SOIL AND PLANT RESPONSES IN THE FIRST CYCLE OF FOUR-YEAR ORGANIC POTATO ROTATIONS

by

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Abstract

Nutrient management is a challenge in organic potato production. A potato rotation experiment was established to determine effects of forages and livestock manures on soil nutrient levels, plant nutrient uptake, and tuber yield in the first cycle of four-year rotations established on long-term pasture. The experiment was a two-stage nested design, with three soil amendments (composted poultry manure, composted beef manure, and alfalfa meal) nested under three forage levels (0-, 1-, and 2-year forage levels represented by wheat/soybean/barley/potato, wheat/barley/forage/potato, and wheat/forage/forage/potato, respectively). In order to equalize soil available nitrogen (N), soil amendments were applied according to their assumed N availability and soil test recommendations. In year four, all plots were seeded with potatoes and split into amended and unamended subplots. Applications of soil amendments increased soil nutrient levels, plant nutrient uptake, and tuber yield compared with residual effects of soil amendments. At the end of year four, soil organic matter was significantly different among treatments; soil mineral N was significantly higher in the 1- and 2-year than in the 0-year forage rotation because of both forage and soil amendment effects. Alfalfa meal had a larger positive effect on soil microbial biomass carbon, and released more mineral N compared with the two composts. Composted poultry and beef manures significantly increased soil P_2O_5 and K_2O levels, respectively, through cumulative compost additions. Plant N uptake was not significantly different, while plant P and K uptake and tuber yield were significantly higher in the 0-year than in the 1-year forage rotation because of possible pest infestations in the forage rotations, and were highest under composted beef manure. Principal component analysis indicated that the 1- and 2-year forage rotations shared similarities, but were separated from the 0-year forage rotation, and that forage and soil amendment combinations shared both similarities and differences, depending on forage levels, types and application rates of soil amendments. Overall, soil isonitrogeneity was not achieved, while plant isonitrogeneity was achieved. Forages improved soil N, but were detrimental to potato production under these specific conditions. Composted beef manure was preferred for nutrient management and potato yield.

List of Abbreviations Used

Alfalfa meal	S
Carbon	C
Cation exchange capacity	CEC
Composted beef manure	R
Composted poultry manure	M
Dehydrogenase activity	DHA
Hour	h
Minute	min
Month	mo
Nitrogen potential mineralization rate	N_0
Nitrogen	N
Phosphorus	P
Potassium	K
Principal component analysis	PCA
Soil bulk density	SBD
Soil microbial biomass carbon	SMBC
Soil organic carbon	SOC
Soil organic matter	SOM
Total carbon	C_{tot}
Total nitrogen	N_{tot}
Year	yr

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CHAPTER 1 INTRODUCTION

1.1 General Introduction

Crop rotations and soil amendment applications are common practices adopted by organic farmers for nutrient management. In Canada, the number of certified organic farms keeps rising, and about 1.5% of total farms were operating as organic farms in 2004 (Macey 2006). In organic cropping systems, nutrient management can be a challenge for farmers because of the restrictions in synthetic chemical fertilizer use. Therefore, it is becoming critical to develop on-farm nutrient cycling strategies, since reliance on on-farming nutrient sources is a principle characteristic of organic agriculture (Drinkwater et al. 1998). Increasing forage frequency in a crop rotation and recycling on-farm nutrients through livestock may be the key strategies for nutrient management on organic farms.

An essential part of organic cropping systems is crop rotations which include fertility building and depleting phases. Soil fertility is susceptible to depletion over time in continuous crops through repeated removals of the same type of minerals; conversely, diversified crops in rotations have the ability to balance soil nutrients. For example, cereals are particularly poor at utilizing phosphorus (P) from rock phosphate (Dann et al. 1996), whereas clover is more efficient (Khasawneh and Doll 1978). Crops with different root systems absorb nutrients at different depths, and redistribute the nutrients after incorporation of residues back into soil. Crop rotations in organic systems may achieve nitrogen (N) self-sufficiency through selecting the legume species and adjusting the length of legume phases (Wani et al. 1994b).

Forages, including legume and grass, are a valuable fertility-building crop in rotations. A mixture of legume and grass not only has an important role in N_2 fixation from air, but also enhances soil organic matter (SOM) and nutrient cycling by preventing soil erosion losses and incorporating root-included residues back into soil. Crop rotations including legumes were regarded as ideal methods for sustaining soil productivity (Izaurralde et al. 1995). Red clover (*Trifolium pratense* L.) and timothy (*Phleum pretense* L.)

mixtures are popularly rotated with other crops because of their N benefits to the succeeding crops (Johnston et al. 1994), easy establishment and termination, and the function of breaking pest, insect, disease and weed cycles. In practice, some farmers grow forages at a relatively high frequency, while others seed forages at a relatively low frequency; hence there are different forage proportions in various rotations. A sound rotation includes a suitable ratio of a fertility-building phase to a fertility-depleting phase.

Livestock manure, especially composted manure, is a valuable on-farm nutrient resource, and is critical for long-term soil fertility management. There are two different types of livestock. One is monogastric livestock such as chicken, and the other is ruminant livestock such as beef. Different feed (e.g. grains for chicken and hay for beef) for these two species makes compost macronutrient concentration and short-term N release different. Hence, after being incorporated into soils, these two composts may have different short and long-term nutrient benefits as a result of different nutrient concentration and chemical composition. Therefore, nutrient values for these two composts may be different (Gagnon and Simard 1999). Some farmers grow crops without access to livestock, and are known as stockless farmers. For stockless cropping systems, alfalfa could be grown and serve as an N source. Hence, three different soil amendments such as alfalfa meal, composted poultry manure, and composted beef manure represent main on-farm nutrient sources in the stockless, monogastric, and ruminant livestock farming systems, respectively.

Different combinations of soil amendments (i.e. alfalfa meal, composted poultry manure, and composted beef manure) and forage-based crop rotations (i.e. 0-, 1-, and 2-year forages in 4-year rotations) are possible and will influence nutrient management practices. For example, in a stockless farming system that relies on forage biological N_2 fixation as the main N source, the forages can be cut and mulched or incorporated directly into soil to increase SOM and provide both short and long-term sources of available N; inadequate N could be supplemented by an on-farm available soil amendment such as alfalfa meal. In an integrated livestock cropping system, N recycling could be efficient by returning livestock wastes to a field if livestock feeds are produced on farms, since 75-90% of major nutrients fed to livestock go directly through animals into the wastes (Wallace 2001). On-farm N self-sufficiency could be obtained through N_2

fixation and livestock manure if the faba beans constituted 33% of rotation phases and livestock was available (Patriquin et al. 1981). In the Breton plots, N balance was maintained by returning 70% of harvested legume N in the form of manure in a legume-based crop rotation in which the forage was comprised 62% of rotation phases (Wani et al. 1994b).The wheat-pasture-sheep system in Australia (Puckridge and French 1983) and the simulated maize-legume-cattle system in Pennsylvania (Drinkwater et al. 1998; Tilman 1998), demonstrated soil fertility improvement in an integrated forage-based crop rotation and livestock system.

Potatoes are one of the most important cash crops in Atlantic Canada, and are also a soil fertility depleting crop. Integration of crop rotations, particularly forage-based crop rotations, and applications of compost or other organic amendments might be suitable management for potato production in building soil fertility and improving agronomic production. Strategies integrating forages and livestock are expected to efficiently utilize on-farm resources by adjusting the length of a forage phase and by calibrating the soil amendment application rates based on the understanding of nutrient cycling processes.

Isonitrogeneity in this thesis is referred to as equalizing soil extractable N levels through adjusting soil amendment application rates, according to soil test recommendations and assumed N availability of soil amendments. Since N application rates significantly affected plant production (Warman 1986; Ma et al. 1999b; Hammermeister et al. 2005); therefore, cropping systems may be much more meaningfully assessed under the same available soil N levels.

A forage-based potato rotation experiment was established on a long-term pasture land and was managed in a way farmers might do under isonitrogeneity regimes. The main goal of the experiment is to determine the effects of forages and livestock (composted manure) on soil nutrient levels, plant uptake, and potato tuber yield in the first cycle of 4-year organic potato rotations.

1.2 Background

1.2.1 Organic agriculture

Organic agriculture is defined by the National Organic Standards Board of the USA as "an ecological production management system that promotes and enhances biodiversity, biological cycles and soil biological activity. It is based on minimal use of off-farm inputs and management practices that restore, maintain and enhance ecological harmony" (NOSB 1995). Organic agriculture is also known as ecological agriculture or biological agriculture, reflecting the reliance on self-sustaining ecosystem management rather than external input (Stockdale et al. 2000). Although there are various understandings of the term "organic farming", the aims and the principles of organic farming are widely accepted as: "to create integrated, humane, environmentally and economically sustainable production systems, which maximize reliance on farm-derived renewable resources and the management of ecological and biological processes and interactions, so as to provide acceptable levels of crop, livestock and human nutrition, protection from pests and diseases, and an appropriate return to the human and other resources" (Lampkin 1994). The term "organic" is referred not only to the use of organic materials, also to the concept of designing and managing a farm as a whole system, whereby the components such as soil, plants, animals, and society are highly integrated (Lotter 2003). The key aspects of organic farming lie in avoiding the use of highly soluble minerals, synthetic pesticides and fertilizers, and maintaining or enhancing soil quality in the long term.

1.2.2 Crop rotations

Crop rotation is defined as "a planned sequence of crops growing in a regularly recurring succession on the same area of land, as contrasted to continuous culture or one crop or growing different crops in haphazard order" (Brady and Weil 1999). As early as two thousand years ago, Roman agronomists proposed the use of legumes and cereals in a rotation (Karlen et al. 1994). A diversified crop rotation has tremendous benefits to plant and soil systems (Table 1.1), and some benefits are detailed in this section. One also needs to bear in mind that there are some disadvantages related to crop rotations. For example, the temporary accumulation of organic acids (e.g. acetic acid) produced in the early phase of plant residue decomposition under anaerobic conditions might result in phytotoxicity to the following crops (Lynch 1983), with symptoms of germination inhibition and stunting (Patrick 1971); leguminous residues are reported to have more of observable detrimental effects on germination than cereal residues (Lovett and Jessop 1982); evaluating crop rotation effects may be a time-consuming process.

Crop rotations are conducted in various sequences to adapt to local soil and climatic conditions. For example, a traditional fallow-wheat system is dominant in drier regions of the Great Plains of the USA and Canadian prairies (Drijber et al. 2000); a potato-based rotation is popular in Atlantic Canada (Carter et al. 2003). Long-term crop rotation studies have been conducted throughout the world, including the Rothamsted plots---the world's oldest crop rotation in England (Tilman 1998), the DOK trial---the world's longest running organic versus conventional crop production study in Switzerland (Mäder et al. 2002), and Alabama's Old Rotation cotton (*Gossypium barbadense*) experiment--the world's oldest continuous cotton experiment in USA (Mitchell and Entry 1998). Other long-term crop rotations include the Breton plots in Alberta (Wani et al. 1994b), the Glenlea Rotations in Manitoba (Entz et al. 1995), and the Rodale institute rotations in Pennsylvania (Drinkwater et al. 1998).

The functioning of a crop rotation is not only determined by the sequence of crops, but also by specific individual crops and by the whole system. The balance between the duration of forages and cash crops is critical in determining crop production and soil fertility (Watson et al. 1999). Different ratios of fertility building to depleting phases in a crop rotation were reported to have an impact on SOM, total N, total and available P, and total K (Soon and Arshad 1996). Rotations characterized of relatively high a proportion of forage phases are likely to have a positive nutrient balance. Angers et al. (1999) found that average soil carbon (C) and N content were 20-27% higher in a crop rotation characterized with 50% of rotation phase as red clovers than in a 9-year potato monoculture. However, in current agricultural practices, soil fertility may be depleted by rotations having high proportion of cash crops (Aref and Wander 1998). For example, continuous potato cultivation depletes soil fertility as a result of a decrease in SOM (Saini and Grant 1980). Data collected from 448 farms suggested that 25-50% of total phases in rotations were required to be soil fertility building crops in the form of forages (Langer

2002). Evans et al. (2001) reported that grain legume–wheat (1:1) rotations did not maintain long-term N sustainability in rain-fed regions. The Breton plots in Alberta also demonstrated that barley forage rotations were not N self-sufficient when the alfalfa phase was 40% of all rotation phases, while crop rotations on simulated livestock farms provided adequate N (more than 90 kg N ha^{-1} yr^{-1}) to the succeeding cereal crops when the alfalfa phase was 62% (Wani et al. 1994b).

Soil fertility changes driven by crop rotations are closely linked with the quality and quantity of returned residues and SOM turnover. SOM is considered the center of nutrient management in organic agriculture. It permits better aeration, enhances the absorption of nutrients, and makes soils less susceptible to leaching and erosion. SOM change is primarily related to climate and soil texture with a slow speed under most conditions, and is influenced by crop rotations, even in a short term (10 years) (Campbell et al. 2000). It is commonly believed that forage mixtures in a crop rotation lead to an increase in SOM levels. For example, over the course of a 38-year period, particulate organic C (>53um) was significantly higher in a pasture-based crop rotation (1.28 g kg^{-1}) than in a non pasture crop rotation (0.52 g kg^{-1}), but there was no statistical difference in SOM between them (Gentile et al. 2005). Similarly, Bronick and Lal (2005) found that particulate organic matter was significantly higher in a meadow-meadow-corn-corn-wheat rotation (3.5%) than in continuous corn (2.4%). Long term cotton rotated with a mixture of winter vetch (*Vicia sativa)* and clover (*Trifolium pratense*) resulted in an increase in SOC (9.5 g kg^{-1}) compared with continuous cotton with no winter cover crop (4.2 g kg^{-1}) (Mitchell and Entry 1998). An increase in SOM contributed by forages is due to both forage shoot and root biomass. Puget and Drinkwater (2001) reported that 50% of the root-derived and 13% of shoot-derived C remained in the soil as organic C in the current year when hairy vetch was incorporated as green manure. However, forage mixtures may be cut and sold, which results in large amounts of organic matter removals. The fresh young organic matter from a legume mixture is broken down very rapidly and may have little effects on SOM. Crops such as wheat and corn produce high C:N ratio residues, which may immobilize the available N and P in the short term and compete for available nutrients with crops, but such residues increase SOM pools in the long run. The low C:N ratio residues from legumes positively affect microbial activity, accelerate SOM mineralization, and increase N availability in the short term.

Nitrogen availability is affected by N losses through leaching, run off, denitrification, and volatilization. The losses of available N explain why the mineral N released from organic sources only represents the maximum potential N benefit to a succeeding crop. For example, a great proportion of N mineralized from green manure may be lost in legume-based rotations, especially at the beginning of a subsequent cropping phase when crop demand is fairly low. Fillery (2001) reported that 25-40% of total N in the applied green manure in temperate or tropical environments could be lost after mineralization.

Soil N content was increased with increased forage proportion in a crop rotation. This was demonstrated in the Breton plots (Wani et al. 1994a). Soil nitrate-N averaged 136 kg ha^{-1} in a wheat-medic (*Medicago* L.) rotation, and was significantly higher than that in a non-fertilized wheat monoculture (48 kg·ha^{-1}) over an 8-year rotation (Weston et al. 2002). Under a chemical fertilizer driven rotation, the average soil N content was 20-27% higher in a rotation with inclusion of 60% to 70% forage phases than in a 9-year continuous potato monoculture (Angers et al. 1999).

Amounts of residues produced in crop rotations with different forage proportions influenced soil biological properties (Chander et al. 1997). The average microbial biomass was significantly higher in the fully phased corn-corn-oat (*Avena sativa*)-alfalfa rotation than either in the fully phased corn-soybean rotations or continuous corn monoculture (Moore et al. 2000). Generally, soil microbial activity is increased with increased forage proportion in cropping systems, and is affected by original SOM levels (Wander et al. 1994).

Tillage is an integral part of crop rotations, and is a good way to incorporate crop residues or soil amendments. Tillage disturbs soil, and makes SOM easily available for microbes to be decomposed as a result of temporarily increasing microbial activities (Silgram and Shepherd 1999), and thus accelerates SOM mineralization (Balloni and Favilli 1987; Cambardella and Elliott 1994; Torbert et al. 1998) and N availability (Solberg 1995; Soon and Arshad 1996). Intensive tillage also deteriorates soil properties characterized by a decrease in SOM (Cambardella and Elliott 1994). Conversely, reduced tillage in high forage proportion rotations increases SOM and enhances soil biological activities. It is critical to adopt proper tillage and adjust tillage depth to balance the retention and release of nutrients stimulated by tillage operations.

Legumes have been used to provide feed for livestock as well as serve as a primary N source for organic cropping systems. Legumes such as alfalfa and red clover are fundamental in a crop phase in organic cropping rotations since they have a great capacity to fix atmospheric N_2 making crop rotations less reliant on external organic N sources. Legumes in crop rotations lower the external N requirements for the following crops as a result of slow release of N from legume residues. The quantity of N_2 fixed by legumes varies, depending on legume species, soil types, climate, nutrient availability, and legume harvesting time. A mixture of red clover and reed canary (*Phalaris arundinacea* L.) grass fixed 141 kg N ha^{-1} in the second year, 83 kg N ha^{-1} in the third year, and 21 kg N ha^{-1} in the fourth year (Heichel and Henjum 1991). Alfalfa hay in southern Manitoba provided 84, 148, and 137 kg net N ha^{-1} in the first, second, and third years, respectively (Kelner et al. 1997). Underseeded grass-clover mixture biologically fixed 185 kg N ha^{-1} in the first year, and 254 kg N ha^{-1} in the second year (Eriksen et al. 1999b).The amount of fixed N_2 was up to 150-200 kg N ha^{-1} per year by a clover-grass mixture if the clover proportion was more than 30% (Cuttle et al. 1992). Nitrogen fixation by clovers averaged 62 kg ha^{-1} in Atlantic Canada (Patriquin et al. 1986). Although N_2 fixed by legumes had a large variation, there is a relationship between total biomass and the amount of N_2 fixation. Peoples et al. (1998) concluded that 20-25 kg N is fixed in every tonne of legume shoot dry matter. On average, red clovers fix between 100 to 150 kg N ha^{-1} yr^{-1}, and soybeans (*Glycine max (L.) Merrily*) fix between 50 to 150 kg N ha^{-1} yr^{-1} (Brady and Weil 1999, P516). Legumes belowground, including nodules, roots and their exudates, were also important N sources. Typically, the belowground N in perennial legume accounts for 7-26% of total legume fixed N (McNeill et al. 1997). Different legume species vary N contributions to the following crops. For example, there are larger N benefits to the succeeding crops from legumes like red clover than from grain legumes like peas (*Pisum sativum* L.) or faba beans (*Vicia faba)* (LaRue and Paterson 1981), since the majority of the fixed N_2 in grain legumes is removed by grain harvest (Beck et al. 1991; Peoples and Craswell 1992; Ravuri and Hume 1993).

Nitrogen availability from legume residues was affected by legume species, maturity, and soil properties. Evans et al (2001) concluded that about 30% of N in the stubble (leaves, stems, and pods) and 20% of N in roots of grain legumes such as lupin and pea might be mineralized in the following year. The N recovery of belowground subterranean clover (*Trifolium subterraneum* L.) residues by a single succeeding wheat crop was reported to be up to 25% (McNeill et al. 1998). Thompson and Fillery (1998) suggested that maximally 30% N in young aboveground legume (clover or alfalfa) residues and less than 10% for the mature aboveground legume residues could be utilized by a succeeding cereal crop. On average, legumes provided 37 kg N ha^{-1} (ranged from 14 to 46 kg N ha^{-1}) to the following cereal crops in a temperate climate (Peoples et al. 1995; Chalk 1998). Nitrogen use efficiency was also improved in legume-based crop rotations; the average N use efficiency across 4 year was 35% higher in a maize-alfalfa rotation and 24.5% higher in a maize-soybean rotation than in the continuous maize monoculture (Ma et al. 2003).

Phosphorus (P) and potassium (K) are important plant nutrients, and have specific effects on legumes. Cropping systems that include legumes such as pigeon pea or white lupin (*Lupinus albus* L.) can mobilize fixed forms of soil P by exudates of organic acids or carboxylates from roots, and subsequently increase soil P availability and plant P uptake (Nuruzzaman et al. 2004). An increase in legume P uptake may result in more P uptake by a following crop through the recycling of mobilized P in the preceding plant residues. VAM (Vesicular-Arbuscular-Mycorrhiza), an association of fungi and crop roots, produces hyphae that help a crop to access P, especially under low soil P conditions (Ae et al. 1990; Hocking 2001).

Potassium is the most plentiful macronutrient held in mineral soils, and is a particularly important element affecting clover N_2 fixation since clover is a poor competitor for K when grown in association with grasses (de Beaucorps 1978). On hay farms, K deficiency is a major practical problem caused by K removals in hay or silage (Gosling and Shepherd 2005).

The forages used in the current trial are a mixture of red clover and timothy (*Phleum pratense*). Timothy is an ideal grass to mix with red clover in the Atlantic region since it is easy to establish and helps red clover survive soil heaving during cold winter when air temperature changes drastically. Another legume crop used in the current trial is soybean.

1.2.3 Soil amendments

Livestock manure is a valuable nutrient source in organic farming systems (Lampkin 1990). The most frequently recommended livestock manure form is composted manure rather than raw manure because of the potential problems associated with raw manure such as odor and difficulties in transportation. Composting is an aerobic and thermophilic biological process with the product of compost, a good nutrient source with a low nutrient-release rate (Lampkin 1990; Paré et al. 1997). Mature composted manure was also characterized by low C/N ratios (N'Dayegamiye et al. 1997) and constant N-mineralization rates (Aoyama and Nozawa 1993).

Well composted manure can make a great contribution to SOM in the long run. Sommerfeldt et al. (1988) reported that SOM was increased by 0.26% as a result of three annual applications of compost at 17.8 t ha^{-1}. Culley et al. (1981) reported that five years of manure application at a rate of 31.2 t ha^{-1} yr^{-1} led to an increase in SOC by 0.9% in the top soil layer of 15 cm in a continuous corn silage field. An increase in SOM improved soil physical, chemical, and biological properties: an increase in water holding capacity (Khaleel et al. 1981); a decrease in soil bulk density (Nemati et al. 2000), which was negatively linearly related to SOM (Khaleel et al. 1981; Shiel and Rimmer 1984; Ekwue 1990; Cannell and Hawes 1994); an increase in total-N (Reganold 1988; Scow et al. 1994) and potentially mineralizable N and biomass-N (Gunapala and Scow 1998) as well as cation exchange capacity (Arden-Clarke and Hodges 1988).

The amount of plant available N from compost depends on inorganic N content and fractions of organic N that is mineralized during the growing season. Evaluation of nutrient mineralization is critical to estimate optimum application rates. Nitrogen mineralization rate is frequently calculated as the cumulative amount of NH_4^+ and NO_3^- by periodical sampling. Nitrogen mineralization is a microbiologically mediated process, through which organic N was converted to an inorganic form. However, immobilization occurs concurrently during mineralization. Recently immobilized N such as microbial biomass N was found to be mineralized more rapidly than native organic N (Nicolardot 1988).

Compost N mineralization varied widely among composts differing in maturity and chemical composition (Fox et al. 1990; Oglesby and Fownes 1992; N'Dayegamiye et al. 1997; Pengoo et al. 2002). Mineralization rates were affected by factors influencing microbial activity, such as soil C: N ratio (Amlinger et al. 2003), soil temperature (Ellert and Bettany 1992), soil moisture (Campbell et al. 1984), application rates (Hébert et al. 1991), soil pH (Stanford and Smith 1972), and soil disturbance. There were slightly different arguments as to effects of C:N ratios on N mineralization. Studies (Castellanos and Pratt 1981; Beauchamp 1986) had indicated that a net immobilization occurred if a C:N ratio is larger than 15:1, and that a net mineralization occurred if a C:N ratio was smaller than 15: 1. This is in accord with the reports that the addition of stable compost with a C:N of 23 did not lead to a substantial increase in the amount of available N (Aoyama and Nozawa 1993). While studies by Sims (1990) and Sullivan et al. (1998) indicated that amendments reduced crop production via microbial immobilization of available N in the first application year if the C:N ratio in amendments was greater than 30:1.

Organic N in composted manures was mineralized slowly (Castellanos and Pratt 1981; Tyson and Cabrera 1993; Vervoort et al. 1998), and 5-33% of total N could be released in the application year (Table 1.2). The rate of compost nutrient release was decreased with time, and large amount of nutrient supplies per year from compost is mainly in the application year; nutrient carryover from compost only released a small amount of plant available N, accounting for from 2% to 8% of total compost N (Eghball and Power 1999a; Eghball 2000; Amlinger et al. 2003).

On organic farms, applied manure that met crop N requirements tended to supply excess P because of a low of N:P ratio (Withers and Sharpley 1995). Total P and organic P in soil were increased after 20 years of manure additions (Dormaar and Chang 1995; Tran and N'dayegamiye 1995). Phosphorus availability from composted manure was as high as 73% of total P (Eghball et al. 2002), while sewage sludge compost P availability was reported lower than 50% of total P for surface application (Warman and Termeer

2005). In a soybean-wheat rotation, P availability in soil was increased significantly and linearly through years of repeated manure applications (Reddy et al. 1999).

Although soil exchangeable K was increased by incorporation of soil amendments (Scagnozzi and Saviozzi 1997), studies (Haraldsen et al. 1999) showed that more K was removed than applied from cropping systems on arable farms with or without animals, and that a significant decrease in soil K was found on stockless farms. Annual K input equal to average plant K removal is capable of balancing soil K levels (Jouany et al. 1996), but luxury K uptake makes it difficult to manage K efficiently.

Organic management was considered to increase the size (Anderson and Domsch 1990), activity (Bolton et al. 1985) and diversity of the microbial community (Hassink et al. 1991), and thus possibly increase the rate of nutrient cycling and crop productivity (Doran et al. 1987). Both microbial biomass and activity are sensitive to management practices, and are important indices for predicting rates of nutrient cycling as affected by management (Pilbeam et al. 1993). Powlson et al. (1987) suggested that changes in microbial biomass C over a short period can be a sensitive index of changes in SOC. Microbial biomass is a small part of total organic fraction but constitutes a large part of labile SOM in soil. About 5% of soil organic N is represented by microbial biomass (Anderson and Domsch 1990). Microbial biomass plays a multiple role in the decomposition, transformation and turnover of organic matter, and serves as a labile source and an immediate sink for C, N, and P. Nutrients in microbial biomass are potentially plant available (Chander et al. 1995). Microbial biomass N size was related to N mineralization and immobilization processes (Aoyama and Nozawa 1993), and was increased during an immobilization phase and was decreased during a mineralization phase. Since organic C in organic amendments serves as an energy source for microbes, soil microbial biomass and activity were increased in cropping systems involved in organic soil amendments (Bonde et al. 1988; Hassink et al. 1991; Scow et al. 1994; Wander et al. 1994; Gunapala and Scow 1998; Rochette and Gregorich 1998; He et al. 2000).

1.2.4 Integration of forages and soil amendments

Forages are critical for improvement of soil fertility by preventing soil erosion, adding C and N, and providing an energy source for soil organisms. Compost is applied not only for a short-term nutrient source, but also for a long-term soil fertility enhancement. For soil fertility building, organic farming not only relies on crop rotations which include fertility building and depleting phases. It also relies on organic soil amendments such as compost or slow-release nutrient sources such as rock phosphate. Cropping systems in the present thesis refer to crop rotations and associated soil amendments. Practices of applying compost and growing mixed forages on organic farms are expected to enhance SOM, which has been linked intrinsically to soil fertility improvement. An increase in SOM over 15 years in legume-based rotations was 6.6 t ha^{-1} if the legumes were directly incorporated into soils, and 12 t ha^{-1} if the legumes were fed to beef cattle and the cattle manure was returned to the field (Drinkwater et al. 1998). A crop rotation characterized by 40% forage phases, maintained SOM without chemical N application, and increased SOM with farmyard manure application over a period of 51 years (Izaurralde et al. 2001). A combination of green manure and animal manure in crop rotations provided a larger increase in SOM (2.7 g kg^{-1}) compared with continuous cereal systems (2.3 g kg^{-1}) over a period of 8 years (Wani et al. 1994b).

The main N sources in most organic farming systems are biological N_2 fixation, crop residues, and compost additions, in addition to the soil N reserve. Under incorporation, legume species and maturity, soil amendment C:N ratios, chemical composition, and application rates affected N availability (Fox et al. 1990; Oglesby and Fownes 1992; N'Dayegamiye et al. 1997) through the process of mineralization and immobilization mediated by a wide range of soil organisms (Beare et al. 1995). Typically, mineralized N may be up to 125 kg in soil to a depth of 15 cm with the assumption of a SOM content of 5% (Brady and Weil 1999, P497).

Organic farming systems enhance effects of soil biotic properties for utilizing organic N pools. Nitrogen availability rather than total N amount is the key in organic N management. Nitrogen availability is mediated by soil microbes, and may be adjusted by organic amendment and judicious crop rotations. Soil pH, temperature, moisture (Campbell et al. 1999), initial soil organic C, soil texture (Cooper and Warman 1997), crop species (Buyer and Drinkwater 1997), and different types of organic amendment influence soil microbial biomass and microbial activity. Microbial biomass was largely governed by soil inherent organic C and recent substrate additions; soil with high levels of organic C tends to have large pools of microbial biomass (Goyal et al. 1993). Microbial biomass C was believed to reflect the cumulative rather than the current-year C input into soil (Rochette and Gregorich 1998), and was greater in zero tillage than conventional tillage (Doran 1980; Franzluebbers and Arshad 1996). An increase in microbial biomass was found in organic and low-input systems associated with high organic matter input (Bossio et al. 1998).

Enzyme activity is not only governed by microbial activity, but also by management practices (Kandeler et al. 1999). Dehydrogenase activity (DHA) is an index of potential microbial activity in the soil microbial community (Cooper and Warman 1997). Dehydrogenase activity was considered a sensitive indicator for assessing microbial mineralization processes in C and N cycles (Monreal and Bergstrom 2000), and an increase in DHA may lead to an increase in N mineralization rates (Haynes and Naidu 1998). Different types of crops resulted in various amounts of residue return, and thus influenced soil enzyme activity. For example, additions of organic residues greatly increased enzyme activities especially during the first year of addition. The average DHA was significantly lower in control plots than in straw or alfalfa incorporation plots (Martens et al. 1992). Dehydrogenase activity was significantly higher in a 67% legume phase rotation than in a 50% legume rotation (Bolton et al. 1985).

Crop yield is one of the most powerful indices of soil fertility, and is influenced by crop rotations and soil amendment. Wheat yield is normally higher in legume-based crop rotations than in monoculture wheat. The average yield of monoculture wheat was 20% lower than yield of wheat following field pea or red clover on a loam soil in Alberta (Soon and Clayton 2002). Similarly, the average yield of spring wheat was increased by 7% in a wheat-pulse (chickpea and lentil) rotation compared with 2-year continuous wheat in Saskatchewan (Gan et al. 2003). The wheat yield in the 16th year in a wheat-legume (vetch) rotation was higher (4.5 t ha^{-1}) than in 16 consecutive years of continuous wheat (3.6 t ha^{-1}) in semiarid regions (Galantini et al. 2000). In a fully phased annual medic-wheat rotation, average wheat yield (2.63 t ha^{-1}) across 10 years was increased compared with either non-fertilized wheat monoculture (1.96 t ha^{-1}), or N fertilized (50 kg ha^{-1} yr^{-1}) wheat monoculture (2.41 t ha^{-1}) (Weston et al. 2002). As the forage proportion was increased from 25% to 38%, average cereal yield was increased from 3.4 t ha^{-1} to 3.7 t ha^{-1} (Eltun et al. 2002). In the Breton plots, average barley yield (4.3 t ha^{-1}) was significantly higher in a grain legume rotation, where the forage proportion was 62% and 70% of the removed legume N was returned in the form of cattle manure, than in continuous barley (3.6 t ha^{-1}), where 90 kg N ha^{-1} yr^{-1} was applied (Wani et al. 1994b). Grain yield following legumes in a legume-based crop rotation generally was increased, but it may be decreased in drought seasons (Entz et al. 2002). Weston et al. (2002) demonstrated that the average grain yield of wheat was decreased during the period of three drought years in medic-wheat rotations (1.05 t ha^{-1}) compared with either a non-fertilized wheat monoculture (1.37 t·ha^{-1}) or an N fertilized (50 kg ha^{-1}) wheat monoculture (1.42 t ha^{-1}). Warman (1990) found that different animal manure amendments (dairy manure, pig manure, chicken manure) had no significant effect on barley yield or red clover biomass under the same N application rate (75 kg N/ha) in a 2-year study, but different chicken and dairy manure application rates did affect timothy yield (Warman 1986). Potato tuber yield may be decreased because of soil erosion or potato diseases when potato frequency in rotations is too high, but it could be maintained when rotated with Italian ryegrass over the course of 11 years (Carter et al. 2003). Crop rotation yield benefits can be masked by external soil amendments, even in low input systems (Porter et al. 2003).

1.3 Objectives and Hypotheses

1.3.1 Objective and hypothesis 1

The organic potato rotations were established after a long-term sod was broken to determine the effects of forages and soil amendments on soil N, P, and K availability in the first cycle of 4-year rotations. The chapter also tests assumptions about N availability of three tested soil amendments and soil isonitrogeneity.

Hypothesis:

Soil N availability will be increased with increased forage frequency in the crop rotations, and will not be different among the three soil amendments. Soil P availability will be increased with increased forage frequency, and will be higher in compost treatments than in the alfalfa meal treatment. Soil K availability will be decreased with increased forage frequency, and will be higher in alfalfa meal treatments than in compost treatments. It is possible to achieve soil isonitrogeneity.

Rationale:

In organic cropping systems, most N sources exist in organic form. Through mineralization, organic N in inherent SOM, crop residues, and soil amendments is transferred into inorganic N. Organic N mineralization rates are affected by available C and N content. With increased forage frequency, both soil N and available C content are increased; thus increasing soil N availability. However, soil N availability may be the same across different soil amendment levels, as different soil amendment treatments are expected to provide the same amount of soil available N by adjusting soil amendment application rates according to soil test recommendations and assumed N availability of different soil amendments.

With increased forage frequency, readily oxidizable C will be increased, and thus increase microbial activity, organic P mineralization rates, and soil available P. Soil P levels are higher in compost treatments than in the alfalfa meal treatment, because more P is applied in composts than in alfalfa meal when adding the same amount of N by soil amendments.

Soil amendment and associated K input have a decreasing trend with increased forage frequency, as a result of an increase in soil N content with increased forage frequency. Therefore, soil K levels will be decreased with increased forage frequency. On the other hand, K content in alfalfa meal is higher than in composted manures, so higher inorganic K in the alfalfa meal treatment is expected.

Isonitrogeneity can be evaluated by the amounts of N available to crops, which almost exclusively take inorganic forms of N. Through mineralization, the organic N inherent in soil organic matter, crop residues, and soil amendments is transferred into inorganic N. Soil amendment N mineralization rates are affected by amendment composition and N content, and also influenced by carbon availability, soil temperature, moisture, and tillage. Soil amendment mineralization rates appear to decrease as soil amendment application rates increase, while soil amendment additions accelerate the inherent soil organic matter to mineralization process through priming effects. Generally, there is a relatively high level of soil organic matter in organic cropping systems, which strengthen the massive soil N pool. Compared with soil amendments and crop residuals, soil organic matter is a major inorganic N contributor, especially in low-input organic cropping systems. Excessive inorganic N also resulted in N leaching and gaseous emission losses. Therefore, it is possible to equalize soil inorganic N through adjusting soil amendment application rates based on a judicious understanding of N mineralization rates in soil amendments.

1.3.2 Objective and hypothesis 2

The organic potato rotations were established after a long-term sod was broken to determine the effects of forages and soil amendments on soil microbiological properties in the first cycle of 4-year rotations.

Hypothesis:

Dehydrogenase activity and soil microbial biomass carbon (SMBC) will be increased with increased forage frequency in a crop rotation, and will be higher in the alfalfa meal treatment than in compost treatments.

Rationale:

Soil biological indices such as DHA and SMBC are sensitive to changes of labile C and N fractions. With increased forage frequency in crop rotations, SOM and N levels will be increased as a result of biological N fixation by legume crops as well as incorporation of the forage residues. The soluble C and N fractions in legume residue compounds can be readily used as energy and nutrients by microbes for proliferation, and thus increase DHA and SMBC. Compared with composted manures, alfalfa meal has higher total and labile C and N content, so it stimulates soil microbial growth and increases DHA and SMBC levels.

1.3.3 Objective and hypothesis 3

The organic potato rotations were established after a long-term sod was broken to determine the effects of forage crops and soil amendments on plant N, P, and K uptake as well as potato tuber yield in the first cycle of 4-year rotations.

Hypothesis:

Plant nutrient uptake and potato tuber yield will be increased with increased forage frequency in crop rotations, and will be higher in composted manure treatments than in alfalfa meal treatments.

As forage frequency increases, net N, P, and K balances (difference between soil amendment nutrient inputs and plant harvest nutrient removals) will be decreased. Net N, P, and K balances will be higher in compost treatments than in the alfalfa meal treatment.

Rationale:

Plant nutrient uptake and potato tuber yield will be increased with increased forage frequency as a result of soil property improvement such as an increase in SOM and nutrient supply rates. Also, problems such as weeds, pests, and diseases in potato fields may be alleviated with increased forage frequency in crop rotations, since forages have a function of breaking weed, pest, and disease life cycles. Among soil amendments, a larger volume in composts may be applied than in alfalfa meal as a consequence of a low N content in composts. Such a large volume of soil amendments may decrease soil bulk density to some extent, and make tuber bulking easier; thus having higher tuber yield.

Increased organic N and P mineralization rates with increased forage frequency will result in an increase in plant N and P uptake and plant harvest removal. Forage crops have a bigger N and K uptake capacity than other crops selected in the current trial; therefore more N and K are removed accompanying with forage harvest in the high forage frequency rotation. On the other hand, soil amendment N input will be decreased with increased forage frequency in order to fulfill forage N_2 fixation capacity. With increased forage frequency, N, P, and K removals will be increased while inputs (i. e. N) will be decreased; therefore net N, P, and K balances will be decreased.

When meeting forage P requirements in forage plots, compost treatments provided additional N and K compared with the alfalfa meal treatment where rock-P is used as the main P source. This additional N and K will lead to a higher net N and K balance in compost treatments than in the alfalfa meal treatment. Composts have a smaller N : P ratio than alfalfa meal has; this results in more P input in compost treatments than in alfalfa meal treatment when applying the same amount of N. High N, P, and K inputs in compost treatments will consequently lead to large net N, P, and K balances.

Table 1.1 Benefits of crop rotations

Benefits	References
Increase SOM content	(Blackwell et al. 1990; Raimbault and Vyn 1991)
Reduce soil erosion	(Stinner and House 1989)
Suppress weeds	(Liebman and Dyck 1993; Entz et al. 1995; Barberi et al. 1997)
Disrupt insect, pest, and disease cycle	(Matson et al. 1997; Matson et al. 1997; Carter and Sanderson 2001)
Improve yield and nutrient use efficiency	(Ma et al. 2003)
Increase economic profits	(Weston et al. 2002)

Table 1.2 Percentage of total compost N available to plants in the application year

Total N available to plants (%)	References
9	(Brinton 1985)
13	(Schlegel 1992)
5-15	(Tester 1989; Amlinger et al. 2003)
10-20	(Beauchamp 1986)
22	(Eghball and Power 1999a; Eghball 2000)
10-30	(DeLuca and DeLuca 1997)
33	(Cheneby et al. 1994)

CHAPTER 2 MATERIALS AND METHODS AND EXPERIMENTAL CONDITIONS

The thesis experiment consists of field and greenhouse trials.

2.1 Field Trial

2.1.1 Site description

The field experiment was established on a long-term pasture in Truro, Nova Scotia in the spring of 2002. The long-term pasture was ploughed in the fall of 2001. The soil is classified as a loam Orthic Humoferric Podzol (Webb et al. 1991, P186), with 40.2% of sand, 38.0% of silt, and 21.8% of clay. Prior to soil amendment application in 2002, the basic soil chemical characteristics were as follows: pH 5.5, total C 29.7 g kg^{-1}, total N 1.9 g kg^{-1}, total P 0.57 g kg^{-1}, total K 3.45 g kg^{-1}, mineral N 0.062 g kg^{-1}, extractable P_2O_5 0.067 g kg^{-1}, extractable K_2O 0.165 g kg^{-1}.

2.1.2 Experimental design

In a forage-based potato crop rotation, nutrient supplies for potatoes highly rely on on-farm nutrient resources. In the current experiment, cropping management practices were mimicked as a farmer might do. Fox example, soil amendment application rates were estimated based on soil test recommendations. A two-stage nested experiment was initiated in 2002, with a soil amendment factor nested under a forage factor. The experiment was a nested design, because the soil amendment application rates were dependent on the forage levels of a crop rotation and were not the same across three forage levels. The forage factor includes three forage levels represented by three different 4-year crop rotations. A 0-year forage rotation (0): wheat, soybean, barley, potato; a 1-year forage rotation (1): wheat, barley, forage, potato; a 2-year forage rotation (2): wheat, forage, forage, potato. The soil amendment factor consisted of three levels: alfalfa meal in a stockless system (S), composted poultry manure in a monogastric system (M), and composted beef manure in a ruminant system (R). The three soil amendments represent the main nutrient sources from three farming systems. 1) a stockless system without livestock: alfalfa meal was primary N source for non-legume crops, and insufficient P supplied by alfalfa meal was supplemented with certified organic rock P (calcium phosphate) as required; rock P was the primary P source for soybean and forage crops; forages, if applicable, were used as mulch in potato crops and cereal straw was retained in the plots; 2) a monogastric system: composted monogastric manure produced within systems was the primary N source for non-forage crops, and P source for forage crops; insufficient P supplied by composted monogastric manure in non-forage crops was supplemented with rock P; forages, if applicable, produced in a monogastric livestock system were exchanged for off-farm feed; cereal straw was removed for bedding, and 3) a ruminant system: composted ruminant manure produced within systems was the primary N source for non-forage crops, and P source for forage crops; insufficient P supplied by composted ruminant manure in non-forage crops was supplemented with rock P; forages, if applicable, produced were used as feed; cereal straw was removed for bedding.

Soil amendment application rates were based on provincial soil test recommendations, soil amendment nutrient contents, and assumed N, P, and K availability from soil amendments. In the current experiment, we assumed that 30% of total N in alfalfa meal, 50% of total N in composted poultry manure, and 25% of total N in composted beef manure were plant available, and that 20% of total P and 90% of total K in alfalfa meal, compost poultry manure, and compost beef manure were plant available in the application year. In order to let red clovers biologically fix atmospheric N_2 rather than absorb soil N, N application rate in year 1 was reduced by 50% in the 2-year forage rotations where wheat plots were underseeded to forage crops. Organic certified rock phosphate (N-P_2O_5-K_2O=0-3-0), with a 15% of total P being plant available, was supplemented if P input associated with soil amendments didn't meet the crop P requirements. Assumed N availability of the three soil amendments (M, R, and S) was tested by determining N potential mineralization rates at an incubation rate of 400 kg total N ha^{-1} under controlled conditions as described in the section of 2.1.4.8. Soil test recommendations were based on each block in year 1 (2002), and based on each plot in the following years for each crop. Soil test recommendations were made by the Quality Evaluation Division, Department of Agriculture and Fisheries, Nova Scotia.

The nine forage and soil amendment combinations were completely randomized within a block, with three blocks (Fig. 2.1). The experimental units were individual plots, and each plot was 3 m wide and 10 m long. Originally, there were 27 plots with three blocks, and a 3-m-wide alley between blocks was spared to facilitate field operations (Fig. 2.1). There is a 1 m buffer zone between plots to avoid soil amendment cross contamination during field operations.

In year 4 (2005), each 3 m by 10 m plot was split into two 3 m by 5 m subplots. One subplot received soil amendments as per soil test recommendations, and was denoted as the amended subplots. Another subplot received no soil amendment, and was regarded as unamended subplots. The amended and unamended subplots were randomly assigned into the two subplots in each original plot. Since the original experimental design was not factorial, the experiment in year 4 was not a split-plot design after splitting into two parts.

In order to determine original soil fertility at the experimental site, and help to assess soil amendment nutrient availability, no-soil-amendment control plots (C) were added at one end of the original (core) plots in year 2, and were depicted as grey color in Fig. 2.1. These added plots had been managed in a similar way to the core plots in year 1, except that some of the control plots received small amounts (less than 1 ton per hectare) of forage mulch applied in the year 1 wheat growing season. However, the forage crops in the 2-year forage rotations in the added control plots were not underseeded with wheat in year 1, but were directly seeded in the spring of year 2. The added control plots were located at one end of core plots and lacked randomization; this may be a problem. Another unforeseen limitation for the added control is that potatoes failed to emerge in one third of the plots as a result of bottomland and heavy flooding damage at the beginning of the potato growing season. The data collected in the remaining unflooded control plots are attached in Appendix 1.

2.1.3 Crop management

Cultivars selected are listed in Table 2.5. Forages were underseeded with the previous cereals in the 1- or 2-year forage crop rotations. The seeding and harvesting dates in the whole crop rotations were shown in Table 2.6. Wheat, barley, and soybean were seeded with an eight row (1.25 m wide) cereal seeder (Hege 80, Kansas). Forages were seeded with a forage seeder (Brillion SS12, Wisconsin). Potato seed tubers were cut into small pieces, each weighing 60-70 g and having at least one eye. Potatoes were seeded by hand after furrowing by a tractor. Red skin potatoes, Norland, were seeded in the 2-m buffer zone between unamended and unamended subplots to facilitate harvest. Wheat, barley, and soybean were harvested with a small plot combine (Hege 1250C, Germany) by a single 1.5-m-wide pass. Forages were cut twice per year at 10% bloom stage with a Haldrup 1500 (Logstor, Denmark). Potatoes were harvested using a single row potato digger (Niplo D-653S, Japan).

In year 2, weeds such as lambsquarter (*Chenopodium album* L.) and buttercup (*Ranunculus bulbosus*) were a problem in soybean and barley plots. To relieve heavy weed pressure, weeds in soybean plots were pulled twice by hand in the early soybean growing season. Barley in year 2 was harvested as silage at the flowering stage (July 17, 2003) because of weed pressure. A tine harrow (Lely Industries N.V., Maasland-Holland) was employed to control weeds in barley plots in year 3 and potato plots in year 4.

Colorado potato beetles (*Leptinotarsa decemlineata*) were controlled by spraying an organically approved insecticide Entrust® after potato flowering at a rate of 0.1 L ha^{-1} three times. To prevent potato late blight (*Phytophthora infestans*), copper sulphate hydroxide was sprayed after flowering at a rate of 3 L ha^{-1} three times.

All plots were ploughed down to a depth of 20 cm in the late fall of year 3. In the spring of year 4 (May 25, 2005), the potato seed beds were prepared by one pass of disc harrowing followed by two passes of the S-tine cultivator (5220 Odense, Denmark). Potatoes were hilled on July 4, 2005 (year 4). Soon after hilling, potatoes in 1- and 2-year forage rotations in S treatments were mulched with forages produced from the adjacent S amended crop rotations. In the 1-year forage rotations, forage mulch rate was equivalent to the first cut forage biomass from a plot size area; in the 2-year forage rotations, forage mulch rate was equivalent to the first cut forage biomass produced in a double sized plot.

In this experiment, we bought poultry and beef manure from local organic farmers, and made poultry-based and beef-based compost. The manure was exposed on the local farms for one year, and was subjected to nutrient losses. The bulking materials were wood chips and straw for composted poultry manure, and ruminant beef manure, respectively. During the one-year composting process, the compost piles were turned 3 times. The alfalfa meal was bought from a local store. The nutrient contents were detailed in Table 2.1. Composts were screened through 5 mm prior to application. Soil amendments and rock P were spread by hand, and immediately incorporated into soil with one pass of a disc harrow for cereal and potato crops. To raise soil pH to 6.5 in year 1, Mosher limestone powder was applied at a rate of 4000 kg ha^{-1} based on the lime requirement test done by Quality Evaluation Division, Department of Agriculture and Fisheries, Nova Scotia, and was incorporated into the soil with one pass of a disc harrow. No nutrients were applied in year 2 because of a high soil amendment application rate in year 1 as well as high background soil fertility, as evidenced by the fact that the average total plant N uptake in the adjacent control plots(122 kg ha^{-1}) was equivalent to that in the core plots (130 kg ha^{-1}) in year 1. Based on the principle of the system design, no soil amendment N was applied to soybean and forage crops. However, in year 3, forage crops in M and R treatments received unavoidable additional compost N when applying P with composts to meet forage P requirements, while forage crops in S treatments received rock P for forage P requirements. Soil amendments were applied in year 1, year 3, and year 4, and the application rates in the whole crop rotation are listed year by year in Table 2.2, Table 2.3, and Table 2.4.

2.1.4 Soil sampling and laboratory analyses

2.1.4.1 Soil sampling

In May, 2002 (year 0) and at the end of each growing season, 15 soil cores per plot (per subplot in year 4) to a depth of 15 cm were randomly collected with a soil probe of 1 cm diameter; these samples were combined to form one composite sample per plot. In the fall of year 4 (2005), before plough operations, composite samples were taken and stored at 4°C for soil biological analyses such as soil microbial biomass C and DHA. Composite samples which were not subjected to soil biological analyses were directly air dried, screened through a 1-mm sieve, and stored for nutrient analyses.

Soil bulk density (SBD) samples were collected with a soil core sampler (5 cm inside diameter) to a depth of 15 cm. Two soil samples were randomly collected per plot. Soil bulk density was collected in May, 2002 (year 0), the fall of year 2, year 3, and year 4 at the end of crop growing season. In year 4, plots were disc harrowed after potato tuber harvesting, and SBD samples were collected 2 wk after disc harrowing.

2.1.4.2 Soil moisture content measurement

Approximately 15 g of field moist soil was weighed and put in an oven (Model 625, Fisher Isotemp® 600 series) at 105°C for 48 h. The oven dried soil was reweighed after cooling down in a desiccator. Soil moisture content was calculated on a dry base as follows: 100 × (mass of moist soil - mass of dry soil)/mass of dry soil.

2.1.4.3 Soil bulk density measurement

The moist soil columns were weighed, and then placed in an oven at 105°C for 48 h, followed by reweighing the soil columns after cooling down in a desiccator. Soil bulk density was calculated: (dry weight of soil column in grams)/(volume of soil column in mL).

2.1.4.4 Soil total C and N content determination

Soil C_{tot} and N_{tot} contents of air-dried soils were determined by combustion at 950°C with an automatic Leco® analyzer (CNS-1000, LECO Corporation, St-Joseph, MI). The sample size was 0.3 g, and one composite sample was determined per plot.

2.1.4.5 Soil extractable nutrient content determination

Soil nitrate-N (NO_3-N) and ammonium-N (NH_4-N) concentrations were extracted using 2 M KCl as described by Maynard and Kalra (1993). Approximately 10 g of air-dried soil was weighed into an 80 mL plastic bottle with a snap lid. Fifty mL of 2 M KCl was added and followed by shaking for 1 h on an oscillating shaker at 200 oscillations per minute. The extract was filtered through Whatman No. 2 filter paper, and analyzed using Technicon® AutoAnalyzer® III (Technicon instruments corporation, Tarrytwon, NY).

Soil extractable P_2O_5 and K_2O were extracted using the Mehlich 3 method (Mehlich 1984). Approximately 10 g of air dried soil was weighed into an 80 mL plastic bottle with a snap lid. After 50 mL of Mehlich 3 was added, these samples were shaken for 1 h on an oscillating shaker at 200 oscillations per minute. The extract was filtered through Whatman No. 5 filter paper, and soil extractable P_2O_5 and K_2O content were determined by inductively coupled argon plasma (ICAP) spectrometry using a Jarrell-Ash ICAP 9000 (Waltham, MA) spectrometer.

2.1.4.6 Soil total P and K content determination

Air dried soil was digested using the modified nitric acid digestion method described by Zarcinas et al. (1987). Approximately 2 g of soil was placed in a 250 mL digestion tube sitting in a digestion block and heated first at 90°C for 45 minutes, then at 140°C for approximately 5 h. A 1% HNO_3 solution was added to prevent the sample from drying. The digestion was cooled down and quantitatively filtered through Whatman No. 42 filter paper into a 100 mL volumetric flask. Total P and K concentrations were determined by inductively coupled argon plasma (ICAP) spectrometry using a Jarrell-Ash ICAP 9000 (Waltham, MA) spectrometer.

2.1.4.7 Soil N supply rate determination

In year 4, in-situ soil nitrate and ammonium N supply rates were monitored at the potato flowering stage using plant root simulator (PRS™) probes (Western Ag. Innovations, Inc., Saskatoon, SK). The PRS™ probes are made of an ion exchange membrane (Qian and Schoenau 2002), and soil N supply rates were reported as ion flux per unit membrane area per unit time. Root exclusion cores made of PVC columns (10 cm in diameter, 15 cm long) were used to eliminate nutrient absorption competition between probes and plant roots. Four PVC columns were randomly installed in each amended and unamended subplot soon after potato hilling (Jul. 4, 2005), and a pair of anion and cation exchange membrane probes was buried in each column at flowering stage for a period of 14 d (Jul. 11 to 25). After being removed, the PRS™ probes were washed free of soil with deionized water, and were eluted for 1 h using 0.5 N HCl; the eluate was analyzed for NO_3-N and NH_4-N concentrations using automated colorimetry.

2.1.4.8 N potential mineralization rate determination

Soil N potential mineralization rates were determined using the method of Campbell et al. (1993). Acrylic columns of 15-cm-length and 2.5-cm- inside-diameter were used to hold the tested soil. A stopper with a glass tube of 13-cm-length and 3-mm-inside-diameter was installed at the bottom end of an acrylic column. Twenty grams of air-dried soil and 40 g of Ottawa sand were mixed and loaded into a column. Glass wool pads were placed above and below the tested soil to minimize the movement of particulates during the leaching process. A layer of glass microfiber filter was placed between the bottom glass wool pad and the tested soil. Columns filled with 20 g of Ottawa sand were used as blanks. The columns were leached with 100 mL of 0.01 M $CaCl_2$ in a 10-mL increment, and were followed by 50 mL of N minus solution consisting of 0.002 M $CaSO_4$, 0.002 M $MgSO_4$, 0.005 M $Ca(H_2PO_4)_2$, and 0.0025 M K_2SO_4 under vacuum at 40 cm Hg. The initial leachate was discarded. The columns were then sealed at the top end by parafilm with three needle size holes to allow for aeration, and were incubated in an incubation chamber at 35°C and nearly 60% relative humidity. The leaching process was repeated every 2 wk for a period of 4 months. The leachate was collected, volumed, filtered, and analyzed for NO_3-N and NH_4-N concentrations using Technicon® AutoAnalyzer® III (Technicon instruments corporation, Tarrytwon, NY).

Soil amendment organic N mineralization rates were estimated in a similar way to soil N potential mineralization rates. Soil amendment incubation rate was equivalent to 400 kg N_{tot} ha^{-1}. The soil incubated with soil amendments was freshly collected from the adjacent potato plots on Aug. 8, 2005 (year 4). Such potato plots did not receive any soil amendment after broken down from a sod since 2001, and were seeded with a mixture of red clover and timothy from year 1 to year 3. The N availability of soil amendments applied in year 1 is attached in Appendix 2.

2.1.4.9 Soil dehydrogenase activity determination

Soil dehydrogenase activity was determined using the method proposed by von Mersi and Schinner (1991). Field moist soil was maintained at 4°C and sieved through a 2 mm sieve prior to DHA analysis. Three portions of the field moist soil, approximately 1 g for each, were weighed. One portion was used as a blank, and the other two were incubated in the dark with buffered 2-p-idolophenyl-3-nitrophenyl-5-phenyl tetrazolium chloride (INT) at 40°C for 2 h. At the end of incubation, N, N-dimethylformamide (DMF)/ethanol extraction solution was added. After being in the dark for one more hour, the solution was filtered and the solution absorbance was immediately read at 464 nm with a spectrophotometer. Enzyme activity was expressed as nmol INTF (iodonitrotetrazolium formazan) g^{-1} dry soil h^{-1}.

2.1.4.10 Soil microbial biomass C determination

Soil microbial biomass C was determined using a chloroform fumigation extraction method (Voroney et al. 1993). Three portions of a field-moist soil were weighed from each soil sample. One was for soil moisture determination. For the remaining two portions, one was fumigated with chloroform and the other was unfumigated control. For the unfumigated control portion, approximately 25 g of field-moist soil was weighed into a 100 mL glass bottle, and was immediately extracted with 50 mL of 0.5 M K_2SO_4 by shaking on a reciprocal shaker for 1 h. The suspension was filtered through Whatman No 5 filter paper and frozen until ready for analysis. For the fumigated control portion, approximately 25 g of the field-moist soil was weighed into a glass bottle, and was fumigated in the dark with alcohol free $CHCl_3$ in a vacuum desiccator for 24 h under a fume hood. After fumigation, the residual $CHCl_3$ vapor was removed by repeated evacuation under a vacuum. Following $CHCl_3$ removal, the fumigated soil was processed similarly to the unfumigated control soil described above. Dissolved organic C in the extracts was measured with Technicon® AutoAnalyzer® III (Technicon instruments corporation, Tarrytwon, NY). The efficiency of extraction of soil microbial biomass C is 0.38 (Vance et al. 1987).

2.1.5 Plant sampling and laboratory analyses

2.1.5.1 Plant sampling

In year 1 (2002), biomass samples of wheat, weeds, and forages were collected using a 1.0 by 0.25 m quadrat on Aug. 27, 2002, at the late dough stage of wheat. In each plot, a composite sample was formed with two randomly collected subsamples. Total biomass was determined after oven-drying at 55°C.

In year 2 (2003), biomass samples of barley, soybean, and forages were collected in the same way as in year 1. At the barley flowering stage, barley biomass samples was collected, and barley were harvested as silage to prevent weed growing seeds. Plant biomass in the soybean plots was collected at the beginning of maturity stage R7 (Fehr and Caviness 1980). Forage biomass was collected twice per year, at the stage of 10% bloom for each cut. In year 3 (2004), plant biomass was collected in the same way as in year 1 or year 2.

In year 4 (2005), potato biomass samples were taken 16 d before tuber harvest by randomly selecting four potato plants per subplot. Potato biomass included potato tops and tubers, but root biomass was not measured. After being washed and sliced, tubers, along with potato tops, were placed in an oven at 55°C for 72 h. Weed biomass was sampled with a quadrat of 0.25 m^2 when potato biomass was collected. An in-row and a between-row weed sample were collected, and formed a composite weed sample per subplot. Of all four rows per subplot, potato tubers were harvested in the centre two rows to the length of 3 m. The tubers with the diameter ranging between 38.1 to 114.3 cm were classified as marketable tubers (Government of Canada 1981). Potato tuber size was the only factor for marketable tuber yield in the current experiment, other damages such as wireworm or scab were not considered when classifying marketable tubers.

2.1.5.2 Plant C, N, P, and K content determination

Prior to nutrient determination, oven dried plant samples were first ground through a Wiley micromill with a 2-mm stainless steel sieve, then through a Retch centrifuge mill with a 1-mm stainless steel sieve. Plant total C and N contents were determined by combustion at 950°C with an automatic Leco® analyzer (CNS-1000, LECO Corporation, St-Joseph, MI). For plant P and K determinations, plant tissue was digested by the modified nitric acid digestion method described by Zarcinas et al. (1987). Approximately 1 g of a ground plant sample was placed in a 250 mL digestion tube sitting in a digestion block and heated first at 90°C for 45 minutes, then at 140°C for approximately 5 h. During the digestion, a 1% HNO_3 solution, if necessary, was added to prevent the digested solution from drying out. The digestion was cooled down and quantitatively filtered through Whatman No. 42 filter paper into a 100 mL volumetric flask. Plant total P and K concentrations were determined by inductively coupled argon plasma (ICAP) spectrometry using a Jarrell-Ash ICAP 9000 (Waltham, MA) spectrometer.

2.1.6 Statistical analyses

The data in the field experiment collected in year 4 were subjected to statistical analysis. To address the residual effects of soil amendments on variables, the data were analyzed in amended and unamended subplots separately. The experimental units were individual subplots. Forage and soil amendment were fixed factors, and block was a random factor. The three soil amendments were nested in the three forage levels. The reason for the nested design is that three levels of soil amendments were not the same across three levels of forages. In year 1, soil amendment application rates in 2-year forage rotations were reduced by half in order to prompt red clovers to fix atmospherical N_2

rather than absorb soil N. In year 3, soil amendment (i.e. M, R, and S) application rates were based on N recommendations in the barley plots for 0-year forage rotations, and were based on P recommendations in the forage plots for 1- and 2-year forage rotations. Therefore, nutrient inputs in 0-year forage rotations were different from that in 1- or 2-year forage rotations. Although soil amendment application rates were based on soil N recommendations for all treatments in year 4, the different cumulative soil amendment residual rates in the first 3 year may have still resulted in unequal nutrient rates for each soil amendment across the three forage levels. The average measurements of variables per subplot in year 4 were subjected to a two-stage nested design using Proc Mixed of SAS (SAS Institute, Inc. 2000). The statistical model used is the following:

$$Y_{ijk} = \mu + \tau_i + \beta_{j(i)} + \in_{ijk}$$

Where, Y_{ijk} represents dependent variables,

μ represents overall mean,

τ_i represents forage level effects (i=1, 2, 3),

$\beta_{j(i)}$ represents soil amendment effect within each forage levels (j=1, 2, 3),

$\in_{ijk}$ represents random error.

Data were transferred, if necessary, to meet statistical assumptions. Least squares means (Ls means) were used in mean comparisons when treatment effects were different at the level of 5%. Difference at the 10% level was regarded as being marginally significant. When forage effects were different at the 10% level, orthogonal contrasts were constructed between the 0-year forage rotation and a group of 1- and 2-year forage rotations to see if there was a significant difference between non-forage and forage treatments. Similarly, when soil amendment effects were different at the 10% level, orthogonal contrasts were constructed between alfalfa meal (S) treatments and composted manure treatments (M and R) see if there is a significant difference between stockless and livestock nutrient sources.

To determine if there is a significant difference between amended and unamended subplots, the data collected in amended and unamended subplots were subjected to a paired t comparison in Minitab (Minitab Inc. 2004). To assess overall variable responses to forage and soil amendment management, all variables in field experiment collected in year 4 were subjected to principal component analysis (PCA) using Proc Princomp of SAS (SAS Institute, Inc. 2000).

2.2 Greenhouse Trial

2.2.1 Experimental design and crop management

In order to assess soil N, P, and K supply rates after the first 3 year of isonitrogeneity management in a 4-year crop rotation, a greenhouse annual ryegrass experiment using the field plot soils was established. A composite soil sample to a depth of 15 cm was collected in each plot after harvesting on Nov. 7, 2004 (year 3). After being air dried and passed through a 2-mm sieve, 2.5 kg of oven-dried equivalent soil from each plot were put in separate pots. The pots were 15-cm diameter in the bottom with five holes, 20-cm diameter for the opening, and 18 cm high.

On Nov. 23, 2004 (year 3), annual ryegrass (*Lolium multiflorum* Lam.) was seeded 1-cm deep at a seeding rate of 30 seeds per pot. The annual ryegrass was thinned to 20 plants per pot 3 wk after seeding. The nine treatment combinations were completely randomized within a block with 3 blocks. All pots were placed in the greenhouse at the Nova Scotia Agricultural College, Truro, Nova Scotia. Soil moisture was maintained at approximately 25% and the temperature was controlled at 20°C.

2.2.2 Plant sampling and N laboratory analysis

Annual ryegrass was cut twice, the first cut on Feb. 22, 2005 at 5 cm above ground, the second cut on Apr. 16, 2005 at the soil surface. Just before the second cut, soil N supplies were exhausted as evidenced by chlorosis of ryegrass leaves. After being washed, the ryegrass roots were pooled with the two cuts of aboveground biomass. Following being ground through a 1-mm sieve, ryegrass N, P, and K contents were measured by the same method described in section 2.1.5.2.

2.2.3 Statistical analysis

The experimental units were individual pots. The annual ryegrass N, P, and K uptake data were subjected to a two-stage nested analysis by Proc mixed of SAS (SAS Institute, Inc. 2000). Forage and soil amendment were fixed factors, and block was a random factor.

Table 2.1 Total nutrient concentrations in soil amendments applied in different years

Nutrient	Yr 1 (2002)			Yr 3 (2004)				Yr 4 (2005)		
	M*	R†	S‡	M	R_E§	R_L**	S	M	R	S
	(g kg^{-1})									
C	207.0	344.0	458.0	79.7	275.0	217.0	456.6	78.5	258.5	442.5
N	16.3	26.3	21.4	6.8	20.9	16.6	29.9	7.1	25.0	22.9
P	14.7	9.6	2.0	5.2	7.1	6.1	2.6	5.3	8.3	2.2
K	13.6	32.1	17.7	3.2	16.4	11.8	23.5	2.8	15.6	21.4
Ca	103.0	19.6	6.5	25.8	15.7	15.2	13.7	25.3	15.4	13.1
Mg	5.7	5.9	1.8	2.9	6.7	5.7	2.0	2.9	7.6	1.7
Fe	3.52	5.07	0.15	10.6	6.18	8.35	0.02	12.0	5.72	0.16
Mn	0.95	0.56	0.04	0.77	0.43	0.51	0.02	0.77	0.4	0.04
Cu	0.03	0.03	0.01	-	-	-	0.02	-	0.02	0.01
Zn	0.33	0.39	0.07	0.15	0.12	0.15	0.02	0.17	0.14	0.08
B	0.02	0.02	0.01	0.01	0.03	0.02	0.16	0.01	0.04	0.02
Na	2.63	4.01	0.3	0.57	0.75	0.73	0.14	0.55	0.85	0.4
C:N ratio	12.7	13.1	21.4	11.7	13.2	13.1	15.3	11.1	10.3	19.3

* M composted poultry manure applied to all plots in monogastric systems.

† R composted beef manure applied to all plots in ruminant systems.

‡ S alfalfa pellets applied to all plots in stockless systems.

§ R_E composted beef manure applied to barley in early growing season in May 20, 2004 (yr 3).

** R_L composted beef manure applied to forage crops in late growing season in Jun. 30, 2004 (yr 3).

Table 2.2 Soil amendment dry matter weight and nutrient inputs in yr 1 (2002)

Trt.[*]	Dry weight	C_{tot}	N_{tot}	$N_{avail.}$[†]	P_{tot}	Avail. P_2O_5[‡]	Rock P Avail. P_2O_5[§]	Overall Avail. P_2O_5	K_{tot}	Avail. K_2O[**]
	(kg ha^{-1})									
0	24 398	8 447	529	170	202	93	24	117	532	574
1	24 398	8 447	529	170	202	93	24	117	532	574
2	12 199	4 223	264	85	101	46	60	106	266	287
M0	20 859	4 318	340	170	307	140	7	147	286	308
R0	25 856	8 894	680	170	247	113	0	113	837	903
S0	26 480	12 128	567	170	52	24	66	90	473	510
M1	20 859	4 318	340	170	307	140	7	147	286	308
R1	25 856	8 894	680	170	247	113	0	113	837	903
S1	26 480	12 128	567	170	52	24	66	90	473	510
M2	10 429	2 159	170	85	153	70	54	124	143	155
R2	12 928	4 447	340	85	123	57	40	97	418	452
S2	13 240	6 064	283	85	26	12	87	99	236	255

[*] For treatment levels, 0, 0-yr forage level; 1, 1-yr forage level; 2, 2-yr forage level; M, composted poultry manure; R, composted beef manure; S alfalfa meal; C_{tot}, total C; N_{tot}, total N; P_{tot}, total P; K_{tot}, total K.

[†] Expected available N based on assumptions for different soil amendments in the application year.

[‡] Expected available P_2O_5 based on assumptions for different soil amendments in the application year.

[§] Insufficient P_2O_5 supplied with soil amendments was supplemented by rock P (calcium phosphate).

[**] Expected available K_2O based on assumptions for different soil amendments in the application year.

Table 2.3 Soil amendment dry matter weights and nutrient inputs in yr 3 (2004)

Trt.*	Dry weight	C_{tot}	N_{tot}	$N_{avail.}$ †	P_{tot}	Avail. P_2O_5 ‡	Rock P Avail. P_2O_5 §	Overall Avail. P_2O_5	K_{tot}	Avail. K_2O **
	(kg ha^{-1})									
0	12 676	2 635	196	62	70	32	45	77	141	152
1	26 370	3 851	304	99	148	68	35	103	195	211
2	23 525	3 166	252	87	130	60	40	100	157	170
M0	18 323	1 460	125	62	95	44	12	56	59	64
R0	14 137	3 888	296	74	100	46	39	85	234	252
S0	5 566	2 558	166	50	14	7	83	90	131	141
M1	40 896	3 259	278	139	212	97	0	97	131	142
R1	38 213	8 292	633	158	232	106	0	106	455	491
S1	0	0	0	0	0	0	105	105	0	0
M2	42 357	3 376	288	144	219	100	0	100	136	147
R2	28 219	6 124	468	117	171	78	0	78	336	363
S2	0	0	0	0	0	0	120	120	0	0

* For treatment levels, 0, 0-yr forage level; 1, 1-yr forage level; 2, 2-yr forage level; M, composted poultry manure; R, composted beef manure; S alfalfa meal; C_{tot}, total C; N_{tot}, total N; P_{tot}, total P; K_{tot}, total K.

† Expected available N based on assumptions for different soil amendments in the application year.

‡ Expected available P_2O_5 based on assumptions for different soil amendments in the application year.

§ Insufficient P_2O_5 supplied with soil amendments was supplemented by rock P (calcium phosphate).

** Expected available K_2O based on assumptions for different soil amendments in the application year.

Table 2.4 Soil amendment dry matter weights and nutrient inputs in amended subplots in yr 4 (2005)

Trt.*	Dry weight	C_{tot}	N_{tot}	$N_{avail.}$†	P_{tot}	Avail. P_2O_5‡	Rock P Avail. P_2O_5§	Overall Avail. P_2O_5	K_{tot}	Avail. K_2O**
	(kg ha^{-1})									
0	14 238	2 743	206	69	77	35	111	146	136	147
1	13 173	2 469	189	63	73	33	113	146	123	133
2	12 248	2 606	190	62	65	30	116	146	131	141
M0	24 222	1 902	172	86	129	59	76	135	69	74
R0	10 080	2 606	252	63	84	39	107	146	159	172
S0	8 412	3 722	193	58	18	8	150	158	182	196
M1	22 641	1 777	161	80	121	55	80	135	64	69
R1	9 997	2 584	250	63	83	38	107	145	157	170
S1	6 881	3 045	158	47	15	7	152	159	149	160
M2	18 416	1 446	131	65	98	45	90	135	52	56
R2	9 437	2 439	236	59	79	36	110	146	149	161
S2	8 891	3 934	204	61	19	9	149	158	194	207

* For treatment levels, 0, 0-yr forage level; 1, 1-yr forage level; 2, 2-yr forage level; M, composted poultry manure; R, composted beef manure; S alfalfa meal; C_{tot}, total C; N_{tot}, total N; P_{tot}, total P; K_{tot}, total K.

† Expected available N based on assumptions for different soil amendments in the application year.

‡ Expected available P_2O_5 based on assumptions for different soil amendments in the application year.

§ Insufficient P_2O_5 supplied with soil amendments was supplemented by rock P (calcium phosphate).

** Expected available K_2O based on assumptions for different soil amendments in the application year.

Table 2.5 Crop cultivars and seeding rates

Crop	Cultivar	Seeding rate (kg ha^{-1})
Wheat spring (*Triticum aestivum* L.)	AC Helena	170
Wheat spring underseeded*	AC Helena	128
Barley (*Hordeum vulgare* L.)	Queens	164
Barley underseeded	Queens	131
Red clover (*Trifolium pratense* L.)	AC Endure	7
Timothy (*Phleum pretense* L.)	Richmond	6
Soybean (*Glycine max* L.)	OAC Vision	90
Potato (*Solanum* L.)	Superior	30 cm in-row space, 90 cm between rows

* Red clover and timothy were underseeded to spring wheat.

Table 2.6 Crop seeding and harvesting dates

Year	Crops	Seeding Dates	Harvesting dates
Yr 1 (2002)	Wheat and forages	May 25	Sep. 10
Yr 2 (2003)	Barley	May 22	Jul. 17
Yr 2 (2003)	Forages	May 22	Jul.3 and Aug.14
Yr 2 (2003)	Soybean	May 22	Nov. 1
Yr 3 (2004)	Barley	May 21	Sept. 6
Yr 3 (2004)	Forage		Jun. 29 and Sep. 24
Yr 4 (2005)	Potatoes	June 1	Sep. 8

Fig. 2.1 Field plots layout from yr 1 (2002) through yr 4 (2005)*†‡§

Block	Year	C0	C2	C1	S0	R1	M1	R0	M2	S2	M0	R2	S1
3	Yr 1 (2002)	W	W	W	W	W	W	W	W	W	W	W	W
	Yr 2 (2003)	S	F	B	S	B	B	S	F	F	S	F	B
	Yr 3 (2004)	B	F	F	B	F	F	B	F	F	B	F	F
	Yr 4 (2005)	P	P	P	P	P	P	P	P	P	P	P	P
		C2	C1	C0	M1	S2	M0	M2	S0	R2	R1	S1	R0
2	Yr 1 (2002)	W	W	W	W	W	W	W	W	W	W	W	W
	Yr 2 (2003)	F	B	S	B	F	S	F	S	F	B	B	S
	Yr 3 (2004)	F	F	B	F	F	B	F	B	F	F	F	B
	Yr 4 (2005)	P	P	P	P	P	P	P	P	P	P	P	P
		C2	C1	C0	M0	S1	R0	M2	M1	S0	S2	R2	R1
1	Yr 1 (2002)	W	W	W	W	W	W	W	W	W	W	W	W
	Yr 2 (2003)	F	B	S	S	B	S	F	B	S	F	F	B
	Yr 3 (2004)	F	F	B	B	F	B	F	F	B	F	F	F
	Yr 4 (2005)	P	P	P	P	P	P	P	P	P	P	P	P

* W, S, B, F, and P represent wheat, soybean, barley, forages (mixtures of red clover and timothy), and potatoes, respectively.

† For treatment levels, 0, 0-yr forage level; 1, 1-yr forage level; 2, 2-yr forage level; C, S, M, and R represent no soil amendment, alfalfa meal, composted poultry manure, and composted beef manure.

‡ In yr 4 (2005), potato plots were divided into two parts; each is 5 m long and 3 m wide. One part received soil amendment as per soil test recommendations, the other did not.

§ The forages in the 2-yr forage control rotations were not underseeded in yr 1 (2002), but were directly seeded in the spring of yr 2 (2003).

CHAPTER 3 SOIL NITROGEN, PHOSPHORUS, AND POTASSIUM AVAILABILITY AS AFFECTED BY ORGANIC POTATO ROTATIONS

3.1 Abstract

Integration of forage and livestock manure into farming systems has increasingly being practiced on organic farms to relieve nutrient management pressure. A potato rotation experiment was established on a sandy-loam soil (Orthic Humoferric Podzol) to assess forage and soil amendment effects on soil N, P, and K availability. Forage levels included 0-, 1-, and 2-year forages in three different 4-year crop rotations: wheat (w)/soybean (s)/barley (b)/potato (p), w/b/forage (f)/p, and w/f/f/p, respectively. The forage crops used in the experiment were a mixture of red clover and timothy. Soil amendments included composted poultry manure (M), composted beef manure (R), and alfalfa meal (S), pertaining to nutrient sources from monogastric, ruminant, and stockless farming systems, respectively. Three soil amendments were nested under each forage level. In the potato year (year 4), the original plots were split into two parts: amended and unamended subplots. No soil amendment was applied in the unamended subplots. The amended subplots received soil amendments as per soil test recommendations, and soil amendment application rates were adjusted to equalize soil extractable N levels based on assumed N availability.

Application of soil amendments to potatoes significantly increased soil N_{tot}, extractable P_2O_5 and K_2O, but did not significantly affect soil extractable N and soil N supply rates compared with the residual effects of soil amendments. Soil extractable N and soil N supply rates determined in the potato year were significantly higher in the 1- and 2- year forage rotations than in the 0-year forage rotations. This high soil mineral N in the 1- and 2-year forage rotations was a result of forage N benefits and N carryover from extra compost N application in the 1- and 2-year forage rotations, and was related to the high soil N potential mineralization rates at the end of year 3. Nitrogen availability was similar to assumed N availability in the alfalfa meal, but was far lower than assumed N availability in two composts. The alfalfa meal had a quicker N release compared with

two composted manures. Soil mineral N was significantly affected by both forages and soil amendments, with the highest soil N supply rates in alfalfa meal amended 1-year forage rotations and the highest soil extractable N in alfalfa meal amended 2-year forage rotations. Soil P_2O_5 and K_2O were not different among forage levels, but were significantly affected by soil amendment rates and types. Across the first cycle of 4-year rotations, forages and soil amendments increased soil N_{tot}, extractable P_2O_5 and K_2O, and soil extractable N was decreased in the first 2 years because of high background soil N, and tended to reach an equilibrium state in the last 2 years. In the cropping management under which soil amendment application rates were adjusted to equalize soil extractable N with assumed N availability, the combination of forages with composted beef manure is recommended in terms of soil N, P, and K management.

3.2 Introduction

In organic potato crop rotations, soil fertility management is crucial for potato production. Soil fertility showed a deceasing trend in intensively managed potato production systems due to a decrease in SOM (Saini and Grant 1980). To prevent soil fertility deterioration, integrated management such as combinations of forage-based potato rotations and application of soil amendments have been increasingly practiced to take advantage of rotation and nutrient benefits (Grandy et al. 2002; Carter et al. 2003).

Nutrient management in a crop rotation is influenced by crop components and soil nutrient inputs based on an understanding of soil nutrient cycling. Forages are commonly used in a crop rotation to supply N, increase SOM, and decrease soil erosion. A mixture of red clover and grass may biologically fix N_2 up to 150-200 kg N ha^{-1} yr^{-1} (Cuttle et al. 1992), with an average of 100 to 150 kg N ha^{-1} yr^{-1} (Brady and Weil 1999, P516). Thompson and Fillery (1998) suggested that maximally 30% N in young aboveground clover residues and less than 10% for the mature residues could be utilized by a succeeding cereal crop. The belowground N in perennial legume accounts for 7-26% of total legume fixed N (McNeill et al. 1997), and is an important N source for the following crop. However, crop rotations have high proportions of cash crops, particularly heavy feeders such as potatoes, may deplete soil fertility.

Soil amendment is valuable in on-farm nutrient recycling, and soil amendment additions also improved soil nutrient availability through a priming effect (Ma et al. 1999a). Compared with forages, soil amendments not only provide nutrients such as N, P, and K, but also have a larger SOM effect than forages in potato production (Grandy et al. 2002). Soil amendments originate from different sources: plant residues such as alfalfa or clovers, animal wastes such as beef or poultry manure, or animal byproducts such as dried blood or feathers. For a given farm, soil amendment sources are restrained, to some extent, by its own farming types (e.g. stockless, or livestock stock farms). Alfalfa meal, composted poultry or beef manure can be representatives of N sources for stockless, monogastric, or ruminant farming systems, respectively. Composted manure not only provides short-term available nutrient benefits, but also offers multi-seasonal plant nutrient benefits by increasing total nutrient pools (Sullivan et al. 2003). Long-term repeated manure applications increased soil total and available P (Dormaar and Chang 1995; Tran and N'dayegamiye 1995; Reddy et al. 1999), while high chicken and dairy manure application rates resulted in high soil extractable N, P, and K concentration (Warman 1986).

Nitrogen is the most important nutrient element for most crop production. In cultivated soil, less than 2% of soil N_{tot} exists as mineral N (Keeney and Nelson 1982). In organic systems, soil N_{tot} is relatively high, but N availability is much more critical than soil N_{tot}. Nitrogen availability mainly relies on mineralization of organic N; however, immobilization may occur concurrently with mineralization. Compost releases plant available N slowly, and 5-33% of total N in compost may be released in the application year depending on the nature of compost chemical composition (Brinton 1985; Cheneby et al. 1994; Eghball 2000; Amlinger et al. 2003). Compared with freshly added composts, N carryover from compost releases mineral N even more slowly, accounting for 2-8% of total compost N (Eghball and Power 1999a; Eghball 2000; Amlinger et al. 2003). Compared with composts, alfalfa meal had a higher N mineralization rate. In a well-controlled growth chamber, 10-40% of N_{tot} in alfalfa meal was plant available when applied to a severely impoverished soil (Hammermeister et al. 2005).

Long term organic cropping systems have demonstrated that forages and livestock manures enhance soil fertility (Wani et al. 1994b; Drinkwater et al. 1998; Mäder et al.

2002). However, there is little information about how forage levels and soil amendments affect soil N, P, and K for potato production managed with mimicked farming practices under isonitrogeneity regimes.

The objectives of this chapter were: (a) to determine forage effects on soil N, P, and K with and without soil amendment application in potatoes at the end of the first 4-year rotations, (b) to determine the effects of soil amendments and the residual effects of soil amendments on soil N, P, and K under the three forage levels in potatoes at the end of the first 4-year rotations, (d) to test assumptions of N availability of three soil amendments.

3.3 Materials and Methods

3.3.1 Experimental design

The experiment was a two-stage nested design, with a soil amendment factor (M, R, and S) nested under a forage factor (0, 1, or 2-year forages in three 4-year rotations). In year 4, the original plots were split into two parts, which were called amended and unamended subplots. The amended subplots received soil amendments as soil test recommended in year 4, and the unamended subplots did not receive any soil amendment in year 4. The newly amended and unamended subplots were two separate two-stage nested design experiments. The whole experimental design was detailed in experimental design section in Chapter 2. The weather station data at the experimental location indicated that temperatures and precipitation were normal in 2005 (Table 3.1).

3.3.2 Soil sampling and laboratory analyses

Soil samples were collected on May 8, 2002 (year 0), Oct. 15, 2002 (year 1), Sep. 22, 2003 (year 2), Sep. 28, 2004 (year 3), and Sep. 23, 2005 (year 4) to a depth of 15 cm. In year 4, soil samples were collected in both amended and unamended subplots. Soil measurements included soil bulk density, soil C_{tot} and N_{tot}, soil extractable N, P, and K, soil N supply rates, and N mineralization rates. Soil C_{tot} and N_{tot} were determined by dry combustion with a Leco® analyzer. Soil extractable N was extracted by 2 M KCl, and analyzed using a Technicon® AutoAnalyzer® III. Soil extractable P and K were extracted by Mehlich 3 solution, and analyzed by inductively coupled argon plasma (ICAP) spectrometry using a Jarrell-Ash ICAP 9000. Soil N supply rates were monitored by

Plant Root Simulator (PRS^{TM}) probes in the potato growing season during the period of Jul. 11 to Jul. 25, 2005 (year 4). Nitrogen mineralization rates were estimated by incubation and a leaching procedure in a controlled environment (Campbell et al. 1993). Soil N mineralization rates were estimated in amended subplots in year 4, and also for year 3 soils collected on Sep. 23, 2004. Soil amendment N mineralization rates were estimated in the similar way to the soil N mineralization rates at the incubation rate of 400 kg N_{tot} ha^{-1}. Soil sampling and nutrient analysis were detailed in soil sampling and laboratory analysis section in Chapter 2.

3.3.3 Statistical analyses

The data in amended and unamended subplots were analyzed separately. Both were subjected to a two-stage nested design using Proc Mixed of SAS (SAS Institute, Inc. 2000). A paired t comparison was conducted to determine if the measured variables were different between the amended and unamended subplots, or between year 0 and year 4. Orthogonal contrasts were constructed between forage treatments (the group of 1- and 2-year forage rotations) and non-forage treatments (the 0-year forage rotation) when P-values of forage effects were < 0.1; similarly, orthogonal contrasts were constructed between compost treatments (the group of composted poultry and beef manures) and alfalfa meal treatments when P-values of soil amendment effects were < 0.1. The data of the cumulative mineral N over a period of 20 wks were subjected to a nonlinear regression analysis with Proc nlin of SAS (SAS Institute, Inc. 2000). The net soil cumulative mineralized N ($N_{\min}$) over time t is described by an asymptotic model (Campbell et al. 1993) as the following:

$$N_{\min} = N_o(1 - e^{-kt})$$

where N_o is potentially mineralizable N, and k is the mineralization rate constant. After the asymptotic model establishment, the parameters, N_o and k, were compared with an incremental parameters model (Bates and Watts 1988) among soil amendments nested under forages, and among the three forage levels.

3.4 Results

3.4.1 Compost N availability

Soil amendments used in year 4 were substantially different in N availability estimated through an aerobic incubation (Table 3.2). During a period of 4 months, the mineralized N percentage of total N was much higher in S than in both M and R. In the first 2 months, cumulative mineral N rates were lower in M and R than in the soil control, suggesting temporary N immobilization in composts, particularly in R (Fig. 3.1). Nitrogen potential mineralization rates and the mineralization rate constant were significantly different among the three soil amendments (Table 3.2). Alfalfa meal had the highest N potential mineralization rates as well as the highest mineralization rate constant, while composted ruminant manure had the highest total N concentration, but the lowest mineralization rate constant. Nitrogen availability of soil amendments used in 2002 was shown in Appendix 2.

3.4.2 Soil N potential mineralization rates

Soil N potential mineralization rates were determined at the end of year 3 and year 4 in amended subplots under controlled aerobic environments. Forage levels had no significant effect on N_o (soil potentially mineralizable N) or k (the mineralization rate constant) in either year 3 or year 4 (Table 3.3). Soil amendments had no significant effect on k in either year 3 or year 4, but significantly affected N_o in both year 3 and year 4 (Table 3.4). In year 3, N_o showed an increasing trend with increased forage levels in the M and R treatments, and tended to be the highest in the R treatment among the three soil amendment treatments nested under forage levels. In year 4, however, N_o showed a decreasing trend with increased forage levels in the R and S treatments.

3.4.3 Soil total N

In amended subplots, soil N_{tot} was marginally significant among the three forage levels; orthogonal contrasts indicated that soil N_{tot} was significantly higher in forage rotations (the group of 1- and 2-year forage rotations) than in non-forage rotations (0-year forage rotations) (Table 3.5; Table 3.6). Soil amendments had a significant effect on soil N_{tot}, mainly in forage rotations (Table 3.5; Table 3.7). Soil N_{tot} tended to be the highest in the R treatments among the three soil amendments nested in forage rotations, and were not different among soil amendments nested in non-forage rotations. In unamended subplots, soil N_{tot} was significantly different among the three forage levels, and was significantly higher in forage rotations than in the non-forage rotation (Table 3.5; Table 3.6). The residual effects of soil amendments on soil N_{tot} were not significantly different (Table 3.5). The detailed soil nutrient content is given in Appendix 3.

3.4.4 Soil N supply rates

In the amended subplots, soil N supply rates were significantly different among the three forage levels, and were significantly higher in forage rotations than in non-forage rotations (Table 3.5; Table 3.6). Soil amendments had marginally significant effects on soil N supply rates; orthogonal contrasts indicated that soil N supply rates were significantly higher in the S treatments than in the compost (the group of M and R) treatments nested in the 1-year forage rotations (Table 3.5; Table 3.7). Soil N supply rates showed an increasing trend with increased forage levels in the M and R treatments, and tended to be the smallest in the M treatments and the largest in the S treatments.

In unamended subplots, soil N supply rates were marginally significantly different among the three forage levels, and were significantly higher in forage rotations than in non-forage rotations (Table 3.5; Table 3.6). The residual effects of soil amendments on soil N supply rates were not significantly different (Table 3.5).

3.4.5 Soil extractable N

In amended subplots, soil extractable N was significantly different among the three forage levels; orthogonal contrasts indicated that soil extractable N was significantly higher in forage rotations than in non-forage rotations (Table 3.5; Table 3.6). Soil amendments had a significant effect on soil extractable N; orthogonal contrasts indicated that soil extractable N was significantly higher in the alfalfa meal treatments than in the compost treatments nested under 0- or 2-year forage rotations (Table 3.5; Table 3.7).

In unamended subplots, soil extractable N was marginally significantly different among the three forage levels, and was significantly higher in forage rotations than in non-forage rotations (Table 3.5; Table 3.6). The residual effects of soil amendments on soil extractable N were not significantly different (Table 3.5).

3.4.6 Soil extractable P_2O_5

In amended subplots, forage levels had no significant effect on soil extractable P_2O_5 concentration, while significant soil amendment effects were observed (Table 3.5). Under each forage level, soil P_2O_5 concentration was the highest in the M treatments, followed by in the R treatments, and was the lowest in the S treatments (Table 3.7). Orthogonal contrasts indicated that soil P_2O_5 concentration was significantly higher in compost treatments than in alfalfa meal treatments nested under each forage level.

In unamended subplots, forage levels had no significant effect on soil P_2O_5 concentration, while the residual effects of amendments on soil P_2O_5 levels were significant (Table 3.5). Within each forage level, the residual effects of M and R on soil P_2O_5 concentration were not significantly different (Table 3.7). Orthogonal contrasts indicated that the residual effects of composts were significantly different from those of alfalfa meal in the 1-year or 2-year forage rotations where composts were applied to meet forage P requirements in year 3, and that the residual effects of composts were not significantly different from those of alfalfa meal in the 0-year forage rotations where rock P was supplemented for barley P requirements in year 3 (Table 3.5; Table 3.7).

3.4.7 Soil extractable K_2O

In amended subplots, forage levels had marginally significant effects on soil extractable K_2O concentration, and significant soil amendment effects were observed (Table 3.5). Within each forage level, soil K_2O concentration was the highest in the R treatments, followed by in the S treatments, and was the lowest in the M treatments (Table 3.7). Orthogonal contrasts indicated that there was no significant difference in soil K_2O content either between non-forage and forage rotations, or between compost and alfalfa meal treatments (Table 3.5).

In unamended subplots, forage levels had no significant effect on soil K_2O concentration (Table 3.5). The residual effects of soil amendments on soil K_2O concentration were significantly different: soil K_2O concentration was the highest in R treatments, followed by S treatments, and was the lowest in M treatments (Table 3.7). In unamended subplots, soil K_2O concentration showed a decreasing trend with increased forage levels in R treatments.

3.4.8 Nutrients in amended and unamended subplots

No difference was observed in soil extractable N and soil N supply rates between amended and unamended subplots. However, soil N_{tot}, extractable P_2O_5, and K_2O were significantly higher in amended subplots than in unamended subplots at the 5% level (Table 3.8).

3.4.9 Soil property trends in the first cycle of 4-year rotations

In amended subplots, the trends of soil properties such as soil bulk density (SBD), soil C_{tot}, soil N_{tot}, soil extractable N, P_2O_5, and K_2O were evident across the first 4 years. Yr 0 samples were collected in the spring of year 1 before any field operation, and the rest samples were collected in the fall of each year. Soil bulk density showed a decreasing trend with time in the first 4 years, with the largest decrease occurred in the R treatments nested under the 2-year forage rotations (Fig. 3.2). Soil C_{tot} trend across 4 years was not so clear as a result of the tremendous soil C pool, and most forage and soil amendment combinations had a slight increasing trend with time (Fig. 3.3). Soil N_{tot} showed an increasing trend for all treatments in the 4-year study (Fig. 3.4). Soil extractable N in all treatments showed a decreasing trend in the first 2 years, and reached an equilibrium level in the 2-year forage rotations in the last 2 years (Fig. 3.5). Soil extractable P_2O_5 was maintained at an equilibrium level in the first 2 years, and showed an increasing trend in the last 2 years, particularly in the M and R treatments (Fig. 3.6). Over the first 4 years, soil extractable K_2O was maintained at an equilibrium level in the M treatments, and showed an increasing trend in the R and S treatments (Fig. 3.7).

Since SBD showed a decreasing trend over 4 years, and was significantly lower in year 4 than in year 0 (Table 3.9), soil nutrients on a per hectare basis at the beginning (year 0) and end (year 4) of the experiment in a layer of top 15 cm were calculated according to SBD and nutrient content. Soil N_{tot}, soil extractable N, P_2O_5, and K_2O in the top 15 cm layer were significantly increased after the 4-year rotation, while soil C_{tot} in the top 15 cm was not different after the 4-year rotation (Table 3.9).

3.5 Discussion

3.5.1 Forage effects with and without soil amendments

The N role of forages in crop rotations has been documented (Wani et al. 1994b; Drinkwater et al. 1998). The current experiment showed N benefits from the preceding forage crops under amended and unamended subplots. However, in both amended and unamended subplots, unavoidable N additions related to P application with M and R in year 3 (Table 2.2; Table 2.3) might have confounded the forage N contributions in the 1- and 2-year forage rotations, and resulted in higher soil total and extractable N as well as soil N supply rates in the 1- and 2-year forage rotations compared with the 0-year forage rotation. There was no difference in soil mineral N between 1-year and 2-year forage rotations because of red clover winter kill in 2-year forage rotations. It is unexpected that soil N potential mineralization rates in year 3 or year 4 were similar among the three forage levels. This could be attributed to the high soil fertility background and consistent soil amendment additions as well as exclusion of forage residues in forage plots when collecting soils for the incubation experiment. Soil N potential mineralization rates were lower in year 4 than in year 3 because of the sampling time. In year 4, soils were taken after heavy feeder potato harvest, while in year 3 determinations were made on soils taken either in forage plots or light feeder barley plots.

As soil N, external nutrient inputs and plant harvest nutrient removals are the main factor affecting soil extractable P_2O_5 and K_2O. In the current experiment, external K input associated with soil amendments was different (Table 2.2; Table 2.3; Table 2.4), and plant harvest K removal may be also different among different forage levels, but such differences may be too small to differentiate among forage levels against soil tremendous K pool; therefore, soil extractable K_2O was not different among the three forage levels. For the similar reasons, soil extractable P_2O_5 was not different among the three forage levels.

3.5.2 Soil amendments and their residual effect

In amended subplots, it is unexpected that soil extractable N and soil N supply rates significantly differed among forage and soil amendment combinations under assumptions of isonitrogeneity. This may be attributed to the difference of soil amendment chemical composition, application rates, actual N availability, and forage N effects. Prior to the experiment, 50% of total N in M, 25% in R, and 30% in S were assumed to be plant available in the application year. However, the incubation experiment demonstrated that 2.4% of total N in M, 1.4% in R, and 26.5% in S were mineralized in a period of 4 months under ideal conditions. The determined N availability in the 2-year old composts (M and R) was far different from the assumed N availability, but was similar to a study where N mineralization rates ranged from 1% to 9% of total initial N in a composted poultry manure (Preusch et al. 2002). Compared with alfalfa meal, the two composts may have similar chemical composition, and thus had the similar mineralized N percentage. Although mineralized percentage of total N was lower in R than in M, total N application rates were higher in R than in M. As a consequence, there was no difference in soil extractable N or soil N supply rates between these two composts. Finally, N benefits from forage residues or N carryover from soil amendments were not considered when estimating soil amendment application rates. This may have partially resulted in a violation of soil isonitrogeneity.

Soil N supply rates were monitored at the potato flowering stage in the field for a period of 14 d, and might provide better insight on N availability compared with soil extractable N determined at the end of growing season. Soil N supply rates were affected by total N input and N mineralization rates. Compared with composts, alfalfa meal may contain more readily decomposable N, and thus had a substantially quicker N release. Such quick N release in S compensated for relatively low N application rates, and was the main reason for the highest soil N supply rates in S treatments among the three soil amendment treatments. For two composts, high N application rates in R compensated for low mineral N release, which might explain the higher soil N supply rates in R treatments than in M treatments. Forages in rotations also affected soil extractable N and soil N supply rates. Without forages in rotations such as in the 0-year forage rotation, soil extractable N and soil N supply rates were significantly different among the three soil amendments. However, with forages in part of rotations such as in the 1- and 2-year forage rotations, soil extractable N or soil N supply rates were not different possibly because of N benefits from the red clover and extra compost N benefits as well. For example, soil extractable N was not different among the three soil amendments in the 1-

year forage rotation, and soil N supply rates were not different among the three soil amendments in the 2-year forage rotation.

In the unamended subplots, soil extractable N and soil N supply rates provided a chance to look into N carryover from soil amendments. Nitrogen carryover from composts could supply 2 to 8% of total compost N after the application year (Eghball and Power 1999a; Eghball 2000; Amlinger et al. 2003). Soil potentially mineralized N rates at the end of year 3 might have provided some explanation to the year 4 soil available N in the unamended subplots. At the end of year 3, there was no significant difference in soil potentially mineralized N among the three soil amendments under each forage level, although there was higher potential N mineralization rate in forage rotations than in non-forage rotations. In other words, the N carryover from the three soil amendments may provide equivalent available N in the following year under the same forage situations. In the potato growing season, N mineralization may be quicker in forage rotations that in non-forage rotations as a result of forage residues being incorporated, leaving less mineral N at the end of potato growing season in forage rotations. As a consequence, soil extractable N and soil N supply rates were not different among forage and soil amendment combinations in the unamended subplots.

Soil amendments provided additional P and K when being applied to meet N requirements. On organic farms, applied manure that met crop N requirements tended to supply excessive P because of a low N:P ratio in manure (Withers and Sharpley 1995; Preusch et al. 2002) and high N:P in plant tissue. In the current experiment, soil amendment application rates were determined by N requirements; therefore, total P input associated with soil amendments was different among the three soil amendments. For example, P input was the highest in M treatments among M, R, and S under isonitrogeneity regimes. Compost P availability was as much as 73% of total compost P (Eghball et al. 2002), and was much higher than the assumed P availability (20%) in the current experiment. Phosphorus additions from two composts, therefore, may be excessive for crop demands. In the amended subplots, the excessive P input with two composts may be a main reason for the significantly higher soil P_2O_5 levels in the two compost treatments than in alfalfa meal treatments. Phosphorus sources also affected soil P_2O_5 levels. The relationship between total P input and soil P_2O_5 levels suggested that soil P_2O_5 levels were more affected by organic P input from soil amendments than mineral P input from rock P. In the unamended subplots, the difference in soil P_2O_5 levels among soil amendments was mainly in nested forage rotations, where P was supplied by two composts in M and R treatments while rock P in S treatments in year 3. On the other hand, there was no difference in soil P_2O_5 levels in non-forage rotations where P was supplied by M, R, or S, and was supplemented by rock P. Overall, soil P_2O_5 levels were related to P input and P carryover from soil amendments.

Since K content in the three soil amendments was not the same, and soil amendment application rates were also different under isonitrogeneity regimes; therefore, K input associated with three soil amendments was different. For example, K input was the highest in R treatments among M, R, and S under isonitrogeneity regimes. Such different inputs, along with different amounts of plant K uptake removals, resulted in a significant difference in soil K_2O among forage and soil amendment combinations in both amended and unamended subplots.

3.5.3 Soil N, P, and K between amended and unamended subplots

Soil amendments as a nutrient source have been widely applied in organic agriculture. Since SBD was not different between amended and unamended subplots, high nutrient content means high nutrient levels in the top soil layer. Soil N_{tot}, extractable P_2O_5 and K_2O content were higher in amended subplots than in unamended subplots suggesting nutrient benefits from soil amendments. However, unexpectedly, soil extractable N and cumulative N supply rates were not different between amended and unamended subplots. This may be related to the fact that all forage plots in M and R treatments received extra N in July in the previous year. This late applied unavoidable N as a result of compost P additions was carried over to the following year, and compensated for the lack of N application in unamended subplots. The compost N potential mineralization experiment indicated that M and R experienced a temporary N immobilization process, and such immobilized N in M and R applied in the previous year could be mineralized in the following year. Eriksen et al. (1999a) demonstrated that municipal solid waste compost N immobilized in the application year became plant available in the succeeding year in a corn study. Such N immobilization and mineralization process in the unamended subplots may partially reduce soil mineral N difference between amended and unamended subplots. From a forage perspective, red clover residues in both amended and unamended subplots supplied certain amounts of plant available N, and reduced the difference in mineral N between amended and unamended subplots. In a temperate zone, clovers could provide the succeeding cereal crops with an averaged 37 kg N ha^{-1} (Peoples et al. 1995; Chalk 1998).

3.5.4 Changing trends in soil N, P, and K

Manure application has been an effective way to maintain or increase soil N, P, and K levels (Schlegel 1992). This experiment also showed nutrient content demonstrated an increasing trend over time except soil extractable N. The decrease in soil extractable N was partially attributed to the sampling time and high N background at the beginning of the experiment. Soil extractable N was extremely high for year 0 samples which were collected in May, 2002, compared with other samples collected in the fall of each year. The increasing trend of soil N_{tot} is attributed to both soil amendment additions and forage residue input. Soil extractable P_2O_5 was largely influenced by soil amendment P input as evidenced by an apparent increase after each soil amendment addition. The substantial increase in soil P_2O_5 in two compost treatments confirmed previous studies that manure application usually resulted in excessive P accumulation (Schlegel 1992; Eghball and Power 1999a; Ferguson et al. 2005). Low K concentration in M, compared with R and S, resulted in a slight increase in soil extractable K_2O in M treatments across 4 years. Overall, nutrient management integrated forages and soil amendments enhanced soil fertility as evidenced by an increase in soil N_{tot}, extractable P_2O_5 and K_2O in the first 4-year rotations.

3.6 Conclusions

Soil total and extractable N as well as soil N supply rates were affected by soil amendments and forages collectively. Forages in rotations mainly improved soil N. Red clover N benefits were confounded with N carryover effects from extra compost N application in the 1- and 2-year forage rotations. No significant difference was observed between 1- and 2-year forage rotations partially because of red clover winter kill in the 2-

year forage rotations. In the application year, mineral N release was quicker from alfalfa meal compared with composted poultry and beef manures, while N carryover from M, R, and S were similar. Soil mineral N was affected by both forages and soil amendments. Soil P_2O_5 and K_2O levels were mainly related to P and K inputs. Phosphorous input from soil amendments had larger effects on soil P_2O_5 levels than from rock P. Composted poultry manure was the best to increase soil P_2O_5 levels, but might have difficulty in maintaining soil K_2O levels. Composted beef manure was the best to increase soil K_2O levels and to manage soil N and P_2O_5 levels. Integration of composted beef manure and forages was recommended for soil N, P, and K management.

Table 3.1 Temperature and precipitation at experimental site in the potato growing season and 30-year average from 1971-2000

	Rainfall (mm)		Temperature (°C)	
	2005	30-year average	2005	30-year average
May	2.7	3.0	8.6	9.8
June	1.9	2.8	14.8	14.7
July	2.7	2.9	18.0	18.4
August	1.2	2.8	18.3	17.8
September	3.7	3.4	15.2	13.4

Table 3.2 N availability of three soil amendments applied in yr 4 (2005) and estimated parameters for asymptotic model of N potential mineralization rates*

	C_{tot} ($g\ kg^{-1}$)	N_{tot} ($g\ kg^{-1}$)	N availability (% of N_{tot})	N_o † ($g\ kg^{-1}$)	k‡ (wk^{-1})
M§	79	7.1	2.4	0.154*b*	0.162*ab*
R**	259	25.0	1.4	0.198a*b*	0.083*b*
S††	443	22.9	26.5	0.210*a*	0.229*a*
Soil control	28	2.2	6.8	0.146	0.191

* Soil amendment incubation rates were 400 kg N_{tot} ha^{-1}; Estimates in the N_o column followed by the same letters were not significantly different at the 5% level, and estimates in the *k* column followed by the same letters were not significantly different at the 5% level.

† N_o represents soil N potential mineralization.

‡ *k* represents soil N potential mineralization rate constant.

§ M represents composted poultry manure.

** R represents composted beef manure.

†† S represents alfalfa meal.

Table 3.3 Estimated parameters for asymptotic model of soil N potential mineralization rates at the three forage levels in yr 3 and yr 4*

Forage	2004 (yr 3)		2005 (yr 4)	
	N_o † (g kg^{-1})	k ‡ (wk^{-1})	N_o (g kg^{-1})	k (wk^{-1})
0	0.215a	0.226a	0.206a	0.110a
1	0.286a	0.130a	0.194a	0.141a
2	0.297a	0.131a	0.182a	0.158a

* Soils used in the N potential mineralization incubation experiment were collected from each field plot in Sep. 28, 2004, and Sep. 25, 2005. N potential mineralization rates were only done in the amended subplots in 2005. Parameters estimates within a column with the same letter were not significantly different at the 5% level.

† N_o represents soil N potential mineralization.

‡ k represents soil N potential mineralization rate constant.

Table 3.4 Estimated parameters for asymptotic model of soil N potential mineralization rates for different forage and soil amendment combinations in yr 3 and yr 4*

Treatment combination	2004 (yr 3) N_o † (g kg^{-1})	2004 (yr 3) k ‡ (wk^{-1})	2005 (yr 4) N_o (g kg^{-1})	2005 (yr 4) k (wk^{-1})
M0	0.169*d*	0.203*a*	0.175*c*	0.123*a*
R0	0.218*bcd*	0.207*a*	0.228*a*	0.108*a*
S0	0.209*cd*	0.191*a*	0.224*ab*	0.125*a*
M1	0.241*abcd*	0.117*a*	0.180*bc*	0.118*a*
R1	0.287*ab*	0.129*a*	0.187*abc*	0.176*a*
S1	0.277*ab*	0.197*a*	0.222*ab*	0.125*a*
M2	0.262*abc*	0.174*a*	0.183*bc*	0.127*a*
R2	0.350*a*	0.103*a*	0.176*bc*	0.178*a*
S2	0.248*abc*	0.167*a*	0.194*abc*	0.165*a*

* Soils used in the incubation experiment for N potential mineralization rates were collected from each field plot in Sep. 28, 2004, and Sep. 25, 2005. N potential mineralization rates were only done in the amended subplots in 2005. Parameters estimates within a column with the same letter are not significantly different at the 5% level.

† N_o represents soil N potential mineralization.

‡ k represents soil N potential mineralization rate constant.

Table 3.5 The *p* values of forage and soil amendment effects on soil N_{tot}, extractable N, P_2O_5, K_2O, and soil N supply rates in yr 4 [*]

Source of variation	Amended subplots					Unamended subplots				
	N_{tot}	N	P_2O_5	K_2O	N supply rates	N_{tot}	N	P_2O_5	K_2O	N supply rates
Forage level	0.052	0.010	0.101	0.088	0.050	0.007	0.063	0.542	0.183	0.081
0 vs (1+2)	0.036	0.007	-	0.779	0.020	0.010	0.021	-	-	0.040
Soil amendment	0.002	0.010	0.002	0.001	0.079	0.730	0.665	0.041	0.001	0.841
S vs (M+R) in 0	0.053	0.003	0.010	0.759	0.078	-	-	0.364	0.777	-
S vs (M+R) in 1	0.150	0.374	0.002	0.450	0.045	-	-	0.013	0.095	-
S vs (M+R) in 2	0.097	0.010	0.011	0.815	0.203	-	-	0.025	0.208	-

[*] Orthogonal contrasts were constructed between non-forage (0-yr forage) and forage (1- and 2-yr forage) rotations if P-value for the forage effects is less than 0.1, and were constructed between alfalfa meal and compost (composted poultry and beef manure) if the P-value for the soil amendment effect is less than 0.1.

Table 3.6 Least squares means for soil N_{tot}, soil extractable N, and soil N supply rates at different forage levels in yr 4*

Forage	Amended subplots			Unamended subplots		
	N_{tot}	N	N supply rates	N_{tot}	N	N supply rates
	-----(g kg^{-1})-----		(μg 10 cm^{-2} 2 wks^{-1})	----(g kg^{-1})----		(μg 10 cm^{-2} 2 wk^{-1})
0	2.28*b*	0.026*b*	724.0*b*	2.12*b*	0.024*b*	668.5*b*
1	2.44*a*	0.030*ab*	836.2*ab*	2.37*a*	0.030*a*	837.8*a*
2	2.36*ab*	0.035*a*	883.2*a*	2.21*b*	0.030*a*	770.4*ab*

* Least squares means in a column followed by the same letter are not significantly different at the 5% level.

Table 3.7 Least squares means for soil N_{tot}, extractable N, P_2O_5, K_2O, and soil N supply rates for different soil amendments nested under forage levels in yr 4*

Treatment Combination	Amended subplots					Unamended subplots	
	N_{tot}	N	P_2O_5	K_2O	N supply rates	P_2O_5	K_2O†
	-------------- (g kg^{-1})---------------				(μg 10 cm^{-2} 2 wk^{-1})	-----(g kg^{-1})-----	
M0	2.20*c*	0.022*c*	0.289*ab*	0.215*c*	580.0*c*	0.142*abc*	0.168*ab*
R0	2.23*c*	0.021*c*	0.179*cd*	0.332*ab*	753.8*abc*	0.171*abc*	0.288*c*
S0	2.41*bc*	0.034*ab*	0.115*d*	0.262*bc*	838.3*ab*	0.132*bc*	0.220*bc*
M1	2.27*c*	0.028*bc*	0.317*a*	0.192*c*	738.5*bc*	0.203*a*	0.149*a*
R1	2.71*a*	0.035*ab*	0.270*abc*	0.411*a*	802.3*abc*	0.182*ab*	0.263*c*
S1	2.35*bc*	0.028*bc*	0.145*d*	0.274*bc*	967.8*a*	0.119*bc*	0.240*c*
M2	2.26*c*	0.028*bc*	0.255*abc*	0.191*c*	788.2*abc*	0.199*a*	0.165*a*
R2	2.56*ab*	0.034*ab*	0.195*bcd*	0.275*bc*	897.8*ab*	0.164*abc*	0.235*c*
S2	2.25*c*	0.042*a*	0.108*d*	0.241*c*	963.7*a*	0.116*c*	0.167ab

* Least squares means in a column followed by the same letter are not significantly different at the 5% level.

† K_2O concentration in unamended subplots were subjected to reciprocal transformation prior to analysis, and back transferred values were reported.

Table 3.8 Means of SBD, soil N_{tot}, extractable N, P_2O_5, K_2O, and soil N supply rates, and the corresponding P-values of paired comparison between amended and unamended subplots in yr 4

	SBD*	N_{tot}†	N	P_2O_5	K_2O	N supply rates
	(g cm^{-3})	---------------(g kg^{-1})---------------				(μg 10 cm^{-2} 2 wk^{-1})
Amended	0.975	2.36	0.030	0.208	0.266	814.5
Unamended	0.992	2.23	0.028	0.159	0.215	758.9
	-----------------------------(*P*-value)-----------------------------					
	0.202	0.009	0.218	0.004	0.001	0.107

* SBD represents soil bulk density.

† N_{tot} represents soil total N.

Table 3.9 Means of SBD, soil C_{tot}, N_{tot}, extractable N, P_2O_5, and K_2O, and the corresponding P-values of paired comparison between yr 0 and yr 4 in amended subplots*

	SBD†	C_{tot}‡	N_{tot}§	N	P_2O_5	K_2O
	(g cm^{-3})	------------------------- (kg ha^{-1}) -------------------------				
Yr 0	1.07	48169	3123	99.3	108.5	266.5
Yr 4	0.97	46082	3440	43.8	306.3	386.4
	----------------------------- (*P*-values)-----------------------------					
	0.000	0.139	0.000	0.000	0.000	0.000

* Yr 0 samples were collected in the spring of yr 1 just before field operations; yr 4 samples were collected in the fall after potato harvest.

† SBD represents soil bulk density.

‡ C_{tot} represents soil total C.

§ N_{tot} represents soil total N.

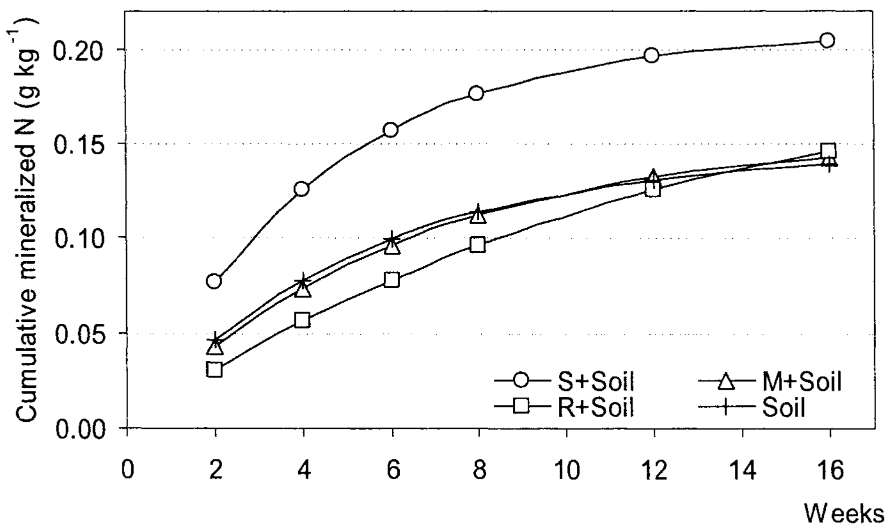

Fig. 3.1 Cumulative mineralized N over 16 weeks incubation of three soil amendments (M, R, and S) applied in 2005 (yr 4) under controlled conditions.

Notes: An incubated soil amendment rate was 400 kg N_{tot} ha^{-1}. Soil was a control soil used to mix with soil amendments in the incubation experiment.

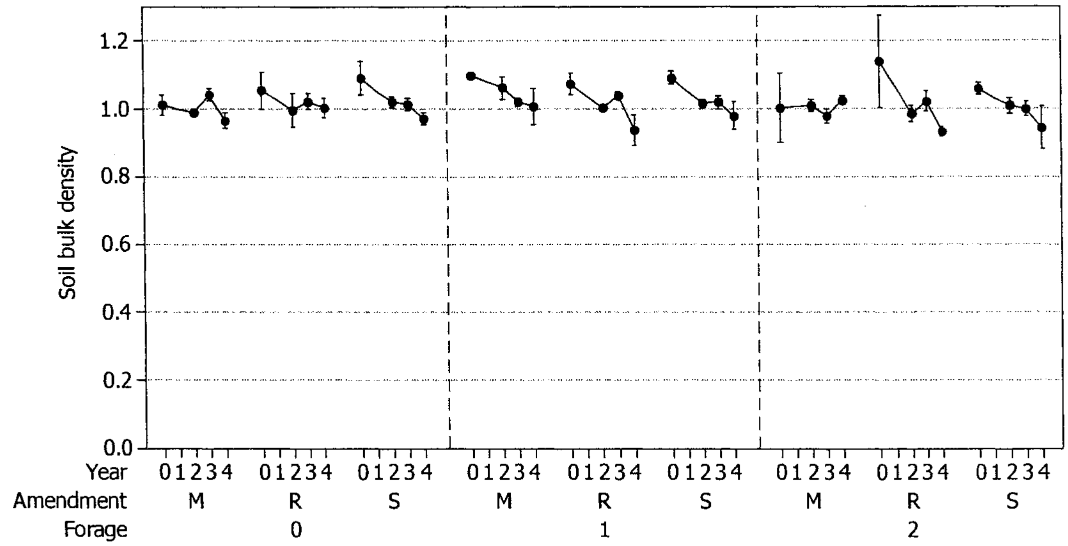

Fig. 3.2 Changes of soil bulk density (g cm^{-3}) over the first cycle of 4-yr crop rotations integrating three soil amendments (M, R, and S) and three forage levels (0, 1, and 2).

Notes: Yr 0 samples were collected in the spring of yr 1 before any field operation, and the rest were collected in the fall of each year. Vertical bars represent standard error of the mean (n=9).

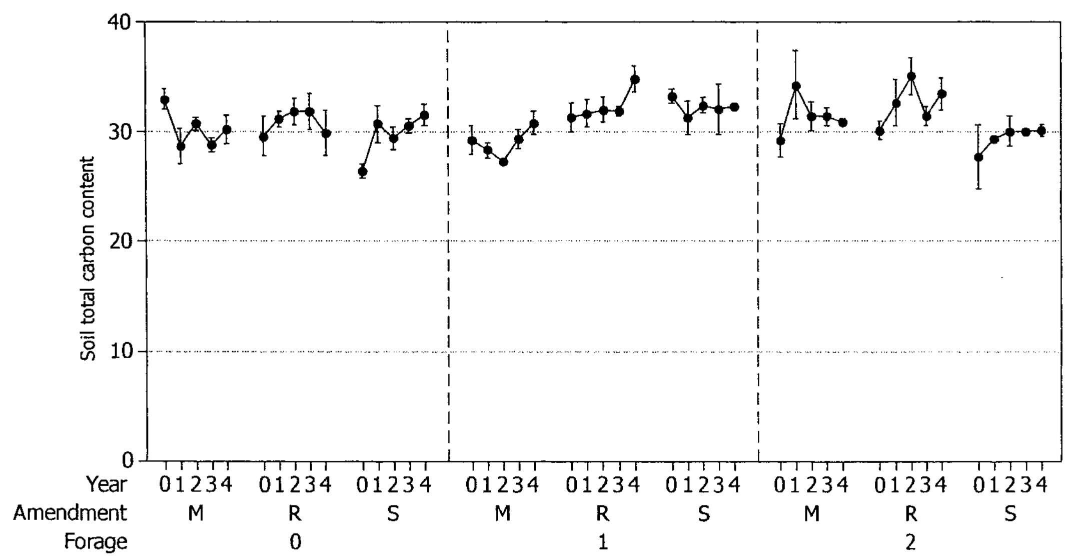

Fig. 3.3 Changes of soil total carbon (g kg^{-1}) over the first cycle of 4-yr crop rotations integrating three soil amendments (M, R, and S) and three forage levels (0, 1, and 2).

Notes: Yr 0 samples were collected in the spring of yr 1 before any field operation, and the rest were collected in the fall of each year. Vertical bars represent standard error of the mean (n=9).

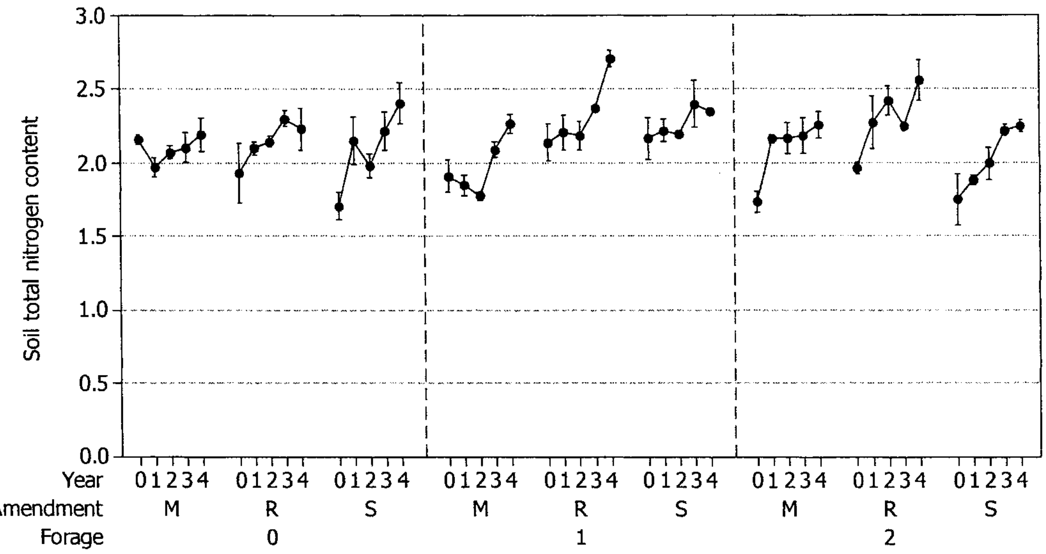

Fig. 3.4 Changes of soil total nitrogen (g kg^{-1}) over the first cycle of 4-yr crop rotations integrating three soil amendments (M, R, and S) and three forage levels (0, 1, and 2).

Notes: Yr 0 samples were collected in the spring of yr 1 before any field operation, and the rest were collected in the fall of each year. Vertical bars represent standard error of the mean (n=9).

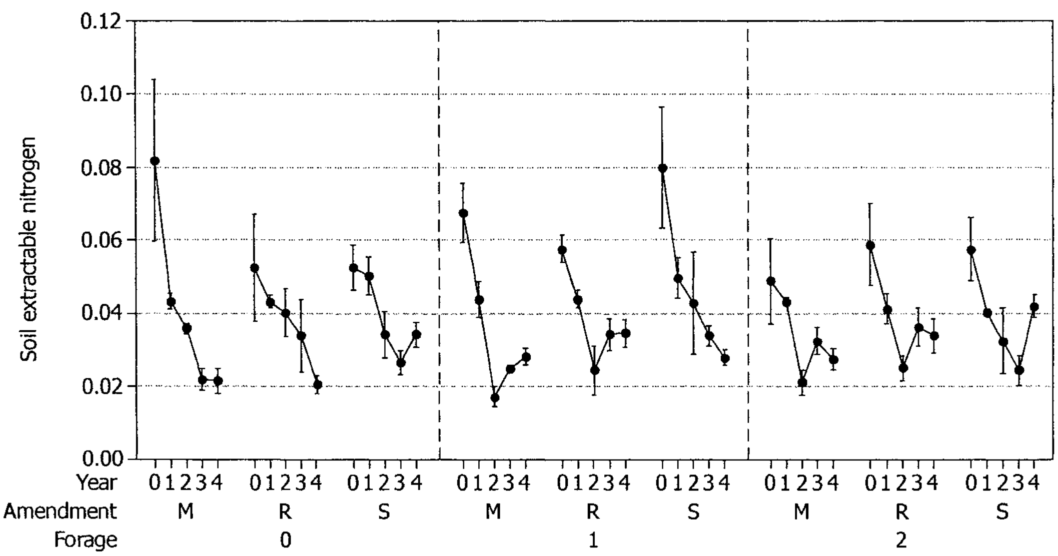

Fig. 3.5 Changes of soil extractable nitrogen (g kg^{-1}) over the first cycle of 4-yr crop rotations integrating three soil amendments (M, R, and S) and three forage levels (0, 1, and 2).

Notes: Yr 0 samples were collected in the spring of yr 1 before any field operation, and the rest were collected in the fall of each year. Vertical bars represent standard error of the mean (n=9).

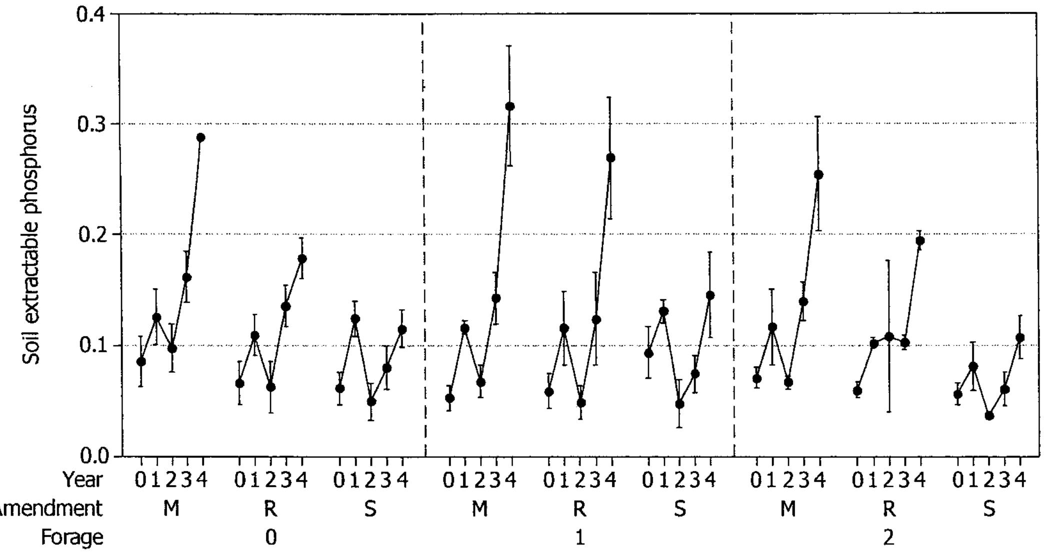

Fig. 3.6 Changes of soil extractable P_2O_5 (g kg^{-1}) over the first cycle of 4-yr crop rotations integrating three soil amendments (M, R, and S) and three forage levels (0, 1, and 2).

Notes: Yr 0 samples were collected in the spring of yr 1 before any field operation, and the rest were collected in the fall of each year. Vertical bars represent standard error of the mean (n=9).

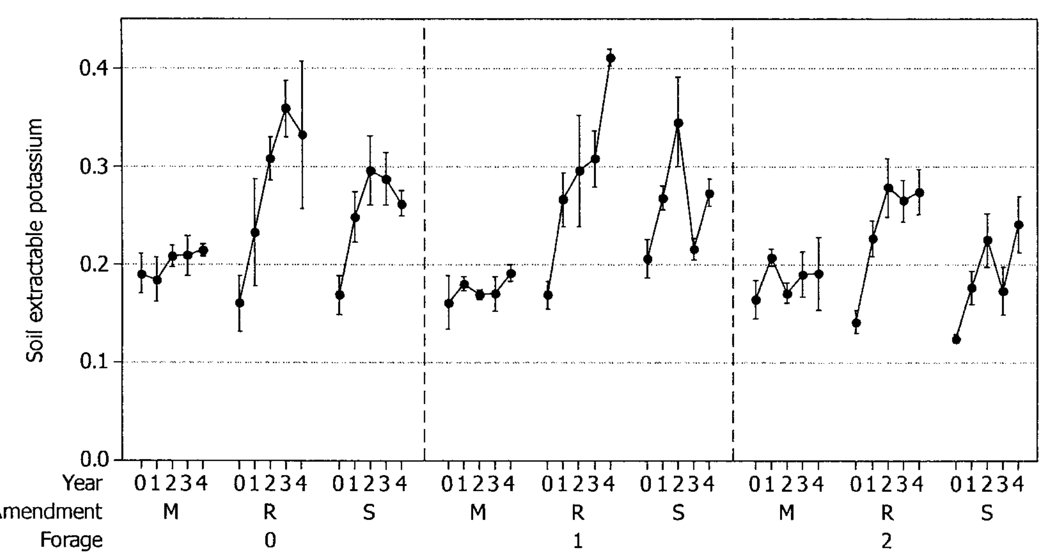

Fig. 3.7 Changes of soil extractable K_2O (g kg^{-1}) over the first cycle of 4-yr crop rotations integrating three soil amendments (M, R, and S) and three forage levels (0, 1, and 2).

Notes: Yr 0 samples were collected in the spring of yr 1 before any field operation, and the rest were collected in the fall of each year. Vertical bars represent standard error of the mean (n=9).

CHAPTER 4 SOIL MICROBIAL BIOMASS CARBON AND DEHYDROGENASE ACTIVITY AS AFFECTED BY ORGANIC POTATO ROTATIONS

4.1 Abstract

Soil microbial biomass and activity quickly respond to soil management practices, and are important indicators in the decomposition, transformation, and turnover of SOM during nutrient cycling. An organic potato rotation experiment, after a long-term pasture was ploughed, was established to assess the effects of three forage levels and three types of soil amendments on SMBC and dehydrogenase enzyme activity (DHA) in the fall. Forage (a mixture of red clover and timothy) levels included 0-, 1-, and 2-year forage crops in three different 4-year crop rotations: wheat (w)/soybean (s)/barley (b)/potato (p), w/b/forage (f)/p, and w/f/f/p, respectively. Soil amendments included composted poultry manure (M), composted beef manure (R), and alfalfa meal (S), pertaining to the main nutrient resources in monogastric, ruminant, and stockless farming systems, respectively. In the potato year (year 4), the original plots were split into two parts: amended and unamended subplots. No soil amendment was applied in the unamended subplots. The amended subplots received soil amendments as per soil test recommendations, and soil amendment application rates were adjusted to equalize soil extractable N levels based on assumed N availability. Application of soil amendments to potatoes did not increase SMBC and DHA significantly compared with the residual effects of soil amendments. In unamended subplots, residual effects of soil amendments on SMBC or DHA were not significantly different. In amended subplots, soil amendments had no significant effect on DHA determined after potato harvest. Alfalfa meal treatments had significantly higher SMBC than compost treatments in the 0-year and 2-year forage rotations possibly because of high readily decomposable C and N as well as high alfalfa meal application rates. In both amended and unamended subplots, SMBC and DHA were increased with increased forage levels, but were not significantly different partially because readily available C in forage residues may be exhausted at the end of potato growing season. The results indicated that alfalfa meal had a larger positive effect on SMBC and DHA than

either of the two composts, and that forage crops had a positive effect on SMBC and DHA.

4.2 Introduction

Nutrient management is essential for crop productivity and long-term sustainability in agriculture systems. In organic farming systems, nutrient availability from the organic nutrient inputs is mainly mediated by soil microbes, so soil biotic properties related to nutrient cycling are of importance in organic farming systems. Soil organic matter exerts a substantial influence on soil biological properties and soil fertility; however, it is hard to monitor a minor SOM change caused by short-term soil management in agricultural systems (Sparling 1992). Carbon input in the form of soil amendments or plant residues is small relative to the C_{tot} in the soil. Alternatively, soil microbial biomass has been found to have a quick response to crop management such as soil amendment inputs and plant residue returns (Lupwayi et al. 2004). The ratio of SMBC to C_{tot} can reflect the dynamics of SOM incorporated into soil, and is a sensitive measurement for SOM changes (Sparling 1992).

Soil microbial biomass is a critical fraction of SOM, and serves as both labile sink and source in nutrient cycling (Gregorich et al. 1994). However, soil microbial biomass itself may not provide adequate information on microbial activity (Jenkinson 1988). Dehydrogenase activity is commonly used as an indicator for metabolic activity of soil microbes, and plays a central role in biological oxidation of organic matter and nutrient cycling (Tabatabai 1982). Dehydrogenase activity was affected by a number of factors such as soil texture (Cooper and Warman 1997), soil amendment types (Martens et al. 1992), pH, moisture, and soil mineral N levels (Moore and Russell 1972).

Intensive potato cropping systems often result in a decrease in SOM because of tillage and low residue returns (Angers et al. 1999; Carter and Sanderson 2001; Grandy et al. 2002), and thus deplete soil fertility. Inclusion of a forage crop in a potato crop rotation not only provides a chance to build up SOM through the developed root systems and the aboveground residues, but also provides fair amounts of N for a succeeding crop (Izaurralde et al. 1995). Soil amendments such as composted manure increased SOM level in an integrated livestock and forage-based crop rotation (Drinkwater et al. 1998). Legume residues in a crop rotation could increase SMBC size and microbial activity (Breland and Eltun 1999; Lupwayi et al. 2004).

The objectives of this chapter were: to determine the forage frequency effects on SMBC and DHA with and without soil amendments in potatoes at the end of the first 4-year rotations, and to determine the effects of soil amendments and the residual effects of soil amendments on SMBC and DHA under three forage frequencies at the end of the first 4-year rotations.

4.3 Materials and Methods

4.3.1 Experimental design

The experiment was a two-stage nested design, with a soil amendment factor (M, R, and S) nested under a forage factor (0, 1, or 2-year forages in three 4-year rotations). In year 4, the original plots were split into two parts: amended and unamended subplots. The amended subplots received soil amendments as soil test recommended in year 4, and the unamended subplots did not received any soil amendment in year 4. The newly amended and unamended subplots were two separate two-stage nested design experiments. The whole experimental design was detailed in experimental design section in Chapter 2.

4.3.2 Soil sampling and laboratory analyses

Soil samples were taken on Sep. 23, 2005 (year 4) to a depth of 15 cm from both amended and unamended subplots. Soil measurements included soil C_{tot}, SMBC, soil soluble C, and DHA. Soil C_{tot} was determined by dry combustion using LECO. SMBC was determined with the chloroform fumigation-extraction method (Voroney et al. 1993). Soil soluble C was estimated in the nonfumigated soil after extracted by 0.5 M K_2SO_4 (DeLuca and Keeney 1994). Soil dehydrogenase activity was determined with the INT method (von Mersi and Schinner 1991). Soil sampling and nutrient analysis were detailed in soil sampling and laboratory analysis section in Chapter 2.

4.3.3 Statistical analyses

The data in amended and unamended subplots were analyzed separately. Both were subjected to a two-stage nested design using Proc Mixed of SAS (SAS Institute, Inc. 2000). A paired *t* comparison was conducted to determine if the measured variables were different between the amended and unamended subplots. Orthogonal contrasts were constructed between forage treatments (the group of 1- and 2-year forage rotations) and non-forage treatments (the 0-year forage rotation) when *P*-values of forage effects were smaller than 0.1; similarly, orthogonal contrasts were constructed between compost treatments (the group of composted poultry and beef manures) and alfalfa meal treatments when *P*-values of soil amendment effects were smaller than 0.1.

4.4 Results

Soil soluble C, SMBC, SMBC/C_{tot}, and DHA were not different between amended and unamended subplots, but soil C_{tot} was significantly higher in amended subplots than in unamended subplots (Table 4.1). In amended subplots, forage frequency had no significant effect on soluble C ($p = 0.773$), SMBC ($p = 0.168$), SMBC/C_{tot} ($p = 0.160$), or DHA ($p = 0.477$), but soil C_{tot} was significantly higher in 1-year forage rotations than in 0-year rotations (Fig. 4.1). Soil amendments had no significant effect on soil soluble C ($p = 0.542$), or DHA ($p = 0.201$), but had significant effects on soil C_{tot} ($p = 0.04$), SMBC/C_{tot} ($p = 0.014$), and SMBC ($p = 0.029$). Soil C_{tot} was significantly higher in R treatments than in M treatments nested under the 1-year forage rotation, and was significantly higher in R treatments than in S treatments nested under the 2-year forage rotation (Fig. 4.2). There was no significant difference in SMBC between M and R treatments, but SMBC was significantly higher in S treatments than in M or R treatments in the 0- and 2-year forages rotations (Fig. 4.3). The SMBC/C_{tot} had a similar response to soil amendment and forage levels as SMBC did (Fig. 4.4).

In unamended subplots, forage frequency had no significant effect on soluble C ($p = 0.844$), SMBC ($p = 0.797$), SMBC/C_{tot} ($p = 0.669$), or DHA ($p = 0.606$), but soil C_{tot} was significantly higher in the 1-year forage rotation than in the 0-year forage rotation (Fig. 4.1). The residual effects of soil amendments on soil C_{tot}, soluble C ($p = 0.768$), SMBC ($p = 0.805$), SMBC/C_{tot} ($p = 0.590$), or DHA ($p = 0.597$) were not significantly different. Some variables such as soil soluble C, SMBC, and DHA were not significantly different in unamended subplots among treatments, and were shown in Appendix 6, Appendix 7, and Appendix 8.

4.5 Discussion

4.5.1 SMBC and DHA between amended and unamended subplots

Background soil C_{tot} (Cooper and Warman 1997), crop species (Buyer and Drinkwater 1997), and different types of organic amendments influence soil microbial biomass and microbial activity. Soils with high levels of organic C, especially water-soluble C pools (Reinertsen et al. 1984), tend to have large pools of microbial biomass. Forage crops in this rotation may compensate for the lack of soil amendments in unamended subplots by increasing soil water-soluble C, SMBC, and DHA. The soil amendments applied in the 4th year may not make a distinguishable difference in SMBC and DHA, since SMBC was believed to reflect the cumulative C input rather than the current-year C input into soil (Rochette and Gregorich 1998). Martens et al. (1992) concluded that the first soil amendment application stimulated a substantial increase in soil enzyme activities compared with an unamended control, but the subsequent soil amendment application failed to maintain high soil enzyme activities. Therefore, the benefits from forage residues and soil amendment residuals in unamended subplots in the first 3 years may explain the lack of difference in SMBC and DHA between amended and unamended subplots in the 4th year.

4.5.2 Forage effects

Crop rotations influence the amounts and types of plant residues, which determine the quality and amounts of C tilled into soil, and thus affect soil biological properties (Abdel et al. 1998). Soil microbial biomass was higher in a forage crop such as red clover treatments than in grain such as corn treatments during an organic transition (Doran et al. 1987). Dehydrogenase activity was also increased with increased forage levels in a crop rotation (Bolton et al. 1985). However, SMBC and DHA did not show differences among different forage levels in this experiment, which was established soon after a long-term pasture was tilled. Moreover, high rates of soil amendments were intermittently applied based on soil test recommendations. All of these might result in the fact that higher forage levels made a numerically but not statistically higher SMBC and DHA at the end of the first 4-year cycle of crop rotations. In this experiment, high soil amendment application rates (Table 2.3; Table 2.4) and plant residue input associated with forage crops resulted in significantly higher SOM in 1-year forage rotations than in 0-year forage rotations, where a high SOM decomposition rate may be induced by annual tillage.

4.5.3 Soil amendments and their residual effects

Soil microbial biomass and activity were increased in cropping systems involving additions of organic soil amendments (Wander et al. 1994; Drinkwater et al. 1995; Rochette and Gregorich 1998). In the current experiment, soil amendment dry weight and C input were higher in R treatments (Table 2.3; Table 2.4) than in M treatments under assumptions of isonitrogeneity. Compared with compost, alfalfa meal is more easily to be broken down and utilized by microorganisms. Therefore, such different application rates and decomposition rates make it possible that soil C_{tot} was significantly higher in R treatments than in M and S treatments. The difference in chemical composition of soil amendments may exert a substantial effect on SMBC and DHA. Compost has a high percentage of stable materials, while alfalfa meal contains a relatively high percentage of microbial utilizable C. This may explain the significantly higher SMBC in S treatments than in M and R treatments in the 0- and 2-year forage rotations. In the 1-year forage rotation, however, SMBC and DHA did not vary significantly among the three soil amendment treatments. Several factors may have contributed to the lack of response. Firstly, in year 3, the proportion of red clover biomass to total forage biomass was higher in the 1-year forage rotation (75%) than in the 2-year forage rotations (42%). Secondly, the alfalfa meal input was relatively low in S treatments in year 4. Comparison of S effects across the three forage levels indicated that the lowest alfalfa meal input in year 4 (Table 2.4) resulted in the lowest SMBC in the 1-year forage rotations; the significantly higher SMBC in the 2-year forage rotation may be partially due to a high rate of forage mulch, which was applied as part of the S treatments.

Water-soluble C was found to be readily available for microbial use, and well-correlated with SMBC size (McGill et al. 1986; Rochette and Gregorich 1998). However, SMBC had a weak negative linear relationship ($r^2 = 0.32$) with K_2SO_4-soluble C in the current experiment. This agreed with the report that SMBC levels were decreased with increased K_2SO_4-soluble C pool in a cultivated soil (DeLuca and Keeney 1994). Moreover, K_2SO_4-soluble C was not equivalent to water-soluble C, and K_2SO_4-soluble C pool size could be doubled water-soluble C pool size (Rochette and Gregorich 1998).

A large labile nutrient pool (e.g. SMBC) and high microbial activity (e.g. DHA) together may indicate high nutrient availability. The ratio of SMBC to soil C_{tot} reflects the quality and dynamic of SOM (Sparling 1992). A higher proportion of soil C_{tot} as SMBC may represent a larger labile nutrient sink and source. Typically, soil microbial biomass is around 1% to 3% of total organic C (Jenkinson and Ladd 1981), and soil microbial biomass turnover rate averaged 0.2 to 3.9 yr^{-1} (McGill et al. 1986). DHA was considered an indicator for assessing the microbial mineralization process of the C and N cycles (Monreal and Bergstrom 2000). Therefore, the increased activity may contribute to an increase in N mineralization rates. In this experiment, a significantly higher ratio of SMBC to soil C_{tot} in the S treatments did result in significantly higher soil extractable N as indicated in Chapter 3, although DHA was not different among soil amendments. A forage corn rotation conducted in Ontario had shown that most improvement in soil structure stability obtained from three consecutive years of forages is lost after one subsequent corn season (Acton and Gregorich 1995, P56). Similarly, after one potato growing season, readily decomposable C and N from the preceding forage residues and soil amendments might be depleted. Therefore, there is no significant difference in living microbial activity indicated by DHA. A significantly lower ratio of SMBC to soil C_{tot} in R treatments may be a good explanation for the slow N mineralization of R soil amendment in the incubation trial.

4.6 Conclusions

Different cumulative C input associated with soil amendments and crop residues resulted in significant difference in year 4 soil C_{tot} among treatments. Soil microbial biomass carbon size was not only affected by compost types and application rates, but also was affected by forage levels. Soil microbial biomass carbon was higher in alfalfa meal treatments compared with two compost treatments in 0- and 2-year forage rotations. Dehydrogenase activity determined after potato harvest was not different among treatments. Residual effects of amendments on SMBC, SMBC/C_{tot}, or DHA were not significantly different, possibly because the readily decomposable C and N fractions were similar among soil amendment residuals in unamended subplots after a potato growing season. High soil C background and C input in this experiment may have masked forage effects on SMBC and DHA, and lack of responses of SMBC and DHA to forage levels is partially attributed to the soil depletion effects of potato cultivation.

Table 4.1 Means of soil total and soluble C, SMBC, and DHA, and the corresponding *P*-values of paired comparison between amended and unamended subplots

	C_{tot} ($g\ kg^{-1}$)	Soluble C ($mg\ kg^{-1}$)	SMBC ($mg\ kg^{-1}$)	SMBC/C_{tot}	DHA ($nmol\ INTF\ g^{-1}\ h^{-1}$)
Amended	31.6	172.8	960.9	0.030	134.6
Unamended	30.4	173.9	880.9	0.029	132.6
	--------------------	--------------------	(*P*-value)	--------------------	
	0.019	0.918	0.180	0.456	0.841

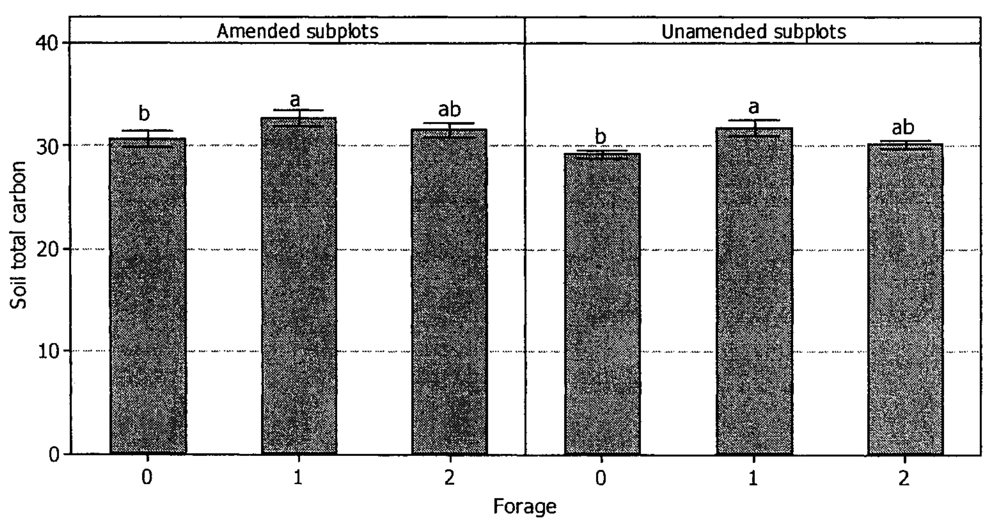

Fig. 4.1 Soil total carbon ($g\ kg^{-1}$) as affected by three forage levels (0, 1, and 2) in amended and unamended subplots in yr 4.

Notes: Within each subplot, means marked with the same letter are not significantly different at the 5% level. Vertical error bars represent standard error of the means.

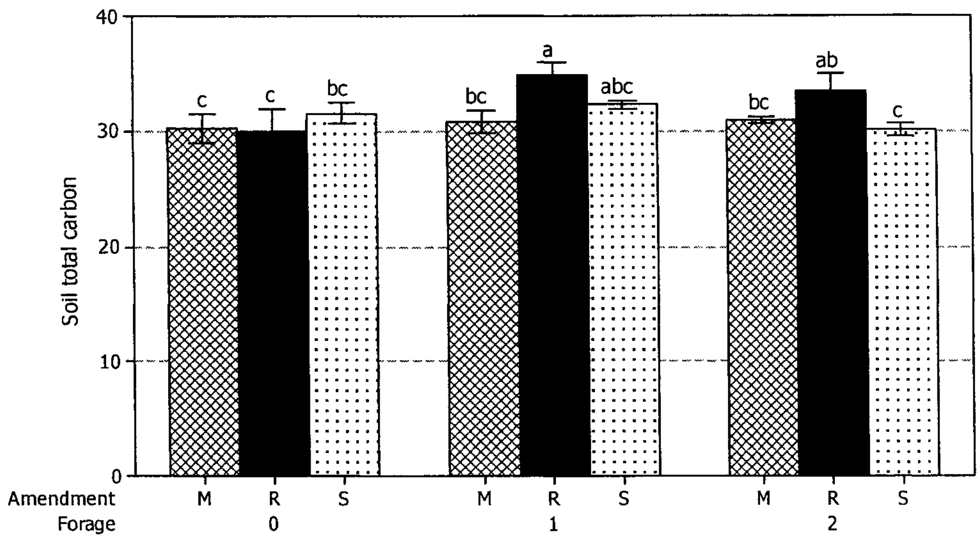

Fig. 4.2 Soil total carbon (g kg^{-1}) as affected by three soil amendments (M, R, and S) nested under three forage levels (0, 1, and 2) in amended subplots in yr 4.

Notes: Means marked with the same letter are not significantly different at the 5% level. Vertical error bars represent standard error of the means.

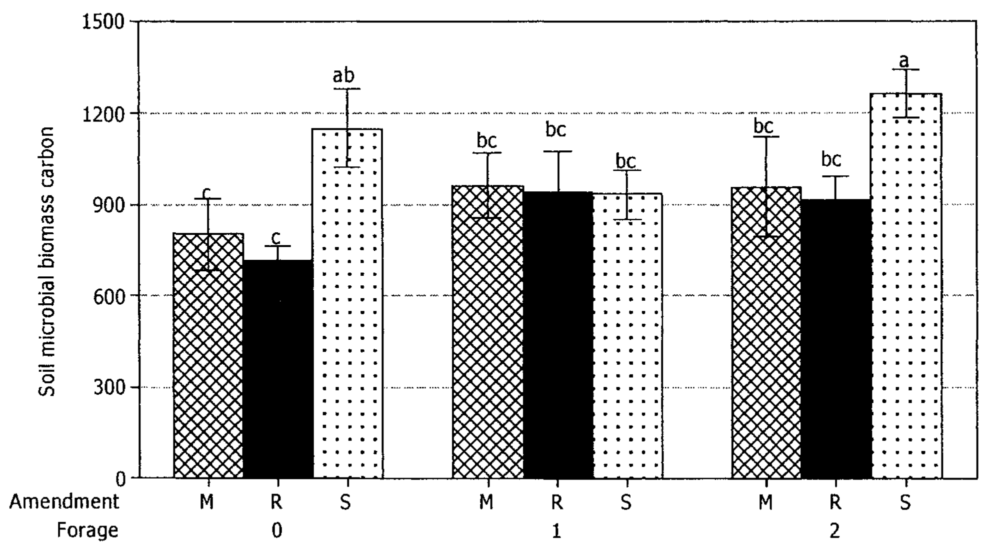

Fig. 4.3 Soil microbial biomass carbon (mg kg^{-1}) as affected by three soil amendments (M, R, and S) nested under three forage levels (0, 1, and 2) in amended subplots in yr 4.

Notes: Means marked with the same letter are not significantly different at the 5% level. Vertical error bars represent standard error of the means.

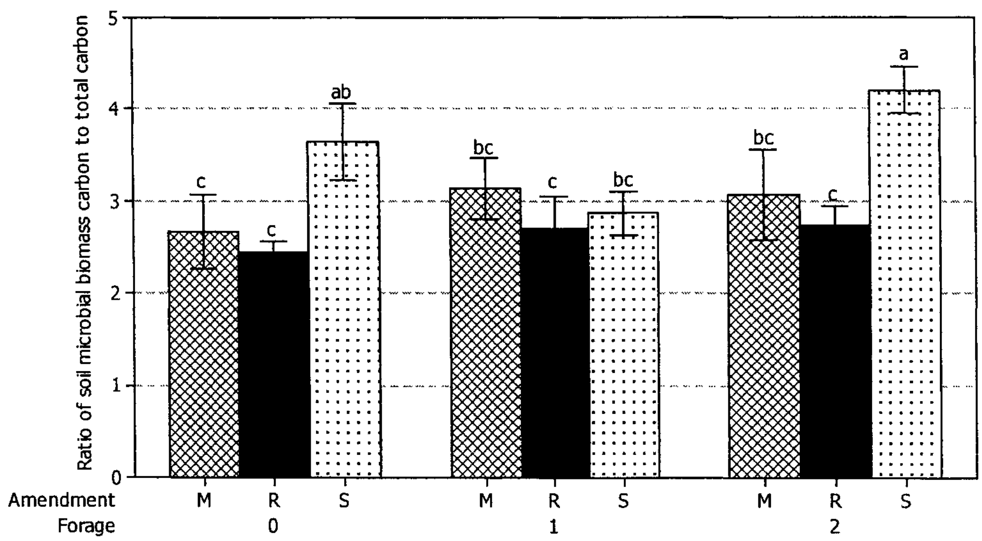

Fig. 4.4 The ratio of soil microbial biomass carbon to total soil carbon (%) as affected by three soil amendments (M, R, and S) nested under three forage levels (0, 1, and 2) in amended subplots in yr 4.

Notes: Means marked with the same letter are not significantly different at the 5% level. Vertical error bars represent standard error of the means.

CHAPTER 5 PLANT NITROGEN, PHOSPHORUS, AND POTASSIUM UPTAKE AND POTATO TUBER YIELD AS AFFECTED BY ORGANIC POTATO ROTATIONS

5.1 Abstract

Nutrient management is a challenge for organic potato production. A potato rotation experiment was established to assess the effects of forage frequency and soil amendment under assumptions of isonitrogeneity on potato tuber yield and plant nutrient uptake. Forage (a mixture of red clover and timothy) frequency included 0-, 1-, and 2-year forages in three different 4-year crop rotations: wheat (w)/soybean (s)/barley (b)/potato (p), w/b/forage (f)/p, and w/f/f/p, respectively. Soil amendments included composted poultry manure (M), composted beef manure (R), and alfalfa meal (S), pertaining to the main nutrient sources in monogastric, ruminant, and stockless farming systems, respectively. In the potato year (year 4), the original plots were split into two parts: amended and unamended subplots. No soil amendment was applied in the unamended subplots. The amended subplots received soil amendments as per soil test recommendations, and soil amendment application rates were adjusted to equalize soil extractable N levels based on assumed N availability. Application of soil amendments to potatoes significantly increased potato marketable tuber yield and plant nutrient uptake compared with the residual effects of soil amendments. Potato marketable tuber yield, plant biomass C, and plant P and K uptake were significantly affected by soil amendment and forage levels, but plant N uptake was not significantly different among treatments in the nutrient management regime under which soil amendment application rates were adjusted to equalize soil available N with assumed N availability. The highest potato tuber yield and the highest nutrient uptake were in R treatments among the three soil amendments because of high application rates. Differences in potato tuber yield and nutrient uptake among soil amendments were mainly in the 2-year forage rotation. This is mainly due to the substantial difference in cumulative soil amendment applications. Forage detrimental effects such as wireworm and nematode infestations resulted in significantly lower potato marketable tuber yield, plant biomass C, plant P and K uptake

in the 1- and 2-year forage rotations than in the 0-1yr forage rotations in amended subplots. The balances in N, P, and K were positive in all treatment combinations except the K balance in the M amended 2-year forage rotations. The results indicated that forages had some detrimental effects on potatoes when used as a preceding crop in the first cycle of rotations established after a long-term pasture was broken, and that the R treatments had the best potato performance among M, R, and S treatments.

5.2 Introduction

Potatoes are one of the most important cash crops in Atlantic Canada, and are also one of the greatest soil fertility depleting crops. In organic cropping systems, nutrient management for potatoes, heavy feeders, can be a challenge because of the restrictions in synthetic chemical fertilizer use. Composted manure is a good on-farm nutrient source on livestock farms. Alternatively, some organic farms growing cash crops without access to the livestock, known as stockless farm, may adopt non-animal waste soil amendments such as alfalfa meal. Soil amendments originated from different sources vary in chemical composition and nutrient availability, and thus may affect plant growth differently (Paul and Beauchamp 1994; N'Dayegamiye et al. 1997; Eghball and Power 1999a; Eghball and Power 1999b; Gagnon and Simard 1999; Eghball 2000; Eghball et al. 2002). Composted manure may effectively maintain and increase soil fertility levels and crop yield (Schlegel 1992); meanwhile, extremely high compost application rates (Simard et al. 1999), high C: N ratio (Eriksen et al. 1999a), or high content of soluble salts and heavy metals in compost (Bar-Tal et al. 2004) could result in a decrease in yield.

Crop rotations also play a critical role in maintaining and increasing crop production, controlling pests, weeds, and diseases. Crop sequences and rotation length in a crop rotation are critical for potato production, influencing nutrient availability and disease severity (Carter and Sanderson 2001). Potato tuber yield was decreased with increased potato cropping frequency, especially when potato cropping frequency was higher than 33% (Vos and van Loon 1989). Sieczka (1989) suggested that forage phases should be around 50% of total rotation phases in a desirable potato crop rotation. In Atlantic Canada, potatoes are often rotated with a forage mixture of red clovers and grasses so that the easily established and terminated forage phase could provide some N to the succeeding potatoes (MacLeod et al. 2000). After the forage is ploughed, the quantity of N released by forage residues to the following crop varies to some extent. Sieczka (1989) estimated that 67 to 101 kg N ha^{-1} from forage residues could be available to the subsequent potatoes, and Li et al. (1999) found that 55-80 kg N ha^{-1} from a 20-year sod breakup was available to the subsequent potatoes. Inappropriate use of forages in potato production, however, could cause some problems such as scab (Powelson et al. 1993), wireworm (Ferro and Boiteau 1993), and nematode infestations (Stark and Love 2003, P82), and thus decrease potato biomass and marketable tuber yield.

Integration of soil amendments and forages in a crop rotation management may enhance crop production. However, little information was available about potato responses to forages and soil amendments under the management that simulates the farmer's normal practices in different farming systems. An organically managed forage–based potato rotation experiment was established after a long-term pasture was ploughed down, and was supplied with three soil amendments pertaining to the main nutrient sources in three farming systems (stockless, monogastric and ruminant livestock systems). The whole experiment management was managed in a way similar to what farmers might do under isonitrogeneity regimes. To assess soil N, P, and K supply rates, a greenhouse annual ryegrass bioassay trial was also conducted using the soil collected from field plots.

The objectives of this chapter were: (a) to determine the forage frequency effects on plant biomass C, plant N, P, and K uptake, with and without soil amendments at the end of the first 4-year rotations, (b) to determine the effects of soil amendments and the residual effects of soil amendments on plant biomass C, plant N, P, and K uptake at the end of the first 4-year rotations, and (c) to evaluate nutrient balances between soil amendment nutrient inputs and plant nutrient removals in different forage and soil amendment combinations across the first cycle of 4-year crop rotations.

5.3 Materials and Methods

5.3.1 Experimental design

The experiment was a two-stage nested design, with a soil amendment factor (M, R, and S) nested under a forage factor (0, 1, or 2-year forages in three 4-year rotations). In year 4, the original plots were split into two parts, which were called amended and unamended subplots. The amended subplots received soil amendments as soil test recommended in year 4, and the unamended subplots did not receive any soil amendment in year 4. The newly amended and unamended subplots were two separate two-stage nested design experiments.

For the greenhouse experiment, a composite soil sample to a depth of 15 cm was collected in each plot on Nov. 7, 2004 (year 3). After being air dried and passed through a 2 mm sieve, 2.5 kg of oven-dried equivalent soil from each plot was put in separated pots in the greenhouse at the Nova Scotia Agricultural College. The nine treatment combinations were completely randomized within a block, with 3 blocks. Annual ryegrass was seeded and cut twice. Just before the second cut, soil N supplies were exhausted as evidenced by chlorosis on the ryegrass leaves. After being washed, the ryegrass roots were pooled with the two cuts of aboveground biomass. The experimental designs were detailed in experimental design section in Chapter 2.

5.3.2 Plant sampling and laboratory analyses

Prior to nutrient determination, oven dried plant samples were ground through a Retch centrifuge mill with a 1-mm stainless steel sieve. Plant total C and N contents were determined by combustion with a Leco® analyzer. Plant P and K contents were determined by inductively coupled argon plasma (ICAP) spectrometry using a Jarrell-Ash ICAP 9000 after digestion with nitric acid (Zarcinas et al. 1987). Plant biomass C, plant N, P, and K uptake were calculated based on nutrient content and dry matter weight, and were comprised of plant biomass C, plant N, P, and K uptake in weeds, potato tops, and tubers. Greenhouse annual ryegrass N, P, and K uptake were converted to kg ha^{-1} according to nutrient uptake per pot, soil weight per pot, and soil bulk density measured in the field. Nutrient balances over 4 years were calculated as the sum of total nutrient inputs minus total nutrient removals. Nutrient inputs included all soil amendment additions and forage mulch applied to potatoes in 1- and 2-year forage rotations while nutrient removals were composed of nutrients in cereal straw in M and R treatments, cereal grain in S treatments, soybean grain, forage biomass, and potato tubers.

5.3.3 Statistical analyses

The data in amended and unamended subplots were analyzed separately. Both were subjected to a two-stage nested design using Proc Mixed of SAS (SAS Institute, Inc. 2000). A paired *t* comparison was conducted to determine if the measured variables were different between the amended and unamended subplots. Orthogonal contrasts were constructed between forage treatments (a group of 1- and 2-year forage rotations) and non-forage treatments (the 0-year forage rotation) when *P*-values of forage effects were smaller than 0.1; similarly, orthogonal contrasts were constructed between compost treatments (a group of composted poultry and beef manures) and alfalfa meal treatments when *P*-values of soil amendment effects were smaller than 0.1. To find relationships in nutrient uptake among the greenhouse trial, amended and unamended subplots, regression analysis was performed using Proc Reg of SAS (SAS Institute, Inc. 2000).

5.4 Results

5.4.1 Plant variables between amended and unamended subplots

No difference in plant P uptake was found between amended and unamended subplots. However, marketable tuber yield, plant biomass C, plant N and K uptake were significantly higher in amended subplots than in unamended subplots at the 5% level (Table 4.1).

5.4.2 Potato tuber yield

On average, 98.3% (with a range of 95.3% to 99.6%) of total tubers in amended subplots and 97.7% (with a range of 91.3% to 99.6%) in unamended plots were marketable size. The average moisture content of marketable tubers was 79.8% (with a range of 76.3% to 84.2%) in amended subplots and 78.8% (with a range of 76.7% to 82.8%) in unamended subplots.

In amended subplots, potato marketable tuber yield was marginally significantly different among the three forage levels, and was significantly higher in non-forage rotations (0-year forage rotations) than in forage rotations (a group of 1- and 2-year forage rotations) (Table 5.2; Table 5.3). Soil amendments had a significant effect on marketable tuber yield, mainly in the 2-year forage rotations (Table 5.2; Table 5.4).

Orthogonal contrasts indicated that compost (M and R) treatments had a significantly higher marketable tuber yield than alfalfa meal (S) treatments in the 2-year forage rotations. Marketable tuber yield showed a decreasing trend with increased forage levels in S treatments, and tended to be the highest in R treatments among the three soil amendments.

In unamended subplots, potato marketable tuber yield was marginally significantly different among the three forage levels, and was significantly higher in non-forage rotations than in forage rotations (Table 5.2; Table 5.3). The residual effects of soil amendments on potato marketable tuber yield were marginally significant, mainly in the 2-year forage rotations (Table 5.2; Table 5.4). Orthogonal contrasts indicated that the residual effects of composts on marketable tuber yield were not significantly different from the residual effects of alfalfa meal. In the unamended subplots, the marketable tuber yield showed a decreasing trend with increased forage levels in both M and S treatments, and tended to be the lowest in M treatments among the three soil amendment treatments.

5.4.3 Plant biomass C, plant N, P, and K uptake

In amended subplots, plant biomass C was significantly different among the three forage levels, and was significantly higher in non-forage rotations than in forage rotations (Table 5.2; Table 5.3). Soil amendments had a significant effect on plant biomass C, mainly in the 2-year forage rotations. Plant biomass C showed a decreasing trend with increased forage levels in S treatments, and tended to be the highest in R treatments among the three soil amendments (Table 5.2; Table 5.4). In unamended subplots, no difference was found in plant biomass C among the three forage levels (Table 5.2). However, the residual effects of soil amendments on plant biomass C were significant, mainly in the 2-year forage rotations (Table 5.2; Table 5.4). In unamended subplots, plant biomass C showed a decreasing trend with increased forage levels in the M and S treatments, and tended to be the highest in R treatments among the three soil amendments.

In amended subplots, no difference was found in plant total N uptake, neither among forage frequency in crop rotations, nor among soil amendment levels (Table 5.2). In unamended subplots, no difference was found in plant N uptake among forage frequency in crop rotations, but the residual effects of soil amendments on plant total N uptake were significant, mainly in the 2-year forage rotations (Table 5.2; Table 5.4). Similar to plant biomass C, plant total N uptake showed a decreasing trend with increased forage levels in M and S treatments, and tended to be the highest in R treatments and the lowest in M treatments among the three soil amendments in unamended subplots.

In amended subplots, plant P uptake was significantly different among the three forage levels, and significantly higher in non-forage rotations than in forage rotations (Table 5.2; Table 5.3). Plant P uptake was significantly different among the three soil amendments and significantly higher in compost treatments than in alfalfa meal treatments in the 0- and 2-year forage rotations, and tended to be the highest in R treatments among the three soil amendments (Table 5.2; Table 5.4). In unamended subplots, no difference was found in plant P uptake among forage treatments; however, the residual effects of soil amendments on plant total P uptake were significant, mainly in the 2-year forage rotations (Table 5.2; Table 5.4). Plant P uptake showed a decreasing trend with increased forage levels in crop rotations in both M and S treatments, and tended to be the highest in R treatments among the three soil amendments in unamended subplots.

In amended subplots, plant K uptake was significantly different among the three forage frequencies in crop rotations, and was significantly higher in non-forage than in forage rotations (Table 5.2; Table 5.3). Soil amendments had a significant effect on plant K uptake, which was significantly higher in compost than in alfalfa meal treatments nested under the 2-year forage rotations (Table 5.2). Plant K uptake showed a decreasing trend with increased forage levels in S treatments, and tended to be the highest in R treatments among the three soil amendments (Table 5.4). In unamended subplots, no difference was found in plant K uptake among forage frequency, but the residual effects of soil amendments on plant total K uptake were significant (Table 5.2). Plant K uptake showed a decreasing trend with increased forage levels in M and S treatments, and tended to be the highest in R treatments and the lowest in M treatments among the three soil amendments in unamended subplots (Table 5.4). Complete plant N, P, or K uptake data are attached in Appendix 3 and Appendix 4.

5.4.4 Annual ryegrass N, P, and K uptake

Annual ryegrass N uptake from soils collected in the fall of year 3 was significantly different among the three forage levels, and was the highest in 1-year forage rotations, followed by 0-year forage rotations, and was the lowest in the 2-year forage rotations (Table 5.2; Table 5.3). The residual effects of soil amendments on annual ryegrass N uptake were significant, mainly in the 2-year forage rotations in which compost (M and R) treatments had significantly higher N uptake than alfalfa meal (S) treatments (Table 5.2; Table 5.4). Annual ryegrass N uptake in M treatments showed a decreasing trend with increased forage levels in crop rotations.

Annual ryegrass P uptake was significantly different among the three forage levels, and was significantly higher in non-forage rotations than in forage rotations (Table 5.2; Table 5.3). The residual effects of soil amendments on annual ryegrass P uptake were significant, and annual ryegrass P uptake was significantly lower in alfalfa meal treatments than in compost treatments (Table 5.2; Table 5.4). Annual ryegrass P uptake tended to be the lowest in S treatments, and showed a decreasing trend with increased forage levels in all soil amendment treatments.

Annual ryegrass K uptake was significantly different among the three forage levels, and was significantly higher in non-forage rotations than in forage rotations (Table 5.2; Table 5.3). The residual effects of soil amendments on annual ryegrass K uptake were significant, mainly in forage rotations (Table 5.2; Table 5.4). Annual ryegrass K uptake tended to be the highest in R treatments and the lowest in S treatments among soil amendments, and showed a decreasing trend with increased forage levels in both M and S treatments.

5.4.5 Relationship of N, P, and K uptake

Plant N uptake determined in the field amended and unamended potato subplots as well as in a greenhouse annual ryegrass trial was plotted. The pattern in the plots indicated that there is a linear relationship in N uptake in amended and unamended subplots, and there are no linear relationships among other nutrient variables. The correlation coefficients and corresponding P-values (Table 5.5) confirmed such a linear relationship. The fitted regression equation was established between N uptake in amended and unamended subplots (Fig. 5.1). For plant P uptake, only plant P uptake in amended subplots against P uptake in unamended subplots showed a linear relationship. For plant K uptake, only plant K uptake in amended subplots against K uptake in unamended subplots showed a linear relationship (Table 5.5; Fig. 5.2; Fig. 5.3).

5.4.6 Total C, N, P, and K balance in the first cycle of 4-year rotations

Of soil amendments nested under the three forage levels, C input in M treatments was the smallest and C removal in S treatments was the smallest. The C balance in M treatments was negative, but was positive in S treatments (Fig. 5.4). The N balance was positive in all treatments; the largest N input and positive balance in three soil amendments occurred in R treatments. Removal of N was the smallest in S treatments (Fig. 5.5). The net P balances were positive in all treatments, and total P input and net positive balance were the highest in S treatments (Fig. 5.6). Potassium input and balance were the highest in R treatments, followed by S treatments, and were the lowest in M treatments. Removal of K was the highest in R treatments, followed by M treatments, and was the lowest in S treatments (Fig. 5.7).

5.5 Discussion

5.5.1 Plant variables between amended and unamended subplots

In a compost study, wheat yield and N, P, and K uptake were increased as compost application rates increased (Bar-Tal et al. 2004). In the current experiment, soil amendments increased plant biomass C, plant N and K uptake, and potato marketable tuber yield compared with counterparts in unamended subplots. Plant P uptake, however, was not affected by soil amendments. Phosphorus availability from compost could be as high as 73% of total P (Eghball et al. 2002), and was much higher than the P availability (20%) we assumed. Low assumed P availability resulted in excessive P applications, which may be the main reason for no P difference between amended and unamended subplots.

5.5.2 Forage effects

Ploughed forages improved crop yield and lowered N input to reach optimum yield compared with arable land, and the benefits from the ploughed forages include a small non-N benefit and a big N benefit (Nevens and Reheul 2002). Nitrogen credit to a 20-year old sod breakup was estimated as much as 55-80 kg N ha^{-1} in potato systems (Li et al. 1999). In unamended subplots, soil extractable N and soil N supply rates (in Chapter 3) were higher in forage (1- and 2-year forage) rotations than non-forage (0-year forage) rotations, as a result of forage N benefits and extra compost N additions in forage rotations. However, potato marketable tuber yield was significantly lower in forage rotations (a group of 1- and 2-year forage rotations) than in non-forage (0-year forage rotation) rotations, and plant nutrient uptake was numerically lower in forage rotations than in non-forage rotations. This contradicts the report that potato plant N uptake was higher when following a preceding forage crop than a preceding cereal crop (Zebarth et al. 2005b). Forages in a potato rotation are underscored for the positive effects on N (Li et al. 2003), but forage may also have negative aspects such as pest and disease infestations (Ferro and Boiteau 1993; Powelson et al. 1993). Since the current experiment was conducted after a long-term pasture was ploughed, the forage (a mixture of red clover and timothy) phase in crop rotations may bring back the pests such as scab, wireworm, and nematodes inhabiting in previous pasture soil, and thus lower marketable tuber yield and plant nutrient uptake.

Theoretically, annual ryegrass nutrient uptake obtained from the greenhouse trial using the end of year 3 soil should highly correlate with the results from the unamended subplots in year 4. This speculation, however, was not supported by the data in the current experiment for several reasons. When the greenhouse soil samples were collected, the plots were not tilled. Therefore, the forage residues and the composts applied in forage plots in year 3 were not incorporated into soil, and were not collected for the greenhouse trial. As a consequence, the data obtained from the greenhouse experiment were not well-related to those from the field experiment in which composts and forages were ploughed into soil. The annual ryegrass nutrient uptake in the 2-year forage rotations was the lowest among the three forage levels. This may be primarily due to the low soil amendment inputs in year 1 (i.e. soil amendment application rates were reduced by half in year 1 in the 2-year forage rotations compared with full rates in the 0- and 1-year forage rotations), and also due to the high forage nutrient uptake and removal in year 2 and 3, leaving less nutrients in soil.

In amended subplots, although soil extractable N and soil N supply rates (in Chapter 3) were higher in forage rotations than non-forage rotations, plant nutrient uptake and potato marketable tuber yield were lower in forage rotations than in non-forage rotations. This may be attributed to high soil amendment C input in year 4, and better seed beds resulting from frequent tillage in non-forage rotations. Potato marketable tuber yield was reported to increase with increased ley frequency in crop rotations because of ley residue N benefits (Ridgman and Wedgwood 1987). However, forage N benefits could be partially masked with soil amendment additions through adjusting soil amendment application rates under isonitrogeneity regimes.

A related issue is that potatoes following legumes, particularly red clovers, may have negative effects. For example, potatoes after red clover may suffer severe diseases such as scab (Powelson et al. 1993). Ferro (1993) found that wireworm (*Limonus agonus*) was a problem in fields that had a history of sod or pasture for several years. Since the current experiment was established on a long-term pasture soil, wireworm may be more severe in forage rotations compared with non-forage rotations. The author observed wireworms boring into potato seed tubers one week after potato seeding in the forage plots, and also noticed that wireworms bored into harvested potatoes. The temporary accumulation of organic acids (e.g. acetic acid) produced in the early phase of plant residue decomposition under anaerobic conditions might result in phytotoxicity to the following crops (Lynch 1983), with symptoms of germination inhibition and stunting (Patrick 1971). The inhibitory allelopathic effects of a preceding red clover on the following corn seedlings were reported by (Sturz and Christie 1996). Yields of oats and wheat following the leguminous crop were restricted by phytotoxicity associated with residues of leguminous crops in a 4-yr rotation fababean-oats-clover-winter wheat (Patriquin et al. 1981). The negative roles of red clovers in this study may be mainly responsible for the decrease in potato tuber yield and plant nutrient uptake as forage levels increase.

Olesen et al. (1999) suggested that at least three cycles of rotations need to be run for determining the effects of crop rotations. Carter and Sanderson (2001) found that crop rotation benefits on tuber yield did not show until the second cycle in 2- or 3-year crop rotations. This experiment did not demonstrate the benefits from the high percentage forage rotation, but forage negative effects did occur in the first rotation cycle under the specific high fertility pasture conditions.

5.5.3 Soil amendments and their residual effects

The main compost effects on crop yield and nutrient uptake were in the first two years, especially in the first year (Eghball et al. 2004). In the current experiment, the 2-year forage rotations only received half rates of soil amendments compared with the 0- and 1-year forage rotations in year 1. In year 3, no alfalfa meal was applied to the forage plots in S amended 2-year forage rotations, while composts were applied to the forage plots in M or R amended 2-year forage rotations for forage P requirements. However, the low cumulative alfalfa meal input in the 2-year forage rotation did not result in low N supply. Conversely, soil mineral N supply rates determined at the potato flowering stage and soil extractable N measured after potato harvest were relatively high in the S treatments nested under the 2-year forage rotation in both amended and unamended subplot. Therefore, in both amended an unamended subplots, the lowest potato tuber yield and plant nutrient uptake in the S treatments nested under the 2-year forage rotations may be due to the apparently least cumulative alfalfa meal input rather than soil available N.

Potato marketable tuber yield showed a positive response to chemical fertilizer application rates up to 200 kg ha^{-1} (Zebarth et al. 2004). In both amended and unamended S treatments, plant biomass C, plant nutrient uptake, and potato marketable tuber yield were decreased with increased forage frequency. This decrease in plant variables was related to the above-mentioned detrimental forage effects, and was also related to the decreasing cumulative alfalfa meal input as forage levels increase. In a dairy compost study, corn N, P, and K uptake showed a positive response to application rates up to 179 t ha^{-1} (Warman 1995). In unamended subplots, in the 0-year forage rotation, alfalfa meal was applied in year 1 and year 3 with full rates; in the 1-year forage rotations, alfalfa meal was applied in year 1 with full rates; in the 2-year forage rotations, alfalfa meal was applied only in year 1 with half rates. As mentioned in Chapter 3, soil extractable N and soil mineral N supply rates were not different in S treatments nested under the three forage levels, despite the substantial difference in alfalfa meal cumulative input. Hence, the apparent decrease in cumulative alfalfa meal input, together with detrimental forage effects on potatoes, resulted in the decrease in plant nutrient uptake and tuber yield as forage frequency increased.

Compared with soil amendment types, soil amendment application rates were found to have a larger effect on crop yield and nutrient uptake (Ferguson et al. 2005). In the current experiment, total N application rates were higher in R treatments than in S treatments, and were only half rates of that in R treatments based on assumptions of N availability. According to the soil amendment incubation experiment, R and S had the smallest and largest percentage of total N were mineralized in a period of 4 months, respectively. This suggested that R and S had the largest and the smallest N carryover to the succeeding crops, respectively. Composted poultry manure (M) was made of poultry manure using bark mulch as a C source, and was of low total N concentration (0.7 g kg^{-1}). The low N content may weaken N availability in the N carryover from M. Therefore, in unamended subplots, soil fertility could be regarded as inadequate in the M and S treatments, but could be adequate in R treatments. This may be the primary reason why plant nutrient uptake and potato tuber yield were the highest in R treatments among the three soil amendments nested under the three forage levels. Similarly, R in amended subplots had the highest potato tuber yield and plant nutrient uptake among the three soil amendment treatments nested under the three forage levels.

Nutrients may be adequate in both amended and unamended R treatments. Under adequate nutrient conditions, the magnitude of cumulative nutrient inputs, which was the highest in the 1-year forage rotation, may not affect potato performance drastically, but forage detrimental effects may be a dominated factor influencing potato growth and nutrient uptake. Red clover roots are preferred by nematode, which could substantially eliminate the yield of potatoes preceded by red clovers (Sieczka 1989). The negative effects of red clovers on the following potato tuber yield were also reported by Hoekstra (1989). Conversely, cereal crops (i.e. preceding crops in 0-year forage rotations) in potato rotations were effective in eliminating the pressure of soil borne pathogens (Vos and van Loon 1989). In the current experiment, red clover mass percentage in year 3 was much higher in the 1-year forage rotation (75%) than in the 2-year forage rotation (42%). Moreover, soil amendment cumulative dry weight input from year 1 to year 4 was 74 Mg

ha^{-1} in the 1-year forage rotation, 50 Mg ha^{-1} in the 0-year forage rotation, and 51 Mg ha^{-1} in the 2-year forage rotation. The highest dry weight input in the 1-year forage rotation may also deteriorate soil diseases and pests, and thus constrain plant growth. All of these, together with forage detrimental effects on potatoes, may explain why potato tuber yield and plant nutrient uptake were the lowest in the 1-year forage rotation and the highest in the 0-year forage rotation among the three forage levels, in both amended and unamended R treatments.

With similar reasons, potato tuber yield and plant nutrient uptake were the lowest in the 1-year forage rotation and the highest in the 0-year forage rotation among the three forage levels in the amended M treatments. However, in the unamended M treatments, there is another scenario, since nutrients were a limiting factor. Higher cumulative nutrient inputs might result in higher plant nutrient uptake and potato tuber yield under limited nutrient conditions. For example, the cumulative nutrient inputs from year 1 to year 3 were higher in the 1-year forage rotation than in the 2-year forage rotation. Therefore, with forage as the preceding crop in both forage rotations, potato tuber yield and plant nutrient uptake were higher in the 1-yr forage rotation than in the 2-yr forage rotation. Because of the detrimental effects of forage crops on potato performance, potato tuber yield and potato nutrient uptake were higher in non-forage rotations than forage rotations, and thus were decreased with increased forage frequency in unamended M treatments.

In the current experiment, soil amendment and forage frequency complicated interacted and affected nutrient availability and disease severity, and thus plant growth and nutrient uptake. Under assumption of isonitrogeneity, the added P and K along with soil amendments were different among different treatments when trying to provide the assumed equivalent N. Such different P and K inputs resulted in plant P and K uptake different, respectively. Compared to soil P and K supply, N supply was tried to adjust soil available N at the same level in potato year under isonitrogeneity regimes. As a consequence, plant N uptake did not show significant differences among treatments in amended subplots despite of violation of the soil isonitrogeneity as showed in Chapter 3.

5.5.4 Nutrient balance

Of nine organic farms adopting crop rotations, seven showed a soil N budget surplus, six showed a soil P budget surplus, and only three showed a soil K budget surplus (Berry et al. 2003). A literature review done by Watson (2002) demonstrated that an N balance between inputs and outputs in organic systems is always positive while P and K balances may be surplus or deficit. This experiment is in accord with an N surplus, despite N budgets being underestimated in the current experiment, as atmospheric deposition and biological fixation of N_2 by legume were not included in N balance estimates. The highest N surplus in R treatments was mainly due to the highest N input under the lowest assumed N availability. In the current experiment, we assumed that 50% of total N in M, 25% in R, and 30% in S was plant available in the application year when determining the soil amendment application rates.

Long-term experiments demonstrated that manure application for crop N usually resulted in excessive P accumulation (Schlegel 1992; Eghball and Power 1999a; Ferguson et al. 2005). The current experiment also showed a P surplus. Total P input and balance were the highest in S treatments, although soil extractable P was the lowest in S treatments. The reason for this contradiction was that rock P was the main P source in S treatments, and total rock P application rates in S were high because of low P availability from rock P.

The K balance was found to be negative in a six-year crop rotation during conversion from conventional to organic, especially on stockless farms (Haraldsen et al. 1999). In the current experiment, total K application rates determine, to a large extent, the K balance. For example, K balance was negative in the 2-year forage rotations with M amendments as a result of low K input and high forage K removal.

The plant biomass C balance reflects the system C change to some extent. The system C input, however, was substantially underestimated in the current experiment, because plant photosynthetic C assimilation input was not included in the balance estimates. In the current experiment, the C balance was always positive in the 2-year forage rotations as a result of low plant nutrient removal and forage residue input. Net C balance was low in M and R treatments as a result of straw removal as livestock bedding materials. The negative C balance in M did not really mean C deficit as the C input was underestimated. The C dynamic may be better reflected by soil C_{tot}.

5.6 Conclusions

Potato tuber yield and plant nutrient uptake were influenced by cumulative nutrient inputs and forage levels. As a preceding crop, forage had a detrimental effect on potato tuber yield and nutrient uptake in the current experiment established on a long-term pasture. Soil borne diseases and pests may be the main reasons for the low production of potatoes preceded by forages. In amended and unamended S treatments, a substantial difference in cumulative application rates is the main factor influencing potato growth and nutrient uptake. In M and R amended 1- and 2-year forage rotations, nutrient supply was adequate, but forage detrimental effects limited potato growth and thus nutrient uptake. In M and R unamended forage rotations, nutrient supply was inadequate, and nutrient supply rates of soil amendments limited potato growth and thus nutrient uptake. Soil amendment applications to potatoes increased plant nutrient uptake and potato marketable tuber yield compared with the residual effects of soil amendments. Potato tuber yield and plant nutrient uptake in R treatments were the highest among the three soil amendments because of high cumulative nutrient inputs with the relatively low assumed N availability. Greenhouse annual ryegrass bioassay was not a good tool to predict soil nutrient levels or field potato nutrient uptake, especially in forage rotations. Nutrient uptake in unamended subplots well predicted nutrient uptake in amended subplots. In a nutrient management regime under which soil amendment application rates were adjusted to equalize plant available N with assumed N availability, net total N and P balances were positive in this 4-year period. Net total K balance showed negative in the 2-year forage rotations amended with monogastric compost as a result of low K input and high forage K removal.

Table 5.1 Means of plant nutrient uptake and dry potato marketable tuber yield, and the corresponding *P*-values of paired t comparison between amended and unamended subplots in yr 4

	N	P	K	C	Tuber yield
			(kg ha^{-1})		
Amended	113.9	14.1	185.7	2925	5706
Unamended	102.8	13.2	142.4	2472	4963
			(*P*-value)		
	0.017	0.190	<0.001	0.003	0.039

Table 5.2 The *p* values of forage and soil amendment effects on plant biomass C, nutrient uptake, dry potato marketable tuber yield in yr 4, and greenhouse ryegrass nutrient uptake in yr 3

Source of variation	Amended subplots					Unamended subplots					Greenhouse trial		
	logC*	N	logP†	K	Tuber yield	C	N	P	K	Tuber yield	N	P	K
Forage level	0.005	0.150	0.016	0.009	0.077	0.201	0.603	0.118	0.196	0.073	0.001	0.001	0.001
0 vs (1+2)	0.001	-‡	0.005	0.003	0.029	-	-	-	-	0.026	0.831	0.004	0.018
Soil amendment	0.029	0.218	0.052	0.009	0.043	0.023	0.029	0.030	0.001	0.082	0.062	<0.001	0.002
S vs (M+R) in 0	0.172	-	0.021	0.115	0.133	0.326	0.553	0.380	0.594	0.846	0.171	<0.001	0.342
S vs (M+R) in 1	0.565	-	0.719	0.886	0.510	0.984	0.597	0.643	0.929	0.157	0.565	<0.001	0.070
S vs (M+R) in 2	0.005	-	0.016	0.043	0.017	0.115	0.075	0.060	0.026	0.536	0.009	<0.001	0.001

* Plant biomass C in amended subplots were subjected to log transformation prior to statistical analysis, and back transferred values were reported.

† Plant P uptake in amended subplots were subjected to log transformation prior to statistical analysis, and back transferred values were reported.

‡ Orthogonal contrasts were not done when P values of forage or soil amendment effect were larger than 0.1.

Table 5.3 Least squares means of plant biomass C, nutrient uptake, dry potato marketable tuber yield at three forage levels (0, 1, and 2) in yr 4, and greenhouse ryegrass nutrient uptake in yr 3*

	Amended subplots				U†	Greenhouse trial		
Forage	C	P	K	Tuber yield	Tuber yield	N	P	K
	(kg ha^{-1})							
0	3 459*a*	16.3*a*	231.6*a*	6 500*a*	5 872*a*	126.7*b*	26.1*a*	200.2*a*
1	2 387*b*	12.2*b*	164.4*b*	5 138*b*	4 648*ab*	137.1*a*	24.7*a*	199.0*a*
2	2 564*b*	12.4*b*	161.3*b*	5 481*ab*	4 368*b*	114.6*c*	21.3*b*	169.5*b*

* Least squares means in a column followed by the same letters were not significantly different at the 5% levels; Plant biomass C and plant P uptake in amended subplots were log transferred prior to analysis, and back transferred data were reported.

† Unamended subplots.

Table 5.4 Least squares means of plant biomass C, nutrient uptake, dry potato marketable tuber yield for three soil amendments (M, R, and S) nested under three forage levels (0, 1, and 2) in yr 4, and greenhouse ryegrass nutrient uptake in yr 3*

	Amended subplots				Unamended subplots					Greenhouse trial		
	C	P	K	Tuber yield	C	N	P	K	Tuber yield	N	P	K
	(kg ha^{-1})											
M0	3 575*ab*	17.5*ab*	212.4*abc*	6 600*ab*	2 545*abc*	99.3*bc*	14.0*ab*	118.4*cd*	5 562*abc*	134.7*ab*	30.1*a*	198.6*b*
R0	3 861*a*	19.5*a*	287.9*a*	7 311*a*	3 332*ab*	127.7*ab*	17.9*a*	225.4*ab*	6 309*ab*	125.1*abc*	27.0*ab*	208.8*ab*
S0	2 997*ab*	12.7*bcd*	194.5*bc*	5 587*abc*	2 477*bc*	102.5*abc*	13.8*ab*	154.1*bcd*	5 745*abc*	120.2*bc*	21.3*c*	193.4*bc*
M1	1 965*cd*	11.1*cd*	110.0*d*	4 274*c*	1 887*c*	89.0*bc*	10.5*b*	82.0*d*	3 779*cd*	132.7*ab*	26.2*b*	186.4*bc*
R1	2 733*abc*	13.0*bcd*	222.0*ab*	5 614*abc*	2 557*abc*	117.5*abc*	13.8*ab*	174.0*abc*	4 562*abcd*	138.9*a*	26.8*ab*	225.2*a*
S1	2 531*bcd*	12.7*bcd*	161.1*bcd*	5 526*abc*	2 232*bc*	93.5*bc*	11.0*b*	125.0*cd*	5 602*abc*	139.7*a*	21.2*c*	185.3*bc*
M2	2 650*bcd*	13.0*bcd*	138.6*cd*	5 147*bc*	1 720*c*	75.1*c*	9.6*b*	74.9*d*	2 775*d*	116.0*cd*	23.8*bc*	170.8*c*
R2	3 441*ab*	15.5*abc*	232.7*ab*	7 349*a*	3 594*a*	144.9*a*	18.8*a*	246.9*a*	6 368*a*	126.6*abc*	23.8*bc*	197.5*b*
S2	1 848*d*	9.5*d*	112.5*d*	3 949*c*	1 897*c*	75.5*c*	9.3*b*	80.8*d*	3 961*bcd*	101.1*d*	16.4*d*	140.4*d*

* Least squares means in a column followed by the same letters were not significantly different at the 5% levels; Plant biomass C and N uptake in amended subplots were log transferred prior to statistical analysis, and back transferred data were reported.

Table 5.5 Correlation coefficients in N, P, and K uptake among the amended and unamended subplots and the greenhouse trial*

	N uptake		P uptake		K uptake	
	A†	U‡	A	U	A	U
U	0.733(<0.001)		0.673(<0.001)		0.744(<0.001)	
GH§	-0.067(0.74)	0.114(0.571)	0.204(0.306)	0.152(0.448)	0.231(0.247)	0.354(0.07)

* Values in each bracket are P-values.

† A represents the amended subplots in yr 4.

‡ U represents the unamended subplots in yr 4.

§ GH represents the greenhouse annual ryegrass trial in yr 3.

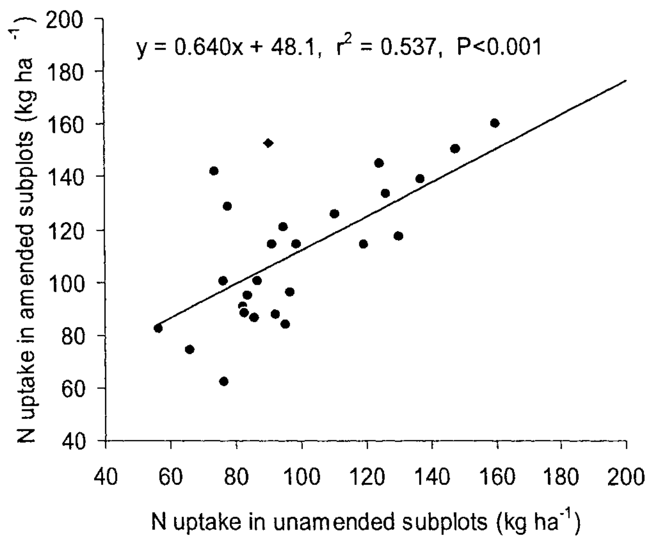

Fig. 5.1 Regression of plant (potato tops, tubers, and weeds) N uptake in amended against unamended potato subplots in yr 4.

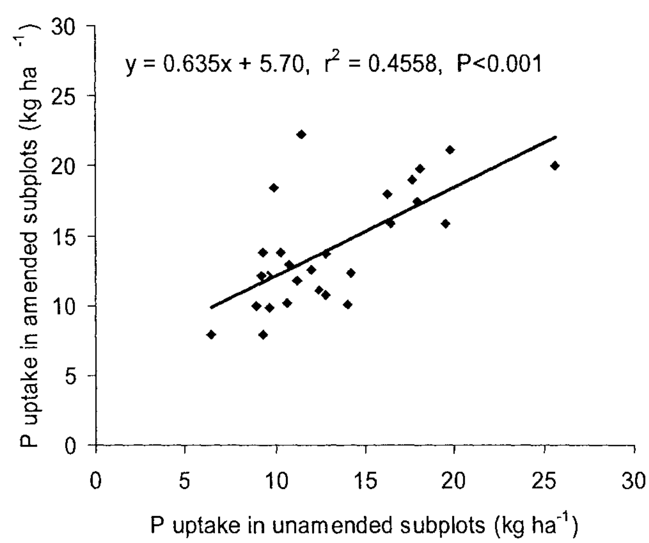

Fig. 5.2 Regression of plant (potato tops, tubers, and weeds) P uptake in amended against unamended potato subplots in yr 4.

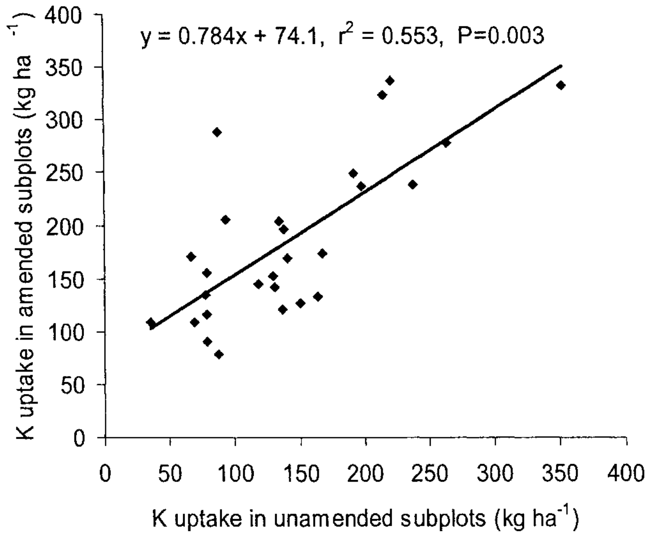

Fig. 5.3 Regression of plant (potato tops, tubers, and weeds) K uptake in amended against unamended potato subplots in yr 4.

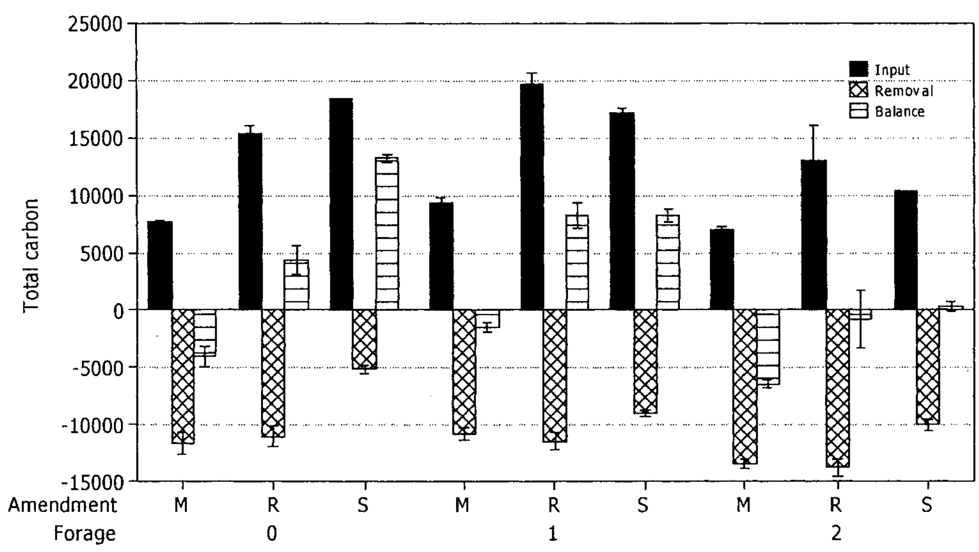

Fig. 5.4 Total C (kg ha^{-1}) input, removal, and balance for three soil amendments (M, R, and S) nested under three forage levels (0, 1, and 2) in the first cycle of 4-yr rotations in amended subplots.

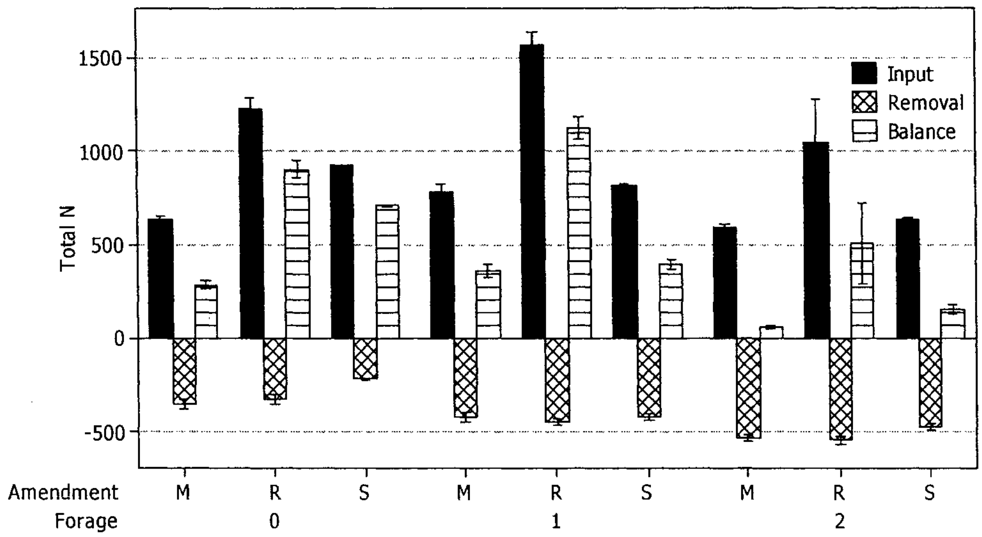

Fig. 5.5 Total N (kg ha^{-1}) input, removal, and balance for three soil amendments (M, R, and S) nested under three forage levels (0, 1, and 2) in the first cycle of 4-yr rotations in amended subplots.

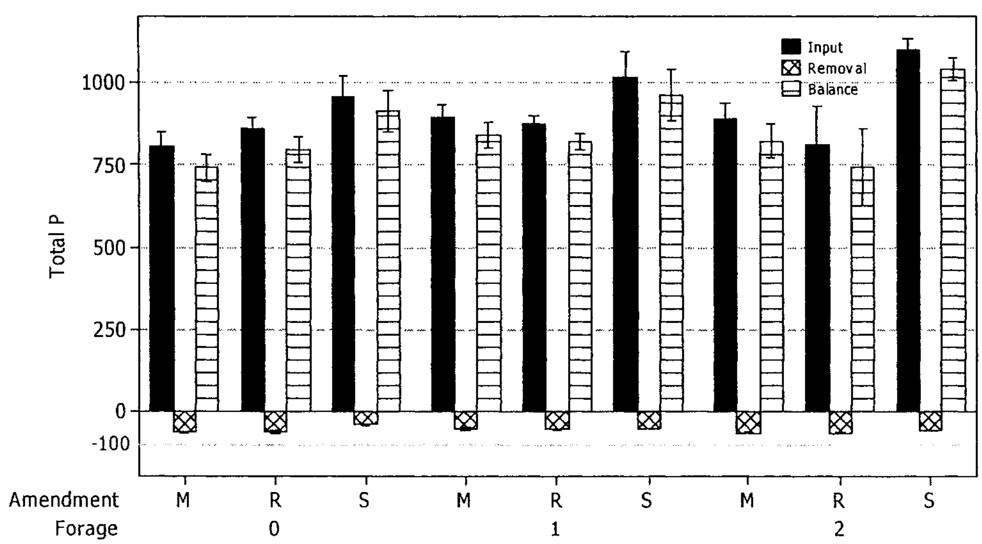

Fig. 5.6 Total P (kg ha^{-1}) input, removal, and balance for three soil amendments (M, R, and S) nested under three forage levels (0, 1, and 2) levels in the first cycle of 4-yr rotations in amended subplots.

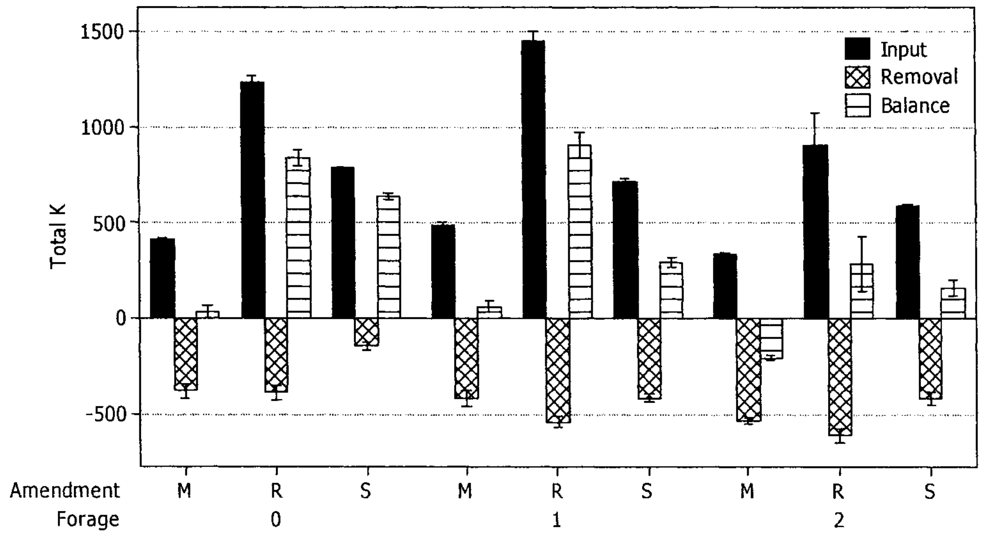

Fig. 5.7 Total K (kg ha^{-1}) input, removal, and balance for three soil amendments (M, R, and S) nested under three forage levels (0, 1, and 2) in the first cycle of 4-yr rotations in amended subplots.

CHAPTER 6 INTEGRATION OF SOIL AND PLANT VARIABLES

6.1 Abstract

Integration of soil and plant variables may be a robust way to assess management practice effects on a cropping system. An organic potato rotation experiment was established to assess the effects of three forages and three soil amendments on cropping systems under assumptions of isonitrogeneity. Forage (a mixture of red clover and timothy) levels included 0-, 1-, and 2-year forage crops in three different 4-year crop rotations: wheat (w)/soybean (s)/barley (b)/potato (p), w/b/forage (f)/p, and w/f/f/p, respectively. Soil amendments included composted poultry manure (M), composted beef manure (R), and alfalfa meal (S), pertaining to nutrient sources in monogastric, ruminant, and stockless systems, respectively. In the potato year (year 4), the original plots were split into two parts: amended and unamended subplots. No soil amendment was applied in the unamended subplots. The amended subplots received soil amendments as per soil test recommendations, and soil amendment application rates were adjusted to equalize soil extractable N levels based on assumed N availability. Principal component analysis was performed to assess the overall soil and plant responses to cropping systems which integrated different forage and soil amendment levels. The 1- and 2-year forage levels shared similarities, but were separated from the 0-year forage level. Three soil amendments were separated from each other. Plant variables such as plant biomass C were the most valuable variable in assessing field management effects on cropping systems. Soil total and extractable N in amended subplots were the most important soil variables in assessing cropping systems, while soil C_{tot} and SMBC were the most important soil variables in unamended subplots. In amended subplots, the overall variables were much more affected by soil amendments than by forages, while the residual effects of amendments on overall variables may be as important as the effects of forage residues on overall variables in unamended subplots. The cropping systems integrating different forage and soil amendment levels did show differences and similarities. The results suggested that plant biomass C was the most important variable

to assess cropping systems, and that similarities and differences did show in different cropping systems represented by the combinations of forages and soil amendments, depending on forage levels, types and application rates of soil amendments.

6.2 Introduction

Assessment of individual variables provides useful information on how forage crops and soil amendments affect farming systems. However, some of these variables may be interdependent, and the others may respond differently to forage levels and soil amendments. Therefore interpretation of individual variables may be confounded. In a soil fertility study, individual indicators showed divergent trends over 6-year crop rotations, making it difficult to draw a conclusion about changes in soil fertility (Bakken et al. 2006). In a complicated soil system study, one or two soil indices may not be sufficient to provide adequate information (Sojka and Upchurch 1999); conversely, system evaluation might be enhanced if integrated indicators were used in a proper way (Gil-Sotres et al. 2005). Principal component analysis is an appropriate way to reduce the number of variables by transferring the original variables to new sets of uncorrelated variables, which are called principal components. Each principal component integrates the original variables in a form of linear combination (Chatfield and Collins 1980, P57). The first principal component explains the largest amount of data variation, and the second component explains the second largest amount of data variation, and so on. Therefore, it is often convenient to focus on the first several principal components. Principal component analysis is widely used in agricultural studies (Goodfriend 1998; Andrews et al. 2002; Larkin 2003; Marinari et al. 2006). In the current experiment, a collection of soil and plant variables provide a chance to assess the overall cropping system responses to different forage and soil amendment levels in an organically managed potato cropping system.

The objectives of this chapter are to: 1) visualize similarities and differences of cropping systems in different treatment levels using PCA; 2) roughly summarize the important variables which are critical in explaining the overall data variations.

6.3 Materials and Methods

Plant and soil variables included in PCA were in Table 6.1. All the variables were collected in both amended and unamended subplots. Soil sampling and analyses were detailed in soil sampling and laboratory analyses section in Chapter 2, and plant sampling and analyses were detailed in plant sampling and laboratory analyses in Chapter 2. All soil and plant data were subjected to PCA using PROC PRINCOMP in SAS (SAS Institute, Inc. 2000). The data in amended and unamended subplots were analyzed separately.

6.4 Results

An ordination plot is a map reflecting similarities and differences among treatments after reduction of a multivariate data set (Clarke and Warwick 2001, P4-1). The smallest distance between treatments can be interpreted as increased similarity between treatments; conversely, the greatest distance between treatments implies larger differences between treatments. In amended subplots, PC 1 accounted for 34.7% of the variation in the data, and PC 2 accounted for 21.6% of the variation in the data (Fig. 6.1). Hence, the first two components explained 56.3% of the overall variation. The 1- and 2-year forage levels were not separated, but both were well separated from the 0-year forage levels (Fig. 6.1a). Three soil amendment levels were also well separated by PC 1 and PC 2 (Fig. 6.1b). The combinations of forage and soil amendment were complicated. Some were separated, and the others were not (Fig. 6.1c). For example, Rs nested under 1- and 2-year forage rotations were clustered, and Ms nested under 1- and 2-year forage rotations were also clustered; however, M and R were well separated in 1- and 2-year forage rotations. Therefore, some cropping systems composed of crop rotation and soil amendment showed similarities while the others showed differences.

In unamended subplots, PC 1 accounted for 33.8% of the variation in the data, and PC 2 accounted for 18.1% of the variation in the data (Fig. 6.2). Hence, 51.9% of total variation was explained by the first two principal components. As in the amended plots, the 1- and 2-year forage levels were clustered, but both were well separated from the 0-year forage level (Fig. 6.2a). Three soil amendment levels were also well-separated by PC 1 and PC 2 (Fig. 6.2b). Compared with the amended subplots, separations between crop rotation and soil amendment combinations were less distinct in unamended subplots (Fig. 6.1c; Fig. 6.2c).

In a loading plot, the vectors pointing in approximately the same direction can be interpreted as positive correlation between variables represented by the vectors. The closer the vectors are, the stronger the relationships are. In contrast, the vectors pointing in opposite directions can be interpreted as negative correlation between variables represented by the vectors. The length of the vectors is proportional to the importance of the variables presented by the vectors in explaining how well the single variable may substitute for a given principal component (James 1990). In the amended subplots, the vectors of plant nutrient uptake and potato total tuber dry weight were closely displayed (Fig. 6.3a). This suggested plant nutrient uptake and potato tuber dry weight were highly correlated. In the PC 1 direction, plant variables such as plant biomass C, plant N, P, K uptake, and total potato tuber dry weight are the longest vectors. In the PC 2 direction, soil total and extractable N are the longest vectors. Therefore, plant variables substantially affected the PC 1, and soil total and extractable N substantially affected the PC 2; therefore, plant variables, and soil total and extractable N were the most important variables in explaining data variations, or the treatment effects.

In the unamended subplots, plant variables such as nutrient uptake and tuber weight displayed closely (Fig. 6.3b); this confirmed that plant nutrient uptake and tuber yield are closely correlated. In the PC 1 direction, plant biomass C, plant N, P, K uptake, and potato tuber dry weight are the longest vectors. In the PC 2 direction, soil C_{tot} and SMBC are the longest vectors. Therefore, plant variables, SMBC, and soil C_{tot} substantially affected the first two principal components, and were the most important variables in explaining data variations, or the treatment effects.

6.5 Discussion

In this experiment, under assumptions of isonitrogeneity, soil amendment application rates across 4 years (Table 2.2; Table 2.3; Table 2.4) were substantially different among the three soil amendments. Therefore, it is difficult to make comparisons among the three soil amendments because of statistical model restrictions as indicated in the model in

Chapter 2. However, PCA is not based on any specific statistical model (Chatfield and Collins 1980, P58; Manly 1986, P72), and provides a chance to look into soil amendment effects. In the current experiment, well-separated soil amendment patterns in both amended and unamended subplots implied that three soil amendments did make different contributions to the cropping systems because of the different chemical composition, nutrient content, and application rates. Compared with unamended subplots, the three soil amendments in amended subplots were more separated. In other words, the residual effects of soil amendments were smaller than newly added soil amendments on overall variables.

Principal component analysis distinguished the forage (a group of 1- and 2-year forage) rotations from the non-forage (0-year forage) rotations. Forage crops in a crop rotation are well-known for supplying N and increasing SOM after being incorporated into soil, and thus improve soil properties (Entz et al. 1995). However, sparse red clover stands in the 2-year forage rotations as a result of winter kill weakened the supposed 2-year forage effects. As a result, the 2-year forage rotations were not separated from the 1-year forage rotations. Forage levels, types and application rates of soil amendments determined whether cropping systems integrating different levels of forage and soil amendment were separated or not.

There is no single variable that can always be used to evaluate soil changes affected by management practices (Letey et al. 2003). Alternatively, soil physical, chemical, and biological properties were often simultaneously used to evaluate field management effects on soil properties (Brejda et al. 2000; Andrews et al. 2002; Shukla et al. 2004). There are some advantages and limits for different variables. For example, soil physical variables change only when soil experiences a drastic change (Filip 2002) over a long period of time, while biochemical and biological variables are relatively sensitive to a slight change and can be used as early indicators for soil changing trends. However, sensitive soil variables such as SMBC and DHA may have large variations and may poorly reflect soil changes (Halvorson et al. 1997). The changes of the relatively stable soil attributes such as SOM may reflect the essence of the farming practice effects (De Clerck et al. 2003). Besides soil properties, plant variables such as yield were also recommended when evaluating management practices in a cropping system (Karlen et al.

2003). In the current experiment, soil and plant variables were integratively assessed. Plant variables in both amended and unamended subplots in year 4 had the longest vectors in the most important principal component, PC 1. This suggested that plant variables, such as tuber yield and nutrient uptake, were the most important variables to assess management practices in cropping systems, because these variables might reflect the whole process involved in an entire plant growing season. Plant biomass C and plant N uptake were in the centre of the plant variable cluster, with a longer vector in plant biomass C. Hence, plant biomass C can be the representative of plant variables.

In amended subplots, N additions along with soil amendment applications may have a substantial effect on overall variables, and made soil N_{tot} and soil extractable N the most important soil variables. This current experiment was established on a fertile soil after a long-term sod was broken. The high inherent SOM and the continual soil amendment additions in amended subplots resulted in high soil C, which may have made the responses of soil biological variables to treatments similar and less important in explaining the overall data variation. Compared with the amended subplots, nutrient availability was mainly affected by nutrient carryover from soil amendments in the unamended subplots. In most cultivated soils, C is a limiting factor (Grayston, et al. 1998) for microbial activity and nutrient availability. Therefore, it is not surprising that soil C_{tot} and SMBC were the most important soil variables in explaining the overall data variation in unamended subplots where no soil amendment was added in year 4. Soil bulk density showed a little response to the management practices in the short-term (4 years) of this experiment, and was not an important variable in explaining the overall variation in the data.

In amended subplots, the pattern of forage and soil amendment combinations in the ordination plot was much easier to divide into groups based on soil amendment levels than based on forage levels. This may suggest that soil amendments had larger effects on overall variables than forages in amended subplots. Forages also had some effects on the pattern. For example, the two compost amendment treatments reacted in a similar way when no forage was in rotations, but responded differently when forages were part of the rotations. In unamended subplots, there is no apparent cluster to divide the whole forage and soil amendment combination pattern in the ordination plots based on either soil amendment or forage levels. This may suggest that the forage residues and residual effects of soil amendments may have similar importance in influencing overall variables in unamended subplots.

Principal component analysis only provides a general idea about response variable and the treatment effects. When explaining PCA results, care must be taken, because PCA does not always work when there are a large number of original variables, especially when these original variables are uncorrelated (Manly 1986, P60). For example, in the loading plots (Fig. 6.3), plant variables and soil extractable N were displayed in opposite directions. However, this did not simply mean that plant variables are negatively correlated with soil extractable N. This only suggests that soil extractable N may not be a main factor limiting plant growth under assumptions of isonitrogeneity. In fact, soil extractable N is not always reliable to predict soil N availability in the Maritimes (Dr. Phil Warman, personal communication). It is speculated that nematode and wireworm infestations are critical factors limiting potato growth in the current experiment.

6.6 Conclusion

Principal component analysis provides a comprehensive way to integrate plant and soil variables to visualize the treatment effects and the variable responses and relationships. Principal component analysis is also a useful tool to evaluate general soil amendment effects, which, otherwise, can not be assessed in the current nested design. The similarities and differences of treatment effects were clearly visualized in ordination plots by PCA. In both amended and unamended subplots, three soil amendment treatments were well separated. The 1- and 2-years forage rotations were not separated, but were well separated from the 0-years forage rotations. Plant variables were the most important variables in explaining overall variation in the data, and plant biomass C may be a representative plant variable. Soil N_{tot} and soil extractable N were the most valuable soil variables in amended subplots, while soil C_{tot} and SMBC were the most important soil variables in unamended subplots in explaining the variation in the data. In amended subplots, the soil amendment factor had a larger effect on overall variables than the forage factor. In unamended subplots, however, there was no clear pattern to determine if one factor was more important than the other.

Table 6.1 Plant and soil variables included in the principal component analysis

Variable	Abbreviation	Sampling date (2005, yr 4)
Soil bulk density	SBD	Sep. 23
Cation exchange capacity	CEC	Sep. 23
pH	pH	Sep. 23
Soil total carbon	SC_{tot}	Sep. 23
Soil total nitrogen	SN_{tot}	Sep. 23
Soil extractable nitrogen	SN	Sep. 23
Soil nitrogen supply rate	SNSR	Jul. 11-25
Soil extractable P_2O_5	SP	Sep. 23
Soil extractable K_2O	SK	Sep. 23
Soil K_2SO_4-soluble carbon	SSC	Sep. 23
Soil microbial biomass carbon	SMBC	Sep. 23
Soil dehydrogenase activity	DHA	Sep. 23
Plant biomass carbon	PC	Aug. 23
Plant nitrogen uptake	PN	Aug. 23
Plant phosphorus uptake	PP	Aug. 23
Plant potassium uptake	PK	Aug. 23
Total potato tuber dry weight	TW	Sep. 8

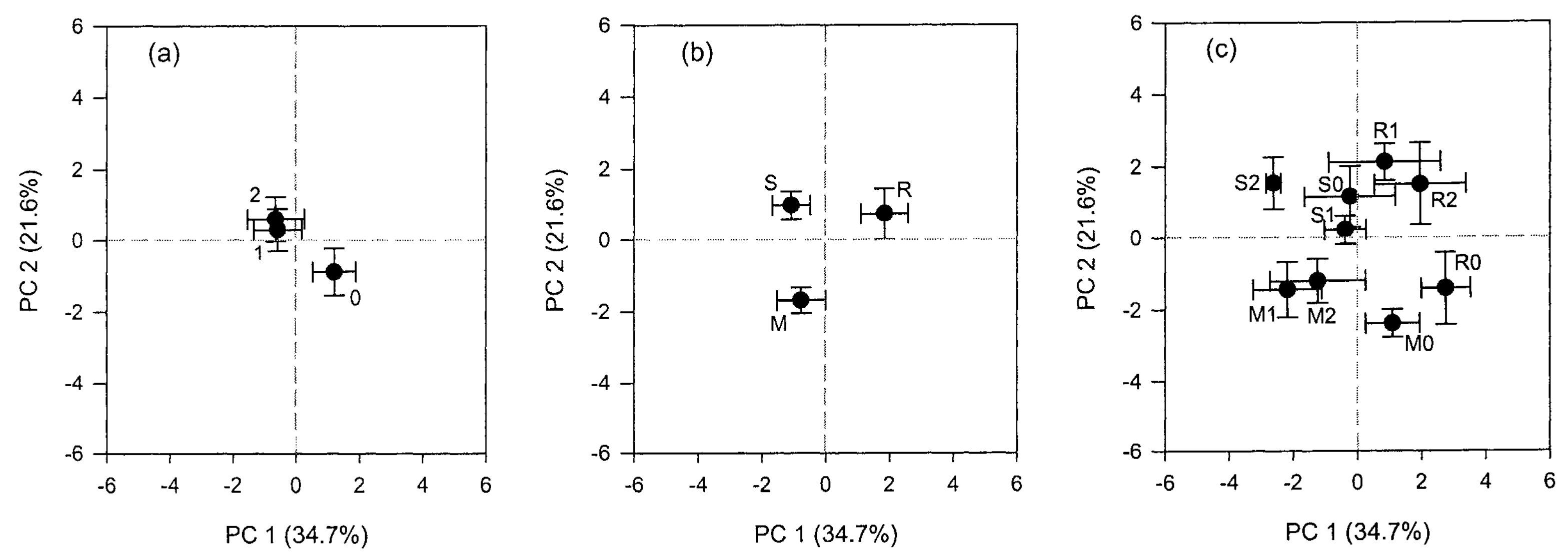

Fig. 6.1 Ordination plots of principal component (PC) 1 and 2 based on plant and soil variables in yr 4 amended subplots at different factor levels.

Notes: (a), three forage levels (0, 1, and 2); (b), three soil amendment levels (M, R, and S); (c), nine farming systems composed of three forage and three soil amendment levels. Bars represent standard error of means.

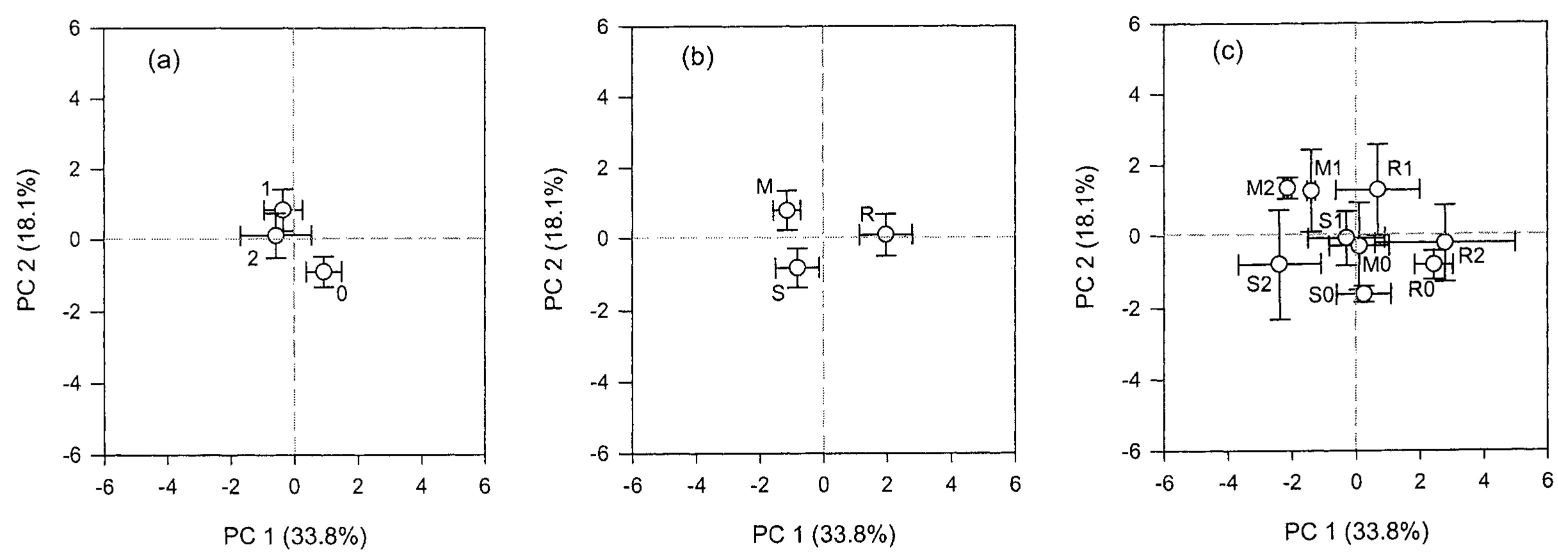

Fig. 6.2 Ordination plots of principal component (PC) 1 and 2 based on plant and soil variables in yr 4 unamended subplots at different factor levels.

Notes: (a), three forage (0, 1, and 2) levels; (b), three soil amendment (M, R, and S) levels; (c), nine farming systems composed of three forage and three soil amendment levels. Bars represent standard error of means. Error bars represent standard error of means.

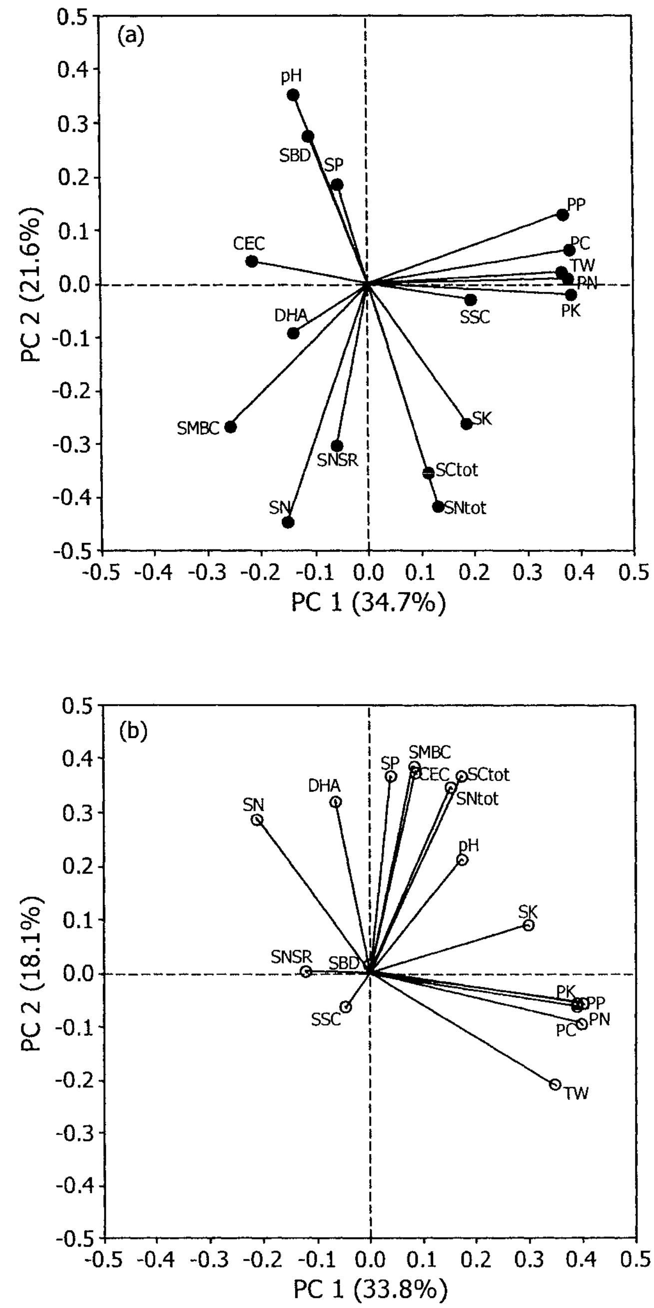

Fig. 6.3 Loading plots for the first two principal components in yr 4 (a) amended subplots and (b) unamended subplots.

Notes: Vectors denoted by line ended with dot are the correlation of the original variables with PC 1 and PC2. SBD, soil bulk density; CEC, cation exchange capacity; SC_{tot}, soil total carbon; SN_{tot}, soil total nitrogen; SN, soil extractable nitrogen; SNSR, soil nitrogen supply rates; SP, soil extractable phosphorus; SK, soil extractable potassium; SSC, soil K_2SO_4-soluble carbon; SMBC, soil microbial biomass carbon; DHA, dehydrogenase activity; PC, plant biomass carbon; PN, plant nitrogen uptake; PP, plant phosphorus uptake; PK, plant potassium uptake; TW, total potato tuber dry weight.

CHAPTER 7 DISCUSSION

7.1 General Discussion

This chapter integrates previous chapters to discuss soil and plant responses in organic potato rotations, especially N responses to soil amendments and forages. This chapter also addresses the methodology, and finally summarizes the results.

7.1.1 Is isonitrogeneity possible in organic cropping system research

Nitrogen management is the focus of nutrient management for most crops in cultivated soils. In organic systems, N availability rather than total N is considered a key factor influencing crop production (Watson et al. 2002). Isonitrogeneity is referred to as equalizing soil extractable N levels by adjusting soil amendment application rates, according to soil test recommendations and assumed N availability of soil amendments. Numerous studies have demonstrated that N application rates tremendously affect soil N content and plant production (Warman 1986; Ma et al. 1999b; Hammermeister et al. 2005). In practical cropping systems, N is applied as minimally as possible to eliminate environmental pollution, and is normally estimated by soil test recommendations. We also recognized that P could cause potential water pollution, since P application rates associated with composts may be higher than crop P requirements. In this current experiment, N was emphasized, and soil amendments application rates was based on N. Nitrogen is considered one of the most important nutrient elements affecting crop production. Crops also have larger N requirements contrasted with P requirements, and respond to different N levels. Therefore, the cropping system assessment might have been more meaningful if the plant available N supplies were controlled at the same levels.

In organic agriculture, N input is mainly in organic form and N availability is affected by types, chemical composition, and rates of soil amendments. Hence, the challenges of isonitrogeneity are increased compared with conventional agriculture. However, isonitrogeneity may be achieved by management practices based on the understanding of soil N cycling in cropping systems.

In addition to soil N, legume biological N_2 fixation and recycling of crop residues as well as soil amendment inputs are main N sources in organic cropping systems. Since 95% of soil total N and most of external N are in organic form, prior to plant uptake, such organic N needs to be converted to inorganic N by a process called N mineralization. Typically, around 2.5% of soil total N is likely to be mineralized annually (Brady and Weil 1999, P497). In the current experiment, soil N availability was primarily regulated by soil amendments and forage residues. Soil amendment N mineralization rates vary substantially because of different chemical composition (Fox et al. 1990; Oglesby and Fownes 1992; N'Dayegamiye et al. 1997; Pengoo et al. 2002), C: N ratio (Amlinger et al. 2003), and application rates (Hébert et al. 1991). Nitrogen availability from legume residues was affected by legume species (McNeill et al. 1998; Evans et al. 2001) and maturity (Thompson and Fillery 1998). Nitrogen mineralization rates were also affected by factors influencing microbial activity such as soil temperature (Ellert and Bettany 1992), soil moisture (Campbell et al. 1984), soil pH (Stanford and Smith 1972), and soil disturbance (Silgram and Shepherd 1999).

As a nutrient sink and pool, soil microbial biomass was considered to be an N mineralization indicator in the current experiment. Soil microbial biomass carbon was not only determined by soil amendment types and rates, but also was affected by forage residues. Among the three soil amendments, alfalfa meal contains the highest content of readily decomposable C and N, and thus had the highest SMBC and mineralizable N percentage. Soil amendment application rates also influenced SMBC. For example, the relatively low SMBC in the alfalfa meal treatment in the 1-year forage rotation was primarily attributed to low alfalfa meal application rates. Forage residues not only increase N input, but also supply a readily decomposable C source for microbial use. Therefore, SMBC was increased with increased forage frequency. Soil microbial biomass turnover rates averaged 0.2 to 3.9 yr^{-1} (McGill et al. 1986). Hence, high SMBC could mean high soil available nutrients. In this experiment, soil mineral N was highly related to SMBC. For example, both SMBC and soil mineral N were not different among the three soil amendments in the 1-year forage rotation or between two composts nested under each forage level, but were significantly higher in S treatments than in M or R treatments in 0-year or 2-year forage rotations.

Compared with SMBC, DHA represents microbial activity only from the living microbes, and was more sensitive to management practices, and thus may have large variations. Studies had shown that the preceding forage benefits may be quickly lost in the following heavy feeder crop (e.g. corn) growing season (Acton and Gregorich 1995, P56). Similarly, soil amendments and forage benefits may be weakened at the end of the potato growing season. Hence, no difference was found in DHA determined after potato harvest.

In the current experiment, SMBC was determined after potato harvest, and may not be the most suitable for assessing soil isonitrogeneity in the potato growing season. Alternatively, soil N potential mineralization rates determined in the previous year or soil N supply rates determined at the potato flowering stage was a good indicator for soil isonitrogeneity. The differences in soil N potential mineralization rates or soil N supply rates demonstrated that soil amendment application timing, types and rates as well as forage levels collectively influenced soil extractable N levels, and thus made soil isonitrogeneity difficult to be achieved. For example, soil amendments affected soil N supply rates not only by their own properties, but also through the effects on soil properties. Large volumes of soil amendment inputs could increase soil moisture retention in a potato trial, which in turn may affect the soil N mineralization process and N supply rates (Dr. Derek Lynch, personal communication).

Generally, the soil massive N pool is strengthened in organic cropping systems, and thus soil N supply ability will be enhanced. Soil amendment additions also increase the mineralization of relatively stable SOM through priming effects (Brady and Weil 1999, P451). Therefore, it is possible to equalize plant available N through adjusting soil amendment application rates based on a judicious understanding of N availability in specific soil amendments. However, N availability from soil amendments was not only determined by soil amendment types, chemical composition, and application rates, but also was influenced by total N content in soil amendments (Patriquin and Kungl 1996). These make it difficult to accurately predict N availability from soil amendments. Compost N availability also varied substantially between years. In a potato study where a mixture of composted solid poultry, solid dairy, and liquid hog manure was applied as a N source, apparent N recovery ranged from 26 to 60% among years (Zebarth et al.

2005a). Soil test recommendations were primarily based on soil nutrient content and crop nutrient uptake, whereas N management based on a soil mineral N test was unreliable in humid areas such as eastern Canada (Ma and Dwyer 1999) or the Maritimes (Dr. Phil Warman, personal communication). Soil N availability is also affected by N losses through leaching, run off, denitrification, and volatilization. Therefore, soil isonitrogeneity is an ideal status, and could be achieved theoretically, but may be difficult to achieve in cropping systems such as in the current experiment.

The reason for soil isonitrogeneity violation in this experiment was primarily due to inaccurate assumptions of soil amendment N availability, and was partially due to no adjustment of soil amendment recommendation rates according to nutrient benefits from forage residues and nutrient carryover from soil amendments. Forage P-based compost application plans also made soil isonitrogeneity impractical. A soil mineral N based soil test recommendation is not always reliable in this humid area, and affects the possibility of achieving soil isonitrogeneity.

However, plant N isonitrogeneity was achieved in the current experiment for the following reasons. For this specific experiment established on a fertile soil after sod was broken, forage detrimental effects (i.e. exacerbated wireworm damage) on potatoes might outweigh the above-mentioned factors causing the failure of soil isonitrogeneity. Plant N uptake was affected by other non-nutrient factors such as weeds and potato diseases. High soil N background may also contribute to plant N isonitrogeneity.

7.1.2 N, P, and K in the first cycle of 4-year rotations

Soil amendment application rates in cash crops were determined by crop N demands. This resulted in different P and K inputs associated with soil amendment additions, and possibly caused excessive P input because of the low N:P ratio in composted manures (Withers and Sharpley 1995; Preusch et al. 2002) and rock P supplement as well. Alternatively, compost application rates in the forage plots were determined by forage P demands. This resulted in excessive total N additions in forage plots. Such complicated soil amendment application plans made external N, P, and K inputs quite different among treatments. Soil nutrient content not only responded to such different application rates, but also responded to types of nutrient inputs. For example, high total P input associated with composted poultry manure resulted in high soil P_2O_5 levels, while high total P input associated with rock P did not result in high soil P_2O_5 levels. High K input associated with composted beef manure resulted in high soil K_2O content. The highest soil mineral N content in alfalfa meal amended 2-year forage treatments was a result of N additions from both forage residues and high alfalfa meal input.

Forages in rotations improved soil N through adding forage residues and increasing SMBC. Soil extractable N and soil N supply rates were significantly higher in 1- and 2-year forage rotations than in 0-year forage rotations. Such forage N benefits were confounded with extra compost N application in the forage plots in year 3. Forage N benefits may not have made a big difference between 1-year and 2-year forage rotations because of red clover winter kill in 2-year forage rotations. As a consequence, forage benefits in potato production were not demonstrated in the first cycle of 4-year rotations under these long-term sod conditions. As a preceding crop, forages in rotations appeared to cause soil pest infestations in this specific experiment established on a long-term pasture, and reduced potato tuber yield and plant (potato tops, tubers, and weeds) nutrient uptake. Forage effects on potato tuber yield and plant nutrient uptake would probably become positive after 2 or 3 cycles of crop rotations.

Plant nutrient uptake was mainly determined by plant biomass accumulation. Factors such as soil available nutrients, weeds, diseases, and pests influence plant growth and play a critical role in plant nutrient uptake. Hence, plant nutrient uptake reflected the whole process involved in an entire plant growing season. In the amended subplots, since nutrient supply was not a main factor limiting potato growth, plant nutrient uptake and tuber yield were mainly determined by non-nutrient effects such as pest damage. Studies (Ferro and Boiteau 1993; Powelson et al. 1993; Stark and Love 2003, P82) demonstrated that preceding forages exacerbated wireworm and nematode damages to the subsequent potatoes. A preliminary observation done in the subsequent wheat plots in 2006 confirmed that the wireworm population in this ongoing experiment was the higher in 1- and 2-year forage rotations than in the 0-year forage rotation. As a consequence, plant nutrient uptake and tuber yield were lower in forage rotations than in non-forage rotations. This contradicted evidence of soil available N which was higher in forage rotations than in non-forage rotations.

Forages and soil amendments interactively affected potato tuber yield and plant nutrient uptake. On the one hand, high rates of soil amendment inputs resulted in high tuber yield and plant nutrient uptake. For example, in the S treatment, substantial differences in cumulative application rates are the main factor influencing potato growth and nutrient uptake; in the 2-year forage rotation, soil amendment cumulative rates also significantly affected potato yield and nutrient uptake. On the other hand, high forage frequency decreased potato tuber yield and plant nutrient uptake obviously. For example, in M and R amended 1- and 2-year forage rotations where nutrient supplies were adequate, red clover limited potato growth and thus nutrient uptake; whereas in S amended 1- and 2-year forage rotations, application rates primarily determined potato tuber yield and plant nutrient uptake.

Plant nutrient uptake was not completely determined by soil nutrient content. Soil N supply rates determined at the potato flowering stage were the highest in the S treatment among the three soil amendments, and soil extractable N determined after potato harvest was also the highest in the S treatments among the three soil amendments in 0- and 2-year forage rotations. However, plant nutrient uptake and tuber yield were the highest in the R treatments among the three soil amendments. Such contradictory results suggested that soil mineral N in the current experiment was not a main restricting factor for potato growth, and that large volumes of compost (i.e. R) may improve soil properties (i.e. soil bulk density and soil water holding capacity) and thus increase potato growth. Therefore, plant nutrient uptake was not always coincident with soil nutrient content. This agreed with a dairy compost study where corn N, P, and K uptake at harvest were not closely related to soil available N, P_2O_5, and K_2O content determined two months prior to corn harvest (Warman 1995).

Total nutrient balances and soil nutrient trends over the first 4-year cycle demonstrated that total N was enhanced, although soil extractable N was decreased in the first 2 years because of the initial fertile soil, and tended to reach an equilibrium status in the last 2 years; P and soil extractable P were increased in all treatments; K and soil extractable K were enhanced in R and S treatments, but were maintained or decreased in M treatments. This nutrient budget or soil nutrient trend was well supported by other organic farming studies (Watson et al. 2002; Berry et al. 2003).

The current experiment was also analyzed from an economics perspective (Ordóñez 2006), showing that the composted beef manure amended 2-year forage rotation was the most profitable cropping system among the nine forage and soil amendment cropping systems.

7.2 Methodology Improvement

The current experiment was originally designed as a long-term trial without a soil amendment control. In a 4-year crop rotation including heavy feeders such as wheat and potatoes, without soil amendment inputs it would be difficult to balance nutrients under long term nutrient management. It is common for farmers to apply soil amendments. Based on these thoughts, plots without soil amendment inputs (control plots) were not included in the initial experimental design. However, it would have been extremely useful to have included a soil amendment control for the short term (4 years) experiment, so that it would have been easier to assess the effects of soil amendments on soil fertility, with control plots as reference values. Fortunately, a control plot in the adjacent trial, which was established at one end of the current (core) plots, provided the valuable plant nutrient uptake data in year 1. The control plots were added in year 2 using the adjacent trial plots. Since the control plots were not originally included, the forages in the 2-year forage rotation in control plots were directly seeded in year 2, whereas the forage crops in the 2-year forage rotations in core plots were underseeded in year 1. The control plots were located at one end of the core plots, but should have been completely randomized with the core plots. In year 4, three of nine control plots were completely flooded after potato seeding, leaving no potatoes growing in these three plots. To compensate for the lack of control plots, the soil nutrients were compared before and after the first 4-year experiment.

The current experiment mimicked the realistic farming practices when making decisions about soil amendment application rates. Both forage and soil amendments were expected to provide crop N, and had complicated effects on crop management throughout the whole experimental period. For example, in order to prompt red clovers to biologically fix atmospheric N_2 rather than absorb soil available N, soil amendment inputs in year 1 were reduced by half in the 2-year forage rotations compared with the 0-

or 1-year forage rotations. In year 3, soil amendment application rates for barley in the 0-year forage rotations were based on soil N test recommendations, while soil amendment application rates for forages in the 1- and 2-year forage rotations were based on soil P test recommendations. Moreover, forage plots in year 3 received rock P in S treatments, composted poultry manure in M treatments, and composted beef manure in R treatments for forage P requirements. Therefore, there were large differences in actual input among the three soil amendments (M, R, and S), and extra N was applied along with composts in M and R amended forage plots. Such soil amendment application strategies were commonly used by farmers for maximal use of on-farm nutrient sources and for avoiding excessive nutrient inputs. The soil amendment application rates were affected by forage frequency, making the examined two factors (soil amendment and forage levels) interdependent. Also, the soil amendments used in year 1 were different from those in year 4, and the total soil amendment applications were different among the three soil amendments; therefore, it is difficult to compare three soil amendment effects on the collected variables using an univariate analysis techniques. Principal component analysis, one popular multivariate analysis, is a good tool to summarize the effects of forage, soil amendment, and forage soil amendment combinations.

The current experiment represents the beginning stage of a proposed long term experiment, and the rotation effects may not show up in the first cycle of a crop rotation. It would be much more valuable to investigate the cropping systems after two or three cycles of crop rotations. The current crop rotations were single phased, and could put the whole experiment at a high risk if the key crop (i.e. potatoes) failed because of unpredictable factors such as uncontrollable weather or severe pest and disease damage. Ideally, a fully phased crop rotation, a rotation where all rotational crops in a crop rotation were planted in any given year, not only reduces the above-mentioned risk, but also makes rotation effect assessment much easier and comprehensive.

The current experiment was established on a high N level soil after a long-term sod was broken down. The long-term pasture background appeared to exacerbate pest damage (i.e. wireworm, scab, or nematode damage), especially in the 1- and 2- year forage rotations, and thus weakened the expected positive forage effects on potato tuber yield. The high N background may also have masked soil amendment N effects, and made it difficult to separate soil amendment effects. Also, the assumed N availability in composts was far from the actual N availability and weakened the cropping system evaluation.

In the current experiment, the plot size was only 30 m^2 and alley ways were 4-m wide. The plot size and alley ways could have been enlarged, so that it would have been much easier to avoid soil amendment cross contamination, and to facilitate field operations, especially for a long-term trial. It may also be necessary to add one more block to further reduce error since the experimental site was not so even in soil fertility. With the increase of replications, the overall soil and plant data could be further analyzed using factor analysis and canonical discriminant analysis to select variables, which were sensitive to forage and soil amendment management.

Since the current experiment was established after a long-term sod was broken, the results generated from the current experiment can not be applied to the similar experiment establish on a cultivated soil. Hence it may be worth replicating the experiment on a cultivated soil.

It is necessary to keep in mind that a fully-phased crop rotation or more replications would increase the experimental cost. On a monogastric livestock farm, the fate of forages may be a dilemma, because the livestock can not directly utilize the forages although forages could be ploughed down or used as a potato mulch as in a stockless farm. To compensate for these factors, changes of the experimental design as the following could be considered. The three levels of the forage factor could remain the same, and the three levels of soil amendment factor could be 1) no soil amendment, 2) alfalfa meal, and 3) composted beef manure. It would also be much more meaningful to include the fully-phased alfalfa meal amended rotations.

Several related parameters could be further investigated. Nitrogen availability in soil amendments is the key to determine application rates. Soil N availability under organic conditions is mainly mediated by soil microorganisms; therefore, the number, type, and activity of microorganisms would be useful in further explaining soil N availability. Amino acid, an important organic N form, plays an important role in N availability under organic conditions, and could have been investigated. As for soil test recommendation, microbiological parameters in soil and compost should also be considered when deciding soil amendment application rates. Pest damage was speculated to be the main reason for the low potato tuber yield and plant nutrient uptake in the specific experiment. Therefore, wireworm and nematode should have been further investigated.

7.3 Conclusions

Soil isonitrogeneity was not achieved. Soil extractable N and soil N supply rates were significantly affected by the three forage levels. As a result of N benefits from forage residues, N carryover from the extra compost N input in the 1- and 2-year forage rotations, soil extractable N and soil N supply rates were increased with increased forage levels. Soil extractable N and soil N supply rates were not significantly different between 1-year and 2-year forage rotations, because of winter kill in 2-year forage rotations. Soil P_2O_5 or K_2O levels were not significantly affected by the three forage levels. Soil amendment application rates and types significantly affected soil extractable N, P_2O_5, K_2O, and soil N supply rates. Nitrogen availability from composts was far lower than the assumed N availability, and N availability from alfalfa meal was similar to the assumed N availability. Among the three soil amendments, soil N supply rates were the highest in the S treatments; soil P_2O_5 levels were the highest in the M treatments and the lowest in the S treatments; soil K_2O levels were the highest in the R treatments and the lowest in the M treatments. In order to avoid P or K depletion in the long term, the 1- or 2-year forage rotations amended with R were preferred from a soil nutrient perspective.

Soil microbial biomass carbon and DHA showed an increased trend with increased forage levels, but were not significantly different among the three forage levels because of high soil background C. Dehydrogenase activity was not significantly affected by soil amendments nested under the three forage levels. However, soil amendment application rates and types as well as forage levels significantly affected SMBC. After 4-year potato rotations, soil microbial biomass carbon was significantly higher in the S treatments than in the M and R treatments in 0- and 2-year forage rotations.

Forages in 1- or 2-year forage rotations had a detrimental effect on potatoes as a result of pest (i.e. wireworm and nematode) infestations in the current experiment, which was established after a long-term sod was broken. Plant biomass C, plant P and K uptake as well as potato tuber yield were significantly affected by forage levels, and were the highest in the 0-year forage rotations among the three forage levels. They were not different between 1-year and 2-year forage rotations. Plant N uptake was not affected by forage or soil amendment levels. Plant biomass C, plant P and K uptake, and potato tuber yield were significantly affected by soil amendment application rates and types, and were the highest in R treatments among the three soil amendments. The actual potato tuber yield and plant nutrient uptake were determined by both soil amendment positive effects and forage negative effects, and were the highest in the 0-year forage rotations amended with R among the nine forage and soil amendment combinations.

Soil amendment application rates and types as well as forage levels affected soil nutrient changing trends and nutrient balances in the first cycle of 4-year rotations. Soil C_{tot}, N_{tot}, extractable P_2O_5 and K_2O content showed increasing trends, but soil extractable N content was decreased in the first two years because of the high background mineral N, and tended to reach an equilibrium state in the last two years. In this short time period, net total N and P balances were positives for all treatments, but the net total K balance showed negative in the 2-year forage rotations amended with monogastric compost as a result of low K input and high forage K removal

Compared with the residual effects of soil amendments, newly added soil amendments to potatoes significantly increased soil N_{tot}, extractable P_2O_5 and K_2O, potato tuber yield, plant (potato tops, tubers, and weeds) biomass C, N and K uptake, and slightly increased soil extractable N and soil N supply rates as well as plant P uptake. Principal component analysis indicated that soil N_{tot} and soil extractable N were the most valuable soil variables in amended subplots, while soil C_{tot} and SMBC were the most important soil variables in unamended subplots in explaining data variation. In the amended subplots, the soil amendment factor had a larger effect on overall variables than the forage factor, while there is no clear evidence to indicate which factors had a dominating effect on overall response variables in the unamended subplots.

Principal component analysis is a useful tool to integrate plant and soil variables, to differentiate treatment effects, and to visualize overall variable relationships. In both amended and unamended subplots, the 1- and 2-year forage rotations were not separated, but were well separated from the 0-year forage rotations. Forage and soil amendment combinations may share similarities or may be well separated, depending on forage levels, types and application rates of soil amendments. Plant variables made more contributions than soil variables to explain overall data variation and to assess field management effects on cropping systems.

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APPENDIX 1 DATA COLLECTED IN THE CONTROL PLOTS IN YEAR FOUR

Block	Forage	SBD	SC_{tot}	SN_{tot}	SN	SP_2O_5	SK_2O	SNSR	SMBC	DHA	TTDW	MTDW	PC	PN	PP	PK
		($g\ cm^{-3}$)	($kg\ ha^{-1}$)						($mg\ kg^{-1}$)	($nmol\ INTF\ g^{-1}\ h^{-1}$)	($kg\ ha^{-1}$)					
1	0	-*	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	2	1.11	23.6	1.77	0.039	0.130	0.148	702	857	72	3391	3347	1498	61	8	66
2	0	0.97	24.7	1.78	0.018	0.080	0.136	651	615	59	2783	2620	1783	69	10	77
2	1	0.98	26.6	2.05	0.028	0.021	0.109	914	622	67	2940	2914	719	36	4	22
2	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	0	1.05	25.4	1.88	0.025	0.111	0.209	756	364	64	2183	2146	1124	57	6	68
3	1	1.05	23.7	1.75	0.031	0.123	0.139	958	652	47	907	869	603	22	2	24
3	2	1.08	25.2	1.84	0.040	0.110	0.166	833	463	57	1099	1054	659	31	3	35

* Data were not available as the plots were flooded in the early potato growing season.

APPENDIX 2 N AVAILABILITY OF AMENDMENTS APPLIED IN YEAR ONE*

	C_{tot} ($g\ kg^{-1}$)	N_{tot} ($g\ kg^{-1}$)	N availability (% of N_{tot})	N_o † ($g\ kg^{-1}$)	k‡ (wk^{-1})
M§	207	16.3	14.6	0.180*a*	0.197*a*
R**	344	26.3	22.0	0.210*a*	0.167*a*
S††	443	22.9	26.5	0.210*a*	0.229*a*
Soil control	28	2.2	6.8	0.146	0.191

* Soil amendments incubation rates were 400 kg N_{tot} ha^{-1}; Estimates in the N_o column followed by the same letter were not significantly different at the 5% level, and estimates in the K column followed by the same letter were not significantly different at the 5% level.

† N_o represents soil N potential mineralization.

‡ k represents soil N potential mineralization rate constant.

§ M represents composted poultry manure.

** R represents composted beef manure.

†† S represents alfalfa meal.

APPENDIX 3 MEANS OF SOIL VARIABLES IN YEAR FOUR*

	Amended subplots						Unamended subplots					
	C_{tot}	N_{tot}	N	P_2O_5	K_2O	N supply rates	C_{tot}	N_{tot}	N	P_2O_5	K_2O†	N supply rates
	(g kg^{-1})					(μg 10 cm^{-2} 2 wk^{-1})	(g kg^{-1})					(μg 10 cm^{-2} 2 wk^{-1})
M0	30*c*	2.2*c*	0.022*c*	0.29*ab*	0.22*c*	580.0*c*	29±0.5‡	2.1±0.05	0.024±0.005	0.14*abc*	0.17*ab*	573±35
R0	30*c*	2.2*c*	0.021*c*	0.18*cd*	0.33*ab*	753.8*abc*	30±0.4	2.2±0.03	0.024±0.001	0.17*abc*	0.29*c*	694±116
S0	32*bc*	2.4*bc*	0.034*ab*	0.12*d*	0.26*bc*	838.3*ab*	28±0.3	2.1±0.09	0.023±0.001	0.13*bc*	0.22*bc*	738±176
M1	31*bc*	2.3*c*	0.028*bc*	0.32*a*	0.19*c*	738.5*bc*	31±1.3	2.3±0.05	0.027±0.001	0.20*a*	0.15*a*	864±31
R1	35*a*	2.7*a*	0.035*ab*	0.27*abc*	0.41*a*	802.3*abc*	33±1.8	2.4±0.14	0.034±0.002	0.18*ab*	0.26*c*	814±81
S1	32*abc*	2.4*bc*	0.028*bc*	0.15*d*	0.27*bc*	967.8*a*	31±1.4	2.4±0.11	0.030±0.003	0.12*bc*	0.24*c*	836±108
M2	31*bc*	2.3*c*	0.028*bc*	0.26*abc*	0.19*c*	788.2*abc*	30±0.5	2.2±0..06	0.033±0.004	0.20*a*	0.17*a*	773±103
R2	34*ab*	2.6*ab*	0.034*ab*	0.20*bcd*	0.28*bc*	897.8*ab*	31±1.0	2.2±0.11	0.026±0.040	0.16*abc*	0.24*c*	726±12
S2	30*c*	2.3*c*	0.042*a*	0.11*d*	0.24*c*	963.7*a*	29±0.4	2.2±0.09	0.032±0.007	0.12*c*	0.17ab	812±23

* Least squares means in a column followed by the same letter are not significantly different at the 5% level.

† K_2O concentration in unamended subplots were subjected to reciprocal transformation prior to analysis, and back transferred values were reported.

‡ The error term is standard error or means.

APPENDIX 4 MEANS OF PLANT VARIABLES AT FORAGE LEVELS*

Forage	Amended subplots					Unamended subplots					Greenhouse trial		
	C	N	P	K	Tuber yield	C	N	P	K	Tuber yield	N	P	K
	(kg ha^{-1})												
0	3459*a*	126±8†	16.3*a*	231.6*a*	6500*a*	2785±213	110±8	15±1	166±19	5872*a*	126.7*b*	26.1*a*	200.2*a*
1	2387*b*	108±9	12.2*b*	164.4*b*	5138*b*	2225±198	100±9	12±1	127±16	4648*ab*	137.1*a*	24.7*a*	199.0*a*
2	2564*b*	109±11	12.4*b*	161.3*b*	5481*ab*	2404±403	99±15	13±2	134±34	4368*b*	114.6*c*	21.3*b*	169.5*b*

* Plant biomass C and plant P uptake in amended subplots were log transferred prior to analysis, and back transferred data were reported. Means followed by the same letter in one column are not significantly different at the 5% level.

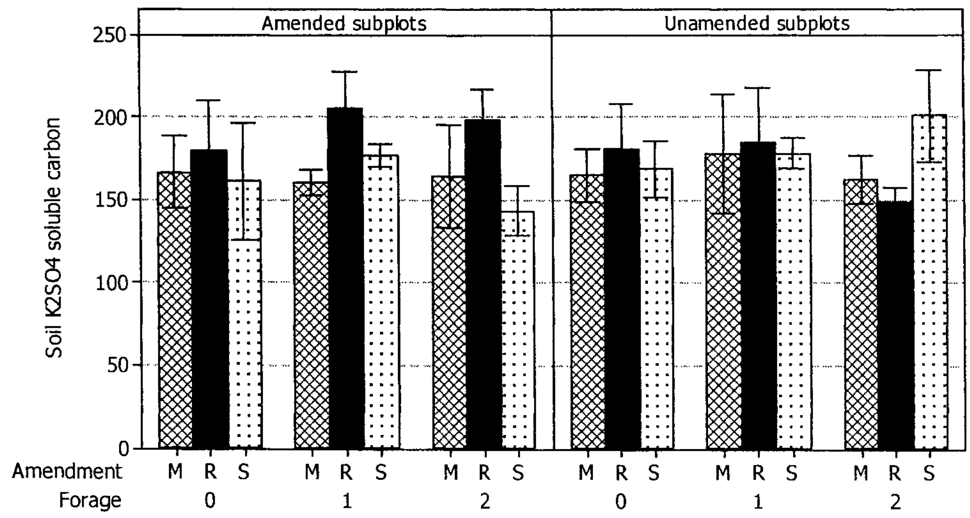
† Error term represents standard error of means.

APPENDIX 5 MEANS OF PLANT VARIABLES AT AMENDMENT LEVELS*

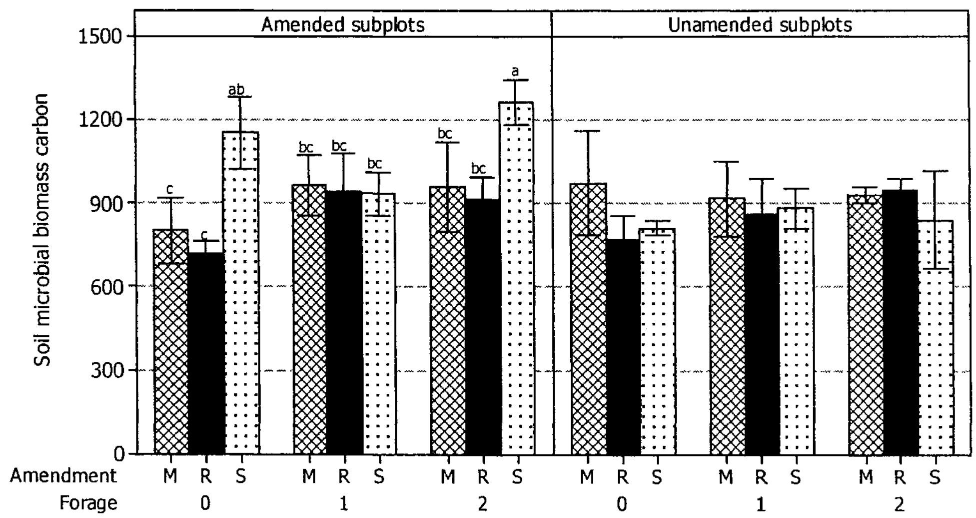
	Amended subplots					Unamended subplots					Greenhouse trial		
	C	N	P	K	Tuber yield	C	N	P	K	Tuber yield	N	P	K
	(kg ha^{-1})												
M0	3575*ab*	124±16[†]	17.5*ab*	212.4*abc*	6600*ab*	2545*abc*	99.3*bc*	14.0*ab*	118.4*cd*	5562*abc*	134.7*ab*	30.1*a*	198.6*b*
R0	3861*a*	141±8	19.5*a*	287.9*a*	7311*a*	3332*ab*	127.7*ab*	17.9*a*	225.4*ab*	6309*ab*	125.1*abc*	27.0*ab*	208.8*ab*
S0	2997*ab*	114±14	12.7*bcd*	194.5*bc*	5587*abc*	2477*bc*	102.5*abc*	13.8*ab*	154.1*bcd*	5745*abc*	120.2*bc*	21.3*c*	193.4*bc*
M1	1965*cd*	97±17	11.1*cd*	110.0*d*	4274*c*	1887*c*	89.0*bc*	10.5*b*	82.0*d*	3779*cd*	132.7*ab*	26.2*b*	186.4*bc*
R1	2733*abc*	114±24	13.0*bcd*	222.0*ab*	5614*abc*	2557*abc*	117.5*abc*	13.8*ab*	174.0*abc*	4562*abcd*	138.9*a*	26.8*ab*	225.2*a*
S1	2531*bcd*	111±11	12.7*bcd*	161.1*bcd*	5526*abc*	2232*bc*	93.5*bc*	11.0*b*	125.0*cd*	5602*abc*	139.7*a*	21.2*c*	185.3*bc*
M2	2650*bcd*	104±20	13.0*bcd*	138.6*cd*	5147*bc*	1720*c*	75.1*c*	9.6*b*	74.9*d*	2775*d*	116.0*cd*	23.8*bc*	170.8*c*
R2	3441*ab*	132±24	15.5*abc*	232.7*ab*	7349*a*	3594*a*	144.9*a*	18.8*a*	246.9*a*	6368*a*	126.6*abc*	23.8*bc*	197.5*b*
S2	1848*d*	90±5	9.5*d*	112.5*d*	3949*c*	1897*c*	75.5*c*	9.3*b*	80.8*d*	3961*bcd*	101.1*d*	16.4*d*	140.4*d*

* Plant biomass C and N uptake in amended subplots were log transferred prior to statistical analysis, and back transferred data were reported. Means followed by the same letter in one column are not significantly different at the 5% level.

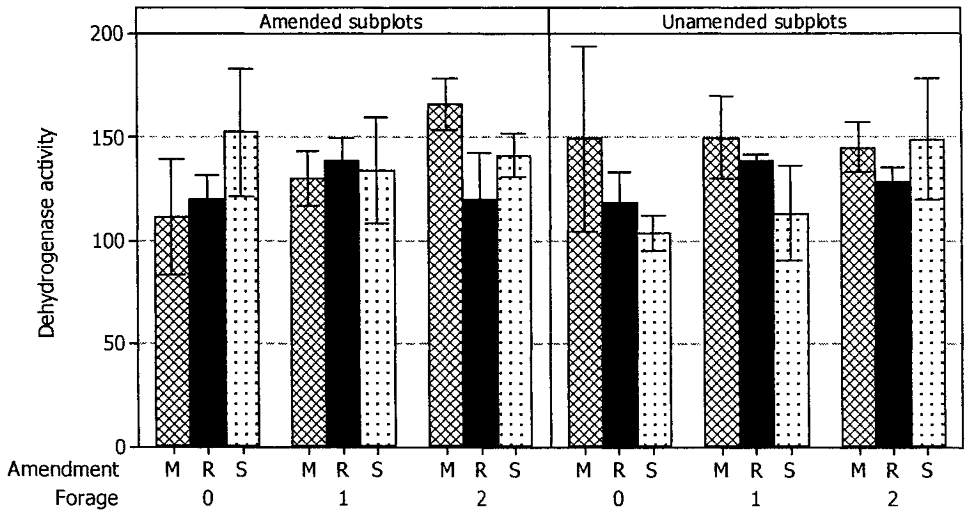
[†] Error term represents standard error of means.



APPENDIX 6 FIGURE OF SOIL K_2SO_4 SOLUBLE CARBON ($mg\ kg^{-1}$) IN YEAR FOUR



APPENDIX 7 FIGURE OF SOIL MICROBIAL BIOMASS CARBON (mg kg^{-1}) IN YEAR FOUR



APPENDIX 8 FIGURE OF SOIL DEHYDROGENASE ACTIVITY (n mol INTF g^{-1} h^{-1}) IN YEAR FOUR