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Review

The impact of heavy traffic on forest soils: A review

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ABSTRACT

Forest soils can suffer from various threats, some of which are human induced. Although mechanized harvesting allows for high productivity, it may also seriously damage forest soils. In recent decades, the use of powerful and heavy machinery in forest management has increased exponentially. The extent, degree, and duration of direct and indirect effects of heavy traffic on soils depend on several factors, such as soil texture, moisture, and organic matter content, slope of the terrain, type and size of vehicles, wheel inflation pressure, tire shape, and number of vehicles trips. Topsoil compaction and the alteration of ground morphology are crucial direct effects of forest harvesting carried out using heavy equipment. Soil compaction results in reduced porosity, which implies limitations in oxygen and water supply to soil microorganisms and plants, with negative consequences for soil ecology and forest productivity. Compaction, especially when confined in ruts, also has dramatic ramifications in terms of runoff and erosion of the most fertile soil compartment (*i.e.*, the top soil). In compacted soils, forest regeneration can be impeded or even prevented for long time periods. A detailed review of the abundant although still insufficient literature on machinery-induced negative effects on forest soils and their ramifications for forest ecology and management is provided here, along with recommendations for best practices to limit such damage.

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1. Introduction

One of the major challenges in forest management is to comply with forest operation ecology, which aims at developing and deploying strategies and technologies able to efficiently use resources, minimising the production of wastes and overall impacts on the structure and function of the environmental spheres – atmosphere, biosphere, hydrosphere, and lithosphere (Heinimann, 2007). Forests cover some 40 million km^2, approximately 30% of the global land area and are therefore a major component of the environment as a whole and a main driving factor in human welfare. Soil plays a crucial role in forest ecosystems, mediating nutrients, water and energy flows that ensure forest productivity and sustain biodiversity (Dominati et al., 2010). Soil is highly sensitive to improper forest management and to large-scale logging activities in particular. Mechanised ground-based logging methods are widely used today on flat or slightly sloping terrain because they generally provide a safe work environment and high labour productivity (Akay and Sessions, 2001). A wide range of equipment, such as rubber-tired vehicles (with varying numbers of axles and wheels, tire characteristics, and inflation pressures) and bogie-tracked or crawler machines, such as skidders, forwarders, and tractors, are employed (Bygdén et al., 2004; Jansson and Johansson, 1998; Picchio et al., 2009, 2011; Seixas and McDonald, 1997). Logs are generally brought to the landing site by skidding or forwarding, thus implying movement of vehicles throughout the forest. In recent years, these vehicles have become progressively more powerful and efficient but also heavier, with increasing impacts on soil (Vossbrink and Horn, 2004; Horn et al., 2007). The soil system can suffer substantial, long-lasting, and sometimes irreversible damage, which negatively affects forest productivity and ecosystem functionality (Hartmann et al., 2014).

Since the 1950s, several studies have investigated the undesired effects of mechanised forest harvesting operations on soil and the possible ways to prevent or limit them (Steinbrenner and Gessel, 1955; Greacen and Sands, 1980; Johnson and Beschta, 1980; Adams and Froehlich, 1981; Jakobsen and Greacen, 1985). A negative consequence of forest harvesting by heavy ground-based logging equipment is soil compaction (McNabb et al., 2001). Forest soils, so often characterised by biologically active top horizons rich in soft humus, are particularly prone to compaction (Horn et al., 2007). Soil compaction implies lower water infiltration and hydraulic conductivity, which contributes to increased waterlogging on flat terrain and runoff and erosion on slopes (Jansson and Johansson, 1998; Grace et al., 2006). Moreover, with the exception of coarse-textured, excessively drained soils, soil compaction reduces oxygen and water availability to roots and microorganisms (Bodelier et al., 1996; Startsev and McNabb, 2000; Frey et al., 2009). A consequence of compaction is depressed forest productivity (Kozlowski, 1999; Ares et al., 2005; Agherkakli et al., 2010).

A goal of forest managers in harvesting should be to minimise the impact of vehicles on soil, whose negative effects can be significant and long lasting, although often unrecognised or neglected. While the causes and possible solutions of soil compaction in cropping systems have been thoroughly investigated (*e.g.*, Defossez and Richard, 2002; Hamza and Anderson, 2005), knowledge of the impact of ground-based logging operations on forest soils is still incomplete. Nonetheless, in recent years, there has been increasing interest in sustainable forest management, and several papers dealing with the consequences of forest operations on soil have been published and are now available to compile a comprehensive review on the topic.

The aim of this review is to summarise (1) the effects of vehicle traffic on the physical properties of soil, (2) the consequences of such effects on aboveground and soil biota, (3) the best approaches for limiting soil degradation due to logging operations, and (4) the main knowledge gaps and goals of future research.

2. Vehicle–soil interaction

In-forest vehicle traffic unavoidably exerts vertical and horizontal stress components as well as shear forces to the soil (Alakukku et al., 2003). The main outcome is soil compaction, the severity of which depends on several factors, such as vehicle mass, axle/wheel/track load, contact area of the vehicle with the soil, slope of the terrain, tire pressure, dynamic shear forces, and soil characteristics and moisture (Jansson and Johansson, 1998; Alakukku et al., 2003; Bygdén et al., 2004).

In forests growing on steep terrain, steel-tracked skidders are the most frequently used machinery. The large and invariable ground contact area of this type of vehicle results in high tractive efficiencies, low ground pressures, and good stability (Agherkakli et al., 2010). On flat or slightly sloping terrain, wheeled machines are generally preferred by virtue of their higher performance in terms of productivity and cost (Spinelli et al., 2012).

The mass of forest vehicles ranges between 5 and 40 Mg (Jansson and Wästerlund, 1999; Eliasson, 2005). This mass exerts direct pressure on the contact area, the portion of the tire or track in contact with the ground. In the case of tires, it is difficult to precisely determine the size and shape of the contact area because it depends on tire deflection, which is influenced by tire characteristics, such as inflation pressure, wheel load, and soil plasticity (Hallonborg, 1996; Saarilahti, 2002; Wong, 2008). Low inflation pressure, high tire load, and soft soils contribute to large contact areas. In forests, vehicles move on a plastic matrix composed of soil, thus producing an asymmetric contact area that is perpendicular to the tire. If vehicles move laterally on a slope, the contact area of the wheels is asymmetrical with respect to the longitudinal axis. The size of the contact area changes continuously due to accelerating/braking, changing payload, and uneven soil surface. Superimposition of stresses from neighbouring contact areas (*e.g.*, tandem tires, pendulum axles, bogies) may occur, leading to stress paths specific for any axle or wheel arrangement (Alakukku et al., 2003). Mathematical expressions for determining the contact area, based on elliptic or super elliptic models, have been provided (Hallonborg, 1996). Nevertheless, they require input data that are not easily acquired, and do not consider the rapid dynamic variation during machine trips.

The average ground contact pressure (AGCP), the load imposed to the soil divided by the contact area, determines the vertical stress on the ground. A simple calculation of the static ground pressure of forest harvesting machines, however, is not a good indicator of the dynamic pressure exerted on soil during skidding (Lysne and Burditt, 1983). Moreover, pressure is not uniformly distributed over the contact area, and its distribution beneath the wheel is complex due to a number of variables, such as tire lug pattern, tire load distribution, and tire carcass stiffness (Peng et al., 1994). The maximum ground contact pressure under lugs or stiff tire sidewalls may be several (even ten) times higher than the estimated average ground contact pressure (Burt et al., 1992; Hillel, 1998; Gysi et al., 2001). In crawler vehicles, peak values of ground pressures, which govern soil stresses (Koolen and Kuipers, 1983), usually cluster under the track rollers (Wong, 1986) and depend on the vehicle's barycentre and track arrangement (Koolen and Kuipers, 1983).

Soil stress includes wheel slippage, which induces pronounced shearing processes at the soil surface (Edlund et al., 2013) and crushing of the macrostructure, even in soils with high structural stability, such as Ferralsols (Schack-Kirchner et al., 2007). Stress duration is usually one-tenth of a second to one second, during