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Impacts of timber forwarding on physical properties of forest soils in southern Finland

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ABSTRACT

Forest harvesting activities can cause soil damage and disturbance through soil compaction, rut formation and soil mixing. These affect the soil structure and functions and forest productivity. Soil compaction results for instance in increased bulk density and decreased porosity, affecting soil moisture, water infiltration and aeration. The effects of timber forwarding on soil physical properties have gained little attention in boreal forests. These issues will become more important in the future since harvesting operations on unfrozen soils are getting more common due to the anticipated climate warming.

In this study, changes of forest soil physical properties (bulk density, moisture content and porosity) after 1–10 forwarder passes on two fine-grained mineral soil sites in southern Finland were analysed. Penetration resistance and rut formation were also measured. The measurements were performed in three periods with different soil moisture conditions. The test drives were carried out with a conventional 8-wheeled forwarder with total mass of 29.8 tons.

Soil bulk density increased and porosity decreased after the machinery passes. However, soil moisture content increased on one site and mainly decreased on another. The first three passes caused the greatest compaction and rutting, the first pass having the strongest impact. After the first and third pass 34–55% and over 70% of the total mean rut depth was formed, respectively. Further passes caused only minor rutting. The compaction and changes of soil physical properties appeared to be greater in dry conditions. Rut formation and soil mixing were greater in moist conditions. The results are, however, site-specific, and more research is needed to achieve a better understanding of the relationships between different factors affecting impacts of timber forwarding on soil.

1. Introduction

Soil is one of the most important components in ecosystems, providing key services such as production of biomass and energy. It is also a key component of carbon, nutrient and water cycles and gas exchange. However, soil is usually not an object of specific protection objectives and targets and is rather brought indirectly in connection with activities aimed at the protection of air, water or vegetation (EUA, 2002). In recent decades, however, soil has gained more importance, social visibility and attention. The European Union published in 2016 a report on the implementation of the Soil Thematic Strategy, which was adopted already in 2012 (European Commission, 2016). The United Nations declared 2015 as the International Year of Soils with the aim to raise awareness on the importance of healthy soil (European Commission, 2014). Sustainable soil management practices, soil protection and preservation are essential for food security, water quality and plant production.

The concern of tree and soil disturbances through forest operations with bigger, heavier and more powerful machines has grown in the past decades (e.g. Ala-Ilomäki et al., 2011; Hartanto et al., 2003; Jansson and Johansson, 1998; Rohand et al., 2004). Forest operations and mechanical stress can result in serious and prolonged changes in soil, affect soil functions and properties, reduce soil and forest productivity and eventually cause financial losses (e.g. Elliot et al., 1999; Jansson and Johansson, 1998; Lüscher et al., 2010; Sutherland, 2003). In recent years, there has been an increasing interest in sustainable forest management, and a detailed review of the available literature on machinery-induced negative effects on forest soils is provided by Cambi et al. (2015).

Mechanized harvesting and terrain transport have been reported to

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cause multiple impacts such as soil compaction, rut formation, changes in soil micro climate, stem damage, reduced tree and root growth, increased soil erosion, vulnerability to fungus infections and loss of biodiversity, organic matter, value and volume of trees (e.g. Bygden et al., 2004; Demir et al., 2007; Elliot et al., 1999; Marshall, 2000; Nugent et al., 2003; Sirén et al., 2013). Soil compaction is of high importance because of its effects on soil functions, processes and properties. For instance, it increases the soil bulk density and shear strength, modifies the pore system and soil structure and decreases soil moisture content, porosity, water and air infiltration, respiration and gas exchange (e.g. Bagheri et al., 2012; Jansson and Johansson, 1998; Marx et al., 2013; Nugent et al., 2003; Rohand et al., 2004; Susnjar et al., 2006). In addition, the absorption of nutrients and water by trees and other vegetation are negatively affected in compacted soil (Susnjar et al., 2006; Rohand et al., 2004).

Soil bearing strength is one of the most important characteristics for the quality of ground usability (Susnjar et al., 2006). It indicates the capacity of the soil to resist external forces and affects the trafficability, production efficiency and damages caused by timber haulage (Susnjar et al., 2006). Soil strength and vulnerability to compaction are mainly influenced by its moisture content and particle size distribution (e.g. Lüscher et al., 2010; Marx et al., 2013; Susnjar et al., 2006). Also other factors, such as coarse roots, can increase the bearing capacity of soil. Thus, soils with high moisture content, fine textured soils and peatlands are sensitive to soil damage and compaction (e.g. Marx et al., 2013; Nugent et al., 2003; Sirén et al., 2013; Spoor et al., 2003; Uusitalo and Ala-Ilomäki, 2013; Zeleke et al., 2007). The most fertile spruce stands are located on moist and fine-grained soils with a low bearing capacity (Eliasson and Wästerlund, 2007). Also, as spruce horizontal roots are superficial, these stands are especially vulnerable to logging damage (Sirén et al., 2013).

Frozen soil has a better bearing strength, which ensures more efficient harvesting and causes less soil disturbance (Susnjar et al., 2006; Sutherland, 2003). In Finland, up to 60% of logging is carried out between October and March, when the soil is frozen (Sirén et al., 2013). However, due to the anticipated climate warming and increasingly mild winters a greater proportion of logging needs to be carried out while the soil is not frozen, which may increase the risk for soil disturbances. Whether dry and warm autumn or mild winter with little snow and frost but high soil moisture content would be a more suitable season for Norway spruce thinning has been brought up by Sirén et al. (2013).

The greatest impact of machinery traffic occurs direct in the extraction trails, after the first passes and in the uppermost soil (0–10 cm) (e.g. Coder, 2007; Elliot et al., 1999; Froehlich and McNabb, 1983; Jakobsen and Greacen, 1985; Naghdi et al., 2007; Rab, 2004). However, influences in nearby areas and in deeper soil layers, at more than 80 cm depth, are also reported (e.g. Ampoorter et al., 2007; Jakobsen and Greacen, 1985; Lüscher et al., 2010; Naghdi et al., 2007). It has also been reported that a wheeled vehicle causes more damage and disturbance to the soil than a tracked vehicle (e.g. Bygden et al., 2004; Jansson and Johansson, 1998; Sakai et al., 2008).

The level of soil and root damage depends mostly on the mass and load of vehicles as well as on soil and site characteristics such as soil type, texture, structure, moisture, content of organic matter and slope. Other affecting factors include machine equipment (tyres, tracks, chains), speed, number of machinery passes, logging method, timing and planning of activity and skillness of on-site personnel (e.g. Demir et al., 2007; Jansson and Johansson, 1998; Kremer et al., 2012; Naghdi et al., 2007; Susnjar et al., 2006).

Soil is a limited, non-renewable resource as it takes up to thousands of years for one centimeter of soil to form and once the soil is damaged, it can take years to recover (European Commission, 2015; HBS, 2015). Soil regeneration is a long process, and it is mainly limited to the top 15 cm (Susnjar et al., 2006). Top soil regeneration time after skidding activities differs from 10 to over 30 years, and even up to irreversibility (e.g. Croke et al., 2001; Froehlich and McNabb, 1983; Lousier, 1990; Rab, 2004). Especially in the deeper soil layers, influences of compaction are very long-term (Alakukku et al., 2003; Sakai et al., 2008). Maintaining the soil in a healthy state is essential for ensuring a stable environment for forest flora and fauna (Sutherland, 2003).

A great deal of research has been conducted on technological and biological issues of timber harvesting in Finland, but hardly any of the work done so far concentrates directly on the pedological approach, i.e. the changes in soil physical properties and the effect of machinery traffic on soil. The aim of this study was to evaluate the effects of heavy machinery traffic on forest soil on two fine textured sites in southern Finland. Soil bulk density, moisture content, porosity and grain size distribution were analysed at two soil depths before and after machinery passes. Rut depth and cone penetration resistance were measured after each pass. The measurements were performed in three periods with different soil moisture conditions in September, November and December 2015.

Our hypotheses were that

– traffic by heavy machinery compacts the soil, which results in increased bulk density and decreased porosity and soil moisture content,
– soil damage, rutting and compaction are greater in moister soil,
– the impacts increase with the number of machine passages,
– the greatest impact to the soil occur after the first passes.

2. Materials and methods

2.1. Study sites

The study sites were located in Vihti in southern Finland and can be classified as the *Oxalis-Myrtillus* forest type (Cajander, 1949). These herb-rich heath forests are relatively fertile sites and comprise approx. 29% of mineral soils in southern Finland (Hotanen et al., 2008). The mean annual temperature is 4.6 °C and the mean monthly temperatures vary between −6 °C in January and February and 17 °C in July. The mean annual precipitation is 650 mm with clearly more precipitation during the second half of the year (Pirinen et al., 2012).

Site A (Rintelä) (60°24.6 N, 24°23.2 E, around 60 m above sea level) was an even-aged Norway spruce (*Picea abies* (L.) Karst) stand on a silty-clayey soil with a shallow (1–5 cm) humus horizon. The relief was an even slope with minor inclination to northwest. The soil was prepared by ploughing before planting approx. 30 years ago and the ploughing furrows are still visible.

Site B (Pervonmäki) (60°24.4 N, 24°22.4 E, around 70 m above sea level) was a forest of natural origin with different tree species and age classes. The stand was mostly Norway spruce dominated with a mixture of birch (*Betula pendula* Roth) and aspen (*Populus tremula* L.). It was located in a dell and characterised by a silty-sandy soil with a variable thickness (5–20 cm) of organic layer with a shallow peat layer in moist patches. The humus form was moder in both sites.

Five plots of 15 × 20 m were established: three on site A and two on site B. The plots were divided in three test trails (5 × 20 m), one for each study period (Sep., Nov., Dec.) (Fig. 1). Each test trail was further divided into four study sections (5 × 5 m). The lines were carefully marked on the ground in order to keep the measurement points constant. The maximal amount of machinery passes was 10, which was always reached except on site B in November as the bearing capacity collapsed due to high soil moisture content after the third pass. In December tests were performed only on site A. Detailed description of the number of the measurements and soil samples is shown in Table 1 and explained in further chapters.

Both sites were clear-cut before the first measurements in September. The harvesting and processing of the trees were carried out from outside the plots to keep them intact. Harvesting residues were collected and the test trails were placed in order to avoid travelling over stumps, as this inevitably causes uneven weight distribution and soil