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Soil Organic Matter Pools Vary Across Management Systems but Weakly Predict Short-Term Nitrogen Cycling

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Abstract. The dynamics of soil carbon and nitrogen are important for soil fertility and ecosystem functioning, and agricultural management and land use strongly affect them. However, it is still not clear how different management systems change soil organic carbon (SOC) and soil organic nitrogen (SON), or if larger SOC and SON pools go together with more available nitrogen through mineralization and nitrification. The data come from the Kellogg Biological Station Main Cropping System Experiment; this site has SOC and SON measurements for several years and depths, and its nitrogen cycling variables were monitored at 0–25 cm depth. Treatment comparison and linear regression were used to test the differences among systems and the relationships between soil organic matter pools and nitrogen cycling. SOC and SON differed significantly among the treatments; the long successional system had the highest concentrations and the conventional system the lowest. Nitrogen cycling had different treatment patterns, and only SON had a significant positive relationship with net nitrification ($R^2 = 0.16$, $p = 0.007$); the other three regressions were not significant. The analysis relied on one experimental site, and the datasets matched only partly in time; therefore, the results cannot be generalized very far. In general, management had a strong effect on SOC and SON, but these pools by themselves predicted short-term nitrogen cycling only weakly.

Keywords: soil organic carbon, soil organic nitrogen, nitrogen mineralization, nitrification, agricultural management

1. Introduction

Soil is the largest active pool in the terrestrial biosphere, so soil carbon (C) and nitrogen (N) dynamics matter a great deal for climate regulation and ecosystem productivity. Globally, soil stores more carbon than the atmosphere and vegetation together; thus, it is a main driver of the global carbon cycle. However, agricultural expansion in the past two centuries has damaged soil organic matter, and a global carbon debt of 133 Pg C has been produced in the top 2 meters [1]. This loss makes climate change worse through CO_2 emissions and weakens farming sustainability, since it lowers soil water retention and crop yields [2]. In addition, nitrogen, the main limiting nutrient in these ecosystems, still limits terrestrial plant growth [3]. The same microbial processes drive both cycles; therefore, nitrogen availability has a close coupling with soil carbon dynamics.

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Soil carbon and soil nitrogen are linked closely. Most of the soil carbon and nitrogen exists as part of soil organic matter. The nitrogen in this organic matter sits in the same molecules as the carbon, such as proteins. In the process called mineralization, nitrogen in organic matter is changed into inorganic ions, ammonium (NH_4^+) and nitrate (NO_3^-). Mineralization takes place as microbes decompose organic matter to get energy from carbon, and in doing so they release part of the nitrogen in the same molecules. Thus, both elements are affected by microbial decomposition at once, and changes in soil carbon will also change nitrogen cycling.

When growth conditions are favorable, a large part of the N taken up by crops can come from the mineralization of soil organic matter (SOM) [4]. The reason is that the active fractions of soil organic matter, that is, labile SOM and particulate organic matter (POM), are the energy and nutrient substrates that microbes use most easily. Therefore, larger pools of these organic carbon and nitrogen fractions lead to higher microbial activity; this directly raises the gross N mineralization rate, and a larger supply of plant-available inorganic nitrogen is released into the soil.

Soil C and N control the availability of nutrients, and agricultural management practices are the main means by which these soil pools change. First, the soil structure is broken up physically by tillage. The organic matter that used to sit protected inside soil aggregates then becomes exposed; thus, decomposition speeds up and soil organic carbon (SOC) declines. Farmers can use residue return and cover cropping to avoid this. Leaving crop stalks in the field and planting cover crops both add carbon inputs, especially in seasons in which the soil would otherwise stay bare [5]. Next, a more diverse crop rotation, for example with legumes, changes both the amount and the C:N ratio of the organic matter that enters the soil. As for nitrogen inputs, fertilization gives N to the plant directly. Also, heavy fertilization can separate the inorganic N from the SOM-derived supply. For this reason, heavily fertilized soils may have a lot of available nitrogen even if SOC is low. Lastly, perennial systems such as alfalfa are quite different from annual row crops, since their roots go deeper and they disturb the soil less. In summary, bulk soil C changes very slowly, and the above management effects cannot be observed within only one or two years. Therefore, long-term experiments such as the Kellogg Biological Station Long-Term Ecological Research (KBS LTER) site are needed to capture these decadal signals [6].

Two questions are put forward in this study. First, how do the concentrations of SOC and soil organic nitrogen (SON) differ among treatments that cover a gradient of disturbance and management intensity? According to the historical management intensity data, the less disturbed management systems (native forest and perennial systems) should have higher SOC and SON concentrations than the intensive tillage systems; intensive tillage physically breaks up the soil aggregates, and the protected organic matter is exposed to microbial decomposition and carbon and nitrogen leave the soil faster, and native forests and perennial systems have very little physical disturbance and deeper, well-developed root systems that have returned carbon and nitrogen inputs to the soil profile continuously for decades. Second, how do the concentrations of SOC and SON affect the net mineralization of inorganic N? In the unfertilized treatments, following the microbial mechanism of soil organic matter mineralization that Booth et al. [7] describe, higher SOC concentrations should increase the amount of both ammonium and nitrate in the soil, and SON should have a similar effect, since SOM is the main native nitrogen source for microbes in these systems; larger standing stocks of SOC and SON give more organic substrates and energy, and microbial activity and gross nitrogen mineralization rise and finally more available inorganic nitrogen enters the soil. In the fertilized treatments, on the other hand, changes in SOC should not have a significant effect on the amount of ammonium and nitrate in the soil, and the effect of SON should differ from the unfertilized case; in the conventional and no-till systems with heavy chemical

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fertilizer inputs, inorganic nitrogen goes into the soil directly from the fertilizer and not through the breakdown of native organic matter, so the standing pool of inorganic nitrogen is disconnected from the organic carbon and nitrogen stocks of the soil.

To answer the above research questions, this study takes the KBS LTER Main Cropping System Experiment (MCSE) as its object. There are several reasons why this site suits the study very well. First, the KBS LTER MCSE has run without interruption since 1989, and there are more than three decades of consistent agricultural management. Second, the treatments at this site form a wide gradient. They go from heavily managed conventional row crops to unmanaged successional vegetation and native forests. This gradient also covers all the management measures that the previous section discussed. Third, the treatments are replicated, and they sit on the same soil type and in the same climate. Due to this design, any difference between treatments can be attributed directly to management practices and not to environmental noise. Lastly, earlier studies at this site have already recorded the historical changes in SOC and soil N [2, 4, 6, 8]. In addition, Liang et al. [9] have modeled the dynamics of inorganic N in these same treatments. This strong literature base links the bulk soil C and N approach directly to this long-term experimental system.

2. Methods

The data of this study were obtained from the Main Cropping System Experiment at the KBS LTER site. The KBS LTER MCSE lies in southwest Michigan (42°24′N, 85°24′W). The climate of the site is humid continental; the mean annual temperature is 10.1 °C and the mean annual precipitation is 1005 mm, and the precipitation spreads evenly over the year [2]. To evaluate how human management practices affect the ecological functions of soil, a management intensity gradient in the annual cropping systems (from conventional tillage to no-till practices) is studied, together with undisturbed successional systems and perennial cropping systems. A randomized complete block design with four replicates per treatment is used in the experiment.

The data of this study were collected in 2013 from two sources. The concentrations of soil organic carbon and nitrogen (SOC, SON) were taken from Córdova et al. [2], who measured C and N at several depth increments in ten soil cores per replicate. In this analysis, the 0–10 cm and 10–25 cm layers of each core were combined into one 0–25 cm value by a mass-weighted average, and the ten cores then gave one average SOC and SON value per replicate. Net nitrogen mineralization and net nitrification come from KBS LTER Datatable 56 [10]; these rest on in situ 21-day buried-bag incubations of surface soil (0–25 cm) that took place between July 23 and August 13, 2013. Merging the two datasets by treatment and replicate gave 44 paired observations in nine treatments.

The soil chemical analyses followed the standard LTER protocols, so the results are rigorous and repeatable. High-temperature combustion with an elemental analyzer gave the SOC and SON concentrations of oven-dried, sieved soil samples. Soil inorganic nitrogen was extracted with a 1 M KCl solution and then measured colorimetrically on a continuous flow injection analyzer. The rate of net nitrogen mineralization was determined by laboratory incubation; it equals the net change in inorganic nitrogen concentration before and after a standardized incubation period.

The effect of treatment on SOC, SON, net mineralization and net nitrification was tested by one-way analysis of variance (ANOVA), one variable at a time. Linear regression tested the relationship between the soil organic matter pools (SOC and SON) and nitrogen cycling (net mineralization and net nitrification); there are four regressions in total. The regression results appear as R^2 and p-value, and $p < 0.05$ is considered statistically significant.

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3. Results

3.1. Effects of agricultural management and land use on soil organic matter and nitrogen dynamics

Soil organic carbon, soil organic nitrogen, net nitrification and net mineralization varied a lot among the treatments (Figure 1). Also, the effect of treatment was significant for all the variables.

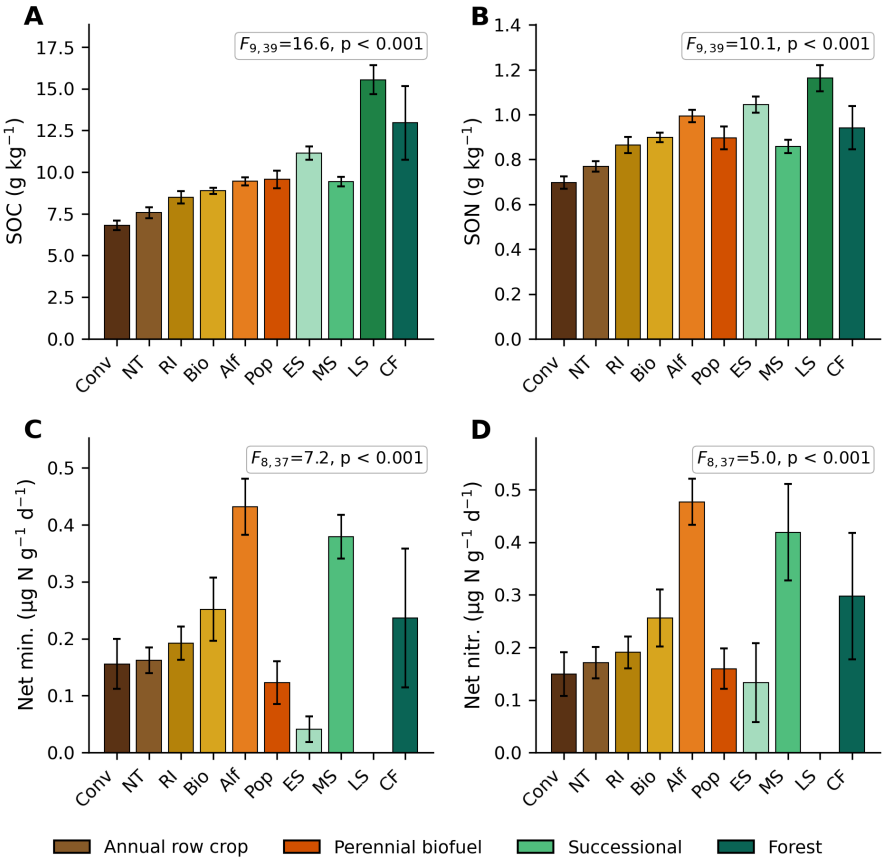

Figure 1. Soil organic matter concentrations and nitrogen cycling across ten treatments at the Main Cropping Systems Experiment at the Kellogg Biological Station measured in 2013 from 0–25 cm soil depth. Shown are: A) soil organic carbon (SOC); B) soil organic nitrogen (SON); C) net mineralization; and D) net nitrification. Bar represents the mean value ± standard error (SE) among replicates

The treatment patterns of SOC and SON were similar; the long successional system had the highest value and the conventional system had the lowest value. Overall, SOC and SON increased from the managed systems (annual row crop and perennial biofuel systems) to the more natural systems (successional and forest). On the other hand, the patterns of net mineralization and net nitrification were different from those of SOC and SON. The early successional and long successional systems had low values, and the highest value among these groups was found in the alfalfa system. For net mineralization and nitrification, there was no clear pattern along the management intensity gradient (from annual row crop to forest).

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3.2. Relationships between SOC and SON vs. net mineralization and net nitrification

The linear regression analyses showed generally weak positive trends between the soil organic matter pools and the nitrogen cycling processes over all sampling plots (Figure 2). In detail, soil organic carbon (SOC) showed weak positive relationships with net N mineralization and with net nitrification, but neither relationship was statistically significant ($R^2 = 0.03$, $p = 0.261$ for Figure 2A; $R^2 = 0.09$, $p = 0.054$ for Figure 2B). Similarly, the positive correlation between soil organic nitrogen (SON) and net N mineralization was weak and not significant ($R^2 = 0.08$, $p = 0.063$; Figure 2C).

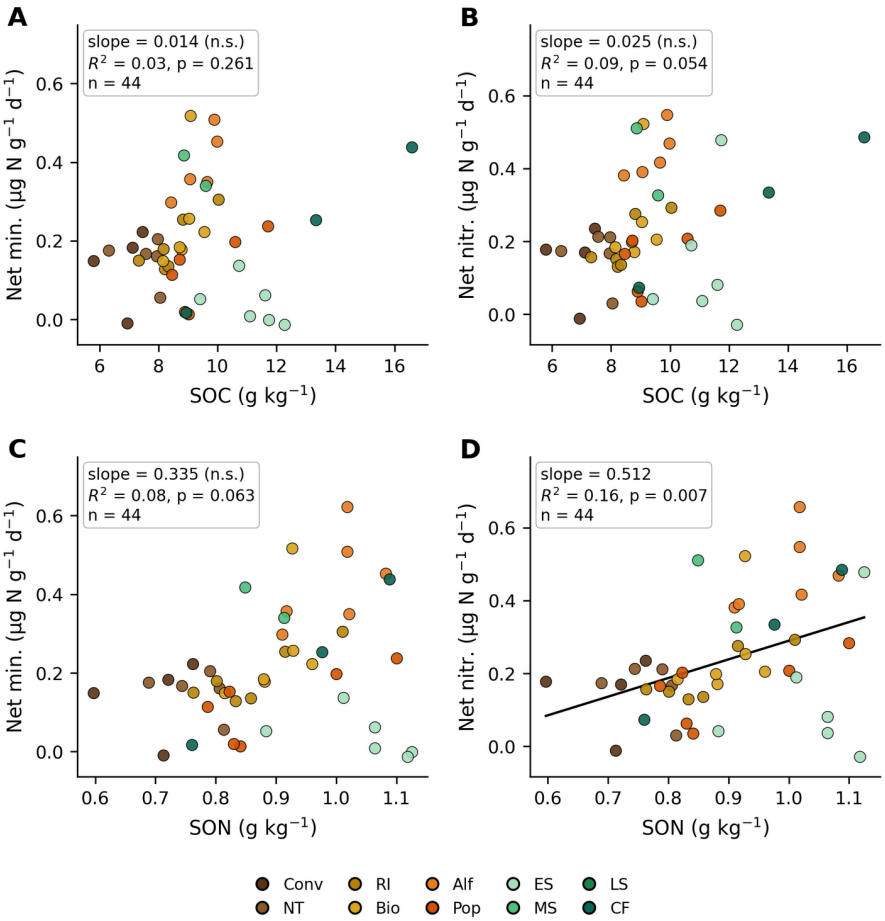

Figure 2. Relationships between soil organic matter pools and nitrogen cycling processes across all samples from the Kellogg Biological Station Main Cropping System Experiment. Relationship between soil organic matter pools and nitrogen dynamics across all plots including: A) SOC versus N mineralization; B) SOC versus net nitrification; C) SON versus net N mineralization, and D) SON versus net nitrification. Each point represents an individual sample (n = 44). R^2 and p-values from a linear regression are shown for each. A best fit line is added only to significant relationships

On the other hand, SON showed a statistically significant positive relationship with net nitrification (slope = 0.512, $p = 0.007$; Figure 2D), but it explained only a small part of the variance ($R^2 = 0.16$). In summary, only the relationship between SON and net nitrification was statistically significant; all the other regression models gave weak positive trends and no significant association.

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4. Discussion

This study has shown that less intensively managed systems held more SOC and SON, but this did not lead to higher rates of net nitrogen mineralization or nitrification. In terms of SOC and SON, the highest value was in the long successional system and the lowest value was in the conventional system. This pattern agrees with the first hypothesis, in which the less disturbed systems were predicted to hold more SOC and SON than the entirely disturbed systems. The higher SOC and SON in the less disturbed systems is probably because soil organic matter inside soil aggregates is protected from microbial decomposition. Intensive tillage breaks up the soil aggregates in which organic matter builds up, so the organic matter inside the aggregate meets microbial decomposition and SOC and SON are lost quickly [8]. In the successional systems, disturbance by tillage no longer exists; thus, SOC and SON were probably able to build up in these aggregates. The above results are consistent with the earlier work of Córdova et al. [2], in which SOC was also highest in the late successional system and lowest in the conventional system, and both SOC and SON generally increased along the management intensity gradient. Syswerda et al. [6] have shown that the effects of management on soil carbon are often clearer near the surface than deeper in the soil; therefore, this study may not fully represent the whole-profile patterns of SOC and SON.

The hypothesis that higher SOC and SON would predict more nitrogen mineralization and nitrification was only partly supported by the regression results. Of the four regressions, the SON and net nitrification relationship was the only statistically significant one ($R^2 = 0.16$, $p = 0.007$). In contrast, the other three relationships were weak and not statistically significant. At first sight this seems to go against the model of Booth et al. [7], in which SOM quantity should be an important control on nitrogen availability, since gross N mineralization is positively related to soil C and N concentrations. However, the present result does not contradict that model. Booth et al. dealt with gross nitrogen transformation rates, and net mineralization is what was measured in this study. Net mineralization is what is left after both the production and the consumption of inorganic nitrogen have taken place. Even when organic N is converted into ammonium by gross mineralization, part of this ammonium may be immobilized by microbes, or converted by nitrification and consumed further before the final measurement. Therefore, if microbial immobilization or other consumption processes removed inorganic N from the measurable net pool, a weak SOC–net mineralization relationship may still be consistent with the model of Booth et al. [7]. The problem may not be that SOM had no influence on nitrogen cycling; it may be that net mineralization does not separate the gross production process clearly enough.

In the Early Successional system, SOC and SON were relatively high, but net mineralization and net nitrification were low. This does not fit the simple gradient predicted by the hypothesis, in which the system with high organic matter should release more inorganic nitrogen. One possible explanation is that a large part of the carbon and nitrogen in early successional soil is physically protected, or is not immediately available for microbial decomposition. Grandy and Robertson [8] found that after land-use intensity is reduced, carbon builds up mainly in the aggregate-associated pools; Six, Elliott, and Paustian [11] also regard aggregates as physical barriers that reduce the contact between microbes and organic substrate. In other words, under this interpretation the Early Successional system can hold a relatively large amount of SOC and SON and at the same time show low net N release. A different anomaly appeared in the alfalfa system; its net mineralization was high, but this pattern may not come only from the decomposition of the existing SOM pool. Since alfalfa is a legume, biological nitrogen fixation can add new nitrogen to the system from atmospheric N gas instead of from soil organic matter alone. Millar and Robertson [12] have

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described biological nitrogen fixation as an important nitrogen input in agricultural systems, and alfalfa removes a large amount of nitrogen in the harvested biomass; this shows that its nitrogen cycle is strongly affected by legume-derived N input. Taken together, the early successional and alfalfa systems give two different reasons why SOC and SON may fail to predict nitrogen availability: in early successional, the organic matter may be present but physically protected; in alfalfa, nitrogen may enter the system by biological fixation, rather than only from SOM mineralization. These patterns together strengthen the conclusion that the quantity of SOC and SON alone cannot explain nitrogen cycling.

There are some limitations in how this result should be understood. First, the data come from one site and one sampling year, so the soil conditions and management history of the site cannot be separated from more general treatment effects. The KBS experiment is useful because the treatments are replicated and located under similar climate and soil conditions, but the data of one year cannot tell whether the same SOC–nitrogen cycling relationships also hold in wetter, drier, warmer or colder conditions. Second, what was measured in this study was net mineralization and not gross mineralization. In fact, this is a limitation of the dataset and also of the buried-bag incubation method for testing the mechanism predicted by Booth et al. [7]. Net mineralization mixes gross production with microbial immobilization and other consumption processes, so it cannot tell how much organic nitrogen was really converted into inorganic nitrogen before part of it was consumed. Third, some treatments may have a smaller sample size than others, and one unusual replicate may then affect the treatment means or regression patterns. These limitations do not make the results invalid, but they mean that the result should be read as support for management-related patterns and possible mechanisms, and not as direct proof of every process that controls nitrogen cycling.

5. Conclusion

In general, the above results show that agricultural management strongly affects the storage of SOC and SON, but nitrogen mineralization and nitrification cannot be predicted by the quantity of SOC and SON alone. In this way the site-level results are linked to the larger global problem described by Sanderman et al. [1]; long-term land use and agricultural disturbance can cause large soil carbon losses, and reduced disturbance, perennial vegetation and successional systems can help rebuild soil organic matter. The SOC and SON patterns found here also agree with Córdova et al. [2], and this further supports the view that conservation and successional management can increase soil carbon and nitrogen storage at the KBS site. However, the regression relationships were weaker, and this indicates that the link between SOM and nitrogen availability is more complex than a simple pool-size model. The data are in favor of the interpretation that net mineralization may be an incomplete way to test the SOM–N availability relationship, since it measures the balance after both the production and the consumption of inorganic N have taken place. To settle this question, future work should measure directly how much organic nitrogen turns into inorganic nitrogen and how much of this inorganic nitrogen is then taken up again by microbes. If gross mineralization, gross immobilization and net mineralization are compared in the same treatments, it will be possible to tell whether high-SOM systems really produce more inorganic N, or whether this N is consumed quickly before it appears in the net mineralization measurement.

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