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Prolonged summer droughts retard soil N processing and stabilization in organo-mineral fractions

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ABSTRACT

Prolonged summer droughts are projected to occur as a consequence of climate change in Central Europe. The resulting reduced soil water availability may lead to alterations in rates of soil processes such as nitrogen partitioning among soil organic matter fractions and stabilization within soil. To study the effect of climate change-induced drought on (1) the distribution of nitrogen among soil organic matter fractions and (2) nitrogen stabilization, we performed a space-for-time climate change experiment. We transferred intact plant–soil–microbe mesocosms of a Rendzic Leptosol with a young beech tree from a slope with northwestern exposure in southern Germany characterized by a cool-moist microclimate across a narrow valley to a slope with southwestern exposure with a warm-dry microclimate, which reflects projected future climatic conditions. A control transfer was also done on the northwest-facing slope within the same area of origin. We combined a homogenous ^{15}N labeling approach using ammonium nitrate with a physical fractionation procedure and chemical soil extraction protocols. Our aim was to follow the partitioning of ^{15}N in different soil organic matter fractions, i.e. light fractions, organo-mineral fractions, and extractable soil fractions including microbial biomass, ammonium, nitrate, and dissolved organic nitrogen. Within less than one growing season, we observed a modified partitioning of recently applied inorganic ^{15}N between different soil fractions in relation to drier summer conditions, with attenuated nitrogen turnover under drought and consequently significantly higher ^{15}N concentrations in the relatively labile light fractions. We ascribed this effect to a decelerated mineralization immobilization turnover. We conclude that prolonged summer droughts may alter the stabilization dynamics because the induced inactivity of microorganisms may reduce the transfer of nitrogen to stabilization pathways. A retarded stabilization in organo-mineral associations enhances the risk of nitrogen losses during extreme rainfall events, which are projected to increase in the 21st century predicted by future climate change scenarios for Central Europe
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1. Introduction

Climate change is expected to have a substantial impact on soil moisture and temperature conditions (Intergovernmental Panel on Climate Change IPCC, 2007), with enhanced frequency and duration of summer droughts (Kunstmann et al., 2004) in Central Europe due to increased evapotranspiration or shifts in precipitation patterns (Borken and Matzner, 2009). This will decrease soil water availability and may thus negatively affect growth, development, and competitiveness of beech forests in Central Europe, particularly on soils with low water retention capacity (Geßler et al., 2007). Furthermore, reduced soil moisture will decrease the uptake kinetics of mineral nutrients by beech trees and thus indirectly limit their growth (Geßler et al., 2004). This vulnerability to the

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increasing incidence of dry summers may hence have an impact on nitrogen (N) fluxes in forest soils. This research topic is important, because European beech forest ecosystems provide important economic and ecological services and dominate the potential natural forest vegetation in Central Europe.

Beier et al. (2008) and Emmett et al. (2004) investigated the response of the N cycle to global warming in European scrubland ecosystems. They found that net N mineralization was sensitive to soil moisture. The effects of drought on the immobilization of inorganic N were described by Compton and Boone (2002) in a ^{15}N labeling study that suggested that low soil moisture inhibited microbial uptake of inorganic N. Yet, few studies have examined how the altered conditions due to climate change will affect N dynamics. This might be due to the complexity of the N cycle arising from a multiplicity of N transformation processes and fluxes involving both organic and inorganic N compounds. Therefore, research on N cycling processes requires a general analysis of different organic and inorganic soil N fractions, including soil microbial biomass (MB-N), dissolved organic nitrogen (DON), ammonium (NH_4^+), and nitrate (NO_3^-) as well as total soil N present in organic and organo-mineral soil organic matter (SOM) fractions. Understanding these processes and their quantitative significance for N fluxes in forest ecosystems is an essential prerequisite for the identification and characterization of competitive mechanisms that determine N partitioning between organisms and soil fractions in a changing environment.

To investigate responses to climate change, Rennenberg et al. (2009) recommended studies using intact plant–soil systems that focus on simultaneous measurements of all major N fluxes including plant uptake and release of organic and inorganic N compounds. Borken and Matzner (2009) also called for further research on the sensitivity of microorganisms involved in the N cycle to drought stress. Most of the studies on microbial N turnover or plant N uptake in forest ecosystems determined N fluxes only after the plant–soil system was totally altered. Only a few studies (Ineson et al., 1998; Hart and Perry, 1999; Hart, 2006) have used soil or soil–plant transplants across climatic gradients, following the space-for-time approach to simulate climate change. This methodology has benefits over controlled laboratory or greenhouse studies in that ecosystem mechanisms are exposed to micro-environmental dynamics that are difficult to simulate in the laboratory (Shaver et al., 2000).

Therefore, we conducted an in situ ^{15}N tracing experiment with intact beech understory–soil systems in a typical European beech (*Fagus sylvatica* L.) forest in southern Germany growing on Rendzic Leptosol. We transferred intact plant–soil–microbe mesocosms each containing a naturally established young beech sapling from a northwest-facing (NW) slope (control) to a southwest-facing (SW) slope (drought) to assess the potential impacts of simulated climate change on soil N. Controls were transferred to the same altitude and elevation on the NW slope, which served as a model for current conditions with a cool-moist microclimate, whereas the warm-dry SW slope represented the climate change conditions in Central Europe (Geßler et al., 2004) as projected by Intergovernmental Panel on Climate Change IPCC (2007). Because the properties of the soil mesocosms and initial size of the beech saplings were similar, the results of this study can be directly related to the differing climatic factors. In order to investigate drought effects on N partitioning to soil and plant fractions of different stability and turnover times, we homogenously applied labeled $^{15}NH_4^{15}NO_3$ to the intact plant–soil–microbe mesocosms. We monitored N in different SOM fractions as well as MB-N, inorganic N, and DON over one growing season. Our main objectives were: (1) to quantify the distribution of the applied ^{15}N between different soil and plant N fractions under ambient control and simulated drought conditions, (2) to determine the mechanisms responsible for N stabilization within SOM fractions, and (3) to evaluate the effects of drought on N stabilization in soil.

We combined a labeling approach with a soil fractionation procedure, allowing for rapid investigation of SOM partitioning in functionally different SOM fractions (Kölbl et al., 2006; Mueller et al., 2009). This method enabled us to assess the stabilization chain including active/labile, intermediate, and long-term stabilized fractions (Bimüller et al., 2013) and the associated mechanisms of selective preservation due to recalcitrance, spatial inaccessibility, and interaction with mineral surfaces and metal ions (von Lützow et al., 2006).

Our approach was based on two hypotheses. First, decomposition is associated with high mineralization immobilization turnover (MIT), which in turn favors the stabilization of organic N in the form of microbial residues in organo-mineral associations. The MIT will be influenced by drought conditions. Second, the N in organo-mineral associations will be less stabilized under drought conditions, due to a lower microbial biomass level.

2. Materials and methods

2.1 Study site description

The experiment was conducted in a long-term ecological beech research forest near Tuttlingen on the Swabian Jura (Baden-Württemberg, Germany) at an elevation of 780 m above sea level (Bimüller et al., 2013). The clay-rich soil is classified as Rendzic Leptosol (Skeletic) according to the International Union of Soil Sciences Working Group WRB (2007). Bulk mineralogy by X-ray diffraction shows a relative enrichment of the clay fractions in phyllosilicates, especially irregular mixed-layer illite-smectite and kaolinite. Quartz dominates in the larger grain sizes (Bimüller et al., 2013). Soil profiles under the mull humus are shallow, underlain by gravel-rich layers of weathered bedrock or periglacial layers derived from limestone. At the field site near Tuttlingen, we took advantage of exposure-induced model ecosystems located on different slopes of a narrow valley, showing a cool-moist (NW aspect) and a warm-dry local climate (SW aspect) within a distance of < 1 km of each other. At both sites, beech is the dominant species, contributing $>$ 90% of the total basal area of all trees (Geßler et al., 2001). The cool-moist NW slope represented the present mesoclimatic circumstances typical of a beech stand in Central Europe (Geßler et al., 2004). The situation on the SW aspect was assumed to be representative of future climatic conditions with higher soil temperatures (1 °C) and summer droughts, as predicted by climate projections for Central Europe (Special Report on Emission Scenarios B1/A1B/B2 scenario range) for the 21st century (Geßler et al., 2004, 2007; Intergovernmental Panel on Climate Change IPCC, 2007). Additionally, the frequency of extreme weather events like heavy rainfall is projected to increase in the 21st century. Continuous measurements of meteorological and edaphic parameters have been carried out at both sites since 1999, showing an advanced soil development with higher fine earth content and less gravel or coarse fragments on the wetter NW slope. Rainfall does not vary significantly between the two sites across the valley (Geßler et al., 2001). Greater radiation on the SW slope, however, results in higher soil temperature and thus less water availability due to greater evapotranspiration (Geßler et al., 2004). A comprehensive dataset on soil microbial, tree physiological, and tree growth parameters has been collected (Geßler et al., 2004).

2.2 Experimental design

The experimental design of this field study consisted of an intact plant–soil–microbe mesocosm transfer simulating climate change conditions coupled with a ^{15}N labeling experiment. A summary of the soil management during the experimental period is listed in Table 1.