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Initial recovery of soil structure of a compacted forest soil can be enhanced by technical treatments and planting

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ABSTRACT

Heavy harvesting leads to harmful soil compaction and negative effects of soil physical properties and rootability. We monitored the recovery of soil structure in a compacted forest soil, which had been treated with a combination of regeneration techniques (mulching, liming, planting of alder trees or a combination of those). Soil physical properties (relative apparent gas diffusion coefficient (D_s/D_0), bulk density and the macropore volume) were measured in three successive campaigns, with two years between each, with fine root densities taken as a biological target variable.

Distinct changes of soil physical properties were detected during the study period, mainly caused by the effects of the applied regeneration techniques. After four years, higher values of D_s/D_0 and macropores indicated significant improvements of soil aeration in the topsoil. The deeper soil showed no distinct evidence of regeneration, regardless of the regeneration technique applied. However, rather a negative impact of mulching on soil physical properties was detected.

The measured physical parameters, D_s/D_0, bulk density and macropore volume correlate highly with observed fine root densities. In the topsoil, root density increases with increasing soil gas permeability, while in the deeper horizons only few macropores are occupied by fine roots for gas exchange.

1. Introduction

The deformation of the unprotected forest soils resulting from timber harvest with heavy skidding machines destroys the natural soil structure, which i) degrades the soil aeration status due to the loss of soil pore volume (attributed to the collapse of inter-aggregate pores) and ii) reduces the pore connectivity. A reduction of the total porosity impedes an adequate gas exchange between soil and atmosphere (von Wilpert and Schäffer, 2006), which depends on a continuous system of air-filled pores throughout the soil (Currie, 1984). Those changes are diagnosable by means of reduced relative apparent gas diffusion coefficients (D_s/D_0) of the soil (Fujikawa and Miyazaki, 2005; Schack-Kirchner, 1994), increased soil bulk densities (Ampoorter et al., 2007; McNabb et al., 2001) and reduced macropore volumes (Ampoorter et al., 2010).

Rooting in soils is limited to horizons where water and nutrient supply as well as gas exchange are simultaneously maintained (Jordan et al., 2003; Kozlowski 1999; Schäffer et al., 2009). Gaertig et al. (2002) showed that roots will be insufficiently supplied with oxygen, once the soil surface “interface” is smeared or compacted. Decreased air permeability and soil porosity limit extension, elongation, density and penetration of fine roots (Naghdi et al., 2016). Also, Gaertig et al. (2002) found evidences that root density decreases significantly with decreasing soil gas permeability.

Since fine roots mainly grow in macropores (Babel 1990), the fine root density can be used as an ecologically sensitive indicator for the evaluation of compaction effects (von Wilpert and Schäffer 2006).

In their preliminary study, von Wilpert and Schäffer (2006) analysed the relationship between gas diffusion coefficient and fine root distributions of comparable sensitive silty loams, with the aim to describe disturbances of soil functions with time delays up to 24 years between wheeling and examination. Reduction of gas diffusivity and rooting were found on the whole skidding trail area and even expanded to the close vicinity of the margin zone. Comparable fine root densities at the wheel track and the control strata, and in all depth layers were only found at plots where the investigations were performed 24 years after machine impact.

In posterior investigations, Schäffer and von Wilpert (2011) found that, 6 to 7 years after the wheeling both, physical soil aeration indicators (pore volume and D_s/D_0) and fine root densities, indicated a recovery from the soil compaction in the upper 10 cm to 20 cm of the mineral soil, but also a high persistence of damage below that depth.

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Consequently active measures for restoration of soils aeration aim to restore the site-specific rooting properties. Since natural regeneration processes are very slow, it is necessary to find active measures to support and accelerate them.

Our investigations focussed on identifying the best combination of regeneration techniques for accelerating the restoration of soil structure in compacted forest soils. The effects on structural recovery through planting subsidiary woody plants in combination with liming and mulching are investigated (Flores Fernández et al., 2015).

Three years after applying the regeneration techniques, the first stages of recovery of soil structure were detected by variations of CO_2 concentrations and rooting intensity between the various treatments applied in the skid trails (Flores Fernández et al., 2017).

In this paper, the relative apparent diffusion coefficient measured at 160 hPa, the bulk density (as an indicative parameter in damaged soil structure) and macropore volume (pore diameter > 10 µm) are used as indicators for the status of soil structure and recovery trends. We assume that at the final stage of an overall soil recovery, fine root propagation will reach a status comparable to undisturbed soils, besides a recovery of soil structure. Any statistically significant differences between skid trails and control plots will therefore reflect the persistence of compaction damages.

The leading hypotheses of this paper state that (1) harvesting and skidding machines reduce pore space whereby D_s/D_0 and macropore volumes decrease and bulk density increases; (2) Mechanical and chemical treatments enhance the natural regeneration effect; (2.1) The regeneration effects take place not only in the topsoil but also in deeper soil horizons depending on the time span of restoration; (2.2) An artificial over-loosening of the soil structure is generated by the mechanical impact of the mulching. Since this artificially high pore volume is not stabilized, it is subject to physical re-setting during the first years, resulting in decreasing D_s/D_0 and macropore volume, as well as increasing bulk density; (3) Planting of subsidiary trees leads to improvements on soil aeration; (4) The combination of active regeneration techniques results in increases in D_s/D_0 values and macropore volumes, and decreases in bulk density, as well as higher fine root density.

2. Material and methods

2.1. Study site

The study site is located close to Merklingen approximately 14 km west of Ulm, on the Swabian Alb (Southern Germany). According to the World Reference Base for Soil Resources (WRB) (IUSS Working Group WRB, 2006), the soil type can be classified as a Luvisol ('Parabraunerde' according to Ad-hoc-AG Boden (2005)). The sequence of horizons is Ah/Al/Bt and the soil has a silt clay loam texture. Detailed physical and chemical properties of the site are given in Flores Fernández et al. (2015).

Weather data for the observation period were obtained from the monitoring site "Blaubeuren-Wennenden" of the German Meteorological Service (DWD) at 705 m a.s.l. about 6 km northeast from the investigation site. The sum of precipitation at the DWD monitoring site was 769 mm, 839 mm, 795 mm, 631 mm and 843 mm for the years 2012, 2013, 2014, 2015 and 2016, respectively. An intense drought was observed at our study site for the year 2015, with temperatures around 27–32 °C for the summer period (July, August) and the highest amount of precipitation of the year registered during May (130 mm). In contrast, 2014 and 2016 showed lower temperatures (25 and 28 °C, respectively) but higher precipitations (160 and 208 mm, respectively) registered for July and August, respectively.

In April 2012, a controlled wheeling experiment was carried out with a HSM 208F forwarder with four axes. The loaded weight of the vehicle was almost 25 t. In order to ensure an equal compaction force during our experiment, the machine properties were kept constant and the wheeling was conducted with constant velocity. The skidding machine made six passages on three previously marked skid trails with approximately 70 m length and 5 m width. During the experiment, soil water content was measured with FDR sensors for the depths 0 to 5 cm (39.2 vol%) and 10 to 20 cm (33 vol%).

Two weeks after wheeling, the skid trails were in parts treated by either mulching and/or soil liming. The first skid trail was divided into two parts – one part was not treated, and the other one was treated with lime. Both the second and third skid trails were treated with mulch. Additionally, lime was added to the third skid trail (Flores Fernández et al., 2015). One month after the skidding process, parts of the skid trails as well as two untreated and undamaged control plots were planted with seedlings of black alder (*Alnus glutinosa*), grey alder (*Alnus incana*), alder buckthorn (*Rhamnus frangula*) and goat willow (*Salix caprea*) (Flores Fernández et al., 2015). We created a grid of four meters width with cells of 1 m × 1 m along the skid trail. The grid is composed of four transversal transects planted with a mixture of the four tree species followed by four transversal transects for each tree species. Five transversal transects were planted for each afforested plot in the two mulched skid trails.

Within two years after the wheeling experiment, yearly inventories were conducted on the survival status of planted trees. Results showed that the survival rate was highest for grey alder (81–100%) (Flores Fernández et al., 2015). Since grey alder grew best, further investigations at the study site were focused on plots where this tree species was planted.

2.2. Soil sampling campaigns

Three different soil sampling campaigns with two years between each (April 2012, April 2014 and April 2016) were conducted in order to characterize the status of soil recovery by analysing soil physical parameters linked to the soil aeration status (D_s/D_0 and macroporosity) and bulk density.

Trenches orthogonal to the skid trails, with a length of 200 cm and a depth of 50 cm to 60 cm were excavated across each studied wheel track and the median strip between the skid trails. Additionally soil profiles with a length of 100 cm and a depth of 60 to 80 cm were dug at the control plots between the skid trails. Soil sampling and fine root counting were performed for the treatments "not treated", "mulched" and "mulched/limed" for the planted and not planted subplots. The "not treated/limed" plot was only investigated on the planted subplot since the unplanted subplot is too small to provide enough space for periodically repeated sampling campaigns.

Sampling rings with a volume of 100 cm^3, a cross sectional area of 25 cm^2 and a height of 4 cm were used to extract the undisturbed soil columns from the following variants: untreated planted and unplanted, limed planted, mulched planted and unplanted, the combination of mulching and liming planted and unplanted, and the control plots. When extracting the soil samples, an additional 0.5 cm of soil material was taken at both ends of the sampling cylinder to eliminate the risk of having too little soil volume for further analysis. This is why following sampling depths are given in steps of 5 cm.

Samples from the wheel track were taken from 5 to 10 cm, 15–20 cm and 30–35 cm. The median strip was sampled at depths of 5–10 cm, 18–23 cm and 35–40 cm, and the control plots were sampled at depths of 5–10 cm, 20–25 cm and 35–40 cm. The sampling depths differ because soil horizons were compressed and relocated within the skid trail through wheeling. Sampling depths were adjusted in order to compare the same horizons in wheel tracks, median strips and control plots. Three sampling rings per depth were manually driven into the soil, extracted and roughly prepared in the field.

2.3. Soil physical analysis

In the lab, bulk density was measured gravimetrically after drying to a constant mass at 105 °C (Hartge and Horn, 2009). Porosity was