamended soil from the beginning of the MPEP (0.15% in 1991 vs. 0.16% in 2004), the results from the current study suggest that there may be N carryover from the previous potato year. Carryover would reduce the estimated contribution of N from the soil, which would in turn increase the contribution attributed to residual manure and increase the apparent residual N effect. Estimates from 2006 are suspect given the unusually low barley N uptakes in that year (Table 4.3).

Table 4.4. Estimated and predicted contributions to barley N uptake from soil, the current year's application of manure (New manure), and previous years' applications of manure (Residual manure), as well as the percent of manure N contributions from New and Residual manure N. Values are estimated from barley N uptake data and predicted from a 25-12-5 manure decay series.

	N sources		
		Manure	
	Soil	New†	Residual
	kg N ha^{-1}		
Barley N content			
2004	57.4	14.7 (67%)	7.3 (33%)
2005	44.4	28.3 (74%)	9.8 (26%)
2006	32.0	17.0 (88%)	2.3 (12%)
Predicted from 25-12-5 decay series			
2004	-	16.0 (73%)	6.0 (27%)
2005	-	29.6 (77%)	8.6 (23%)
2006	-	13.9 (72%)	5.4 (28%)

† Includes available manure NH_4^+-N, estimated as 50% of applied manure NH_4^+-N. Available manure N was 3.7, 12.2, and 2.9 kg N ha^{-1} in 2004, 2005, and 2006, respectively.

4.5 Conclusions

Barley performed equally well in terms of biomass and yield in an amended, manure-based soil management system as in a nonamended, fertilizer-based soil management system. Soil N availability was not optimally synchronized with barley N uptake in either system – both fertilizer-based and manure-based soil management systems demonstrated periods of N_i excess and potential N loss. Nitrogen was available more rapidly in the fertilizer-based system, with excessive soil N_i and the potential for N loss occurring in the spring before barley N uptake began. Nitrogen was released more slowly in the manure-based system, with continued mineralization and accumulation of soil N occurring after crop uptake ceased. The manure-based system showed the potential for N loss in the fall, underlining the importance of including fall trap crops in these systems. Apparent N recovery of manure organic N was less than predicted by a standard decay series for beef manure. Concomitantly, the relative contribution of residual manure N to total manure N uptake was more than predicted from the decay series, providing support for a residual N effect from repeated manure applications. Standard manure recommendations may underestimate the N contribution from past applications.

Chapter 5

IMPACTS OF SOIL AMENDMENT HISTORY ON NITROGEN AVAILABILITY FROM MANURE AND FERTILIZER

5.1. Chapter Abstract

Repeated, long-term additions of organic materials not only increase stocks of mineralizable soil N, but also bring about changes in soil characteristics that influence N dynamics. We conducted an aerobic incubation to explore how soil amendment history affects the transformation and availability of recently added N. Soil was collected from plots under contrasting amended and nonamended soil management systems in a 13-yr cropping systems experiment. Nitrogen source treatments were: no added N (control), NH_4^+ fertilizer (Fert), a net mineralizing manure (MManure), and a net immobilizing manure (IManure). Soil NH_4^+ and NO_3^- concentrations were monitored for 282 d. A two-pool, first-order model with fixed rate parameters was fitted to the NO_3^- accumulation data. When no N was added, net mineralization in the historically amended soil was twice that in the historically nonamended soil, mostly due to differences in soil total N stocks. When N sources were added, NH_4^+ consumption, net N mineralization, and estimated N pools were affected by both soil amendment history and N source, with a significant interaction between the two factors. Historically amended soil reduced the availability of recently added N relative to the nonamended soil. This reduction occurred in the active pool (N_1) for MManure and in the slow pool (N_2) for Fert. It appeared to be related to the timing of C availability. Future work modeling N availability should

consider soil amendment history not only for its effects on soil N supply capacity, but also for its effects on the availability of recently added N sources.

5.2. Introduction

Tightening the N cycle by optimizing N use efficiency is fundamental to the design of sustainable agricultural systems (Christensen, 2004). Achieving this goal requires the ability to predict N release from soil organic matter and added N sources (Christensen, 2004; Honeycutt et al., 1991). Soil N dynamics are influenced by environmental factors such as temperature (Andersen and Jensen, 2001; Griffin and Honeycutt, 2000; Honeycutt, 1999) and soil moisture (Griffin et al., 2002; Thomsen et al., 1999). Even under similar environmental conditions, however, N dynamics are also substantially affected by substrate and soil characteristics.

For animal manures, there has been considerable effort to identify chemical characteristics that can be used to refine predictions of N mineralization potential (Cabrera et al., 2005). Most of these studies have focused on the release of plant-available N from manure within a single cropping season. The repeated addition of manure and other organic materials, however, brings about important changes in the soil that can affect N dynamics. Most obvious is the enhancement of the soil organic N pool. Only a portion of the organic N in manure is mineralized during the year of application; the remainder accumulates in the soil. While any given application contributes only a small amount to mineralized N in a subsequent year, the combined contributions of organic N from repeated applications can lead to a substantial residual N effect (Eghball et al., 2004; Schröder, 2005), emphasizing the need for consideration of soil amendment history in nutrient management plans (Beauchamp et al., 1986; Feng et al., 2005; Whalen et al., 2001).

In addition to the quantitative increase in the size of the soil organic N pool, repeated long-term application of organic amendments also brings about changes in soil characteristics that could affect N dynamics. As reviewed recently by Cabrera et al. (2005), reduced net N mineralization has been observed repeatedly in finer vs. coarser textured soils following organic N additions, with effects attributed to adsorption of N by clays (Van Veen et al., 1985), greater protection of microbial biomass N (Kuikman et al., 1991; Van Veen et al., 1985), pore-size effects on water availability (Thomsen et al., 1999), and differences in the microbial and grazer communities (Hassink et al., 1994). While organic amendment does not alter soil texture, added organic matter can affect all of the above processes.

Repeated application of organic amendments also adds to the pool of available soil C (Aoyama et al., 1999a; Cambardella and Elliott, 1992; Griffin and Porter, 2004; Sommerfeldt et al., 1988) and enhances microbial biomass and activity (Fauci and Dick, 1994b; Gunapala and Scow, 1998; Houot and Chaussod, 1995; Witter et al., 1993). Carbon and N cycles are tightly coupled in the soil (Chantigny et al., 2001). The site of this coupling is the soil microbial community, which acts as an important source and sink of both C and N. Research on untilled soils illustrates this linkage. Barrett and Burke (2000) found a positive linear relationship between soil C concentration and gross rates of mineralization (slope = 0.595) and immobilization (slope = 0.934) in grassland soil, with greater influence on immobilization. Similarly, Hatch et al. (2000) detected a greater increase in immobilization in high- vs. low-C pasture soil 3 months after a one-time surface application of manure. If these results can be translated to tilled soils, higher gross N transformation rates and retention of added N would be expected in historically amended soil than nonamended soil.

Few studies have investigated the influence of soil amendment history on the mineralization and availability of recently added N substrates. Soil amendment history had no effect on net mineralization of added N (Hadas et al., 1996; Sanchez et al., 2001) or microbial biomass and enzyme activity (Fauci and Dick, 1994b) following additions of composted manure and plant residues. These researchers concluded that the response of soil to current N additions far outweighs any differences due to long-term soil management, with no interaction between the two factors. This conclusion may be premature. For instance, both soil amendment history (organic amendments vs. fertilizer) and N source (fertilizer, manure urea, solid manure, and combinations of these), as well as their interaction, significantly affected plant uptake of added N (Langmeier et al., 2002). In their study, where soil C and N differed by only 7 and 15%, respectively, between the contrasting soil treatments, the effect of soil amendment history was an order of magnitude smaller than the effect of N source. A larger soil treatment effect might be expected for soils with more discrepant soil C and N stocks.

The Maine Potato Ecosystem Project provided an ideal opportunity to further explore the potential influence of soil amendment history on N dynamics. Thirteen years of contrasting amended (manure, compost, and green manure) and nonamended soil management systems has resulted in soil with highly divergent C and N stocks. An aerobic incubation of these soils was conducted to: (i) compare the N supplying capacity of historically amended vs. historically nonamended soil; (ii) investigate the effects of soil amendment history on N transformations following addition of fertilizer or manure; and (iii) quantify these possible effects on N pools of differing lability.

5.3. Materials and Methods

5.3.1. Soils and Manures

Soil was collected from the Maine Potato Ecosystem Project, a large, interdisciplinary potato cropping systems experiment located in Presque Isle, ME, on a gravely, well-drained Caribou loam soil (fine-loamy, mixed, frigid Typic Haplorthod). This experiment has included a comparison of contrasting amended and nonamended soil management systems in the context of 2-yr potato rotations since 1991. The amended soil management system relied largely on organic sources of nutrients, supplemented with small inputs of inorganic fertilizer. Beef manure and potato compost were applied annually from 1991 to 1993 and semiannually (potato year only) from 1994 to 1998. From 1999 to 2003, manure was applied to both potato and rotation crops, but compost applications were discontinued. The amended soil system also included a pea–oat–hairy vetch green manure as the rotation crop until 1998, when it was changed to barley undersown with red clover. The nonamended soil management system followed industry standards, including inorganic fertilizers and a barley–red clover rotation crop. The soil treatment factor was in factorial combination with other treatment factors (pest management and potato variety from 1991–1998, and rotation and pest management from 1999–2003) in a split plot design with four replicates. Plot size was 14.6 by 41.0 m. Further details about the soil management systems, other treatment factors, and cultural methods are provided elsewhere (Alyokhin et al., 2005; Gallandt et al., 1998b; Mallory and Porter, 2007; Porter and McBurnie, 1996).

Griffin and Porter (2004) reported total, particulate organic matter, and soil microbial biomass (SMB) C and N pools for soil collected in the spring of 1999 from the contrasting soil management systems (Table 5.1). Identical methods were used to collect and characterize soil in the fall of 2002. Ten-day CO_2 evolution rates on both sets of samples were determined as part of the SMB procedure. Soil pH of the 2002 samples was measured in a 1:1 soil/water slurry (Thomas, 1996).

Soil for the aerobic incubation was collected after barley harvest in August 2003 from the four replicate amended and nonamended plots that were in a 2-yr potato–barley rotation and conventional integrated pest management. Six individual soil cores were taken to a depth of 15 cm using an 8-cm-diameter bulb corer. Soil was bulked by soil treatment (i.e., historically amended and historically nonamended), mixed gently, sieved to 2 mm, and stored at 4°C. A 100-g sample of each soil was air dried, from which 5 g was pulverized and analyzed in quadruplicate for total C and N concentration by combustion using a CE Instruments NA2500 Elemental Analyzer (ThermaQuest Italia S.p.A., Rodano, Italy).

Table 5.1. Characteristics of the historically amended and nonamended soils from the Maine Potato Ecosystem Project, 1999† and 2002.

					Carbon			Nitrogen		
Year	Soil history	df	Soil pH	CO_2 evol	Total	POM‡	SMB§	Total	POM	SMB
				mg kg^{-1} day^{-1}	g kg^{-1}					
1999										
	Amended		–	38.6	21.8	8.24	0.48	1.96	0.62	0.12
	Nonamended		–	22.1	16.6	4.02	0.29	1.50	0.33	0.07
2002										
	Amended		6.3	33.5	33.9	13.68	1.27	2.92	1.02	0.30
	Nonamended		5.5	27.3	17.3	3.79	0.39	1.60	0.31	0.09
					ANOVA					
Source of variation										
	Year	1	–	ns#	***	***	***	***	***	***
	Soil history	1	**	***	***	***	***	**	***	***
	Year*Soil	1	–	ns	***	***	***	***	***	***
	CV, %		2.2	15.1	5.4	10.4	10.7	5.1	10.0	10.6

† From Griffin and Porter (2004).
‡ Particulate organic matter (POM).
§ Soil microbial biomass (SMB).
# ns, not significant.
*, **, *** Significant at the 0.05, 0.01 and 0.001 probability levels, respectively.

Two freeze-dried dairy manures were used in the aerobic incubation, based on N dynamics in a previous incubation experiment (Griffin et al., 2005). The MManure, which resulted in net N mineralization when added to two soils of different textures, had lower total C concentration, higher total N and NH_4^+ concentrations, and a lower C/N ratio than IManure, which resulted in net immobilization of N (Table 5.2). While the total C concentration of IManure was only 9% higher than that of MManure, fibrous C concentration (measured as neutral detergent fiber, NDF; Mertens, 2002) was 281% higher. Griffin et al. (2005) found the ratio of NDF to NH_4^+ to be the best predictor of net nitrification and final NO_3^- concentration following manure addition, compared with C/N or other ratios of manure components.

Table 5.2. Characteristics of the net mineralizing (MManure) and net immobilizing (IManure) dairy manures used in the incubation experiment†.

	MManure	IManure
Total C, g kg^{-1}‡	415	451
Neutral detergent fiber (NDF), g kg^{-1}	162	617
Total N, g kg^{-1}	55.8	14.7
Organic N, g kg^{-1}	40.0	12.1
NH_4^+, g kg^{-1}	15.8	2.6
Total C/N	7.4	30.7
Total C/NH_4^+	26.3	173.5
NDF/NH_4^+	10.3	237.3

† From Griffin et al. (2005).
‡ Dry-matter basis.

The MManure was obtained from a sample submitted to the Maine Agricultural and Forest Experiment Station Analytical Laboratory and IManure was collected directly from a commercial dairy. The fresh manures were homogenized using a food processor. Subsamples were analyzed for total Kjeldahl N (Kane, 1998) and NH_4^+ concentration via distillation with MgO (AOAC Method 973.49). Organic N was estimated as the difference in these values. The remaining manure samples were frozen (−20°C), freeze-dried (−80°C), and ground (2 mm). Ammonium concentrations of the freeze-dried manures used in this study were in the range for fresh manures used by others (Griffin et al., 2005).

5.3.2. Incubation Procedure

Soils were preincubated in the dark for 5 d at 25°C before N additions were made. One hundred and fifty grams of soil (dry-weight equivalent) were added to 250-mL acid-washed, plastic containers and packed to a density of 1.1 g cm^{-3}. During the preincubation period, soils were adjusted to a water content of 200 g H_2O kg^{-1} by either allowing evaporative losses from open containers or adding deionized water.

The MManure (528 mg), IManure (3409 mg), and a fertilizer solution (Fert) (22.3 mg NH_4Cl in 5 mL H_2O) were mixed with samples of each soil on Day 0, an approximate addition rate of 50 mg NH_4^+ kg^{-1} dry soil. This rate is roughly equivalent to 100 kg ha^{-1} to a depth of 15 cm. A soil-only control treatment was also mixed but no N was added. All treatments were replicated five times. After mixing, a 3-g subsample of the soil (approximately 2.5 g dry-weight equivalent) was placed in a 25-mL centrifuge tube with 25 mL of 2.0 *M* KCl, shaken for 1 h, and centrifuged (2700 × *g* for 10 min). The supernatant was filtered (0.45 μm) and analyzed for NH_4^+ and NO_3^- colorimetrically on a

Lachat Autoanalyzer (Lachat Instruments, Mequon, WI). The remaining soil was repacked to a density of 1.1 g cm^{-3}. Deionized water was added to increase the water content to 250 g H_2O kg^{-1} (47% water-filled pore space, WFPS) and the containers were recapped and returned to the incubator.

Soil NH_4^+ and NO_3^- concentrations were determined at 1, 3, 7, 14, 28, 56, 112, 171, and 282 d. At each sampling date, the soil was stirred, subsampled, and processed as above, repacked, and returned to the incubator. The soil was aerated by leaving the containers open for 1 h daily for the first 2 wk, and weekly thereafter. Moisture content was maintained by adding deionized water as needed on a weekly basis. Nitrate concentration represented net N mineralization after 3 or 7 d, depending on soil treatment, since NH_4^+ concentrations decreased to and remained near zero for the remainder of the incubation. The proportion of added N that was net mineralized by the end of the incubation was calculated from

$$\text{N\% mineralized} = (282\text{d}NO_3^-{}_{\text{tmt}} - 282\text{d}NO_3^-{}_{\text{control}})/(\text{Nadded})_{\text{tmt}} \qquad [1]$$

where $282dNO_3^-$ is the NO_3^- concentration at 282 d and Nadded is the total N added (as NH_4^+ and organic N) in the N treatments.

Soil microbial biomass N was estimated at 28 d following the microwave irradiation procedure of Islam and Weil (1998), with the following modifications. After stirring the soil for NH_4^+ and NO_3^- sampling, 20-g subsamples (dry-weight equivalent) were removed and placed in small glass beakers, packed to density of 1.1 g cm^{-3}, wetted to 70% WFPS, irradiated in a microwave oven to receive 400 kJ kg^{-1} dry soil, stirred, allowed to cool, and then irradiated again. The irradiated soil was inoculated with 1 g untreated soil, repacked to the original density, rewetted to 60% WFPS, and incubated in sealed jars with 5 mL of water in the bottom for 10 d at 25°C. After the incubation period, soil was extracted for NH_4^+ and NO_3^- determination as above. Soil microbial biomass N was calculated following Voroney and Paul (1984).

5.3.3. Statistical Analysis

A double exponential model has been found to provide the best description of NO_3^- accumulation in disturbed soil with or without N additions (Benbi and Richter, 2002; Cabrera and Kissel, 1988; Christensen and Olesen, 1998; Deans et al., 1986; Dou et al., 1996; Lindemann and Cardenas, 1984; Wang et al., 2004). This two-pool model allows the separation of N into two conceptual pools: a small, active pool comprised of easily transformed material responsible for an initial rapid phase of NO_3^- accumulation (N_1), and a larger, resistant pool with a slower turnover time (N_2), each described by first-order kinetics. The cumulative amount of accumulated NO_3^- at time t is given as

$$N_t = N_1[1 - \exp(-k_1 t)] + N_2[1 - \exp(-k_2 t)] \qquad [2]$$

where k_1 and k_2 are the rate constants associated with the active and slow N pools.

There are concerns that estimates of N_1, N_2, k_1, and k_2 obtained from fitting all four parameters of the double exponential model simultaneously are highly sensitive to incubation conditions, particularly duration (Benbi and Richter, 2002; Böttcher, 2004; Dou et al., 1996; Wang et al., 2004), and that the rate constants and pool sizes are strongly correlated (Christensen and Olesen, 1998; Wang et al., 2004). For these reasons, some researchers have proposed fixing the rate constants to increase the certainty of the pool size estimates (Christensen and Olesen, 1998; Wang et al., 2004). This approach focuses on the effects of pool size alone on mineralization.

The double exponential model was fit to NO_3^- accumulation data using both fixed and unfixed rate constants. The values of the fixed rate constants were determined by fitting Eq. [2] to the combined data set of all treatments simultaneously with common k_1 and k_2 parameters but individual N_1 and N_2 for each treatment. The rate constants estimated by this global model were $k_1 = 0.1989$ d^{-1} and $k_2 = 0.0031$ d^{-1} ($R^2 = 0.99$). Model fitting was done with Nonlinear Model (SYSTAT Software, 2004) using the least squares loss function and the Marquardt option. Data were first standardized by subtracting the Day 0 soil NO_3^- concentration for each treatment. Curves were fit for each treatment replicate. Extra sums of squares analysis was used to distinguish significantly different curves between soil pairs. The effects of treatment on estimated N_1 and N_2 parameters were analyzed with ANOVA (SYSTAT Software, 2004). Parameter means were separated with Fisher's protected LSD procedure, with a Bonferroni adjustment of critical probability values due to multiple tests (Sokal and Rohlf, 1995). The IManure NO_3^- accumulation data could not be fitted with a reasonable model. Instead, repeated measures ANOVA was used to determine the significance of amendment history and sampling date.

5.4. Results

5.4.1. Soil Properties

A history of soil amendment increased both total C and N concentrations by 31% by 1999, and by 96 and 83%, respectively, by 2002 compared with the historically nonamended treatment (Table 5.1). The more labile pools of C and N were disproportionately enhanced; particulate organic matter and SMB-C and -N concentrations were two to three times greater in the historically amended soil than in the nonamended soil. Microbial respiration and soil pH were also greater in the historically amended soil than in the nonamended soil. The soil samples used for the incubation were representative of these treatment differences, with total C and N concentrations of 30 and 2.5 g kg^{-1}, respectively, for the historically amended treatment and 18 and 1.4 g kg^{-1}, respectively, for the historically nonamended treatment.

5.4.2. Soil Nitrogen Mineralization

Net mineralization in the historically amended soil was twice that in the historically nonamended soil during the 282-d incubation when no N sources were added (Fig. 5.1a). Final soil NO_3^- accumulated was 168 vs. 84 mg kg^{-1} soil, respectively. Nitrate concentrations reflect net mineralization, as well as nitrification, since NH_4 concentrations were negligible in the control soil throughout the incubation. The proportion of total soil N that was net mineralized during the incubation was also higher in the historically amended soil (6.8%) than the nonamended soil (5.8%; Fig. 5.1b). Curves fit to the contrasting soil treatments in Fig. 5.1a and 5.1b were significantly different ($p < 0.001$), as determined by extra sums of squares analysis.

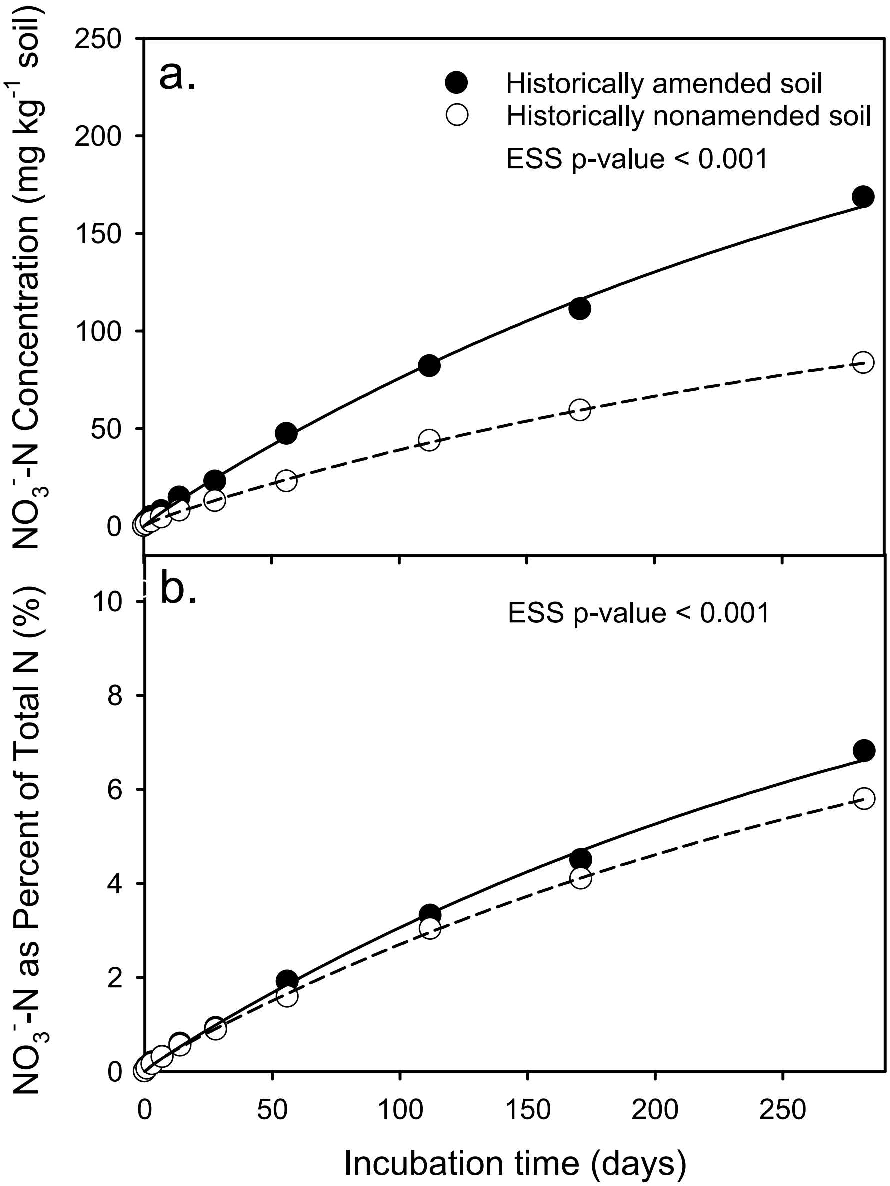

Figure. 5.1. (a) Nitrate concentration and (b) NO3⁻ as a percentage of total soil N for historically amended and nonamended soils, fitted with a two-pool, first-order model. Individual data points are the mean of five replicates (n = 5). EES, extra sums of squares comparison of fitted soil treatment curves.

5.4.3. Short-Term Nitrogen Dynamics following Nitrogen Additions

Soil NH_4^+ concentrations immediately following the addition of MManure or Fert were equivalent to the target NH_4^+ addition rate (50 mg kg^{-1}) at 0 d and declined at approximately the same rate, reaching zero within 3 to 7 d (Fig. 5.2). Soil NH_4^+ concentrations in all treatments remained nominal (i.e., <1 mg kg^{-1} soil) for the remainder of the incubation (data not shown). In the Fert treatment, NH_4^+ consumption and NO_3^- accumulation appeared to be strongly linked, as the rapid disappearance of NH_4^+ was matched by rapid accumulation of NO_3^- (Fig. 5.2 and 5.3a). Rates of NO_3^- accumulation slowed once concentrations reached 50 mg kg^{-1}, suggesting complete nitrification of the added fertilizer NH_4^+. In comparison, consumption of NH_4^+ from MManure occurred slightly faster than from Fert, but initial NO_3^- accumulated more slowly. Nitrate concentrations in the MManure treatment reached only 31 and 35 mg kg^{-1} in the historically amended and nonamended soils, respectively, by 7 d when NH_4^+ was depleted (Fig. 5.2 and 5.3b).

Initial NH_4^+ concentrations in the IManure treatment exceeded the target application rate by 10 mg kg^{-1} soil (Fig. 5.2). Soil NH_4^+ concentrations showed relatively little change at 1 d, but then decreased rapidly, disappearing by 3 or 7 d. Soil NO_3^- concentration in the IManure treatment increased rapidly during this period of NH_4^+ consumption, as with the other N treatments. Unlike the other treatments, however, soil NO_3^- concentrations began to fall once NH_4^+ was fully consumed, at 3 d for the historically amended treatment and 7 d for the historically nonamended treatment (Fig. 5.3c).

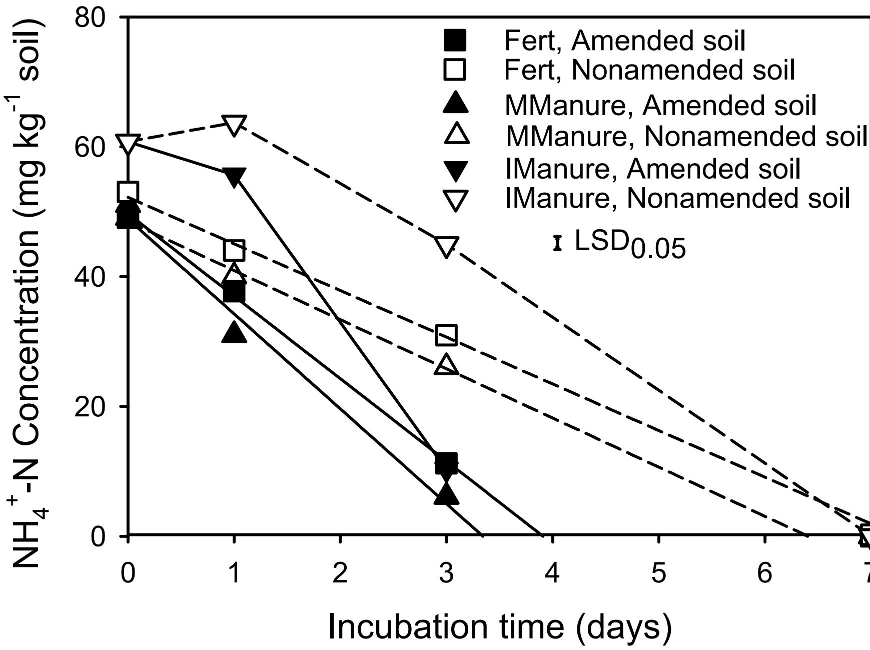

Figure. 5.2. Ammonium consumption in historically amended and nonamended soils following incorporation of NH4+ fertilizer (Fert), net mineralizing manure (MManure), or net immobilizing manure (IManure). Individual data points are the mean of five replicates (n = 5). The MManure and Fert data were fitted with linear models ($R^2 > 0.97$). LSD between all treatments, from a repeated measures ANOVA.

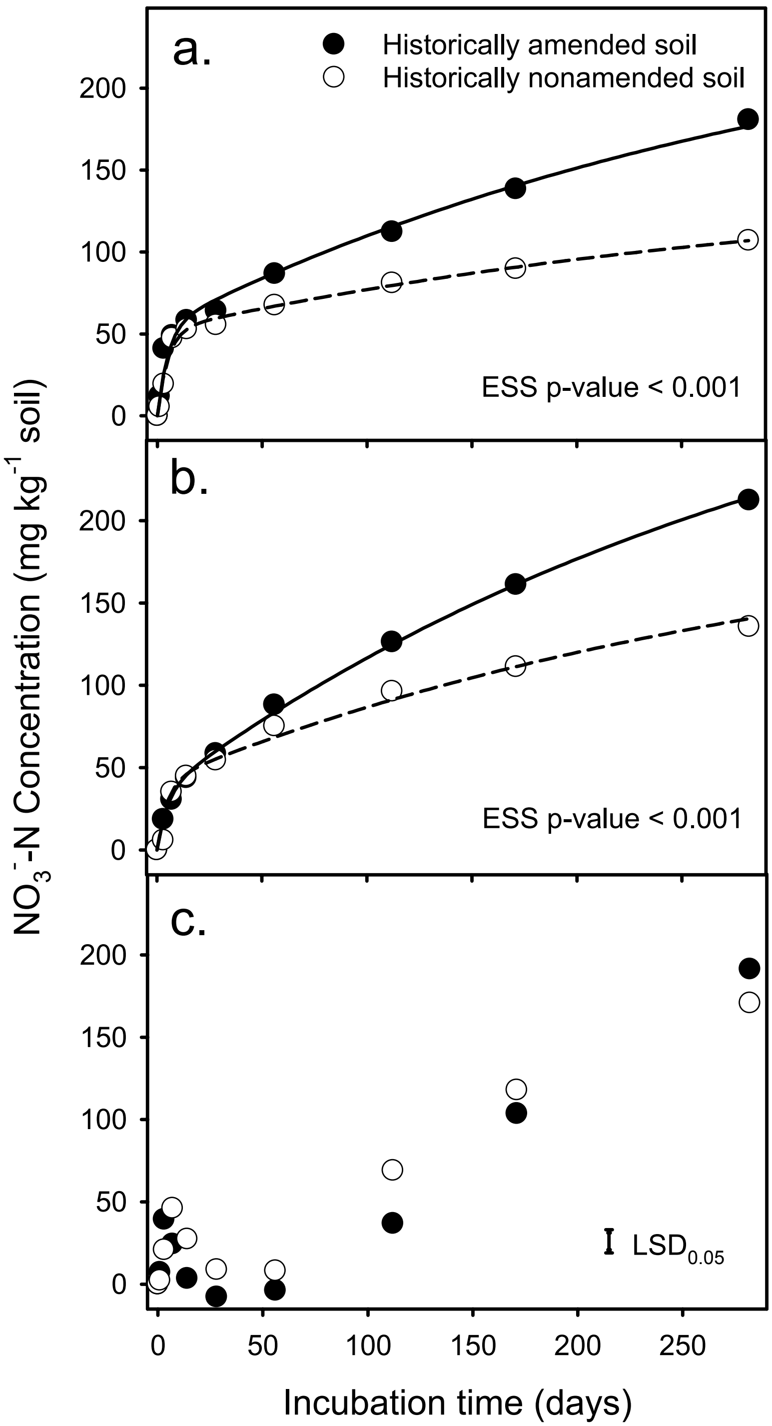

Figure. 5.3. Nitrate concentration in historically amended and nonamended soils following the incorporation of (a) NH4+ fertilizer (Fert), (b) net mineralizing manure (MManure), and (c) net immobilizing manure (IManure). Individual data points are the mean of five replicates (n = 5). EES, extra sums of squares comparison of fitted soil treatment curves; LSD between soil treatments, from a repeated measures ANOVA of IManure.

While N source defined the overall shape of the NH_4^+ consumption and NO_3^- accumulation curves, amendment history affected N transformation rates. Soil NH_4^+ disappeared and NO_3^- accumulated more rapidly in the historically amended soil than the nonamended soil for all N sources during the first 7 d of the incubation. Curves fit to the NO_3^- accumulation data of the contrasting soil treatments were significantly different ($p < 0.001$ for both Fert and MManure), as determined by extra sums of squares analysis (Fig. 5.3a and 5.3b).

5.4.4. Long-Term Nitrogen Dynamics following Nitrogen Additions

The Fert and MManure NO_3^- accumulation curves resembled those for the control soils after the initial flush of NO_3^-, with accumulation occurring more rapidly in the historically amended soil (Fig. 5.1a, 5.3a, and 5.3b). In the IManure treatment, soil NO_3^- concentration remained near zero after 3 or 7 d until it began to increase after 56 d. There were relatively small differences between the soil treatments. The negative NO_3^- concentrations observed at 28 and 56 d are an artifact of standardizing the data by subtracting Day 0 NO_3^- concentrations.

Nitrogen source, soil amendment history, and the interaction of these two factors all affected the proportion of recently added N that was found in the mineral pool at the end of the incubation (Table 5.3). Within each soil history treatment, Fert was the most available source of N, followed by MManure and IManure. For each N source, less of the recently added N was found in the NO_3^- form at 282 d in the historically amended soil than in the historically nonamended soil. The interaction between the treatment factors was due to the difference between soil treatments being smaller for MManure (4.7 units) than for Fert (22.5 units) or IManure (18.8 units). Soil microbial biomass N, determined at 28 d, was two to three times greater in the historically amended soil than the historically nonamended soil (Table 5.4). Soil microbial biomass N was also affected by N source, with IManure causing the greatest increase in SMB-N relative to the control and Fert resulting in almost no change.

Table 5.3. Nitrate pool at the end of the 282-d incubation, expressed as a percentage of N added (NH_4^+ plus organic N), for the historically amended and nonamended soil treatments.

N Source†	df	Amended	Nonamended
		%	
Fert		24.5‡	47.0
MManure		22.3	27.0
IManure		6.7	25.5
		ANOVA	
Source of variation			
Replicate	4	ns§	
Soil history (S)	1	***	
N source (N)	2	***	
S × N	2	**	
LSD(0.05)		0.07	
CV, %		21.3	

† Fert = NH_4^+ fertilizer; MManure = net mineralizing manure; IManure = net immobilizing manure.
‡ Calculated by dividing control-corrected NO_3^- concentrations at 282 d by the sum of NH_4^+ and organic N added for each N source.
§ ns = not significant at the 0.05 probability level.
, * Significant at the 0.01 and 0.001 probability levels, respectively.

Table 5.4. Soil microbial biomass (SMB) N concentration at 28 d after N source treatments were added to the historically amended and nonamended soil treatments.

N Source†	df	Amended	Nonamended
		mg kg^{-1}	
Control		259	77
Fert		241	72
MManure		308	129
IManure		513	285
		ANOVA	
Source of variation			
Replicate	4	ns‡	
Soil history (S)	1	***	
N source (N)	3	***	
S × N	3	***	
LSD(0.05), mg kg^{-1}		9	
CV, %		2.8	

† Fert = NH_4^+ fertilizer; MManure = net mineralizing manure; IManure = net immobilizing manure.
‡ ns = not significant at the 0.05 probability level.
*** Significant at the 0.001 probability level.

5.4.5. Estimated Nitrogen Pool Sizes

The double exponential model provided good fits for NO_3^- accumulation curves of the Fert and MManure treatments, regardless of whether rate constants were fitted or fixed (R^2 values ranged from 0.98 to >0.99 in both cases). The control treatment could be fit with the two-pool model when rate constants were fixed ($R^2 > 0.99$), but with only a single-pool model when the rate constant was fitted ($R^2 > 0.99$). Fitting all the parameters simultaneously produced more variable parameter estimates than fixing the rate constants, as seen with higher ANOVA CVs (Table 5.5). Also, correlations between the fitted rate constants and pool sizes were high (−0.62 to −0.86 for N_1 and k_1; −0.84 to −0.99 for N_2 and k_2), which makes interpretations of the parameters uncertain

(Christensen and Olesen, 1998; Wang et al., 2004). Finally, differences in rate constants are difficult to interpret as they represent only the net rate of change in the size of the NO_3^- pool, which is the result of multiple opposing processes and cannot be equated with microbial activity. For these reasons, the remaining discussion of pool sizes refers to the estimates of N_1 and N_2 when the rate constants were fixed (Table 5.5).

Estimated active and slow pools (N_1 and N_2, respectively) were significantly affected by both N source and soil amendment history (Table 5.5). There were also significant interactions between these two factors for both N_1 and N_2. The size of the active pool (N_1) was minimal in the control treatment; this rapidly available N pool may have been exhausted during the 5-d preincubation period. In the Fert treatment, the size of the N_1 pool was equivalent to the amount of NH_4^+ added and was unaffected by soil amendment history. In contrast, N_1 for the MManure treatment was less than the amount of manure NH_4^+ added, and was 25% lower in the historically amended soil than in the historically nonamended soil. Rankings of N_2 for the N treatments were: MManure > control > Fert. The difference in N_2 between soil treatments for MManure was equivalent to that for the control (135 and 137 mg kg^{-1}, respectively), yet this difference was smaller in the Fert treatment (117 mg kg^{-1}). The IManure NO_3^- concentration data could not be fit with the two-pool model, nor could pool sizes be estimated.

Table 5.5. Estimated active (N_1) and slow (N_2) N pool sizes determined by fitting a double exponential model to NO3$^-$ accumulation curves resulting from the addition of N sources to the historically amended and nonamended soil treatments (Figures 5.3a-c). Pool sizes, expressed as mg N kg$^-$1 soil, were estimated either by 1) allowing rate constants (k_1 and k_2) to be fit simultaneously, or 2) fixing the rate constants at k_1=0.1989 day^{-1} and k_2=0.0031day^{-1}.

	Rate constants fitted						Rate constants fixed		
Treatment†	df	N_1	k_1	df	N_2	k_2	df	N_1	N_2
Control									
Amended		-	-		302.0	0.0025		1.5	277.8
Nonamended		-	-		131.9	0.0036		1.5	140.8
Fert									
Amended		47.5	0.5574		250.5	0.0028		53.6	211.3
Nonamended		50.9	0.2140		93.3	0.0034		51.9	94.4
MManure									
Amended		34.2	0.1607		288.9	0.0035		32.1	307.9
Nonamended		43.6	0.1310		117.3	0.0050		41.0	172.5
						ANOVA			
Source of variation									
Replicate	4	ns‡	ns	4	ns	ns	4	ns	ns
Soil history	1	***	***	1	***	***	1	***	***
NSource	1	***	***	2	*	***	2	***	***
SxN	1	*	***	2	ns	ns	2	***	**
$LSD_{0.0125}$§, mg kg^{-1}		5.7	0.1075		65.6	0.0012		3.1	9.1
CV, %		6.0	18.8		19.1	17.6		5.9	3.0

† Fert = NH_4^+ fertilizer; MManure = net mineralizing manure.
‡ ns = not significant at the 0.05 probability level.
*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
§ Bonferroni adjusted LSD for experiment-wise Type I error of 5%.

5.5. Discussion

5.5.1. Amendment History Effects on Soil Nitrogen Availability

Thirteen years of organic amendment application created a soil distinct from its nonamended counterpart, with greatly enhanced soil C and N stocks, especially the more readily available pools of C and N, and increased microbial biomass and activity (Table 5.1). Historical amendment application also doubled the capacity of the soil to supply N. Nitrate accumulation during the incubation and the estimated size of N_2 in the historically amended soil were twice those of the historically nonamended soil when no N was added (control treatment; Fig. 5.1a and Table 5.5). Repeated, long-term application of manure has consistently been shown to increase the N supplying capacity of soil (Burger and Jackson, 2003; Griffin and Laine, 1983; Hadas et al., 1996; Langmeier et al., 2002), with higher application rates resulting in proportionally more potentially mineralizable N (Whalen et al., 2001). In the present study, total soil N concentrations were 79% higher in the historically amended soil than in the historically nonamended soil. Most of the difference between soil treatments was removed when net mineralized N was expressed as a proportion of total soil N (Fig. 5.1b). This suggests that the size of the substrate pool was the major determinant of N mineralization, and agrees with findings that total soil N is a good predictor of potentially mineralizable N (Cabrera and Kissel, 1988; Griffin and Laine, 1983; Hadas et al., 1986). Total N did not explain all of the difference in net N mineralization, however. At the end of the incubation, 6.8% of total soil N was net mineralized in the historically amended soil vs. 5.8% in the historically nonamended soil. This difference may reflect the relative enhancement of the more readily available pools of N in the historically amended soil.

Numerous edaphic factors other than N pool size also have been shown to influence N mineralization, largely through their effects on microbial activity. These include soil C content (Barrett and Burke, 2000), pore size and water status (Thomsen et al., 1999), soil pH (Curtin and Wen, 1999; Gordillo and Cabrera, 1997), microbial community composition (Hassink, 1994; Hassink et al., 1994), and grazer communities characteristics (Griffiths et al., 2003; Kuikman et al., 1991). Most of these factors or mechanisms are potential contributors to differences in N mineralization between soils with divergent soil amendment histories. It is possible that differences in soil characteristics such as these played a role in the present study, especially given the measured differences in soil C, pH, microbial biomass, and microbial activity (Table 5.1). Their combined effects were small, however, compared with the effect of the size of the mineralizable N pool.

5.5.2. Nitrogen Mineralization from Recently Added Nitrogen Sources

Nitrogen from manure became available more slowly than fertilizer N. Despite similar NH_4^+ inputs and rates of NH_4^+ consumption for the MManure and Fert treatments (Fig. 5.2), NO_3^- accumulation was slower (Fig. 5.3) and estimated N_1 was smaller (Table 5.5) in the MManure treatment. The proportion of recently added N that was found in the mineral pool at the end of the incubation was also smaller in the MManure treatment than in the Fert treatment (Table 5.3). These results are congruent with findings that manure is a more gradual source of plant-available N than fertilizer (Langmeier et al., 2002; Ma et al., 1999). Whereas the primary transformation of added fertilizer NH_4^+ is nitrification, immobilization and nitrification are both stimulated by manure additions, with the possibility that immobilized N can later be remineralized via mineralization–

immobilization turnover (Jansson and Persson, 1982). Greater SMB-N in MManure than in the control at 28 d provides evidence that immobilization was indeed an important alternative pathway for this treatment, but not for Fert, which showed no such increase (Table 5.4). Denitrification has recently been shown to be another important alternative sink in aerobic incubations of manure-amended soil, with losses of manure NH_4^+ up to 30% (Calderón et al., 2004). These losses result from the addition of readily available C and N; C stimulates intense microbial activity, which consumes the local O_2 supply, and NO_3^- fuels denitrification in the anoxic microsites (Calderón et al., 2004; Calderón et al., 2005). Denitrification most likely did not play an important role in the present study, however, because the soil was aerated daily and stirred periodically during the period of intense microbial activity and O_2 consumption (0–2 wk).

Alternative pathways for recently added N were even more important for IManure than MManure. In this treatment, there was an initial flush of NO_3^- accumulation, presumably from nitrification of the added NH_4^+, followed by a steep drop in NO_3^- concentration to near zero at 28 d (Fig. 5.3c). A similar pattern of N availability was observed for this particular manure in a previous incubation experiment and reflects manure with a high concentration of C relative to NH_4^+ (Griffin et al., 2005). Greater SMB-N in the IManure treatment than the control at 28 d (Table 5.4) suggests that microbial immobilization was responsible for the drop in NO_3^- concentration. Appreciable rates of NO_3^- assimilation by microbes have been observed in tilled and untilled soils, and have been associated with C availability (Burger and Jackson, 2003; DeLuca and Keeney, 1995; Schimel, 1986). The IManure added seven times more total C than MManure at the same NH_4^+ addition rate (10,247 vs. 1460 mg C kg^{-1} soil, respectively) due to its high C/NH_4^+ ratio (Table 5.2). Additionally, IManure C was substantially more recalcitrant than MManure C, probably becoming available more slowly. Calderón et al. (2005) observed that lower cumulative N_2O flux correlated with lower CO_2 flux regardless of manure total C concentration. They hypothesized that slow and gradual sources of C favor immobilization over denitrification, as would a well-aerated soil status. Following the drop to near zero at 28 d in the present study, NO_3^- concentrations began accumulating in IManure, indicating a shift in the relative importance of ammonification and subsequent nitrification over immobilization.

Net mineralization of organic N was observed for MManure as an increase in $N_1 + N_2$ compared with the control (61 and 72 mg kg^{-1} for the historically amended and nonamended soils, respectively) that was greater than the amount of NH_4^+ added (approximately 50 mg kg^{-1}). Organic N can contribute to active, slow, and recalcitrant pools of N (Wander, 2004), while NH_4^+ is assumed to be part of the active N pool. The relative contributions of organic N and NH_4^+ to N_1 and N_2 cannot be determined in the present study. The coincidence of NH_4^+ disappearance and NO_3^- accumulation during the first 7 d, however, suggests that NH_4^+ was the largest contributor to N_1. Net mineralization of organic N was probably responsible for the greater N_2 in MManure relative to the control.

The Fert treatment resulted in a smaller N_2 pool relative to the control. Reduced NO_3^- concentrations could have occurred from loss of mineral N, suppression of soil N mineralization, or both. Denitrification is not a likely mechanism for lowering NO_3^- levels in the Fert treatment for the reasons mentioned above and because Fert did not introduce a source of readily available C. It is more probable that net mineralization was suppressed by the addition of N fertilizer. Mineralization of organic N is known to decrease progressively with decreasing pH below pH 6 (Adams and Martin, 1984). The pH of the incubation soils started in this range (Table 5.1) and could have been reduced by nitrification of the added NH_4^+ fertilizer (Brady and Weil, 1996). While a pH effect is a more likely explanation than denitrification, the actual cause of the reduced Fert N_2 relative to the control remains unclear.

5.5.3. Amendment History Effects on Mineralization of Recently Added N

Results from the historically amended and nonamended soils indicate that the effects of soil amendment history on mineralization of recently added N can be more important than previously documented. Although the N source treatment factor defined the overall shapes of the NO_3^- accumulation curves, soil amendment history also clearly influenced N dynamics. In the short term (0–7 d), initial rates of NH_4^+ disappearance and NO_3^- accumulation were higher in the historically amended soil than the nonamended soil in almost all cases (Fig. 5.2 and 5.3a–c), presumably due to a larger, more active microbial biomass (Table 5.1). In the long term, however, historical amendment had the opposite effect, reducing rather than increasing the availability of recently added N. Recovery of added N as NO_3^- at the end of the incubation was lower in the historically amended soil than in the historically nonamended soil (Table 5.3), suggesting that immobilization of recently added N was more important in the historically amended soil.

Previous research has found little or no effect of soil amendment history on the availability of current N additions (Hadas et al., 1996; Langmeier et al., 2002; Sanchez et al., 2001). Langmeier et al. (2002) reported a significant effect of soil management (organic vs. mineral fertilizers) on plant uptake of N from mineral and organic N sources, but the soil effect was an order of magnitude smaller than N source effects, and was only observed for organic N sources. In contrast, our results demonstrate that the effects of soil amendment history on the availability of N from organic and inorganic N sources can be as important in scale and duration as N source effects. One possible reason why our results do not concur with others is that the historically amended and nonamended soils were far more disparate than the pairs of contrasting soils used in the other studies. For example, total soil C and N concentrations, 67 and 79% higher, respectively, in the historically amended soil than in the historically nonamended soil, differed between soil pairs by only 7 and 15% in Langmeier et al. (2002), by 36 and 30% in Sanchez et al. (2001), and by 61% (reported for total soil N only) in Hadas et al. (1996).

Estimating the active and slow N pools with the double exponential model revealed that, although the historically amended soil reduced the availability of all sources of N, the pools affected were not the same. Historical amendment affected N_1 for MManure and N_2 for Fert (Table 5.5). One possible explanation involves the relative availability of the different sources of C that could facilitate N immobilization, namely soil and manure. Although soil C was much more abundant in the historically amended soil than the historically nonamended soil, the preincubation period may have depleted both soils of the most readily available C pools. If so, immobilization of Fert NH_4^+ may have been C limited in the short term, thereby favoring nitrification. With time, however, mineralization of soil organic matter would have liberated soil C, with more becoming available in the historically amended soil, and allowed immobilization in the Fert treatment. This apparent lag time for C availability could explain why historical amendment affected N_2 but not N_1 in the Fert treatment. In the MManure treatment, this lag time for C availability may have been overcome by the addition of labile C in the manure. In this case, the reduction of N_1 in the historically amended soil could be attributed to an interaction of a more active soil microbial community with the added C and NH_4^+ (Burger and Jackson, 2003), resulting in increased immobilization relative to nitrification (Barrett and Burke, 2000; Hatch et al., 2000).

Although pool sizes were not estimable for IManure, the NO_3^- accumulation results (Fig. 5.3c) show a reduction in soil NO_3^- concentration in the historically amended treatment relative to the nonamended treatment. This reduction did not occur until after the initial flush of NO_3^- (after 3 d), suggesting that C availability was delayed in the historically amended soil receiving IManure. In this case, the apparent lag time for C availability was due to recalcitrance of the manure C (Table 5.2) as well as soil C.

5.5.4. Implications of an Amendment History Effect

Two factors determine how N use efficiency might be impacted by the reduced availability of recently added N in a historically amended soil: (i) the magnitude and timing of plant N demand relative to N supply, and (ii) the fate of the recently added N not recovered in the inorganic N pool. Inorganic N in excess of plant demand is susceptible to loss via leaching or denitrification. Creating better coincidence between N supply and plant demand is central to improving N use efficiency and tightening the N cycle (Christensen, 2004). Delaying or reducing N availability from added sources, as occurred in the historically amended soil, may increase synchrony with plant demand and reduce potential N leaching losses (Ma et al., 1999), but may also lead to potentially leachable end-of-season excesses of NO_3^- (Schröder, 2005).

The fate of recently added N not recovered in the NO_3^- pool of the historically amended soil depends on the mechanism responsible for the soil history effect. It appears that reductions were related to microbial activity and available manure C in the short term (0–7 d), and to available soil C in the longer term. Carbon-enhanced immobilization is a probable mechanism since it is microbiologically driven, dependent on a readily available source of C, and provides an alternative pathway for NH_4^+. Immobilized NH_4^+ enters the microbial biomass instead of the NO_3^- pool. As mentioned above, denitrification can be another important pathway for manure N (Calderón et al., 2004), although of unlikely importance in the present study. Distinguishing between immobilization and denitrification of recently added N is not necessary for predicting plant-available N during the first growing season after application, but it is critical for estimating the longer term N supply effects (Lindemann and Cardenas, 1984) as well as the environmental impact of manure amendments. While both processes reduce current-season plant-available N, denitrification results in net loss of N from the system to the environment. In contrast, immobilization builds the N supply capacity of the soil, reduces potential N losses via leaching, and thereby increases the overall N efficiency of the agricultural system (Christensen, 2004).

Soil amendment history had the largest impact on soil N mineralization capacity through the accumulation of residual N, but it also altered the dynamics of recently added N. As such, future work to develop and refine predictive models for N availability should include consideration of soil amendment history not only for its effects on the ability of the soil to supply N, but also for its effects on the availability of recently added N sources. Additionally, an understanding of the fate of added N not recovered in the

NO_3^- pool in historically amended soil, and how it is influenced by manure and fertilizer characteristics, is clearly needed to predict the long-term availability and the potential environmental impact of N added to these soils.

Chapter 6

ON-FARM ASSESSMENT OF SOIL QUALITY IN INTEGRATED POTATO-DAIRY SYSTEMS

6.1. Chapter Abstract

Integrating potato and dairy systems can improve the quality and crop production potential of soil used for growing potatoes through manure additions and longer rotations. We investigated whether effects of integration were observable at a landscape level by assessing the soil quality status of 48 potato and dairy farm fields under various degrees of integration in Maine. Fields were in one of six cropping systems: 2 yr potato–small grain or grain corn rotations, no manure (2YrPot-M0); 2 yr potato–small grain or silage corn rotations, manure every other year (2YrPot-M50); 3 yr potato–corn silage–corn silage or small grain rotations, manure two of three yr (3YrPot-M67); continuous corn silage, manure every yr (CornSil-M100); mixed forage grass, no manure (Hay-M0); and mixed forage grass, manure every yr (Hay-M100). Soil was analyzed for total and particulate organic matter (POM) C and N, Modified Morgan P, $CaCl_2$ P, pH, cation exchange capacity, soil texture, and bulk density. Soil pH and P were higher in integrated potato systems (2YrPot-M50 and 3YrPot-M67) than nonintegrated potato systems (2YrPot-M0) but there were no detectable differences in total or POM C or N among potato systems. Soil C and N pools were significantly higher in dairy systems (CornSil-M100, Hay-M0 and Hay-M100) than in potato systems. A nonlinear relationship between POM C and total C was observed. Intensively-tilled potato-based

systems appear to need greater increases in C inputs and reductions in tillage to produce changes in soil C and N that can be detected at a landscape level.

6.2. Introduction

Improving or maintaining soil quality is recognized as fundamental to preserving the crop production potential of soil. Maintaining soil quality is difficult in potato cropping systems because they are typified by high levels of soil disturbance and low levels of crop residue return. In Maine and northeastern Canada, intensive potato production has led to measurable decreases in SOM, porosity, and structural stability (Saini and Grant, 1980). The use of manure, composts, and other organic amendments in potato systems in this and other regions have been shown in research station studies to increase C and nutrient inputs, improve SOM levels, increase potato yields (Black and White, 1973; Grandy et al., 2002; Snapp et al., 2003), and enhance the stability of those yields (Mallory and Porter, 2007). Thus, relinking C and nutrient cycles between potato and livestock farms is seen as a promising strategy to assure soil quality and productivity in potato systems (Files and Smith, 2001; Russelle et al., 2007; Stark and Porter, 2005).

In Maine, regional integration of potato and dairy farms has developed over the last 15 years (Files and Smith, 2001; Hoshide et al., 2004). In some cases, integration consists solely of excess dairy manure being applied to nearby potato farm fields, and is thus a unidirectional flow of organic matter and nutrients from dairy to potato farms. In other cases, integration is more complex and bidirectional, with farmers sharing land between operations, expanding the potato rotation to include feed crops (e.g., silage corn or barley as forage or grain) for the dairy operation, and trading services such as tillage or spraying. Integrated dairy farmers identified an expanded land base for applying manure and a local source of feed as the key benefits of integration (Files and Smith, 2001). Integrated potato farmers noted increased crop yields and crop quality, which they attributed in large part to improvements in soil quality (experienced as improved friability and water holding capacity) resulting from the use of manure and longer rotations. While the benefits to soil quality have been observed on an individual field level, the question remains whether the adoption of integrated potato dairy systems has produced changes in soil quality that are measurable on a landscape level across fields and farming operations.

The primary objective of this study was to assess the impact of different levels of potato-dairy integration on soil quality. A secondary objective was to develop guidelines for nonintegrated farmers on the level or degree of integration necessary to achieve observable improvements in soil quality. We assessed the soil quality status of 48 integrated and nonintegrated potato and dairy farm fields in Maine using total soil and POM C and N content as our indicators. Soil organic matter attributes are regarded as the best indicators of soil quality status (Gregorich et al., 1994). Whereas total soil C and N pools integrate inherent site characteristics with historical management effects, POM C and N are early indicators of management-induced SOM changes (Cambardella and Elliott, 1992; Gregorich et al., 1994; Wander and Bollero, 1999). We also assessed the P status of the soils because of concerns that manure use can cause the accumulation of soil P to excess levels (Edmeades, 2003; Stark and Porter, 2005), which is especially relevant to potato systems with a history of heavy P fertilizer use (Erich et al., 2002).

6.3. Materials and Methods

6.3.1. Site Descriptions

Initially, 49 potato and dairy farm fields located within 50 km of one another in Central Maine were selected for this study. All surface soils were developed from glacial till and belong to one of three related silt loam series: Bangor silt loam (coarse-loamy, isotic, frigid Typic Haplorthods); Dixmont silt loam (coarse-loamy, isotic, frigid Aquic Haplorthods); and Thorndike silt loam (loamy-skeletal, isotic, frigid Lithic Haplorthods). Clay concentration in the original 49 samples ranged from 57 to 145 g kg^{-1}.

The fields were selected to cover the existing range of integrated and nonintegrated potato and dairy cropping systems. All of the selected fields had been managed consistently over the previous 10 years, according to farmers' accounts. The fields were assigned to one of six cropping system categories based on crop rotation and frequency of manure applications (Table 6.1). The cropping systems were ordered according to what we hypothesized to be their relative levels of net annual carbon inputs to the soil. The systems, in ascending order of estimated C input, were: 2-yr potato–small grain or corn grain rotations with no manure (2YrPot-M0); 2-yr potato–small grain or corn silage rotations with manure applied in non-potato year (2YrPot-M50); 3-yr potato–corn silage–corn silage or small grain rotations with manure applied in the non-potato years (3YrPot-M67); continuous corn silage with manure applied every year (CornSil-M100); mixed forage grass with no manure (Hay-M0); and mixed forage grass with manure applied every year (Hay-M100). The manure applied was liquid dairy manure with sawdust, sand, or both as bedding. Both integrated and nonintegrated potato rotations also often included barley or rye (*Secale cereale* L.) cover crops after the potato or small grain harvest. The 2YrPot-M50 systems represent the lowest level of potato-dairy integration in which the only change is that manure is added to the pre-existing potato rotation. The 3YrPot-M67 systems represent the next level of integration in which the rotation is expanded to include an annual forage crop for the dairy operation and manure is applied. Higher levels of integration are possible, including expanding the potato rotation to include a perennial forage crop, but they are not currently practiced in this area of Maine.

Table 6.1. Characteristics of the 48 potato and dairy farm fields sampled.

			Manure application†	
Cropping system‡	Number of fields	Crop rotation	Percent of years	Average annual rate§
			— % —	– Mg ha^{-1} –
2YrPot-M0	12	Potato – small grain or corn grain	0	0.0
2YrPot-M50	7	Potato – small grain or corn silage	50	4.3
3YrPot-M67	10	Potato – corn silage – corn silage or small grain	67	6.4
CornSil-M100	8	Continuous corn silage	100	10.0
Hay-M0	3	Continuous grass	0	0.0
Hay-M100	8	Continuous grass	100	5.3

† The manure was liquid dairy manure with sawdust, sand, or both as bedding.

‡ 2YrPot-M0 = two-year potato–small grain or corn grain rotations with no manure, 2YrPot-M50 = two-year potato–small grain or corn silage rotations with manure applied in non-potato year, 3YrPot-M67 = three-year potato–corn silage–corn silage or small grain rotations with manure applied in the non-potato years, CornSil-M100 = continuous corn silage with manure applied every year, Hay-M0 = mixed forage grass with no manure, and Hay-M100 = mixed forage grass with manure applied every year.

§ Dry matter basis.

6.3.2. Soil Sampling and Analysis

Samples were collected from commercial fields after crop harvest in October and November of 2003 and 2004. Four locations per field were sampled and analyzed separately. The position of each location was determined by visually dividing a field into quadrats and then choosing a position in each quadrat such that locations were in a staggered pattern. Field edges, depressions, knolls, and other extreme areas were avoided. In sloping fields, locations were chosen so that one was upslope, one was down slope, and two were midslope. Fields ranged in size from approximately 6 to 60 acres. In fields larger than 30 acres, an approximately 30-acre subsection was chosen that was representative of the whole field and that did not contain extremely variable areas.

At each location, six soil cores (2 cm dia) were taken to a depth of 15 cm from a 1-m^2 area, bulked, and mixed thoroughly. A 500-g subsample was sieved to 2 mm, of which 200 g was air dried at room temperature and stored in cardboard boxes until analysis. Bulk density was determined in each of the 1-m^2 areas using the core method described by Blake and Hartge (1986). Metal rings (7.2 cm dia by 7.6 cm height) were pounded into the soil to 1cm below the soil surface using a cylindrical sleeve. The sample rings were removed, capped, dried at 50°C, and sieved to 2 mm to separate coarse fragments. Both fractions were weighed and bulk density estimates were corrected for coarse fragments.

Total soil C and N concentrations were determined on a pulverized 5-g subsample of the air-dried soil. Analysis was by dry combustion using a Carlo Erba Instruments NA2500 Elemental Analyzer (ThermaQuest Italia S.p.A., Rodano, Italy). Particulate organic matter C and N were determined following the method described by Cambardella et al. (2001) with minor modifications. A 5-g subsample of the air-dried soil was dispersed in 15 ml of 0.5% hexametaphosphate for 16 h on a reciprocal shaker at 120 RPM. The soil slurry was poured through a 0.053 mm sieve. The material retained on the sieve, the sand fraction (0.053 – 2 mm), was washed thoroughly with deionized water, transferred to aluminum weighing crucibles, dried at 50°C, and weighed. This fraction was pulverized and analyzed for POM-C and -N concentration by dry combustion as above. The liquid fraction was collected in plastic pails to determine the size of the silt fraction (Kettler et al., 2001). Samples were stirred and allowed to sit undisturbed for 4 hr at which point the liquid, containing the clay fraction, was carefully decanted and discarded. The remaining silt fraction was dried at 50°C and weighed. The size of the clay fraction was determined by difference. Mineral-associated C (and N) was calculated as the difference between total soil C (or N) and POM-C (or -N).

Soil test P and cations were determined using a modified Morgan extraction (McIntosh, 1969; 3 g air-dried soil in 15 mL of pH 4.8, 0.62 *M* NH_4OH + 1.25 *M* CH_3COOH, shaken for 15 min) and inductively coupled plasma emission spectroscopy (ICP). Effective CEC was estimated by summing cation concentrations and exchangeable acidity (Sumner and Miller, 1996). Samples from 2004 were also extracted for soluble P with 0.01 *M* $CaCl_2$ (2 g air-dried soil in 20 mL, shaken for 1 h) and analyzed using ICP. Soil pH was determined using the soil slurry method (Thomas, 1996).

6.3.3. Carbon Inputs

Ten-year average annual carbon inputs to each field from seed, manure, above-ground and root residues were estimated using field history information recorded from interviews with the cooperating farmers. Above-ground residue inputs were estimated based on yield data and published harvest indexes, and root biomass inputs were estimated using published root:shoot ratios (Bolinder et al., 1997; Bolinder et al., 1999; Buyanovsky and Wagner, 1986; Janzen et al., 2003; Johnson et al., 2006; Kolbe and Stephan-Beckmann, 1997; Marra, 1996; Opena and Porter, 1999; Vos and van der Putten, 2000). Dry matter was converted to C assuming a ratio of 0.4 (Johnson et al., 2006). Estimations of carbon input from rhizodeposition were not attempted due to the great uncertainty in these estimates (Johnson et al., 2006). Rhizodeposition is known to contribute relatively high amounts of C in perennial sod systems compared with annual systems (Paustian et al., 1997). For this reason, it was deemed inappropriate to compare estimated C inputs between the annual and perennial systems; only estimates for the annual systems are presented. The relative intensity of soil disturbance for each of the cropping systems was estimated using the Soil Tillage Intensity Rating (STIR) online program (USDA-NRCS, 2007).

6.3.4. Statistical Analyses

The distribution of average soil clay concentration among the fields was inspected. One outlier was identified and removed from the data set. The remaining fields ($n = 48$) had clay concentrations that ranged from 72 to 145 g kg^{-1}. Relationships between soil parameters were analyzed using Pearson correlation and verified with Spearman correlation analysis if some of the parameter distributions deviated from normality. Analysis of covariance was used to test the effect of cropping system on soil C, N, pH, and P variables with soil clay concentration and the crop grown before sampling as covariates (SYSTAT Software, 2004). The relationship between POM C and total soil C was evaluated by testing linear and cubic regression models using Nonlinear Model (SYSTAT Software, 2004).

6.4. Results and Discussion

Bulk density in the 0 to 7.6 cm soil layer was significantly affected by cropping system and current crop. Bulk densities were generally highest in soil in hay systems and lowest in soil sampled following potato harvest (data not shown). Thus, concentration data were corrected for bulk density and converted to an area basis (15-cm depth). Clay concentration was negatively correlated with soil C and N pools (Table 6.2), contrary to most observations that clay and organic matter attributes tend to be positively associated (Brady and Weil, 1996). The negative correlations can be explained as an artifact of the confounding of clay concentration and cropping system. Fields in the systems with lower C inputs (and lower soil C and N pools) had higher clay concentrations than fields in the systems with higher C inputs (and higher soil C and N pools). The negative association between cropping system and clay concentration was probably due to chance or to farmers' land use decisions. Its confounding effect was removed via ANCOVA.

Table 6.2. Pearson correlation coefficients (r) between measured soil parameters for potato and dairy farm fields. (n=48)

Soil measurement	Cropping system†	Total soil C	POM C	Total soil N	POM N	CEC	pH
Total soil C	0.79***						
POM C	0.76***	0.90***					
Total soil N	0.83***	0.96***	0.87***				
POM N	0.75***	0.87***	0.98***	0.85***			
CEC	0.72***	0.70***	0.60***	0.72***	0.59***		
pH	0.50**	0.29	0.25	0.32	0.27	0.75***	
Clay	-0.37	-0.46*	-0.46*	-0.42	-0.38	-0.43*	-0.17

† Cropping systems were put on an ordinal scale from 1 to 6 in ascending order of estimated C input: 2YrPot-M0, 2YrPot-M50, 3YrPot-M67, CornSil-M100, Hay-M0, Hay-M100.

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

6.4.1. Soil Carbon and Nitrogen Pools

Soil C and N pools were strongly correlated with one another and with CEC (Table 6.2), and were significantly affected by cropping system (Tables 6.3 and 6.4). Total soil C in the hay systems was 82% higher than in the potato systems and 27% higher than in continuous corn silage (Table 6.3). Similar differences among these cropping systems were observed for mineral-associated and POM C and are congruent with previous findings that sod systems have higher soil quality characteristics than arable systems (Cambardella and Elliott, 1992; Haynes, 2000). These differences are attributed to the absence of tillage, because tillage stimulates the respiration of soil C, and to the relatively high, but difficult to estimate, below-ground C contributions from perennial sods (Paustian et al., 1997).

Table 6.3. Soil carbon pools, average estimated C inputs, and average estimated soil tillage intensity ratings for soil sampled from 48 potato and dairy farm fields with a minimum 10-year consistent history of one of six cropping systems.

Cropping system	n	Total soil C	Mineral-associated C	POM C	POM C / total soil C	Average estimated C inputs	Average soil tillage intensity rating†
		Mg ha^{-1}			%	Mg ha^{-1}	
2YRPOT-M0	12	31.8c	23.8c	8.2c	27.1	2.0	130
2YRPOT-M50	7	32.7c	24.8c	7.9c	24.7	3.3	124
3YRPOT-M67	10	32.8c	24.3c	8.5bc	26.5	3.2	108
CornSil-M100	8	46.5b	34.2b	12.3b	26.3	5.4	68
Hay-M0	3	57.5a	42.8a	14.6a	25.1	‡	<1
Hay-M100	8	60.5a	42.1a	18.4a	30.1	‡	<1
			ANCOVA (p-values)				
Source of variation	df						
System	5	0.000	0.000	0.000	0.305		
Clay	1	0.124	0.356	0.038	0.605		
Crop(System)	7	0.243	0.066	0.900	0.044		
C.V.(%)		17.6	18.5	25.5	16.6		

† Calculated using the Soil Tillage Intensity Rating (STIR) program (USDA-NRCS, 2007).

‡ Carbon inputs were not estimated for the hay systems because of the high uncertainty associated with carbon estimates for perennial system.

Table 6.4. Soil nitrogen pools for soil sampled from 48 potato and dairy farm fields with a minimum 10-year consistent history of one of six cropping systems.

Cropping system	n	Total soil N	Mineral-associated N	POM N	POM N / total soil N
		Mg ha^{-1}			%
2YRPOT-M0	12	2.65c	2.07c	0.58cd	22.7
2YRPOT-M50	7	2.86c	2.30c	0.55d	19.4
3YRPOT-M67	10	2.81c	2.20c	0.62cd	22.2
CornSil-M100	8	3.86b	3.03b	0.84bc	21.3
Hay-M0	3	4.61a	3.59a	1.02ab	21.7
Hay-M100	8	4.98a	3.74a	1.24a	24.8
			ANCOVA (p-values)		
Source of variation	df				
System	5	0.000	0.000	0.000	0.415
Clay	1	0.512	0.811	0.287	0.983
Crop(System)	7	0.140	0.093	0.939	0.698
C.V.(%)		14.0	15.0	27.0	20.1

There were no detectable differences in any of the soil C or N pools among the potato systems (Tables 6.3 and 6.4). Neither of the two levels of potato-dairy integration evaluated here, the application of manure every other year (2YrPot-M50) or the inclusion of an annual forage crop with manure two of three years (3YrPot-M67), was sufficient to alter total, mineral-associated, or POM C or N, despite 65% higher estimated C inputs and reduced tillage intensity (Table 6.3). The only arable system that had measurably higher soil C and N stocks than the nonintegrated potato system (2YrPot-M0) was CornSil-M100, a dairy system with 2.7 times more C inputs and almost half the soil tillage intensity rating.

Examining total and POM C as a function of estimated C inputs (Fig. 6.1) reveals a consistent range of total and POM C content across the range of C inputs in the potato systems. It appears that the increases in C inputs in the integrated compared with the nonintegrated potato systems were not large enough to produce measurable increases in soil total C or POM C. Estimated C inputs in many of the 3YrPot-M67 fields were actually less than those of most of the 2YrPot-M50 fields. The manure used on most of the 3YrPot-M67 fields contained sand bedding and therefore had lower C content than manure with sawdust bedding. Griffin and Porter (2004) found a positive linear relationship between C inputs and resulting soil total C and POM C in a series of field trials in Maine that included soil amendment or cover crop and green manure treatments in the context of intensively tilled two-year potato or sweet corn rotations. Differences in C inputs between the contrasting treatments in the Griffin and Porter (2004) study ranged from -1 to 8 Mg C ha^{-1}.

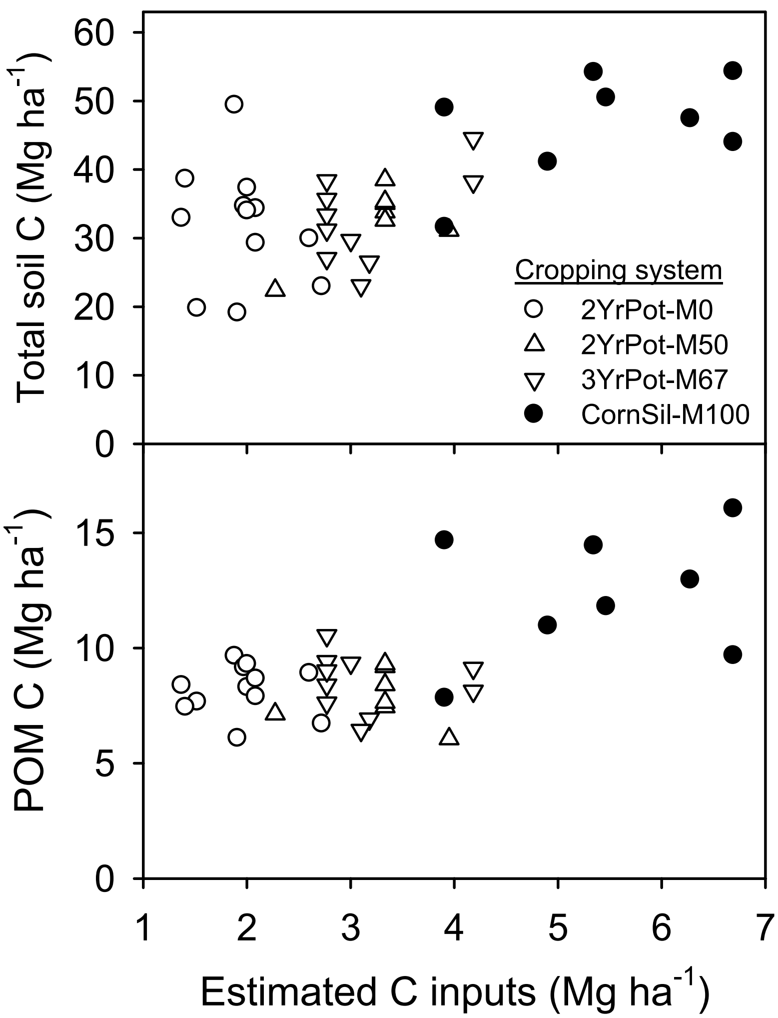

Figure 6.1. Relationship between soil total C or particulate organic matter (POM) C and estimated 10-yr average C inputs for soil sampled from 37 potato and dairy farm fields with a minimum 10-year consistent history of one of four cropping systems. Individual points are the mean of four samples (n = 4).

Applying the linear model derived in Griffin and Porter (2004) to the differences in C inputs between treatments from Table 6.3 yielded expected increases over 2YrPot-M0 in total soil C of 1.0, 0.9, and 2.5 Mg ha^{-1} and in POM C of 0.2, 0.1, and 2.0 Mg $ha^{-1}$for 2YrPot-M50, 3YrPot-M67, and CornSil-M100, respectively. The expected changes in soil total C and POM C for the manured potato systems are small and within the range of variation observed among fields for those treatments. The observed increases in soil total C and POM C for CornSil-M100 over 2YrPot-M0 exceeded the expected changes (14 vs. 2.5 Mg total C ha^{-1} and 4.1 vs. 2.0 Mg POM C ha^{-1}, respectively) most likely due to the substantial reduction in soil disturbance (Table 6.3), which is not accounted for in the Griffin and Porter (2004) model. While these comparisons should be treated lightly because of the uncertainty associated the methods used to estimate C inputs in both studies, they do underscore the fact that the increases in net C inputs in the integrated potato systems compared with the nonintegrated system are relatively small. Higher levels of integration, such as the inclusion of sod crops, would be expected to produce greater changes in soil C and N stocks in potato-based systems (Angers et al., 1999), as would longer histories of integration.

The proportion of total soil C that resided in the POM pool was not statistically different among the cropping systems (Table 6.3), yet the similarity of the cropping system treatment averages obscures a nonlinear relationship between POM-C and total soil C (Fig. 6.2). This disproportionate enhancement of the POM pool at relatively high soil C levels has been observed elsewhere (Conant et al., 2004; Griffin and Porter, 2004), although not consistently (Haynes, 2000; McLauchlan and Hobbie, 2004), and is described in a conceptual model of SOM accumulation by Carter (2002). Whereas the size of the mineral-associated fraction is constrained by the amount of clay plus silt with which it is associated, the POM pool is governed largely by C input and respiration rates, and can continue to increase once the mineral-associated fraction is saturated. Thus, under high soil C concentrations, POM constitutes a larger portion of total C than under low C concentrations. POM is also the fraction most susceptible to decomposition and most responsive to short-term changes in soil management (Haynes, 2000). In Fig. 6.2, POM increases only incrementally with increasing soil C until about 45 Mg ha^{-1}, at which point POM increases more rapidly. The cropping systems segregate along this curve into potato and dairy systems. In both groups, the range of total soil C is wide, reflecting variation in the long-term histories and uncontrolled edaphic factors of the fields sampled. The scale and range of POM reflects recent inputs and management regimes. In the potato systems, the C inputs that maintain a relatively low level of total soil C are apparently not enough to overcome the high rates of degradation in these systems, and POM does not accumulate. In the dairy systems, with higher C inputs and less or no tillage, net rates of C addition appear to have exceeded degradation and POM accumulates. Results for nitrogen mirrored those for carbon (data not shown).

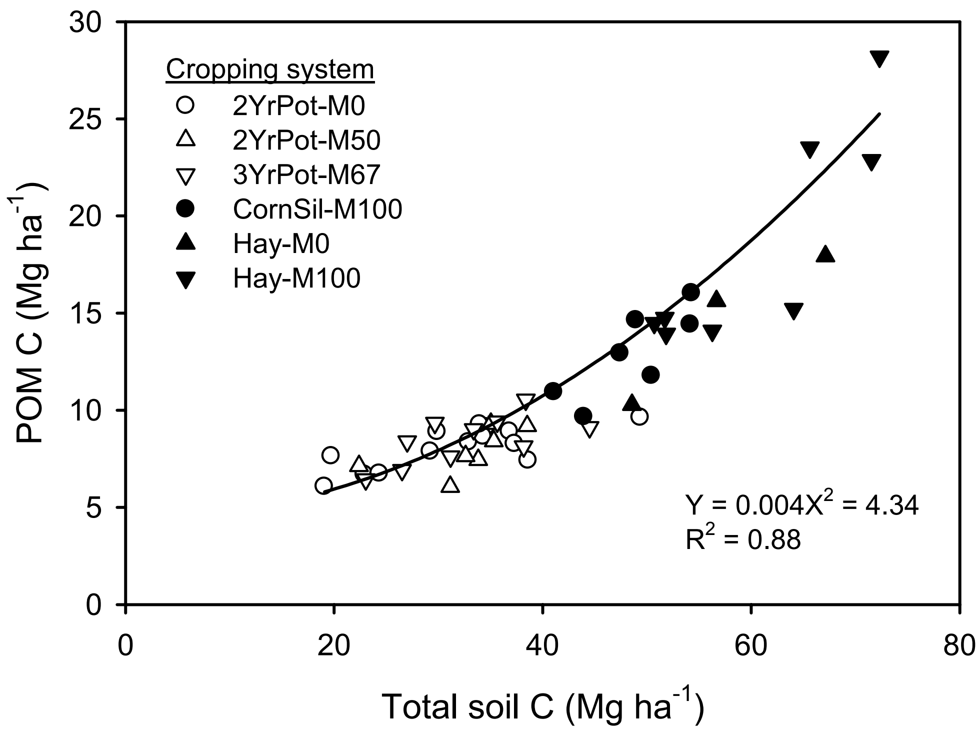

Figure 6.2. Relationship between particulate organic matter (POM) C and total C for soil sampled from 48 potato and dairy farm fields with a minimum 10-year consistent history of one of six cropping systems. Individual points are the mean of four samples (n = 4).

Our results suggest that it is difficult to bring about measurable changes in soil quality in intensively tilled potato-based systems through the use of annual crops and dairy manure at the rates applied here over this 10 to 20 yr time period. Yet at least two of the farmers whose fields we sampled said they have observed functional differences in the quality of their soil with integration, such as improved friability and water holding capacity, and they cite these improvements as a key benefit to integrating their farm with a neighboring dairy farm (Files and Smith, 2001). It is possible that our measures of soil quality, which focus primarily on total soil C and POM C stocks, fail to reflect the changes that farmers witnessed. For instance, water stable aggregates or water infiltration may have been more representative and sensitive indicators of observed changes in soil function. It also is possible that this type of multi-field study, conducted over a range of field characteristics and management systems, can not provide the resolution needed to detect the changes in soil quality that can be observed at a field scale with longitudinal observations or controlled research station studies. Haynes (2000) and Wander and Bollero (1999) observed measurable soil quality changes across the landscape among systems differing in the proportion of arable versus sod crops and in the intensity of tillage, respectively, but these are relatively large system changes compared with the changes occurring with the different levels of integration studied here.

6.4.2. Soil pH and Phosphorus

The manured cropping systems had higher pH than those that received fertilizer alone (Table 6.5), congruent with previous observations that manure can have a liming effect on soil pH (Eghball et al., 2004; Vitosh et al., 1997). Integrated potato fields had the highest levels of Modified Morgan P (Table 6.5). These fields had inputs of P from both manure and fertilizer, and only one of the three cooperating integrated potato farmers reported applying a reduced rate of P fertilizer compared with the average applied by the nonintegrated farms (175 kg ha^{-1} P_2O_5). All of the fields, however, were below the level considered excessive according to Maine nutrient planning guidelines, 45 kg ha^{-1} (USDA-NRCS, 2004). Continuous corn silage, which received no P fertilizer but the highest rates of manure application (Table 6.1), had Modified Morgan P levels similar to the nonintegrated potato system, which received P only as fertilizer. Hay-M100, which received P only as manure, had the lowest Modified Morgan P level. No significant differences were detected between the cropping systems for soluble, $CaCl_2$ P, most likely due to high variability (Table 6.5).

Table 6.5. Soil pH, Modified Morgan P, and $CaCl_2$-extracatable P for soil sampled from potato and dairy farm fields with a minimum 10-year consistent history of one of six cropping systems.

Cropping system	n	pH	Modified Morgan P	n†	$CaCl_2$ P
			— kg ha^{-1} —		– kg ha^{-1} –
2YRPOT-M0	12	5.3c	22.4b	8	11.0
2YRPOT-M50	7	6.0ab	25.4a	3	15.8
3YRPOT-M67	10	6.1ab	27.5a	6	17.3
CornSil-M100	8	6.5a	19.2b	3	6.1
Hay-M0	2	5.5bc	13.1bc	0	-
Hay-M100	8	6.2a	8.5c	4	4.6
			ANCOVA (p-values)		
Source of variation	df			df	
System	5	0.008	0.000	4	0.595
Clay	1	0.934	0.516	1	0.097
Crop(System)	7	0.413	0.098	-	-
C.V.(%)		9.1%	34.3		65.6

†Modified Morgan P was determined for 2003 and 2004 samples. $CaCl_2$ P was determined for 2004 samples only.

6.5. Conclusions

A multi-field study comparing integrated potato systems, at two levels of integration, with non-integrated potato systems detected small increases in soil pH and soil test P with integration but no measurable changes in total soil C or N nor POM C or N. Soil C and N pools were significantly higher in dairy systems (manure corn silage, manure hay, and nonmanured hay) than potato systems. These differences were attributed to increased C inputs and reduced soil disturbance. A nonlinear relationship between POM C and total C was observed, with disproportionate enhancement of the POM pool at relatively high soil C levels. Intensively-tilled potato-based systems appear to need greater increases in C inputs and reductions in tillage, as with the inclusion of sod crops, to produce changes in soil C and N pools that can be detected at a landscape level over a 10 to 20 year time frame.

Chapter 7

SUMMARY AND CONCLUSIONS

A soil management system that improved soil quality characteristics through organic amendments demonstrated aspects of increased resilience for crop production and N cycling. The amended soil management system buffered the effects of adverse growing conditions, particularly low rainfall, and produced greater and more stable potato yields (Chapter 2). These results are unique in providing direct evidence that managing for soil quality can enhance yield stability by creating a more robust growing environment for crops.

The amended soil management system also demonstrated the potential to buffer excess N by retaining a greater proportion of excess N (N input – output) than the nonamended system (Chapter 3). Increased N retention in the amended system may be attributed in part to reduced early season losses of N. *In situ* spring soil N_i concentrations were lower in the amended system compared with the nonamended system (Chapter 4) and C-enhanced immobilization of excess N_i may have played a role in this reduction (Chapter 5). Other factors that possibly contributed to greater N retention in the amended system compared with the nonamended system include C-enhanced immobilization throughout the rest of the season, physical protection of N as organic matter in soil aggregates, and greater recalcitrance of manure and compost N relative to fertilizer N.

The potential of the amended soil management system to provide resilience regarding N dynamics through greater N retention efficiency is compromised by its high rate of N loss, in absolute terms, relative to the nonamended system (Chapter 3).

Repeated applications of manure, compost, and green manure in the amended soil system greatly enhanced soil total N stock, especially the more readily available pool of N (POM-N), increased microbial biomass and activity, and doubled the capacity of the soil to supply N relative to the nonamended system (Chapter 5). A manifestation of this increased N mineralization potential was observed *in situ* in the fall of 2003 as accumulation of soil N_i during a period with low rainfall (Chapter 4). High rates of N mineralization in the amended soil relative to the nonamended soil may have occurred in the other years of the study but may not have been detected due to more consistent precipitation and possible leaching of N_i below the sample zone.

Results of the N dynamics in the contrasting soil management systems of the MPEP have two key implications for tightening the N cycle of amended soil management systems. First, soil amendment history should be taken into account both in future work to develop and refine predictive models for N availability and also in on-farm nutrient management plans. Increased N credits should be given for residual manure N than is done using the standard decay-series model in order to avoid over application of manure or fertilizer N to soils with a history of manure amendments (Chapter 4). Additionally, the predicted availability of current year applications of manure or fertilizer may need to be adjusted to account for lower availability in soil with a history of amendment (Chapter 5).

Second, amendment loading rates should be lower than those used for experimental purposes in the MPEP. Lower rates can still bring about increases in SOM (Grandy et al., 2002), and possibly its attendant benefits for crop production, N cycling, and N retention, while reducing levels of excess N (and P) and potential loss. This statement seems to contradict results from the soil quality assessment of integrated potato-dairy systems in Central Maine (Chapter 6). Annual net C inputs in the integrated potato systems surveyed were 37% lower than inputs to the amended soil management system, but appeared to be too low to produce changes in soil C and N pools that could be detected at a landscape level over a 10 to 20 year time frame in intensively-tilled potato systems. It is difficult to directly compare the MPEP with this type of multi-field study because the latter is conducted over a range of field characteristics and management systems, and therefore can not provide the same resolution as a controlled research station study like the MPEP. The landscape level study may not have been sensitive enough to detect changes in soil quality resulting from the levels of integration currently practiced. Results from the MPEP, however, can inform conclusions drawn from the soil quality assessment. Namely, efforts to increase C inputs further should include alternative strategies, together with current levels of manure application, such as tillage reduction and the inclusion of sod crops. Additionally, annually cropped soil systems that maintain high SOM should include fall trap crops and, if possible, deep-rooted rotation crops to capture excess N_i.

Lastly, results from the MPEP and the on-farm soil quality assessment, taken together, highlight the need to find balance points for SOM content that enhance soil's crop production and N cycling functions, while avoiding N excesses and potential loss.

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BIOGRAPHY OF THE AUTHOR

Ellen Mallory was born in Paducah, Kentucky. She graduated from Ogden High School, Ogden, Utah in 1983 and from Swarthmore College, Swarthmore, Pennsylvania with a Bachelor's of Arts degree in Biology. A post-graduation internship at the Rodale Research Center in Kutztown, PA launched Ellen's interest in sustainable agriculture. Advancing agricultural systems that balance food production with environmental stewardship has since been her career focus. She has worked as an agricultural researcher and educator in Wisconsin, Maine, Washington, West Africa (with Peace Corps) and Central America (with Volunteers in Overseas Cooperative Assistance). In 1994, she earned two Masters of Science degrees (Agronomy and Land Resources) from the University of Wisconsin. Ellen is the author of an award-winning series of 16 extension bulletins and six peer-reviewed journal publications.

Ellen entered the Ecology and Environmental Sciences Doctor of Philosophy program at the University of Maine in 2003 while working as a technician at the USDA-ARS New England Plant, Soil and Water Laboratory. She spent the 2006-2007 academic year as a visiting Ph.D. student in the Plant and Soil Science Section of the Department of Agricultural Sciences, Faculty of Life Sciences, University of Copenhagen. During her graduate studies, she received a Switzer Environmental Fellowship, a University Graduate Research Assistantship, the Norris Charles Clement Award, and two Louise Cies Graduate Fellowship Awards. Ellen is a candidate for the Doctor of Philosophy degree in Ecology and Environmental Sciences with a concentration in Sustainable Agriculture from The University of Maine in December, 2007.