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Structural recovery in three selected forest soils after compaction by forest machines in Lower Saxony, Germany

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ABSTRACT

Harvesting and logging with heavy forest machines cause soil damage that may restrict forest soil functions. Although the recovery ability of compacted forest soils depends on the soil properties, little is known about the long-term structure recovery of different soils following forest operations. The aim of our study was to evaluate the soil structure recovery of three different soil types. Therefore, we applied a space-for-time substitution approach (10, 20, 30 and 40 years after the last machine impact) to study selected sites in Lower Saxony, Germany, using the following as proxies: bulk density, carbon dioxide (CO_2) concentration in soil gas, and the relative apparent gas diffusion coefficient (D_S/D_0). At sites with high biological activity and high clay content (Cambisols on limestone), recovery occurred 10–20 years after last traffic impact. At these sites, 10 years after the last traffic impact, gas diffusivity at the wheel track was half of the gas diffusivity of the undisturbed soil, and soil gas CO_2 concentrations were significantly higher at the wheel tracks. At the 20-, 30-, and 40-year-old skid trails, there were no significant differences between the untrafficked reference and the soil frequented by vehicles. Regardless of the kind of traffic impact (wheel track, mid line, side strip or undisturbed reference soil), all investigated parameters indicated that soil structure becomes more favourable with increasing time since the last forest interference. In contrast, loamy sandy soils (Podzols on glacial drift and sand) showed low recovery ability. Forty years after the last machine impact, gas diffusivity was still significantly reduced at the wheel track. Cambisols at loess-covered sandstone showed neither strong impact of forest traffic on soil structure nor changes in soil structure 20–40 years after last traffic impact. In general, bulk density turned out not to be a sufficient proxy for soil structure recovery.

1. Introduction

The use of heavy forestry vehicles is indispensable for rational forest management, although driving on forest soils causes soil damage. Compaction and displacement of the soil alter the soil pore space and consequently modify soil physical properties. Total porosity and pore continuity decreases and soil strength increases. Furthermore, transfer processes like gas and water fluxes are affected, which may lead to a reduction of aeration and root growth. Tree vitality may also be affected (Arnup, 1998; Gaertig et al., 2002; Gebhardt et al., 2009; Greacen and Sands, 1980; Page-Dumroese et al., 2006).

To describe the structural changes of the soil due to heavy traffic, different methodologies are used. The traffic impact on soil structure is commonly described using bulk density (Brais and Camiré, 1998; Goutal et al., 2012b; Page-Dumroese et al., 2006), as it is very easy to assess. The gas diffusivity is a well-established method to assess soil structure (Frede, 1986; Glinski and Stepniewsks, 1985; Rolston, 1986). Gaertig et al. (2002) showed that the CO_2 concentration in soil gas increases with decreasing gas diffusivity in the topsoil. High concentrations of CO_2 were found only when the gas diffusion coefficient was low. Recently, several authors have used the CO_2 concentration in the soil gas to assess changes in the soil structure. Conlin and van der Driesche (2000) found different ranges of increased CO_2 concentrations after soil compaction in Central British Columbia. Gaertig et al. (2002) reported a relationship between oak decline in Southwest Germany and soil aeration deficiency measured by gas diffusivity as well as CO_2 concentration. Ampoorter et al. (2010) also observed a higher CO_2 concentration after skidding.

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Moreover, they found soil CO_2 concentration to be a more reliable indicator of soil compaction than bulk density or penetration resistance. These findings correspond with the results of Weltecke and Gaertig (2011).

As operations with heavy vehicles cause damage to soil structure, information on soil recovery is necessary in order to assess or improve sustainable forest management practices. The structure of forest soils can be determined as a floating equilibrium of pore-creating and pore-destroying forces (Hildebrand, 1987). When forest vehicles destroy the soil structure, its recovery depends on various physical and biological processes. The key biological factors of recovery are plant-root penetration (the growth and decay of roots) (Bottinelli et al., 2014; Meyer et al., 2014), and faunal activity (e. g. earthworms) (Beylich et al., 2010). Shrink–swell- and freeze–thaw-cycles are the most important physical soil processes, whereby shrinking and swelling is restricted to soils with high clay content. Freeze–thaw-cycles occur on soils with a high water holding capacity and in regions where winter temperatures induce soil freezing for a longer period of time (Bottinelli et al., 2014). Consequently, the extent to which the compacted soil will recover depends on the soil type. Soils with high biological activity may regenerate faster than soils with lower levels of biological activity. Similarly, clayey soils are expected to have higher recovery potential than sandy soils (Ampoorter et al., 2007; Greacen and Sands, 1980).

Since the impact of forest machinery on soil structure was first discussed in the 1980s (Leutz et al., 1980), an increasing interest in soil compaction, its effects on plants, and possible recovery processes has emerged (Ballard, 2000; Cambi et al., 2015; Greacen and Sands, 1980; Hildebrand, 1983). Particularly when considering the recovery of forest soils, most studies restrict themselves to single soil types (Goutal et al., 2013; von Wilpert and Schäffer, 2006) or cover only a short period of time of one to ten years (e.g. Goutal et al., 2012a; Meyer et al., 2014; Page-Dumroese et al., 2006) or a maximum of 24 years (von Wilpert and Schäffer, 2006). The recovery rates stated by different authors show remarkable differences depending on site-specific factors like soil texture, biological activity of the soil, or organic matter content (Cambi et al., 2015). Furthermore, the recovery rate depends on the soil structural characteristic that is evaluated, as not all of these characteristics recover at the same rate. For instance, Goutal et al. (2013) reported a limited recovery of the soil specific volume of a silt loam Luvisol after three to four years, but no recovery of porosity. Croke et al. (2001) found no recovery of a coarse-textured soil within five years. For a loamy soil, bulk densities were still significantly elevated after ten years (Rab, 2004). Von Wilpert and Schäffer (2006) recorded a slight recovery of a compacted silty loam soil after 24 years.

Hence, the aim of the present study was to assess the recovery of three different soil types (Cambisols on lime stone, Cambisols at loess-covered sandstone, Podzols on glacial drift and sands) 10–40 years after last traffic in Lower Saxony, Germany. The soil structure was characterized using bulk density, soil gas CO_2 concentration, and gas diffusivity. We expected to find a strong traffic impact at the clay-rich limestone site and the loess-covered sandstone, but faster soil structure recovery on the limestone soil than at the sandstone-derived soil. For the sandy soil, we expected less compaction, but also a slower recovery.

2. Materials and methods

2.1. Investigation sites

The ability of structure recovery in forest soils was investigated using different old skidding tracks at 11 beech stands in three different geographic regions of Lower Saxony, Germany. The soils in the Göttinger Wald region (G) were (eutric) Cambisols on limestone. In the Heide region (H), (haplic) Podzols on glacial drift and sands predominated. The soils in the Solling region (S) were (haplic) Cambisols at loess-covered sandstone (Table 1). At each site, the forest canopy was dominated by mature beech (*Fagus sylvatica*). Accompanying broadleaved trees were ash (*Fraxinus excelsior* L.), sessile oak (*Quercus petraea* [Matt.] Liebl.) and pendunculate oak (*Quercus robur* L.). The climate of the study regions was characterized by a mean annual temperature of 8.7 °C (G), 8.4 °C (H), and 7.3 °C (S). Total annual precipitation amounts 650 mm (G), 750 mm (H), and 1000 mm (S).

This study was conducted in regularly or formerly regularly managed forest and was not an experiment under controlled conditions. In each region, we identified skid trails that had 5–10 years (G10/H10/S10), 15–20 years (G20/S20), 25–30 years (G30/H30/S30), and 35–45 (G40/H40/S40) years of time to regenerate after the last compaction by harvesting machines (Table 1). The sites G10, H10 and S10 were located in regularly managed forests. With the help of local forest officials, the date of the last machine impact could be precisely determined from inventory documents. The site G40 was part of a former collaborative research centre. All other sites of the space-for-time substitution were part of strict forest reserves that have not been managed since the year of designation. Strict forest reserves have been established in Germany mainly since the 1960s and 1970s for the purpose of both nature conservation and research of forest development (Meyer et al., 2007). Therefore, the date of the last vehicle impact could be reconstructed precisely. In the Heide region it was not possible to find skidding tracks that had been unaffected for 20 years.

In addition to the exact date of the last traffic impact and comparable site characteristics, the machine weight is important. Heavy forest machines with loads of 10 Mg have been used in Germany since the 1970s. In recent years, the machine loads have increased to 35 Mg. The timber harvesting commonly takes place during the winter months and since the 1970s, the traffic has been concentrated on permanent skid trails (Hamberger, 2003). Several studies have revealed that the majority of the impact occurs during the first machine passes (Ampoorter et al., 2011; Brais and Camiré, 1998; Canillas and Salokhe, 2001; Riggert, 2015; von Wilpert and Schäffer, 2006). As a consequence, we assume that the impact on the soil was the result of multiple passes with heavy forest machines in the same season.

2.2. Experimental design and data collection

Changes in soil structure were assessed using the soil physical parameters of bulk density and soil gas diffusivity, and the integrative parameter topsoil CO_2-concentration. The sampling of soil cores to measure bulk density and soil gas diffusivity took place at two soil pits on each test site, one in the untrafficked soil and one in the skidding trail. From each soil pit, undisturbed 100 cm^3 soil cores were collected at a soil depth of 0–5 cm, 5–10 cm, 10–30 cm, 30–60 cm and 60–90 cm (five soil cores at each depth). Additionally, soil cores were sampled along a transect line across the skid trail at the soil depth of 0–5 cm. The transect line consisted of 31 sampling points covering the typical area of a skid trail (wheel track, side strip, mid line) as well as the untrafficked soil next to the skidding trail as a reference. Due to this experimental design, the number of observations at the wheel track, side strip, mid line or untrafficked reference differed according to the particular width of the skid trail areas (Fig. 1). In each case, the same soil cores were used for the analysis of the bulk density and the gas diffusion coefficient.

We used 100 cm^3 steel cylinders to measure the dry soil bulk density. To measure bulk density, the soil cores were dried and weighed.