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Evidence for increased P availability on wheel tracks 10 to 40 years after forest machinery traffic

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ABSTRACT

The use of heavy machinery for timber harvesting causes soil damage, which may restrict forest soil functions over decades. Numerous studies have demonstrated the negative impact of soil compaction on soil physical properties, but the effects of compaction of forest soils on soil chemical and biological processes like the phosphorus availability are largely unknown. Aim of our study was to analyze the effect of skidding activity on the P dynamics on skid trails and the soil recovery ability after skidding. Furthermore, we wanted to assess if acid phosphatase activity is an appropriate indicator of soil structure damage after compaction.

We investigated the phosphorus availability, acid phosphatase activity, TOC, pH value, and fine root density of soil samples from skid trails and from control plots without any skidding effect. We conducted our studies at three sites (Göttingen: Cambisols on limestone, Heide: Podzol on glacial drift and sand, and Solling: Cambisols at loess-covered sandstone) in Lower Saxony, Germany 10 to 40 years after last traffic impact in a space-for-time substitution.

We observed mainly higher P concentrations and higher pH values at the wheel tracks than in the control. TOC was predominantly higher at the wheel tracks, but lower TOC at the wheel tracks was also found. In the acidic loams of the Solling region, the amount of mineralized phosphate was much higher in the tracks compared to the control areas 10 to 30 years after last traffic impact. This suggests a decoupling of P mineralization from P uptake in the wheel tracks for several decades. Furthermore, higher as well as lower phosphatase activity at the wheel tracks compared to the untrafficked control was found, but higher phosphatase activities at the wheel tracks were predominant. Acid phosphatase activity was strongly correlated with TOC, but did not correlate with the time since last traffic impact and the gas diffusivity of the soil. Therefore, our results did not confirm that acid phosphatase activity is an appropriate soil biological indicator of soil compaction and structural recovery.

1. Introduction

Forest soils are known to be sensitive systems of high biological, chemical, and physical complexity. The functionality depends largely on the pore system of the soil, which ensures transfer processes like gas and water transport. For a rational forest management, the establishment of skid trails is essential as it contributes to soil protection at the area outside the skidding trails. However, the soil of the skidding trails becomes compacted due to heavy machines (Ballard, 2000; Greacen and Sands, 1980; Hildebrand, 1983; Schäffer et al., 2012). Total porosity, pore continuity, and aeration decrease and soil strength increases in comparison to soils beside the skidding trail (Arnup, 1998; Greacen and Sands, 1980; Page-Dumroese et al., 2006). Soil compaction has been reported to reduce fine root density (Eppinger et al., 2002; Greacen and Sands, 1980; von Wilpert and Schäffer, 2005) and to restrict plant growth (Gaertig et al., 2002; Hetsch et al., 1990; von Wilpert and Schäffer, 2005). The effects of soil compaction on soil biota and biological processes have been reviewed by Beylich et al. (2010) mainly on agricultural soils. They found positive as well as negative effects of moderate to severe soil compaction on soil fauna and microbial biomass. Only at bulk densities above 1.7 g/cm^3 did negative effects on microbial biomass and C-mineralization predominate. The reaction of the soil microbiome to soil compaction as a result of logging

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has been investigated by Hartmann et al. (2014) and Frey et al. (2009). They found a strong shift of the microbial community towards taxa with anaerobic metabolism in severely affected wheel tracks. Among the fungi, they reported a reduction of mycorrhizal fungi and an increase in saprophytic fungi.

Soil enzyme activities are used to assess the influence of various environmental factors on soil organisms (Kandeler and Dick, 2007) and have been related to soil disturbances like fire (Boerner et al., 2000), logging (Adamczyk et al., 2015), or soil compaction (Hawkins and Weintraub, 2011; Jordan et al., 2003; Lucas-Borja et al., 2011; Pupin et al., 2009; Tan et al., 2008). Compacted soils often exhibit lower enzyme activity than undisturbed soils. Hawkins and Weintraub (2011) found lower acid phosphatase activity, but no differences in alkaline phosphatase and arylsulfatase activity due to soil compaction. These results are confirmed by Jordan et al. (2003). They reported that compaction clearly reduced the acid phosphatase activity but not alkaline phosphatase. In contrast, Tan et al. (2008) found that compaction of forest soils reduced acid phosphatase as well as alkaline phosphatase and protease activity. After compaction of agricultural soils, decreased urease, dehydrogenase, and acid phosphatase activity is reported (Pupin et al., 2009). Furthermore, Lucas-Borja et al. (2011) found reduced phosphatase, β-glucosidase and dehydrogenase activity due to human trampling at hiking trails, but no differences in urease activity. However, increased enzyme activity due to soil compaction was also observed; Buck et al. (2000) measured higher values of acid phosphatase activity in the compacted soil. In general, the results of these studies show that acid phosphatase activity in particular reacts to soil compaction.

Acid soil phosphatases are excreted by plant roots and soil microbiota into their environment (exo-enzymes). They hydrolyse organic phosphate esters, thus releasing inorganic P for biological uptake. Alkaline phosphatases are released by bacteria and fungi while acid phosphatases are delivered primarily by plant roots and fungal hyphae into the rhizosphere (Spohn and Kuzyakov, 2013). Little is known about the persistence of enzyme activity in soil over time (Kedi et al., 2013). The persistence is determined by factors such as soil texture and organic matter content. Furthermore, extracellular enzymes can be stabilized by soil colloids (Burns, 1982; Renella et al., 2006). Kedi et al. (2013) found differences in the stability of phosphatase activity depending on the enzyme-delivering organism. Renella et al. (2007) studied the production and persistence of enzymes in soil. They found that net acid phosphomonoesterase activity peaked six to seven days after substrate-induced microbial stimulation.

It is assumed that soil compaction affects enzyme activity in two ways. Soil compaction is generally thought to decrease enzyme activity by changing the porosity and causing low aeration. Furthermore, compaction has been related to restricted root growth which in turn limits enzyme activity (Brzezinska et al., 2001; Dick et al., 1988; Pagliai and de Nobili, 1993). However, little is known about the impact that the soil compaction of forest soils has on phosphorus dynamics. Naghdi et al. (2016), Jaafari et al. (2014), and Makineci et al. (2007) found decreased P concentration after skidding. However, it should be considered that driving with heavy forest machines may lead to the occurrence of lanes having a thickness of several centimeters, in which organic matter accumulates. This may lead to nutrient concentration, including P, on the skid trails. Furthermore, the accumulation of harvest residues and the use of brash mats for reasons of soil protection concentrate nutrients on compacted wheel tracks (Stutz et al., 2015).

Numerous studies have demonstrated the negative impact of soil compaction on soil physical properties (Ampoorter et al., 2007; Brais and Camiré, 1998; Hildebrand, 1983; McNabb and Boersma, 1993) and the recovery potential of compacted forest soils with respect to the soil structure (Croke et al., 2001; Goutal et al., 2012, 2013; von Wilpert and Schäffer, 2005). In contrast, only a few studies consider the impact of soil compaction on changes in phosphorus availability and phosphatase activity (Hawkins and Weintraub, 2011; Jordan et al., 2003; Tan et al., 2008). Available studies on enzyme activity at skidding trails concentrate on the impact of the disturbance on the enzyme activity at a given time. The question of the recovery of compacted soils at skidding trails over time has not been considered.

The results of soil physical indicators in a previous study showed soil recovery 10–20 years after last traffic impact at sites with high biological activity and high clay content (Cambisols on limestone). In contrast, the soil structure in loamy sandy soils (Podzols on glacial drift and sand) was significantly disturbed even 40 years after last machine impact (Ebeling et al., 2016). The goal of this study was to examine the impact of machinery traffic on phosphorus dynamics and acid phosphatase activity at different sites in a space-for-time substitution. We expected to find lower enzyme activities at the wheel tracks and a regeneration of enzyme activity with increasing structural recovery of the compacted soil. We wanted to assess if acid phosphatase activity is an appropriate indicator of soil structure damage and recovery after compaction. In addition to the time since last traffic impact, we assumed fine root density, P availability, TOC, clay content and pH value to influence phosphatase activity.

2. Methods

2.1. Investigation sites

Eleven forest stands, distributed over three regions in Lower Saxony, Germany, were selected for this study. Four sites were in the Göttingen forest on (eutric) Cambisols on lime stone (G). All the sites are located on flat terrain. The soils of these sites are carbonate buffered with a high bioturbation activity as indicated by mull humus. In the Heide region (H), where three sites were found, (haplic) Podzols at glacial drift and sands were predominate. The pH is in the Al-buffer range and the bioturbation activity is very low (humus form mor-moder). Four sites were in the Solling region (S) on (haplic) Cambisols at loess covered sandstone. These soils are characterized by rather low bioturbation activity as indicated by the dominant moder humus forms.

In each region, we identified different old skidding tracks as a chronosequence without any traffic impact for 5–10 years (G10/S10/H10), 15–20 years (G20/S20), 25–30 years (G30/S30/H30), and 35–45 years (G40/H40/S40). The skid trails were not covered with brash mats during harvesting. At each site, the forest stand canopy was dominated by mature beech (*Fagus sylvatica*). Accompanying trees were ash (*Fraxinus excelsior* L.), sessile oak (*Quercus petraea* [Matt.] Liebl.), and pedunculate oak (*Quercus robur* L.). Further site characteristics are summarized in Table 1. Detailed information about forest management practice and machine loads during harvesting can be found in Ebeling et al. (2016).

2.2. Analysis of soil biological, chemical, and physical properties

A transect was placed across the skid trail and the untrafficked stand. 31 soil samples at each site were taken along this transect line at a soil depth of 0–5 cm to analyze total organic carbon, pH value and acid phosphatase activity. Undisturbed 100 cm^3 soil cores were taken at the same sample points to measure the relative apparent gas diffusivity of the soil. At each site, we also took three soil cores in the undisturbed control area and the wheel tracks, respectively, to analyze P availability. For a more detailed description of the study design see Ebeling et al. (2016).

The soil samples were kept at 4 °C, sieved (4 mm), and then analyzed for enzyme activity. Aliquot replicates of the samples were dried at 40 °C and sieved (2 mm) to analyze total organic carbon and the pH value. Acid phosphomonoesterase activity was measured following *p*-nitrophenol release from *p*-nitrophenyl-phosphate. This method was suggested by Tabatabai and Bremner (1969) and modified by Margesin (1993) and (Kremer, 1994) for an incubation temperature of 37 °C. Results are expressed as μg of *p*-nitrophenol released h^{-1} g^{-1} of soil. Total organic carbon (TOC) of the soil samples was determined