CHAPTER 14

Soil C Sequestration Management Effects on N Cycling and Availability

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CONTENTS

INTRODUCTION

The impact of soil C sequestration on nitrogen (N) cycling and fertilizer use efficiency by crops has received little attention in the context of long-term fertility. It is generally taken for granted that more soil organic matter (SOM) is a key indicator of enhanced soil quality and thus leads to sustainable soil fertility. The importance of SOM in cropping system sustainability is in its ability to store nutrients and improve soil structure. The challenge in determining nutrient availability in cropping systems designed to accumulate SOM is in assessing the (1) temporal availability of nutrients, (2) interaction of fertilizer N with organic N pools, and (3) relationship of SOM turnover dynamics to nutrient availability. For these reasons, soil C sequestration benefits for mitigation of carbon dioxide-related climate change and soil quality enhancement must carefully be weighed against potential N and other nutrient availability as a result of increased SOM.

The increase in stable SOM under soil C sequestration management may lead to the immobilization of N and other essential nutrients such as phosphorus, sulfur, and essential micronutrient metals. However, as SOM increases, components of the soil controlling nutrient cycling, such as the active fraction, also increase (Paul and Clark, 1996). The active fraction is composed of plant residues, root exudation, light fraction, labile SOM, and the microbial biomass (Tisdall and Oades, 1982). As SOM begins to accumulate initially in soil, the ability of the active fraction to supply nutrients for plant uptake is limited, due to mineralization-immobilization reactions associated with changes in microbial substrate use efficiency caused by changes in the quality and increase in C inputs.

As soil C sequestration proceeds, an equilibrium between C inputs and nutrient availability occurs, leading to sustained plant nutrient availability (Doran et al., 1988). This scenario is ideal in natural ecosystems or with perennial plants where nutrient uptake can occur over the growing seasons. However, in agronomic systems, nutrient uptake occurs in a narrow time frame not fully taking advantage of the potential N mineralization from increased SOM. In addition, interaction among nutrient sources and C inputs may affect their availability.

Interaction among fertilizer sources and C inputs has been demonstrated under a variety of field and laboratory conditions (Jenkinson et al., 1985; Hart et al., 1986; Powlson and Barraclough, 1993). The priming of soil N or the added nitrogen interaction (ANI) is often caused by changes in fertilizer sources or quality of plant residue inputs to soil. The ANI often causes changes in the N-use efficiency of crops (Azam et al., 1985; Ehaliotis et al., 1998). The implication of ANI is that the contribution of N from residue management practices or manure additions is underestimated when compared with fertilizer N additions. An increased level of soil C directly influences ANI, increasing the size of the soil microbial biomass and exacerbating its role as a source and sink for essential plant nutrients.

The low recovery of N from organic amendments is in part attributable to not determining belowground N allocation, which often leads to underestimates of N-use efficiency (Juma, 1993). The role of the rotational effect must also be considered (Elliott et al., 1987). Another reason may be that components of organic residues will be mineralized at different rates as the system stabilizes over time (Parr and Papendick, 1978). The size and activity of the microbial biomass are critical factors that regulate the turnover and stabilization of N in SOM. For these reasons, the influence of residue management practices designed to sequester soil C must be understood to determine plant N availability.

The consequences of soil C sequestration management may impact nutrient availability through the immobilization of essential nutrients or interaction with the quality and quantity of soil C inputs. Results are presented that examine the effect of managing for soil C sequestration on available N in soil. In addition, data are presented on the efficiency of plant residue conversion into stable SOM. These results are critical to understanding agronomic performance under soil C sequestration management.

MATERIALS AND METHODS

Site Description

The Sustainable Agriculture Farming Systems (SAFS) Project was established in 1988 at the agronomy farm of the University of California at Davis. The 11.3-ha site is dedicated to the study of agronomic, economic, and biological aspects of conventional and alternative farming systems in California’s Sacramento Valley. The soils are classified as Reiff loam (coarse-loamy, mixed, nonacid, thermic Mollic Xerofluvents) and Yolo silt loam (fine-silty, mixed, nonacid, thermic Mollic Xerofluvents).

Description of the Farming System

The study consists of two conventional and two alternative systems that differ primarily in crop rotation and use of external inputs. These include 4-year rotations under conventional (Conv-4), low-input (LI), and organic (Org) management and a conventionally managed 2-year (Conv-2) rotation. The three systems in the 4-year rotations include processing tomatoes, safflower, bean, and corn. In the conventional 4-year treatment, beans are double-cropped with winter wheat. In the low-input and organic treatments, beans typically follow a biculture of oats and vetch that serves as either a cover crop or cash crop. The conventional 2-year treatment is a tomato and wheat rotation typical of farming systems of the region. Table 14.1 shows details of the farming system treatments.

The organic system is managed according to practices recommended by California certified organic farmers (Anonymous, 1990) that do not allow synthetic chemicals. Fertilizer N sources include legume and grass cover crops, composted animal manures, and occasional organic supplements. The low-input system has legume cover crops to reduce the amount of synthetic fertilizers. The conventional systems are managed with standard chemical inputs of pesticides and various N fertilizers. Each cropping system has four replications for each of the possible crop rotation entry points, resulting in a total of 56 plots, each measuring 68 m $\times$ 18 m. Treatments are arranged in a split-plot design, with cropping systems as the main plot treatments, and crop point of entry as subplot treatments. Total C and N inputs to the various farming systems over a 10-year period from 1988 to 1998 are summarized in Table 14.2.

Fertilizer and Vetch N Uptake

During the winter of 1997 to 1998, a 9 m^2 area of vetch (*Vicia* spp.) cover crop was labeled with ^{15}N labeled $(NH_4)_2SO_4$ (49 atom% ^{15}N) in the low-input and organic system entry points to be planted with maize in the spring of 1998. In order to ensure uniform labeling of plant components, vetch received ^{15}N-labeled $(NH_4)_2SO_4$ on October 23, 1997, November 22, 1997, and February 27, 1998, totaling a rate of 9 kg N ha^{-1}. In April of 1998, the ^{15}N labeled vetch shoots were harvested

Table 14.1 Description of Treatments, Crop Rotations, and Agronomic Management

Treatment	Crop Rotation	Agronomic Management
Organic (Org)	Tomato, safflower, corn, oats/vetch, bean	Four-year, five-crop rotation using composted manure, legume and grass cover crops, and organic supplements; no synthetic pesticides or fertilizers
Low-input (LI)	Tomato, safflower, corn, oats/vetch, bean	Four-year, five-crop rotation relying on legume and grass cover crops and one half synthetic fertilizer applied
Conventional 4-year (Conv-4)	Tomato, safflower, corn, wheat, bean	Four-year, five-crop rotation using synthetic fertilizer and pesticides
Conventional 2-year (Conv-2)	Tomato, wheat	Two-year, two-crop rotation relying on synthetic fertilizer and pesticides

Table 14.2 Amount of C and N Inputs over a 10-Year Period to the Various Farming Systems

	Input (Mg ha^{-1})	
Farming System	**C**	**N**
Organic	42.9 (d)	1.96 (c)
Low-Input	39.4 (c)	1.65 (a)
Conventional-4	36.1 (b)	1.92 (c)
Conventional-2	29.3 (a)	1.74 (b)

and shredded to simulate mowing. Similar sized areas of unlabeled vetch were also harvested and shredded at this time.

Subplots measuring 4 m^2 were established in the maize entry point of the conventional, low-input, and organic cropping systems in April of 1998. To ensure integrity, subplots were established a safe distance from the areas of enriched vetch in the low-input and organic systems. The vetch cover crop was cleared from these subplots in the low-input and organic systems before application of ^{15}N labeled and unlabeled additions. Characteristics and quantities of inorganic and organic N additions to each subplot are recorded in Table 14.3. Incorporation of the vetch was performed 6 days prior to seeding the maize. Side dressing of ^{15}N urea was applied 36 days after seeding.

Table 14.3 Characteristics of N Amendments to Three Cropping Systems at SAFS

Cropping System	Subplot	Amendment	Quantity (kg ha^{-1})
Conventional	1	^{15}N urea	220[a]
	2	—	—
Low-input	1	^{14}N vetch	100
	2	^{15}N urea	90[a]
	3	^{15}N vetch	120
		^{14}N urea	90[a]
		—	—
Organic	1	^{15}N vetch	105
	2	^{14}N manure	330
		—	—

[a] An additional 7 kg unlabeled N ha^{-1} was applied as starter fertilizer at seeding.

Soil and Plant Sampling

The soil collection for C dynamics consisted of taking 30 separate soil cores at depth of 0 to 15 cm from each experimental plot and then compositing them for the analysis of SOM humic fractions. The soils were dried at 35°C, sieved to pass through a 4-mm screen, and stored at 4°C until processed. Plant sampling from the ^{15}N microplot studies consisted of taking punches of leaf material from the centers of all microplots.

Sample Preparation and Analysis

Subsamples of air-dried soil were ball milled. Separated humic fractions were freeze-dried and ground to a fine powder prior analysis for total N and C content and determination of $^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratios by dry combustion-continuous flow isotope ratio mass spectrometer GC-IRMS (Europa Scientific, Crewe, England). Ash content of isolated humic fractions was determined after heating at 550°C for 2 hours. Plants were ground and analyzed for N and ^{15}N and analyzed as above.

Chemical Separation of Soil Humic Fractions

The chemical fractionation procedure for the isolation of humic fractions was adapted from Stevenson (1994). Prior to extraction with a 0.4N NaOH solution under N_2, air-dried soil samples were washed with a 0.1N HCl solution to remove carbonates and plant debris. The NaOH extraction was repeated until no humic substances could be extracted. The humic acids were separated from fulvic acids by precipitation after acidification to pH 2. The humic acid, fulvic, and humin fractions were freeze-dried and analyzed on a GC-IRMS (Europa Scientific, Crewe, England) for ^{15}N, ^{13}C, and total N and C.

Statistics and Calculations

Statistical analyses were performed using StatView Software (StatView 4.5, Abacus Concepts Inc., Berkeley, CA); significant differences between treatments were measured after Fisher's PLSD at a significance level of 5% and analysis of variance (SNK). Determination of plant C to SOM was done using the isotope mixing model described by Balesdent and Mariotti (1996).

RESULTS AND DISCUSSION

Changes in soil C content will affect N cycling through changes in the amount and quality of soil C inputs. In addition, the conversion of plant residues into stable organic matter is also related to the amount, quality, and timing of soil C inputs. Together these processes affect the sustainability of cropping systems through changes in nutrient availability. A major question to ask is whether the influence on nutrient availability is short-term (occurring during the transition) or long-term. If the change in nutrient availability is long-term, then fertilizer practices would need to be reevaluated to compensate for changes in long-term soil fertility. Substantial increases in fertilizer input could offset the gains in soil C sequestration management efforts. These questions can only be answered by examining long-term experiments to assess changes in soil management practices designed to examine N interactions and SOM dynamics.

Soil Carbon Dynamics

Analysis of the soils from the cropping system treatments showed that the Org and LI treatments experienced significant increases in soil C and N compared to the conventional treatments (Figure 14.1). Soil C levels increased by 36%, 18%, and 13% in the ORG, LI, and CONV-4 treatments, respectively, compared to the CONV-2 treatments in the 0 to 15 cm soil depth. Similar increases were noted for soil N. The increase in soil C and N in the ORG and LI treatments can be attributed to the use of manure and cover crops. The increase in total soil C in the CONV-4 compared to the CONV-2 treatment is most likely attributable to the crop rotation effect. The increase in soil C and N was a result of input rather than changes in tillage. The organic and low input actually received more tillage because of the extra operations associated with incorporating the cover crops and manure. These results show the value of C inputs to soil to sequester C.

Changes in soil C occurred only in the surface 0 to 15 cm depth of soil. The organic system showed the highest increase in total C to a depth of 60 cm. (Figure 14.1). There is no significant difference between the LI (legume-based system) and the CONV-4 (fertilizer-driven system) treatments. These results suggest that the composted manure applied in the organic system is mostly responsible for the increase in SOM-N and SOM-C. The shift from 2-year rotation to 4-year rotation in the conventional system was enough to promote the build-up of total SOM and shows the value of crop rotation in sequestering soil C.

Conversion of C Inputs into SOM Fractions

The proportion of the total C input converted into SOM is equivalent in both Org and CONV-4 systems (Figure 14.2). Significantly less C was converted into SOM in the LI treatment. The LI treatment also had the lowest amount of fulvic acids compared to the other treatments. However, considering the high input of C in the Org system compared with the others, significantly more C (T ha^{-1}) was lost in this system while the Conv-4 treatment lost the least (data not shown). These results indicate that, as C input increases, the efficiency of conversion to stable SOM declines as seen in other studies (Collins et al., 1997). However, the quality of C inputs also can have a great

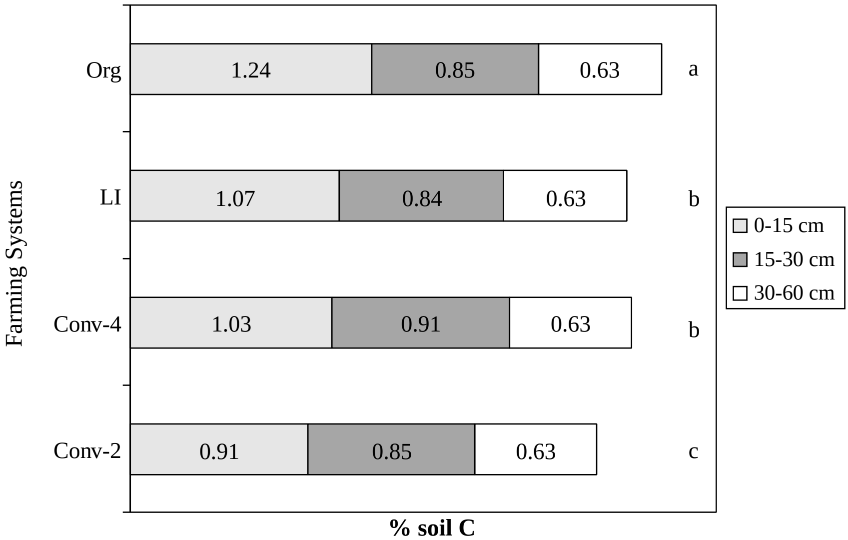

Figure 14.1 Accumulation of soil C (%) by depth in the different farming systems to a soil depth of 60 cm. Significant differences (ANOVA, SNK, P, <0.05) are indicated to the right of the bars and relate only to the 0 to 15 cm soil depth.

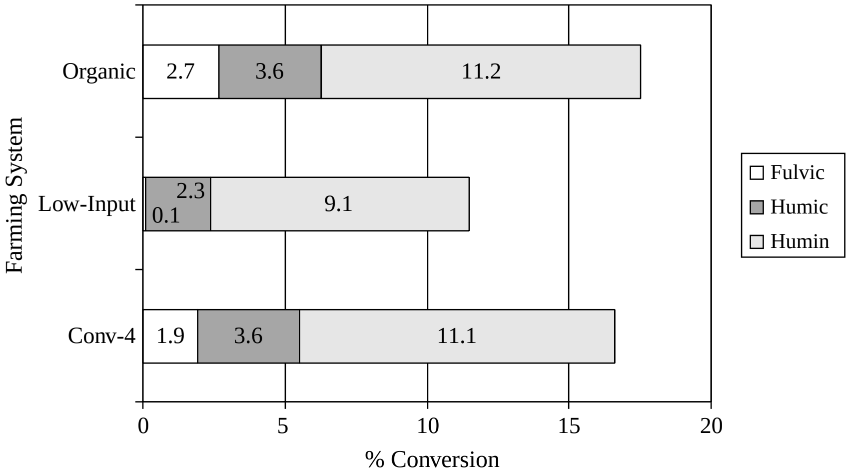

Figure 14.2 The percent conversion of C input into stable SOM fractions.

influence on soil C sequestration. The results show that farming system management can greatly influence the amount of C sequestered into soil. For these reasons, C sequestration strategies must consider fertilizer practices (conventional and alternative) and crops within rotations.

Added N Interactions

Alternative agricultural management, such as organic and low-input, is often applied in agriculture to change or reduce dependence on synthetic fertilizers. These systems are also suited to sequestering soil C. Such systems commonly substitute nitrogen-fixing cover crops, green waste, or manure for all or a large part of a conventional application of fertilizer. Initially, alternative systems receive nitrogen additions in excess of conventional systems in order to produce comparable

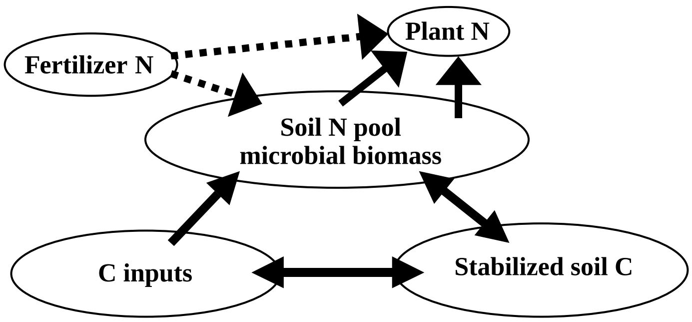

Figure 14.3 Fate of fertilizer N in soil as influenced by the microbial biomass and stable SOM.

yields, possibly leading to adverse environmental impact. However, as soil nitrogen pools increase, these systems retain nitrogen more effectively than conventionally managed systems. It remains a challenge to synchronize soil nitrogen availability with plant uptake in alternative systems. In addition, the management of soil nitrogen availability in alternative systems is complicated because of interactions among different fertilizer sources and soil nitrogen that influence the amount of nitrogen that becomes available to the crop.

The possible fates of fertilizer N in soil are shown in Figure 14.3. The competition for the N between the soil microbial biomass and the crop plant determines the fate of the fertilizer N. The influence of C inputs and stable soil SOM influence microbial activity, thereby influencing the competition for fertilizer N between the microbial biomass and crop plant. In this study, two inputs (manure or mineral fertilizer) were found to increase net recovery of cover crop vetch-derived nitrogen in a corn crop. Manure N significantly increased the uptake vetch N by corn from 13 to 19.6 kg N ha^{-1} (Figure 14.4). Mineral N also induced significantly greater plant uptake of vetch N from 8.9 to 22.7 kg N ha^{-1}. These results show an added N interaction whereby the uptake of vetch N by corn was increased through the addition of another source of N. This N interaction has been demonstrated in numerous other studies (Jenkinson et al., 1985; Azam et al., 1985; Ehaliotis et al., 1998).

As an organic input, greater plant uptake of vetch N could have been the result of increased microbial activity, by which more vetch N would have been mineralized, or increased microbial growth, in which case more vetch-derived N would have potentially been released through turnover of the microbial biomass (Ciardi et al., 1988). The microbial community, stimulated into growth by addition of vetch C, would have been able to capture a considerable part of the fertilizer N applied 1 month after decomposition of vetch residues began, if its N demand was still high. It is more probable, however, that this demand would have been satisfied by that time, although activity resulting from the build-up of microbial biomass could still have been high. More of the (unneeded) N still present in vetch was therefore made available for plant uptake.

The addition of vetch residue to a system receiving fertilizer as urea did not alter either the total N uptake or the amount of fertilizer N taken up by the corn. Since no difference in corn yield was noticed (data not shown), the presence of vetch residue simply reduced the amount of N acquired from SOM by an amount proportional to its own contribution to plant uptake (~14%). In other words, part of plant uptake of soil N was substituted by vetch N. The net availability of fertilizer N, however, remained unchanged. Either the great majority of fertilizer uptake was direct in both treatments, or the indirect pathway through the microbial biomass was unaffected by the previous stimulation of microbial activity following incorporation of vetch residue. Considering that fertilizer was introduced 1 month after vetch residue, the initial surge of activity following addition of high-quality residue had likely subsided by this time, so that, as suggested previously, uptake of fertilizer N by microorganisms was presumably minimal. Organic sources of N such as vetch, applied prior to a crop, provide useful benefits associated with rapid stimulation of microbial

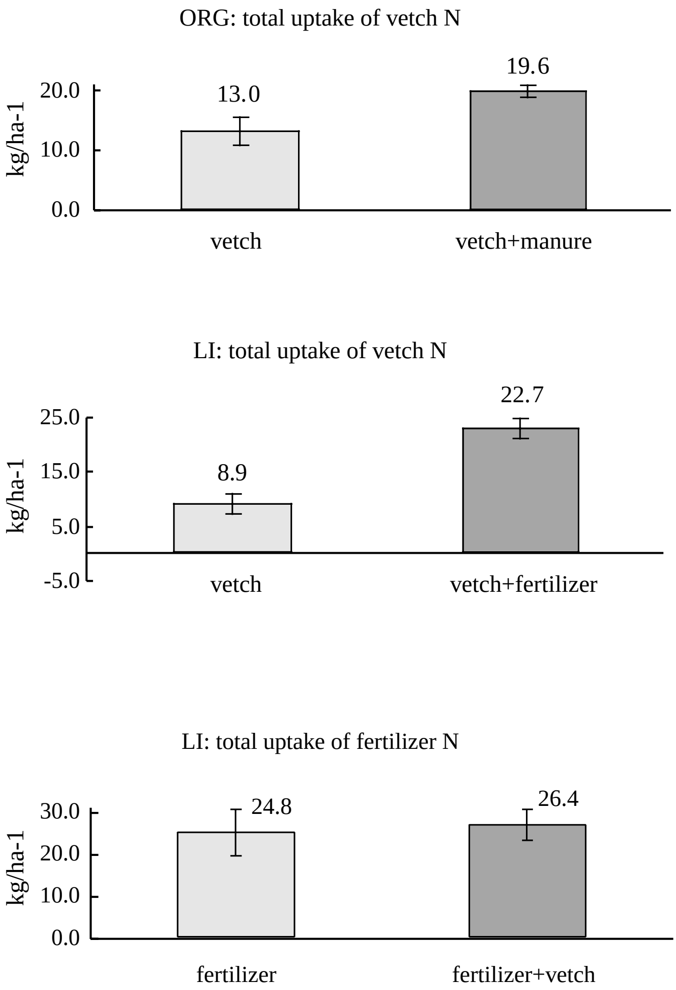

Figure 14.4 Uptake of vetch N as influenced by the interaction with manure and fertilizer urea N in the different farming systems. Stand errors of the mean (n = 4) are shown as line bars.

growth and activity, including the immediate release of N from both this source and enhanced release of nutrients from soil pools otherwise less accessible (Harris et al., 1994). In addition, these residues compliment soil C sequestration management. However, the results show that fertilizer practices need reevaluation when utilizing organic N sources to both build SOM and provide fertility.

CONCLUSIONS

This study addressed the interaction of various fertilizer inputs with relation to plant uptake and the impact of alternative management on soil C sequestration. Under the conditions of this study, two inputs complementary to a vetch cover crop (mineral fertilizer or aged manure) were found to increase net recovery of vetch-derived N in a corn crop. The effect of vetch on uptake of fertilizer N, however, was negligible. Both observations help describe a unique scenario of microbial dynamics; nonetheless, these observations are net results, and the exact progress of microbial dynamics in each system is not certain. The overall effect of one input on another is clearly dependent upon a wide range of circumstances, including site conditions, nature of C inputs, and time of application. Such potential interactions, though complex, provide numerous unique possibilities for studying the effects of C sequestration on sources of fertilizer N, which in turn can aid in understanding the processes at work in multiple-input systems.

The most profound changes in SOM occurring during this study were observable by simple analysis of the whole soil (the sum of all pools). Other effects were identified only upon fractionation — in this case, chemical fractionation into humic substances. Similarly, Balesdent and Balabane (1992) used separation by particle size (physical fractionation) to more precisely identify, using ^{13}C measurements, the effect of different C inputs with respect to these fractions. As summarized by Collins et al. (1997), the current theory of humus formation is based on a step-by-step process involving decomposition of plant material to simple C compounds, assimilation and repeated cycling of C through the microbial biomass, and simultaneous joining of microbially synthesized and altered plant-derived compounds (such as lignin) to form large polymers. Results suggest that SOM and its fractions may respond more dynamically than commonly thought to changes in external inputs and conditions.

It is important to understand the impact of different C inputs intended to sequester soil C on influencing sources of fertilizer N uptake by crop plants. Some complications with these sorts of studies lie in the effect of time on both C and N dynamics. Major conclusions drawn from this study were only possible after the management for soil C sequestration was observed for 10 years. For this reason, long-term studies on soil C and N processes are required to determine adequately the effects of soil C sequestration management on the long-term fertility of agricultural systems.

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