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Review paper

Long-term effects of mineral fertilizers on soil microorganisms – A review

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ABSTRACT

Increasing nutrient inputs into terrestrial ecosystems affect not only plant communities but also associated soil microbial communities. Studies carried out in predominantly unmanaged ecosystems have found that increasing nitrogen (N) inputs generally decrease soil microbial biomass; less is known about long-term impacts in managed systems such as agroecosystems. The objective of this paper was to analyze the responses of soil microorganisms to mineral fertilizer using data from long-term fertilization trials in cropping systems. A meta-analysis based on 107 datasets from 64 long-term trials from around the world revealed that mineral fertilizer application led to a 15.1% increase in the microbial biomass (C_{mic}) above levels in unfertilized control treatments. Mineral fertilization also increased soil organic carbon (C_{org}) content and our results suggest that C_{org} is a major factor contributing to the overall increase in C_{mic} with mineral fertilization. The magnitude of the effect of fertilization on C_{mic} was pH dependent. While fertilization tended to reduce C_{mic} in soils with a pH below 5 in the fertilized treatment, it had a significantly positive effect at higher soil pH values. Duration of the trial also affected the response of C_{mic} to fertilization, with increases in C_{mic} most pronounced in studies with a duration of at least 20 years. The input of N per se does not seem to negatively affect C_{mic} in cropping systems. The application of urea and ammonia fertilizers, however, can temporarily increase pH, osmotic potential and ammonia concentrations to levels inhibitory to microbial communities. Even though impacts of fertilizers are spatially limited, they may strongly affect soil microbial biomass and community composition in the short term. Long-term repeated mineral N applications may alter microbial community composition even when pH changes are small. How specific microbial groups respond to repeated applications of mineral fertilizers, however, varies considerably and seems to depend on environmental and crop management related factors.

1. Introduction

Mineral fertilizers, especially nitrogen (N) inputs, have been a major contributor to the impressive crop yield increases realized since the 1950s (Robertson and Vitousek, 2009). Nitrogen is also the limiting nutrient for primary production in many terrestrial ecosystems and increased N input often leads to higher net primary production (LeBauer and Treseder, 2008).

Below ground communities are also affected by inputs of nutrients to the soil. In a literature review, Allison and Martiny (2008) found that 84% of 38 studies reported that microbial community composition is sensitive to N, phosphorus (P), and potassium (K) fertilization. While net primary production in terrestrial ecosystems is generally N limited, soil microorganisms may be carbon (C) or N limited (Wardle, 1992). The response of soil microbes may therefore differ from the response of the plant community. In fact, recent meta-analyses based on data predominantly from unmanaged ecosystems suggest that increasing N inputs suppress soil microorganisms (Treseder, 2008; Liu and Greaver, 2010; Lu et al., 2011).

The sensitivity of soil microbial communities likely differs between unmanaged and agricultural ecosystems. In agricultural fields, fertilizer N inputs exceed rates of atmospheric deposition and fertilizer N is often added in one or just a few large applications per year. High application rates lead to temporarily very high osmotic potentials and potentially toxic concentrations of the N forms added (Eno et al., 1955; Omar and Ismail, 1999). At higher application rates, short- and long-term effects on soil pH may also be more pronounced in agricultural systems. In addition, with the exception of weeds, plant community composition in cropping

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systems is little changed by fertilization, and is also intensively managed, which is in contrast to the case in unmanaged ecosystems (Clark et al., 2007; Cleland and Harpole, 2010). Furthermore, the substantially higher productivity brought on by fertilization in agricultural systems increases inputs of organic material in the form of root exudates, decaying roots and aboveground residues, and thus, increases the pool of C sources for soil microorganisms. A conceptual model of these interactions in agricultural systems is presented in Fig. 1.

Long-term fertilization trials allow investigations of the effects of repeated additions of mineral fertilizer on soil microorganisms. Many long-term trials were established primarily to study the impact of fertilizers on crop production; however, an increasing number of scientists are taking advantage of these well documented experiments to study soil microbial communities under different fertilization regimes.

The objective of this review is to test the hypothesis that long-term fertilization of agricultural crops with mineral fertilizers leads to changes in soil microbial biomass and community composition. We synthesize the results from a number of long-term cropping systems trials to investigate both direct and indirect effects of mineral fertilizers on soil microbial communities. Our review focuses specifically on the effects of mineral N fertilizers. However, in most long-term trials, P and K are also applied. Therefore, the observed effects cannot be attributed solely to N inputs.

2. Material and methods

2.1. Selection criteria

To quantify the effect of long-term N fertilizer application on soil microorganisms, we analyzed results from peer-reviewed studies in a meta-analysis. We searched the online database Web of Science for papers using the keywords “long-term’, ‘fertil*’, ‘microbial’, and ‘nitrogen’. In addition, articles cited in review papers that analyzed data from long-term agricultural trials were included in our search.

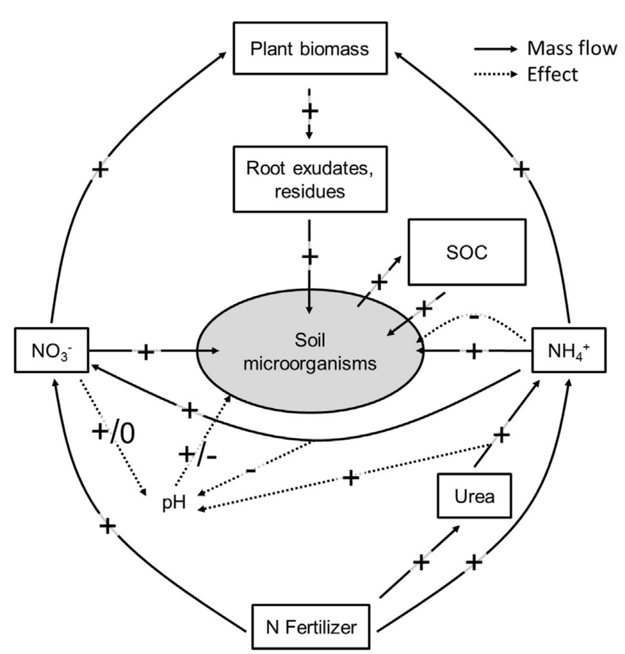

Fig. 1. Conceptual model of the direct and indirect effects of mineral N fertilizer on microorganisms in agricultural soils.

The following criteria were applied to select appropriate studies: (i) The data were from field trials with annual crops (except lowland rice cropping systems in paddy soils), (ii) the trials had been initiated at least five years prior to soil sampling, and (iii) the study reported microbial biomass and soil organic carbon (C_{org}) from an unfertilized control and a treatment with mineral N fertilization. Although urea is chemically an organic molecule, its behavior in soil is much more like that of a mineral fertilizer and we consider it as such in this review.

When studies reported data from several soil layers, only data from the topsoil were included. When different studies reported data from the same trial and treatments, the most recent dataset was included. Different crop rotations at one site were entered as individual datasets when an unfertilized control for that rotation was present. Treatments which differed in their N application rates and types of N fertilizers were also entered as individual treatments. In contrast, at sites where different tillage treatments were investigated in addition to N fertilization, only data from the conventional tillage plots were included. Some trials include treatments of different combinations of N, P or K fertilizers with identical N rates. In these cases, we only used data from the NPK treatment, which is the most common treatment in trials with only one mineral fertilizer treatment. Therefore, even though this review focuses on the effects of N fertilization, it is important to bear in mind that P and K fertilizers may have contributed to the observed effects.

A total of 107 datasets, each including an unfertilized control and a mineral N fertilizer treatment, from 64 long-term trials from across the world met our criteria and were included in the analysis (Table 1). Of these, 18 studies also reported specific respiration (qCO_2) values, and between 8 and 26 datasets included data on individual enzyme activities.

The sampling depth across all studies ranged from 5 to 50 cm, with 85% of the soil samples being taken to a depth of 15–20 cm. The duration of the trials ranged from 5 to 130 years, averaging 37 years. The annual N application rate ranged from 10 to 650 kg ha^{-1} averaging 136 kg ha^{-1}, with urea or ammonium salts being the most commonly used fertilizers. For more information about the trials and treatments, see Supplementary Tables S1 and S2.

Additional short- and long-term studies were included for the discussion to provide a broader perspective for the results of the meta-analysis and to investigate effects of fertilization on microbial community composition.

2.2. Data analysis

When organic matter was reported, we multiplied it by 0.59 to calculate C_{org}. Total PLFA was converted to microbial biomass C (C_{mic}) using a conversion factor of 5.8 mg C $nmol^{-1}$ PLFA (Joergensen and Emmerling, 2006).

Table 1
Geographic location of the trials included.

Region	Trials	Datasets
Europe	10	16
North America	21	45
USA	*16*	*31*
Canada	*5*	*16*
Latin America	2	3
Australia	2	2
Asia	26	36
China	*13*	*14*
India	*12*	*21*
Africa	3	3
Total	64	107