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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

Table 1
Summary of the missing information in studies cited in this review and dealing with field trials.

Subject	Number of papers	Factor	Missing information %
Soil	49	Soil type	14
		Particle-size distribution	16
		Organic matter content	65
		Duff thickness	88
		Moisture	16
Wheeled vehicles[a]	45 (92%)	Tire type	40
		Inflation pressure	38
		Contact area	82
		Total weight	13
		Ground contact pressure	82
Tracked vehicles[a]	19 (39%)	Contact area	63
		Total weight	26
		Ground contact pressure	84

[a] 15 (31%) papers take into consideration both wheeled and tracked vehicles.

which very short loading/unloading cycles ("vibrations") are transferred from the vehicles to the soil (Soane, 1986). As vehicle velocities increase, the duration of loading and the amount of stress borne by the soil decrease (Alakukku et al., 2003; Horn et al., 1989).

Forty-nine papers included in this review that dealt with field experiments and focused on the impacts of logging operations on soil were selected to prepare Table 1, which summarises the crucial information on soil (*e.g.*, soil type and soil moisture) and logging machines (*e.g.*, tire type and inflation pressure) that is not provided in these papers. This lack of information prevents making exhaustive inferences regarding the role any factor plays in vehicle-soil interactions. Greater attention to reporting all of these crucial data should be devoted in future works to allow more uniform comparison of results from different trials and, possibly, meta-analysis or even more robust statistical tests on the datasets.

3. Impacts on soil

The main effect of vertical and horizontal stress components on forest soil from ground-based operations is increased compaction, which is directly expressed as bulk density or indexed by soil strength measurements (Ares et al., 2005). The most evident outcome of soil compaction is the formation of ruts (*i.e.*, deep tracks created by one or more passes of wheeled or tracked vehicles). Topsoil mixing, puddling, and displacement are associated with rutting and may have major ecological impacts in some environments (Ryan et al., 1992; Heninger et al., 2002; Agherkakli et al., 2010).

3.1. Soil compaction

Compaction is the densification of any material (*i.e.*, a reduction in total porosity when it undergoes pressures exceeding its intrinsic mechanical resistance). With the exception of a few strongly cemented soils, which are unsuitable for tree growth, soils are matrices highly susceptible to compaction. Soil compaction can occur naturally due to freezing–thawing and wetting-drying cycles (Hillel, 1998), earthquake-induced liquefaction (Scalenghe et al., 2004), and animal trampling (Raper, 2005) or be induced by human activities that impose major forces with a vertical component to the ground. For a given AGCP, soil deformation depends

Table 2
Factors affecting vehicle-induced compaction of forest soils and summary of their effects. The number of upward or downward arrows is proportional to the role any characteristic plays in favouring or preventing soil compaction, while an equal sign means no substantial role.

	Affecting factor	Overall effect on soil compaction	Reference articles
Soil	Initial low bulk density	↑↑	Hillel (1998), Williamson and Neilsen (2000), Powers et al. (2005) and Ampoorter et al. (2012)
	Moisture	↑↑ (until critical threshold)	McDonald and Seixas (1997), Hillel (1998), Williamson and Neilsen (2000), McNabb et al. (2001), Han et al. (2006), Raper (2005) and Ampoorter et al. (2012)
	Frozen soil water	↓↓↓	Šušnjar et al. (2006)
	Particle size distribution	↑↑	Hillel (1998), McNabb et al. (2001), Berli et al. (2004), Sakai et al. (2008) and Magagnotti et al. (2012)
		=	Ampoorter et al. (2012) and Brais and Camiré (1998)
	Aggregate stability	↓	Yee and Harr (1977), Dorel et al. (2000) and Page-Dumroese et al. (2006)
	Organic matter content	↑	Soane (1990), Jurgensen et al. (1997), Aragon et al. (2000), Arthur et al. (2013) and Johnson and Curtis (2001)
	Slope	↑	Agherkakli et al. (2010) and Jourgholami et al. (2014)
Works	Number of trips	↑↑↑ until 5–10 trips, ↑ >10 trips	Gent et al. (1984), Wang (1997), Williamson and Neilsen (2000), Wallbrink et al. (2002), Han et al. (2006), Jourgholami et al. (2014) and Brais and Camiré (1998)
	Harvesting method	↑↑ forwarding, ↑ winching	Picchio et al. (2012)
		Cable yarding = ground skidding	Miller and Sirois (1986)
	Harvesting system	CTL = WTS	Han et al. (2009)
	Harvesting direction	↑↑↑ uphill, ↑ downhill	Jourgholami et al. (2014)
	Weight of vehicles	↑↑↑	Jansson and Wästerlund (1999)
	Speed	Missing information	–
	Operators' expertise	Insufficient information	–
	Contact pressure	↑↑	Sakai et al. (2008)
	Tire/track characteristics	Tire = track	Jansson and Johansson (1998) and Sheridan (2003)
	Wheel inflation pressure	↑	Alakukku et al. (2003) and Sakai et al. (2008)
Stand	Forest type and density	Missing information	–

on several factors, such as initial bulk density, particle size distribution, soil organic matter and moisture, ground slope, type of harvesting, number of skidding cycles, and the caution and expertise of machine operators (Ballard, 2000; Jamshidi et al., 2008) (Table 2).

Generally, the lower the bulk density of the soil, the more prone it is to compaction (Hillel, 1998; Williamson and Neilsen, 2000; Powers et al., 2005). Soils with bulk densities $\geqslant 1.4\,\text{Mg m}^{-3}$ are rather resistant to compaction (Powers et al., 2005), but forest soils in most cases have much lower values in their upper layer due to its richness in organic matter and biotic activity, which promotes formation of well-developed crumb structure and high porosity (Corti et al., 2002). Volcanic soils developed on ashes or pyroclastic materials are friable and have low densities (often much less than $1\,\text{Mg m}^{-3}$) and are thus intrinsically susceptible to compaction, rutting, and mixing (Allbrook, 1986; Page-Dumroese, 1993; Parker, 2007). Once compacted, any soil is relatively resistant to further compaction because of the increased proportion of micropores at the expense of macropores (Ampoorter et al., 2012).

When dry, soil has a high degree of particle-to-particle bonding, interlocking, and frictional resistance to deformation (Hillel, 1998). An increase in soil water content implies a reduction in the frictional forces between soil particles, and hence a reduction in the bearing capacity of the soil (McNabb et al., 2001; McDonald and Seixas, 1997; Han et al., 2006) and a higher susceptibility to compaction. Soil susceptibility to compaction increases up to a critical moisture content at which time additional moisture may result in lower susceptibility (Hillel, 1998). In fact, the higher the moisture content, the greater the number of pores filled with water that cannot be compressed (Ampoorter et al., 2012). Above the critical moisture content, machine-induced stresses turn into topsoil churning or puddling, and eventually deep rut formation (Hillel, 1998; Williamson and Neilsen, 2000).

Fine-textured soils are generally more susceptible to compaction than coarse-textured ones (Wästerlund, 1985; Hillel, 1998; McNabb et al., 2001; Sakai et al., 2008; Magagnotti et al., 2012). However, a recent meta-analysis by Ampoorter et al. (2012) showed that the impact of mechanised harvesting on clayey soils is not significantly different from that on sandy soils, although the authors suggest caution due to the limited number of studies dealing with clay soils. Particle size distribution plays a major role in soil water retention, and, therefore, in making soil more susceptible to soil deformation under heavy traffic.

The effect of forest traffic on soil bulk density declines with increasing soil depth (Koolen et al., 1992). McNabb et al. (2001) showed that extraction of logs by wide-tired skidders and forwarders on a medium-textured soil close to field capacity after three machine passes had caused bulk density increases of 10%, 7% and 4% at 5, 10, and 20 cm soil depths, respectively. Similar decreasing trends were recorded by Han et al. (2009) and Williamson and Neilsen (2000) at depths down to 30 cm. In Sweden, Jansson and Johansson (1998) found that traffic increased bulk density of a silt loam podzol down to 40–50 cm for both a wheeled machine and a tracked one. Maximum compaction (42% relative to the control) occurred at a depth of 10 cm after eight passes with the tracked machine, whereas with the wheeled machine, the highest compaction (37% relative to the control) occurred at a depth of 15 cm after six passes. On the contrary, in a loam to silt loam forest soil, Jourgholami et al. (2014) found that magnitudes of change in bulk density, penetration resistance and total porosity after trafficking with a UTB/Universal 650 Engine UTB tractor were not consistently greater in the upper 5 cm compared to the 20 cm depth class. In summary, the impact of forest traffic on soil bulk density usually declines with increasing soil depth, but machine type and management, topographic conditions, and soil properties greatly affect the depth trend of such impact.

Soil susceptibility to compaction strictly depends on soil structure, and, in particular, the capacity of aggregates to withstand pressure without breakage (Page-Dumroese et al., 2006). Soil organic matter is the main binding agent in forest soils, at least in the uppermost soil layer (Aragon et al., 2000; Arthur et al., 2013). Any type of organic matter, but humic substances in particular, may reduce the susceptibility of soil to compaction by increasing the resistance to deformation and/or the elasticity of aggregates (rebound effect), while roots provide a filamentous network that somewhat contributes to aggregate stability (Soane, 1990). Harvesting may induce major changes in soil organic matter abundance and composition (Jurgensen et al., 1997; Johnson and Curtis, 2001), with potentially negative ramifications on soil structure and soil susceptibility to compaction. Stronger cementing agents than organic matter, such as Fe, Al, or Mn oxides (in acidic soils) and carbonates (in calcareous soils), promote formation of a very resistant soil structure, which endows high soil shear strength (Yee and Harr, 1977).

Harvesting-induced soil compaction increases with increasing slope because of more confined distribution of loads on the ground. In a mixed broadleaf forest in Iran, Agherkakli et al. (2010) demonstrated that post-logging soil bulk densities were considerably higher than pre-logging ones and that slopes steeper than 20% were significantly more compacted by a steel tracked skidder LTT-100A than the slopes that were less than 20%.

The way loaded vehicles move on slopes is another factor that controls soil compaction. For example, in a mixed deciduous forest growing on loam to silt loam Alfisols in Iran, Jourgholami et al. (2014) found that changes in three investigated properties (bulk density, penetration resistance, and total porosity) in response to machine traffic differed significantly among slope gradient/forwarding direction classes, being the largest on the 0-10% uphill forwarding slope, followed by the 10-20% downhill and 0-10% downhill forwarding slope.

Most of the impact on soil usually occurs in the first few machine passes, while later soil density increases little (Han et al., 2006; Wang, 1997; Wallbrink et al., 2002). The progressive effect of machine passes differs significantly according to soil physical properties and depth; regardless, it strictly depends on soil texture. In their study of six clay to gravelly sandy soils, Williamson and Neilsen (2000) found that, on average, 62% of the compaction experienced by the top 10 cm soil occurred after a single machine pass, with little increase after subsequent traffic. Below, in the 10–20 and 20–30 cm layers, compaction increased up to the third pass, when it achieved 80–95% of the final compaction. In medium-textured Luvisols of Alberta, Startsev and McNabb (2000) observed that between 7 and 12 machine passes the incremental increase in soil bulk density to a depth of 10 cm was less than 3%. On fine- to medium-textured soils, Brais and Camiré (1998) determined that half of the effect of skidding cycles on soil bulk density at 0–10 and 10–20 cm depth intervals and soil strength at a depth of 10 cm occurred in the course of the first two cycles. On coarse-textured soils, the same authors recorded that half of the total effect on soil bulk density at a depth of 0–10 cm occurred after three passes, while 50% of the total impact on soil strength occurred after 9, 14, 7, and 6 cycles for depths of 2.5, 5, 10, and 20 cm. In a loam to silt loam textured soil, Jourgholami et al. (2014) found that the majority of changes in bulk density and total porosity occurred after fewer than 5 passes, while considerable increases in penetration resistance occurred even after 10 passes.

It is a fact that some harvesting methods have lower impacts on soil than others. In logging operations carried out by lightweight forest machinery (5–9 Mg), Jansson and Wästerlund (1999) found minor increases in penetration resistance of sandy loam soils sustaining young stands of Norway spruce [*Picea abies* (L.) Karst.] in

Sweden. In two forests in Italy growing on loamy soils where trees were motor-manually cut (by chainsaw) and extracted with a 3 Mg heavy tractor with a winch at one site, or felled and bunched by a 19.2 Mg heavy harvester and extracted with a 8.2 Mg heavy tractor with a trailer at the other site, Picchio et al. (2012) verified that the former treatment generally produced a lower impact on soil bulk density. Nevertheless, the penetration resistance increased by approximately 50% and shear resistance by almost 40% at both sites. Han et al. (2009) compared two harvesting systems, Cut-To-Length and Whole Tree Harvesting, on ashy over loamy Andisols and found that they caused significant and comparable increases in soil bulk density and penetration resistance. However, the first harvesting system used less area to transport logs to the landings and did not significantly impact the centre of trails, whereas the second system did.

Other factors potentially able to affect soil compaction caused by forest harvesting, such as vehicle speed, operators' expertise, and type of forest cover, are investigated very little or not at all (Table 2). Related research is thus needed.

3.2. Rutting

Ruts are the result of vertical and horizontal soil displacement to either the middle or the sides of the skid trail associated with shearing stresses and soil compression in moist or wet soils (Horn et al., 2007). Beyond a critical water content, in fact, tire or track forces cause soil displacement and rut formation rather than simple compaction (Hillel, 1998; Horn et al., 2007; Vossbrink and Horn, 2004; Williamson and Neilsen, 2000). On flat terrain, ruts are collectors of rain or depressions where the water table surfaces, while on slopes they are preferential routes for runoff, which become deeper and deeper because of erosion (Schoenholtz et al., 2000). The consequences for site productivity can be considerable, so much so that rut number and depth have been proposed as rough indicators of decreased site productivity (Lacey and Ryan, 2000).

Rut formation is proof that loaded vehicles have exceeded soil bearing capacity (Muro, 1982; Yong et al., 1984). Rut depth and extent chiefly depend on vehicle weight, ground contact device (wheel, tire width, inflation pressure, semi-track, or track), ground slope, and soil moisture and properties (Bygdén et al., 2004) (Table 3).

The weight applied to the ground plays a major role in rut formation; hence, the lightest possible machinery should be used on soils with low bearing capacity. Indeed, Jansson and Wästerlund (1999) recorded very shallow ruts (1–2 cm) in a forest harvested with lightweight forest machinery (5–9 Mg).

Apparently, soil texture is a controlling factor of rut depth; nonetheless, Naghdi et al. (2009) did not find any significant correlation between rut depth and soil texture during skidding operations carried out in loam, clay loam, sandy loam and sandy clay loam soils in northern Iran. The effect of the slope of the terrain on rut formation is much clearer. In forest soils, Agherkakli et al. (2010) and Najafi et al. (2009) demonstrated that rut depth increased with increasing slope, evidently because the vertical component of the force from the load is distributed on a smaller surface. In particular, the former authors ascertained that 9 passes of an 11 Mg skidder on a loamy to silt loamy soil with 30% water content made ruts 12 and 9 cm deep on slopes more and less than 20%, respectively. Naghdi et al. (2009) found significant correlations between the three slope classes 0–15, 15–25 and more than 25% and the volume of displaced soil; however, there was no significant correlation between slope and rut depth.

Due to their lower contact area, wheeled vehicles generally disturb soil more dramatically, creating deeper ruts, than tracked ones (Johnson et al., 1991; Jansson and Johansson, 1998). Bogie tracks, in spite of increasing the mass on the trailer by 10–12%, may reduce rut depth by up to 40% compared to rather wide and soft tires, likely because of a reduction in the relative rolling resistance coefficient (Bygdén et al., 2004). Sheridan (2003) found the same rut depth for a steel-tracked and a rubber-tired skidder on a silty clay loam soil with 28% water content, although the static ground pressure was 30% higher for the wheeled skidder.

The intensity of machine traffic (number of passes) is a main controlling factor of rut depth, as demonstrated by several authors (*e.g.*, Jakobsen and Greacen, 1985; McNabb et al., 2001; Nugent et al., 2003; Bygdén et al., 2004 Eliasson, 2005; Eliasson and Wästerlund, 2007).

The effects of machine characteristics or how the machine is managed in the field on rut formation seem to be insufficiently investigated. In this regard, Edlund et al. (2012) compared the impact of two forwarders with similar carrying capacities but different transmission drive and steering systems: an El-forest

Table 3

Factors affecting vehicle-induced rutting in forest soils and summary of their effects. The number of upward or downward arrows is proportional to the role any characteristic plays in favouring or preventing soil compaction, while an equal sign means no substantial change.

	Affecting factor	Overall effect on soil rutting	Reference articles
Soil	Moisture	↑↑	Hillel (1998), Williamson and Neilsen (2000) and Naghdi et al. (2009)
	Particle size distribution	=	Naghdi et al. (2009)
	Organic matter content	Missing information	
	Slope	↑↑	Agherkakli et al. (2010) and Najafi et al. (2009)
		=	Naghdi et al. (2009)
Works	Contact pressure	Missing information	–
	Ground contact device	↑↑↑ wheel ↑↑ bogie track ↑ track	Jansson and Johansson (1998), Bygdén et al. (2004) and Johnson et al. (1991)
	Tire width	↓↓	Myhrman (1990) and Neri et al. (2007)
	Tire inflation pressure	↑↑	Foltz (1995) and Neri et al. (2007)
		=	Eliasson (2005)
	Number of trips	↑↑↑	McNabb et al. (2001), Nugent et al. (2003), Bygdén et al. (2004), Eliasson (2005) and Eliasson and Wästerlund (2007)
	Weight of vehicles	↑↑	Jansson and Wästerlund (1999)
	Type of machines	↓ assisted drive systems	Edlund et al. (2012)
	Speed	Missing information	
	Harvesting method	Missing information	
	Harvesting system	↑ bulges of ruts for wheeled respect to tracked	Neruda et al. (2010)
		↑↑↑ forwarder; ↑ excavator	Jansson and Johansson (1998)
	Harvesting direction	Missing information	–
	Operators' expertise	Missing information	
Stand	Forest type and density	Missing information	

F15 with three individual steerable axles without bogies, large wheels and an electric hybrid transmission drive system, and a Valmet 860 with conventional transmission drive. On an S-shaped or circular course, the El-forest and Valmet produced equally deep ruts with a single pass; however, with additional passes, the Valmet made deeper ruts. Driving in a straight line, the El-forest generally made shallower ruts than the wheeled Valmet (*i.e.*, without bogie tracks).

Ruts are bordered by bulges, which are usually higher for wheeled than for tracked vehicles (Neruda et al., 2010). Such bulges further contribute to modify the original soil hydrology, and runoff in particular. In a silt loam soil in Sweden, Jansson and Johansson (1998) further unravelled the differing impacts of different types of equipment on topsoil morphology by measuring bulges of approximately 15 and 2 cm after eight passes of a SMV 21 six-wheeled forwarder and an Akerman H7 excavator, respectively.

Other factors potentially able to play a role in rutting in forest harvesting, such as vehicle speed, harvesting method (CTL, WTH), movement direction (uphill, downhill), operators' expertise, and type of forest cover, have not been sufficiently investigated to infer any general rule (Table 3).

4. Consequences of soil compaction

4.1. Soil properties

The impact of vehicles on physical soil properties during forest operations, widespread or confined in ruts, implies ramifications – most often negative – on movement of fluids and, as a consequence, on chemical and biological soil properties (Worrell and Hampson, 1997; Powers et al., 2005) (Table 4). The affected area may range between 10% and 70% of the logged stand; therefore, the impact on the soil environment is substantial (Grigal, 2000; Frey et al., 2009; Picchio et al., 2012).

Reduction in soil porosity implied by compaction imposed by machine traffic in forest soils may amount to 50–60% (Ares et al., 2005; Ampoorter et al., 2007; Demir et al., 2007; Frey et al., 2009; Picchio et al., 2012; Solgi and Najafi, 2014). Such a reduction chiefly occurs at the expense of macropores, which are functional in soil drainage, while micropores are little affected or even increased by compaction (Seixas and McDonald, 1997; Ampoorter et al., 2007). In a silt loam soil, van der Linden et al. (1989) found that uni-axial compression caused reduction of pores larger than 5 μm, whereas pores in the range of 0.2–5.0 μm did not experience any substantial change. However, Kutílek et al. (2006) demonstrated that there is no general valid rule on changes in pore size distribution due to compression and that aggregate stability is crucial for soil to resist compaction. The reduction of macropores greatly depends on the type of disturbance. For example, in a loamy sand to silty clay loam soil, Dickerson (1976) found an average reduction in macropores of 68% for wheel-rutted soils and 38% for log-disturbed ones, although micropore space in both cases only increased by approximately 7%. The effect of the number of machine passes on soil flow channels is apparently different from that on bulk density (*i.e.*, while bulk density primarily increases after the first trip, flow channels continue to decrease considerably after additional trips). As an example, in a forest soil developed on volcanic ash, which is a highly porous parent material, Lenhard (1986) found that flow channels continued to decrease up to the 16th pass of a rubber-tired skidder.

Alteration of natural flow channels does affect plant-water relations, aeration, and depth of freezing in soil, possibly resulting in an environment less favourable to plant growth. Compacted soils retain more water at field capacity than non-compacted soils (Van der Weert, 1974; Currie, 1984), although it does not necessarily imply that more water is available to plants. This water shortage may occur because the finest pores hold water so strongly that roots cannot extract it. Nadezhdina et al. (2012) studied the effect of soil compaction by a two-wheeled trailer with 0.2 MPa

Table 4
Effects of vehicle-induced compaction on forest soil properties. The number of upward or downward arrows indicates the extent of the increase or decrease, respectively, while an equal sign means no substantial change.

Effect	Reference articles
Soil porosity: ↓↓ Macropores: ↓↓↓ Micropores: ↑	Seixas and McDonald (1997); Berli et al. (2004), Ampoorter et al. (2007), van der Linden et al. (1989), Kutílek et al. (2006) and Lenhard (1986)
Water infiltration and permeability: ↓↓ Water retention: ↑	Currie (1984), Berli et al. (2004), Frey et al. (2009), Ares et al. (2005), van der Weert (1974) and Arthur et al. (2013)
Runoff: ↑↑	Rab (1996), Startsev and McNabb (2000), Christopher and Visser (2007) and Croke et al. (2001)
Waterlogging: ↑↑	Rab (1996), Startsev and McNabb (2000) and Christopher and Visser (2007)
Air permeability and Oxygen supply: ↓↓	Frey et al. (2009)
CO_2 concentration: ↑↑	Conlin and van den Driessche (2000), Ampoorter et al. (2010), Magagnotti et al. (2012), Goutal et al. (2012), Fernandez et al. (1993), Bekele et al. (2007), Goutal et al. (2013b) and Qi et al. (1994)
Root growth: ↓	Greacen and Sands (1980), Taylor and Brar (1991), Qi et al. (1994), Whalley et al. (1995), Kozlowski (1999), Schäffer et al. (2012), Gaertig et al. (2002) and Viswanathana et al. (2011)
Tree growth: ↓	Ares et al. (2005), Brais (2001), Gomez et al. (2002), Smith (2003), Wästerlund (1985), Demir et al. (2010), Blouin et al. (2005), Egnell and Valinger (2003) and Ampoorter et al. (2007)
Forest regeneration: ↓↑	Pinard et al. (2000), Williamson and Neilsen (2000), Perala and Alm (1990), Prévost (1997) and Löf et al. (2012)
Soil fauna: ↓	Heisler (1995), Addison and Barber (1997), Radford et al. (2001), Battigelli et al. (2004), Marshall (2000), Brussaard and van Faassen (1994), Jordan et al. (1999), Bottinelli et al. (2014) and McIver et al. (2003)
Bacteria and fungi: indefinable effect	Marshall (2000), Torbert and Wood (1992), Li et al. (2004), Jordan et al. (2003), Tan et al. (2005), Wronski and Murphy (1994), Startsev et al. (1998), Schnurr-Putz et al. (2006), Hartmann et al. (2014), Frey et al. (2009, 2011), Smeltzer et al. (1986), Dick et al. (1988), Šantručkovă et al. (1993), Breland and Hansen (1995), Tan et al. (2008), Niemalä and Sundman (1977), Lundgren (1982), Entry et al. (1986), Edmonds et al. (2000), Shestak and Busse (2005), Busse et al. (2006), Ponder and Tadros (2002), Hassink et al. (1993) and Bakken et al. (1987)
Emission of GHG: CO_2: ↓ N_2O: ↑ CH_4: ↑	Yashiro et al. (2008), Teepe et al. (2004), Hartmann et al. (2014), Conlin and van den Driessche (2000), Goutal et al. (2012) and Frey et al. (2011)
Soil C sequestration: indefinable effect	Gartzia-Bengoetxea et al. (2011), Johnson (1992) and Sanchez et al. (2006)

pressure on root water uptake in two spruce stands in the Czech Republic growing on soils with different textures. Using heat-field-deformation sap flow sensors in the superficial roots and stem bases of trees close to machinery trails, they found that in moderately wet soil the majority of the impacted roots did not cease their water supply functions; however, some 20–30% of them responded to the loading by sap flow decreases. In a highly productive Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] stand in northwest USA, Ares et al. (2005) assessed that ground-based logging caused on average a 27% increase in soil bulk density, a 10–13% reduction in soil porosity and a 40–52% reduction in macropore space at a depth of 0–30 cm in clay to silty clay soils, which implied an immediate increase in water holding capacity and had no detrimental effects on tree height and diameter four years after soil compaction. In coarse-textured, excessively drained soils, some compaction has been shown to be positive to roots and soil-dwelling biota because it increases the amount of available water (Agrawal, 1991; Jakobsen and Greacen, 1985). In this regard, Gomez et al. (2002) found that in a sandy loam soil in California's Sierra Nevada, compaction both extended the period of plant-available water (86 and 48 days in the top 15 cm and the 15–30 cm soil depths, respectively) and reduced midday stem water stress.

Puddling, the destruction of the soil structure that seals the soil surface, is a frequent effect of wheel slippage at the bottom of ruts that inhibits water infiltration. When infiltration rate is lower than rainfall, waterlogging and/or surface runoff are obvious consequences of puddling (Rab, 1996). In flat terrain, water can reside in ruts for a long time (Fig. 1), so much so that "redoximorphic figures" – chromatic soil features revealing enduring anoxic conditions – may form (Herbauts et al., 1996). Abundant rains may saturate the soil contiguous to ruts, eventually causing mudflows (Fig. 2) or landslides. Ruts are preferential paths for runoff, thus in steep terrain they may become dangerous foci for erosion (*i.e.*, gullies) (Startsev and McNabb, 2000; Christopher and Visser, 2007).

Soil compaction may also imply a strong reduction in air permeability. Frey et al. (2009) found that logging carried out by heavy machinery at 5–10 cm caused reductions in soil air permeabilities of 96% in case of deep rutting, 88% in case of churned, compacted and partly removed topsoil and 51% when no rutting was evident.

Fig. 1. Ruts created by a wheeled tractor during logging operations in the silt loam soil of a coppice oak forest in the Chianti region, Tuscany, Italy. Visible damage includes broken roots, soil displacement and compaction. Soil compaction is so extreme that water does not percolate into the soil and induces anoxic conditions in the top layer. During the rainy season, ruts become preferential flow paths and result in erosion.

Fig. 2. A mudflow that originated after a major rainfall impacted the ruts left in a skid trail during logging in a beech forest at La Futa, Central Italy.

Forest soils are normally characterised by increasing CO_2 levels with depth (Certini et al., 2003; Bekele et al., 2007) due to decreasing soil diffusivity with depth. Mechanised harvesting has a complex impact on both CO_2 production and soil diffusivity (Fernandez et al., 1993; Bekele et al., 2007; Goutal et al., 2012). Once compacted, topsoil characteristically shows higher CO_2 and lower O_2 concentrations compared to uncompacted conditions because of decreased gas diffusivity (Goutal et al., 2013b). In a loamy sand soil sustaining Mediterranean pine plantations, Magagnotti et al. (2012) found that machine traffic during thinning doubled CO_2 concentration, which in machine tracks changed from 0.4% in volume to 0.8%. In stands with Pedunculate oak (*Quercus robur* L.) and Sessile oak [*Quercus petraea* (Mattuschka) Liebl.], Gaertig et al. (2002) found that compacted soil portions showed CO_2 concentrations up to three times higher than the control and that root density decreased significantly with decreasing soil gas permeability. High soil CO_2 concentrations may in fact inhibit root respiration (Qi et al., 1994) and growth (Viswanathana et al., 2011), thereby substantially affecting nutrient supply to trees and whole plant carbon allocation (Kozlowski, 1999; Conlin and van den Driessche, 2000). Root growth is also restricted following compaction due to the increased penetration resistance of soil (Taylor and Brar, 1991; Wästerlund, 1985). Root growth of many trees is limited when soil penetration resistance exceeds 2.5 MPa (Greacen and Sands, 1980; Whalley et al., 1995), which is often reached during forest harvesting.

In a forest stand on sand in Belgium, Ampoorter et al. (2010) noticed that after a single skidding cycle, CO_2 concentration, unlike bulk density and penetration resistance, was significantly higher within and between wheel tracks. Such a finding suggests that carbon dioxide concentration is a rather sensitive indicator of soil compaction, although the former is affected by several other factors partly independent of soil compaction (*e.g.*, soil water content, temperature). Further research on this topic would be welcome.

4.2. Soil biota

The effects of compaction on soil biota vary. Soil fauna is generally altered significantly, chiefly because soil compaction changes the relative proportions of water and air volumes in soil (Brussaard and van Faassen, 1994). Light displacement of soil due to harvesting may result in a short-term increase in the abundance of soil microarthropods (McIver et al., 2003); however, any soil disturbance, compaction in particular, typically results in a negative impact on soil communities. A persistent negative effect of compaction has been recorded for litter microarthropods (Radford et al., 2001), with lower numbers observed in compacted litter layer a year after harvest. Addison and Barber (1997) ascertained that using a feller-buncher harvester or a single-grip harvester implied negligible damage to microarthropods, but on trails, reductions in mites and collembolans were evident. In a variety of soils under different types of forests, Battigelli et al. (2004) found that a combination of whole-tree harvesting and forest floor removal with heavy soil compaction reduced total soil mesofauna densities up to 93% relative to the uncut forest. Ecosystem engineers (*e.g.*, earthworms) are able not only to (sooner or later) recover but also to partly counteract detrimental effects caused by soil compaction. In an oak-hickory forest in Missouri growing on loamy-skeletal Typic Paleudults, Jordan et al. (1999) verified that an almost complete recovery of earthworm density, which had been significantly reduced by soil compaction, occurred two years after logging. Slower recovery of earthworm populations was recorded by Bottinelli et al. (2014) in two forests in northeastern France that were trafficked by a 8-wheel drive forwarder with a load of approximately 23 Mg. At one site, the detrimental impact on the density and biomass of three earthworm functional groups (endogeic, anecic, and epigeic) was still detectable four years after compaction, while at the other site, earthworm populations, represented exclusively by epigeic species, had fully recovered three years after compaction.

Soil microorganisms have perhaps an even more varied reaction to logging-induced soil compaction than meso- and macro-organisms. Several studies have unravelled significant changes in biological variables due to soil compaction (*e.g.*, Niemalä and Sundman, 1977; Lundgren, 1982; Entry et al., 1986; Edmonds et al., 2000; Li et al., 2004; Ponder and Tadros, 2002). In general, microbial biomass and activity are substantially reduced by soil compaction (Torbert and Wood, 1992; Marshall, 2000; Li et al., 2004; Jordan et al., 2003; Tan et al., 2005, 2008; Frey et al., 2009) due to negative changes in total porosity and pore size distribution and connectivity (Wronski and Murphy, 1994; Startsev et al., 1998). Šantručková et al. (1993) and Breland and Hansen (1995) demonstrated that once compacted, the soil partly loses its microbial biomass solely due to limited air supply. Such a loss mainly involves bacteria and fungi (Smeltzer et al., 1986), which are the two main microbial groups. In a 4-year-old clear-cut area in west-central Oregon, Dick et al. (1988) found that in the 10–20 cm depth interval, the silty clay loam soil had 38% less biomass C and 41–75% lower enzyme activity (dehydrogenase, phosphatase, arylsulphatase, and amidase) in the compacted skid trails than elsewhere. In contrast, Busse et al. (2006) found that severe compaction had no detectable effect on community size or activity at three sites in the North American Long-Term Soil Productivity study: two loblolly pine (*Pinus taeda* L.) forests in North Carolina and Louisiana, growing on loamy sand and sandy loam textured soils, respectively, and a mixed conifer forest (*Abies concolor*, *Pinus ponderosa*, *Pseudotsuga menziesii*) growing on a loam soil in California. Also, Shestak and Busse (2005) did not find any major effects of compaction on microbial community size, activity, or diversity in a clay loam and a sandy loam forest soil under either laboratory or field conditions for a wide range of soil compaction levels. In actuality, microorganisms occupy a minor portion of the available surface area in the soil (Hassink et al., 1993), and a reduction in porosity may still leave the majority of such area uninhabited.

4.3. Emission of greenhouse gases from soil

Because of their vitality, forest soils are important sources or sinks of greenhouse gases (Leifeld, 2006). Logging-induced soil compaction can substantially modify the set of gases released and their rates of exchange with the atmosphere. Studying the differences between soil microbial communities from wheel tracks and the adjacent undisturbed soil, Schnurr-Putz et al. (2006) found that the compacted soil portions showed lower eukaryotic/prokaryotic ratios and yielded higher iron-reducing, sulphate-reducing and methanogen potentials than the others. Bacteria capable of anaerobic respiration, including sulfate, sulphur, and metal reducers of the Proteobacteria and Firmicutes, are favoured overall by soil compaction (Bakken et al., 1987; Ponder and Tadros, 2002; Hartmann et al., 2014). An outcome of such structural shifts in soil biota is reduced carbon dioxide and increased methane and nitrous oxide emissions (Frey et al., 2011; Hartmann et al., 2014). Teepe et al. (2004) measured the fluxes of N_2O and CH_4 from soil in skid trails at three European beech forest sites with soils of different textures after two passes with a forwarder. They found that soil compaction in the middle of the wheel track caused a considerable increase in N_2O emissions, with values elevated by up to 40 times those observed in non-compacted soils. Moreover, compaction had reduced the CH_4 consumption at all studied sites by up to 90%, and a silty clay loam soil even became a source of CH_4. These changes in N_2O and CH_4 fluxes were essentially due to a reduction in macropores and an increase in water-filled space. After monitoring a tropical rain forest in Peninsular Malaysia for more than a year, Yashiro et al. (2008) did not disentangle any substantial difference in CO_2 flux from soil between logged and unlogged sites, although soil temperature was usually higher at the logged than at the unlogged site. Nonetheless, N_2O fluxes were elevated significantly for at least 1 year after logging because of an increase in soil nitrogen availability, while the soil behaviour in terms of CH_4 was irregular and incomprehensible. In a loamy soil covered by a forest dominated by European beech and Norway spruce, Hartmann et al. (2014) recorded a highly variable response in the CO_2 flux in relation to the compaction level. They found that unlike with severe compaction, moderate compaction increased CO_2 emissions, possibly because of enhanced microbial mineralisation of freshly exposed organic matter with a still sufficient oxygen supply. Once water permeability reaches critical limits, CO_2 emissions decrease due to reduced aerobic microbial activity, root respiration and gas diffusivity (Conlin and van den Driessche, 2000; Goutal et al., 2012). As a general rule, soil compaction favours the occurrence of anoxic conditions, thus depressing soil respiration and promoting production and release of the powerful greenhouse gas methane to the atmosphere.

4.4. Soil carbon stock

The consequences of harvesting-induced compaction on the C stock of forest soils are still partly unknown, in spite of the recent attention devoted to soil as a major reservoir and sink of C on Earth and, thus, a controlling factor of climate change. Apparently there is no immediate or short-term significant effect, except in cases of severe disturbance or wet soils (Johnson, 1992). In a study of several sites covering a broad range of soil types, particle size distributions, climatic conditions, and tree species, Sanchez et al. (2006) demonstrated that after 5 years there were no detrimental effects of soil compaction on soil C and N contents or C/N ratios in any of the sites, even in the most severely treated sites where soil bulk densities approached root-limiting levels. Soil compaction breaks soil aggregates and exposes the organic matter they contain to microbial decomposition, but plausibly leads some free organic matter to become physically protected from decomposition (Fleming et al., 2006), hence making difficult any inference on the medium- to long-term fate of soil C stock. Only one study by Gartzia-Bengoetxea et al. (2011) has specifically focused in this regard, and the authors hypothesised no major negative effects or even positive ones. These authors, in fact, investigated how soil

C stock, soil structure and unprotected, physically protected and resistant C pools recover 0, 7 and 20 years after mechanical harvesting and site preparation in Monterey pine (*Pinus radiata* D. Don) stands from a mountain temperate humid area in northern Spain. They measured an immediate release of at least 30 Mg C ha^{-1} from the top 5 cm of soil. Nonetheless, total organic C contents were similar 0 and 7 years after disturbance, and even doubled after 20 years, with mean values of 25, 28 and 52 Mg C ha^{-1}.

4.5. Forest growth and regeneration

There is high tree- and site-specificity in forest productivity response to soil compaction; however, in most cases, the outcome is negative (Brais, 2001; Gomez et al., 2002; Parker et al., 2007; Smith, 2003). Froehlich et al. (1986), for example, found that total growth and the last 5 years of growth in ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson) in south-central Washington on or near compacted skid trails were significantly related to the percent increase in soil bulk density; on the contrary, the same variables in interspersed lodgepole pine (*Pinus contorta* Dougl.) did not show any relationship.

Compaction or removal of the surface soil horizons, which tend to be the most fertile, by forest operations may result in reduced plant growth and/or regeneration difficulties (Williamson and Neilsen, 2000). Soil compaction makes skid trails inhospitable to roots in terms of water and oxygen availability and can result in a long-term reduction in natural regeneration (Fig. 3). In these areas, vegetation diversity may be negatively affected. Pinard et al. (2000) found significantly lower density and richness in young woody plants on skid trail tracks than in adjacent areas of old-growth forests growing on Acrisols, Luvisols, and Cambisols in Malaysia. These differences were higher where conventional logging was used compared to reduced impact logging. Both richness and density increased with the amount of time since logging, but even 18 years after logging, abandoned skid trails were poorer in small woody stems relative to surrounding areas. Conlin and van den Driessche (1996) reported that the decreased needle length and net photosynthesis and increased shoot respiration observed in lodgepole pine seedlings growing on a loam textured volcanic ash soil were associated with soil compaction. In a study of long-term timber skidding effects on a sandy clay loam soil in a stand of Oriental beech (*Fagus orientalis* Lipsky) in Turkey, Demir et al. (2010) verified that soil compaction caused decreased herbaceous cover on the forest floor on a skid road, while no significant differences were found in soil chemical properties between the skid road and adjacent undisturbed areas. There are cases where logging-induced topsoil mixing and displacement are positive in terms of regeneration; for example, it may be beneficial in forests where the organic horizons are so thick as to prevent seedling roots from reaching the mineral soil to access water and nutrients (Perala and Alm, 1990; Prévost, 1997; Löf et al., 2012).

Fig. 3. The clear-cut area of a maritime pine coastal forest in Central Italy, where regeneration is absent in the skid trails.

Forest landings are areas located adjacent to haul roads where harvested trees extracted from the cut block are processed and loaded onto trucks. Soils on landings are often excessively compacted by heavy timber harvesting machinery and may take many years to recover from such disturbance. A study by Blouin et al. (2005) examined the properties of soils developed on sandy-skeletal glaciofluvial parent material and the lodgepole pine growing on it, both in non-rehabilitated landings and adjacent naturally regenerated clearcuts, 23 years after landing construction. Landings without natural regeneration had the least favourable soil conditions, including significantly greater bulk density and mechanical resistance and lower total porosity and C and N concentrations, which actually might account for the lack of natural regeneration.

5. Soil recovery

The amount of time necessary for trafficked forest soils to recover has received relatively little attention, which has been nearly completely devoted to short-term investigations (*e.g.*, Rab, 2004; Zenner et al., 2007). Recovery time is highly variable for both physical and biological soil properties because it is strictly dependent on several site-related factors, such as terrain slope, soil thickness, texture, and organic matter content, pedoclimate, biomass and activity of soil biota (Reisinger et al., 1992; Suvinon, 2007; Zenner et al., 2007). For example, clay soils endowed with expandable phyllosilicates, which swell and shrink during wetting-drying cycles, recover their original bulk density faster than less dynamic sandy soils (Greacen and Sands, 1980). In the latter, the consequences of soil disturbance by traffic of harvest machinery can persist for several years or even decades. Rab (2004) showed that granite-derived deep soils in native forests in the Victorian Central Highlands of Australia recovered very slowly from logging-induced compaction, so much so that after ten years, soil bulk density was significantly greater and organic matter content and macroporosity were still significantly lower than in undisturbed areas. Croke et al. (2001) followed the recovery of coarse-textured soils supporting native eucalypt forests in southeast Australia that were subject to timber harvesting activities. Bulk density did not show any significant recovery over the 5-year monitoring period, although runoff and sediment production decreased markedly within the same time period. Goutal et al. (2013b) reported that three to four years following heavy traffic were not sufficient to allow a pair of silt loam Luvisols of northeast France to recover their porosity. Jansson and Wästerlund (1999) recorded a 40% decrease in rut depth one year after harvesting performed with lightweight forest machinery (5–9 Mg). Nevertheless, in mature pine-hardwood forests growing on a range of soils from loamy sand to silty clay loam in northern Mississippi, wheel-rutted soil required twelve years to recover, and soil portions between the ruts that were compacted by the movement of logs required eight years (Dickerson, 1976).

The time necessary for impacted soils to recover their previous physical state is variable according to depth. In this regard, Page-Dumroese et al. (2006) found that 5 years after harvest, some coarse-textured soils had recovered the original bulk density in the top 10 cm layer, but not at 10–30 cm depth. In west-central

Idaho, Froehlich et al. (1985) studied the recovery of bulk density at 5.1, 15.2, and 30.5 cm depths in major skid trails in two forest soils (a mixed, frigid, Typic Xeropsamment formed on granite and a fine-loamy, mixed Dystric Cryochrept developed on volcanic material) following chronosequences (five-year periods) of time since compaction. With the exception of the upper 5.1 cm of the granitic soil, none of the bulk densities in skid trails had returned to their undisturbed values after 23 years since logging. Evidently, the higher biological activity and/or repeated wet-dry cycles in the topsoil promoted faster reclamation than in the subsoil.

Very few studies have investigated the recovery of soil biota after compaction-induced depression. The most focused of them – Hartmann et al. (2014) – assessed that at 4 years post-disturbance, soil microbial communities of a forest dominated by European beech and Norway spruce had recovered in lightly but not in severely compacted soil portions, suggesting that such a recovery is strongly controlled by the severity of soil compaction. The time required for recovery of soil biota, however, also depends on the type of organism and a number of soil properties. Further research on a variety of forest soils that have undergone compaction of different severities is required to collect sufficient data to make a well-grounded conclusion on this subject.

6. Preventing forest soil disturbance

In recent decades, the increasing importance of reduced-impact logging methods has been recognised (FAO, 2004), and several studies dealt with areas where sound practices were applied (*e.g.*, Putz et al., 2001, 2008; Healey et al., 2000; Pinard et al., 2000; Holmes et al., 2002). The starting point for limiting the environmental impact of traffic is a good knowledge of the area involved to calibrate interventions based on the susceptibility of the environment to damage and its resilience. In particular, the decision of whether to use heavy vehicles should rely on an accurate soil properties risk assessment within a geographic information system. Kimsey et al. (2011) developed such a risk assessment for a timber-producing region in the Northern Rocky Mountains, using soil and geology databases to construct geospatially explicit best management practices to maintain or enhance soil-site productivity in that ecoregion. The most frequently indicated measures for limiting the negative effects of heavy logging machinery on susceptible soils appear to be: (i) leaving woody residues on the ground for topsoil reinforcement, (ii) reducing, as much as possible, the contact pressure between machines and soil, (iii) waiting for relatively dry soil conditions, when load-bearing capacity of the soil is higher, and (iv) planning the logging design appropriately.

If harvest residues are left on the ground, as in cut-to-length forest operations, the load of the machine is distributed over a greater area than its actual footprint; hence, the pressure of the equipment per unit contact area is lower (Ampoorter et al., 2007; Labelle and Jeager, 2011). Hutchings et al. (2002) clearly showed the importance of creating a slash mat instead of working on bare soil to reduce compaction in a clay loam Umbric Planosol under a Sitka spruce forest in northeast England. Labelle and Jaeger (2012) tested the effect of harvesting residues on improving trafficability of strip trails in the laboratory by recording peak loads of an eight-wheel forwarder driving on brush mats of different thicknesses by means of a load test platform. They found a significant reduction of the peak load using a >10 kg m^{-2} slash mat compared to a no slash mat scenario. The same authors recommended leaving at least 15–20 kg m^{-2} of slash over highly susceptible soils and concluded that, even though slash mats lose some of their ability to distribute the applied loads with increasing machine passes, they are still beneficial at high traffic frequencies, such as 12 forwarder cycles. On an Andisol under a mixed coniferous forest in northern Idaho, Han et al. (2009) estimated that 7–40 kg m^{-2} of slash must be left on the ground to have a significant effect in terms of soil compaction prevention. Eliasson and Wästerlund (2007) showed that creating a 10 cm thick slash mat on strip roads reduced compaction of a silty clay soil by 12.9% at a 10 cm depth and by 4.5% at 20 cm. Ampoorter et al. (2007) found significant advantages in terms of bulk density and penetration resistance after reinforcing trafficked sandy soils under pine in the southern Netherlands with slash mats in both 10–20 and 20–30 cm depth intervals, with more pronounced advantages in the upper interval. Leaving slash on the ground is thus an efficacious practice to limit soil compaction, although in a silty clay forest soil in Sweden Eliasson and Wästerlund (2007) did not find any significant reduction of rut depth after 1, 2 and 5 machine passes on top of a 10–20 cm thick slash mat.

Slash cover is particularly useful on wet soils or soils with low bearing capacities (McDonald and Seixas, 1997). Han et al. (2006) highlighted an interaction between soil moisture, slash mat thickness, and number of machine passes on penetration resistance in a fine loamy to loam soil in cut-to-length harvesting. In particular, they noticed both a decreasing positive effect of slash treatment (0, 7.5 and 15 kg m^{-2}) with an increasing number of machine passes, as well as the fact that moist soil required a greater amount of slash to produce the same positive effect. However, such a method is efficient when logs are carried, not when they are dragged, which would exclude all extraction systems based on skidding (Wood et al., 2003). In summary, complete removal of the slash cover is not recommended if there is a need to protect the soil from post-harvesting erosion (Rice and Datzman, 1981; Edeso et al., 1999). For this purpose, the type of slash materials is crucial for reducing soil compaction: tree limbs and tops are more efficient than chips and sawdust, independent of the number of passes (Akay et al., 2007). The increased interest in utilising any logging residue for energy production unfortunately competes with the opportunity for leaving large enough amounts of slash for soil reinforcement and also contributes to the depletion of soil chemical fertility (Zabowski et al., 1994), with negative consequences for tree growth (Egnell and Valinger, 2003; Ampoorter et al., 2007).

Technical solutions designed to reduce the contact pressure of vehicles with the ground, such as using lower tire pressures, larger tires, and bogie-tracks, may be applied to limit soil compaction (Foltz, 1995; Alakukku et al., 2003). Tire pressure of forest machinery is generally high because wheels have to sustain high loads and face uneven terrain, with stumps and stones that easily damage tires with low inflation pressure; as a consequence, decreasing air pressure in tires requires careful technical considerations because low pressure may make tires prone tearing. Tire pressure-control systems (TPCS) that optimise tire pressures to match a specific tire's working conditions are a reliable technological solution that helps to improve traction and mobility and extend access during rainy seasons (Lotfalian and Parsakhoo, 2009). Another winning strategy based on the increase of contact area the use of bogie tracks. Sakai et al. (2008) tested this strategy using a Rottne Rapid 8WD forwarder loaded with 9.5 Mg of timber fitted with low or high tire pressures or provided with bogie tracks on a coarse-textured soil with 60% moisture. Essentially, they found that high-pressure tires caused heavy compaction in the subsoil and that the compacted zone for a loaded forwarder with tracks was shallow in depth and had the lowest degree of compaction. Bygdén et al. (2004) assessed that tracks could reduce rut depth by up to 40% and cone index by approximately 10% compared to wide and soft tires in spite of the higher (by 10–12%) mass of tracks. On a wet, soft, shallow peat-based soil, Neri et al. (2007) recorded a reduction in rut depth from 2 to 16 cm after 4 forwarder passes just by decreasing the inflation pressure of 700 mm wide tires from 350 to 100 kPa. In contrast, Eliasson (2005) did not find any significant effects of three forwarder tire pressures (300, 450, and 600 kPa) after 2 and 5 machine passes on rut depth on Norway spruce-covered dry or moist sandy loam soils in Sweden.

Increasing tire width has been recognised as an effective solution for reducing rut depth. Myhrman (1990) reported that an increase of tire width from 600 to 800 mm on an eight wheeled 22 Mg forwarder approximately halved rut depths.

Using lighter machinery definitely seems to be the best solution for reducing the logging impact on soil, but it may be equally valuable to delay harvesting activities until periods when soils are drier or frozen (*i.e.*, less prone to compaction) (Stone, 2002; Sutherland, 2003). Ice-cemented soils actually have high bearing capacity (Šušnjar et al., 2006), however pressures imposed by heavy equipment may melt ice and cause major moulding of the soil surface (Slaughter et al., 1990). As an interim guide, Stone (2002) recommend a minimum of 7.5 cm of frozen uppermost soil for small equipment and 15 cm for large equipment, while Shoop (1995) developed a simple equation that allows the calculation of the maximum load that a frozen topsoil layer of given thickness may sustain.

Good design and planning are very important for reducing the detrimental impact of logging on soil. In particular, designated skid trails allow operations to be confined, thereby limiting soil disturbance onto a few selected areas (Chamen et al., 2003; Horn et al., 2007; Picchio et al., 2012). Actually, guidelines aimed at reducing the areal extent of vehicle movement off permanently used skid trails are being increasingly adopted (Schäffer et al., 2012). The development of a permanent skid track system requires careful planning focused on the reduction of soil disturbance but also on maximising the extraction system performance (Lotfalian and Parsakhoo, 2009). Computer simulation can be helpful for this purpose. Wang and LeDoux (2003) developed an estimation model that is useful for evaluating alternative skidding configurations and their impact on cost, production, and traffic intensity.

Using an analytical model to predict forest soil compaction under forwarder traffic seems to be a promising approach. Goutal et al. (2013a) found that one of these models, SoilFlex, is able to yield satisfactory estimations of the risk of compaction and may effectively support forest managers in selecting the most appropriate machinery for given soil conditions. Additionally, new, more environmentally friendly machinery is expected in the near future. Edlund et al. (2013) used computer simulation to investigate the performance on soft and rough terrain of a new design for a tracked machine bogie (long track bogie) that had: (i) a large wheel connected to and aligned with the chassis main axis, (ii) a bogie frame mounted on the wheel axis but left to rotate freely up to a maximum angle, and (iii) smaller wheels covered by a single conventional metal track, which rotate freely and are mounted on the frame legs with axes plane parallel to the driving wheel. Such a prototype has higher mobility and causes less ground damage than a conventional tracked bogie, although it requires larger torque to create the same traction force as a conventional bogie.

Last but not least, detailed short- and long-term post analyses aimed at assessing the real impact of any work should be systematically performed by control agencies, particularly in forests growing on slopes, which are most prone to erosion. Rehabilitation techniques to ameliorate compacted soils do exist and must be applied when necessary. Rab (1998) reviewed their effectiveness, concluding that ripping with tines mounted on a back of a dozer is useful, and its efficiency can be improved by adding winged boots with tines. Excavators should be used in rehabilitating landings and skid tracks. Reshaping of the ground and creation of environmentally sound anti-erosion barriers may also be meaningful approaches. Unfortunately, the high cost of rehabilitation techniques makes their application limited, except in those cases where the law or a landowner requires them. On the other hand, high costs also discourage the use of skyline or helicopter based logging methods, which would minimise soil compaction problems (Stampfer et al., 2002; Marchi et al., 2014), at least in highly susceptible areas.

7. Conclusions

Soil compaction is a universal concern associated with any soil use and management. Forests are one of the best land uses for soil conservation; however, logging can have large impacts because of the significant ground pressures produced by the equipment used to extract logs. Soil displacement and rut formation are other effects of logging, which in sloping terrain may create dangerous foci for erosion. In recent decades, forest machinery has experienced a welcome development in terms of machine performance during forest operations; however, these developments implied increased power and weight. As an obvious consequence, the generally soft forest topsoil is now subject to severe compaction because of harvesting operations. The soil properties most directly impacted by compaction are total porosity, pore-size distribution and connectivity. Related soil properties, such as permeability, water retention, shear and penetration resistance, are consequently changed. This generally implies that the soil is more prone to erosion and fertility depletion. Soil biota is often negatively affected by soil compaction, and biological processes may change their rate or direction, chiefly due to oxygen depletion. Logging-induced compaction may also indirectly depress the C sink capacity of forest soils and, in the worst case, make them anoxic environments functioning as net sources of the highly efficient greenhouse gases methane and nitrous oxide.

Despite the current reinvigorated interest in employing low-impact methods in various land uses, practices aimed as much as possible at preserving soil in logging operations are commonly adopted. Reasons for this lack of adoption could be the insufficient scientific and technical information available for land managers or the high cost of applying best management practices. Devoting more effort to preserve the soil, a finite natural resource, must become an imperative in forestry. Filling the gaps in our knowledge of the impacts of harvesting should contribute to meet this pressing goal. Unfortunately, few papers address the impact of forest machinery on soil biota, and even fewer address the direct impact on the chemical fertility of soil. Additionally, many papers focused on the topic do not report basic information about the characteristics of the equipment used, logging systems, landscape morphology, soil properties, or environmental conditions, all of which are crucial to conduct meta-analyses of data and prepare reliable technical guidance to operators. The current available literature allowed the compilation of this thorough, but incomplete, assessment of the effects of harvesting on forest soils. A balanced series of new studies could provide a more comprehensive view of the soil conservation issue in forest management. Scientifically sound papers on (i) methods to assess logging-induced soil degradation, (ii) strategies and facilities for reducing soil degradation, and (iii) systems for reclaiming or restoring degraded forest soils are particularly necessary in the near future.

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