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INVESTIGATING THE IMPACT OF GROUND-BASED LOGGING SYSTEMS ON SOIL CHARACTERISTICS APPLYING EMERGING METHODS.

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Investigating the impact of ground-based logging systems on soil characteristics applying emerging methods.

Abstract

Reducing the soil impact of forest operations is a priority for improving sustainable forest management. Logging activities may alter soil in terms of both compaction and rutting. The overall aim of this thesis was to use an emerging methods approach to summarize how ground-based logging systems affect the soil in different working conditions. The thesis is based on four studies: the first applied a meta-analytic approach to machinery-induced soil compaction and its effect on the growth of forest plants; two studies tested new methods of rutting estimation after the trafficking of forest machinery; the last study addressed soil damage caused by skidding and forwarding under specific work conditions. The studies investigated the effects of ground-based extraction systems, including physical soil parameters for assessing compaction (i.e., bulk density and soil penetration resistance) and emerging methods for rutting measurements (i.e., 3D soil models obtained by portable laser scanning and Structure from Motion derived from photogrammetry, with images collected from a ground-based stand or higher altitudes by drones). The results of the meta-analysis showed the effects of soil compaction caused by machine trafficking on both morphological and physiological plant characteristics, especially in fine-textured soil. The most notable results of the other studies highlighted the irrelevant role of driving direction on soil damage during forwarding on a 25% slope. On the contrary, to reduce soil compaction, downhill skidding is preferable to uphill skidding. The results showed that low tyre pressure may mitigate the effects of forwarding on soil compared with higher tyre inflation pressure (i.e., 150 kPa vs. 350 kPa). The pressure on the ground caused by logging vehicles affects the wheel tracks, but to some extent, also the soil between the tracks. In general, the area affected by soil impacts was larger in skidding than forwarding due to the effect of dragged logs. Rutting estimation with photogrammetry and portable laser scanners showed promising results in terms of high-resolution data. It also reduced the time necessary for field surveys and obtaining accuracy compared to manual measurements. Nevertheless, the presence of free water in ruts or brush mats can affect the accuracy of results.

Keywords: photogrammetry, portable laser scanner, structure from motion, sustainable forest operations, soil damages, rutting, soil compaction, skidding, forwarding.

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List of publications

This thesis is based on the work contained in the following papers:

I Mariotti, B., Hoshika, Y.*, Cambi, M., **Marra, E.**, Feng, Z., Paoletti, E., Marchi, E., 2020. Vehicle-induced compaction of forest soil affects plant morphological and physiological attributes: A meta-analysis. Forest Ecology and Management, 462, 118004.

II **Marra, E.***, Cambi, M., Fernandez-Lacruz, R., Giannetti, F., Marchi, E., Nordfjell, T., 2018. Photogrammetric estimation of wheel rut dimensions and soil compaction after increasing numbers of forwarder passes. Scandinavian Journal of Forest Research, 33(6), 613–620.

III **Marra, E.**, Laschi, A.*, Fabiano, F., Foderi, C., Neri, F., Mastrolonardo, G., Nordfjell, T., Marchi, E. Impacts of wood extraction on soil: assessing rutting and soil compaction caused by skidding and forwarding. Submitted manuscript.

IV **Marra, E.***, Wictorsson, R., Bohlin, J., Marchi, E., Nordfjell, T., 2021. Remote measuring of the depth of wheel ruts in forest terrain using a drone. International Journal of Forest Engineering, 11, 1494-2119.

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The contribution of Elena Marra to the papers included in this thesis was as follows:

I Planned the study with the co-authors. Collected the bibliographic information for meta-analysis. Performed the database curation and analysis. Performed additional writing, editing, and review duties.

II Planned the study with the co-authors. Carried out the fieldwork and laboratory work. Prepared the data, including photogrammetry reconstructions, and performed the analysis. Wrote the manuscript with input from the co-authors.

III Planned the study with the co-authors. Carried out the fieldwork and laboratory work. Prepared the data and performed the analysis, including laser scanner and photogrammetry reconstruction. Wrote the manuscript with input from the co-authors.

IV Prepared and analysed the collected data. Planned and wrote the manuscript with input from the co-authors.

Abbreviations

BD	Dry bulk density
BtwR	Between wheel tracks
DTM	Digital terrain model
kPa	Kilopascal
InR	Inside wheel track
PLS	Portable laser scanner
PR	Penetration resistance
SfM	Structure from motion
VI	Soil volume increased
VR	Soil volume removed
vs.	Versus

Papers at a glance

Paper	Reference	Aims and experimental sites	Materials and methods	Main findings
I	Vehicle-induced compaction of forest soil affects plant morphological and physiological attributes: A meta-analysis. Mariotti, B., Hoshika, Y., Cambi, M., Marra, E., Feng, Z., Paoletti, E., Marchi, E.	To summarize responses of seedling physiology and morphology to machinery-induced soil compaction. To analyse plant responses to soil compaction dependent on soil type, taxonomic class, plant age and experiment type.	In total, 45 scientific articles for morphological and 17 articles for physiological traits were identified and collected in a database. MetaWin 2.0 statistical software was used to analyse the data.	The growth reduction due to soil compaction was higher: i) in below-ground than above-ground traits; ii) in younger plants; iii) in pots than in the field; iv) in arenic soils than in finer-textured loamic or siltic soils; v) in conifers than broadleaf only for root-collar diameter.
II	Photogrammetric estimation of wheel rut dimensions and soil compaction after increasing numbers of forwarder passages. Marra, E., Cambi, M., Fernandez-Lacruz, R., Giannetti, F., Marchi, E., Nordfjell, T.	To compare traditional and photogrammetric methods for evaluating rutting (rut depth and rut volume) and estimate soil compaction after multiple passages of a loaded forwarder with two different tyre-pressure levels in flat cropland in Sweden (Umeå).	BD and PR collected within wheel tracks until 60 passages with a forwarder (tyres on the right side inflated to a pressure of 150 kPa and 300 kPa on the left side). Rutting was quantified with photogrammetry and a standard camera mounted on a 3 m height tripod. Manual measurements were used as a reference method.	The rut depths were already higher for a tyre pressure of 300 kPa after 3 passages. The rut volumes measured after only 60 passages were much higher in wheel tracks for tyre pressures of 300 kPa. Close-range photogrammetry is an accurate method for the morphological description of forest soil disturbance after forest logging.
III	Impacts of wood extraction on soil: assessing rutting and soil compaction caused by skidding and forwarding. Marra, E., Laschi, A., Fabiano, F., Foderi, C., Neri, F., Mastrolonardo, G., Nordfjell, T., Marchi, E.	To measure soil compaction and rutting of skidding and forwarding considering driving direction on steep terrain. To compare the accuracy of PLS and close-range photogrammetry in rut estimations, in Italy (Tuscany).	BD and PR within and BtwR wheel tracks after 10 passages for forwarding and 10 and 45 passages in skidding driving in uphill and downhill directions. DTMs derived by PLS and close-range photogrammetry were compared pixel by pixel.	When skidding, soil compaction was higher in uphill than downhill driving direction. This difference was not found for forwarding. Skidding gives a larger soil displacement than forwarding. All the DTMs show high accuracy.
VI	Remote measuring of the depth of wheel ruts in forest terrain using a drone. Marra, E., Wictorsson, R., Bohlin, J., Marchi, E., Nordfjell, T.	To develop a method for measuring rutting caused by machine traffic on uneven forest terrain and flat farmland as a reference, using images acquired by drones in Sweden (Ulricehamn).	Rut-depth measurements by SfM and images taken at 60 and 120 m drone altitudes were compared with manual measurements. The study was done after a logging operation with an ordinary mid-sized harvester and forwarder on a final felling site.	Rutting estimation using drones covered the whole logging site and was comparable to the accuracy of manual measurements. The small error showed at the control site in 120 m drone flight is considered an acceptable error, especially for operational use.

1 Introduction

1.1 General

Since the development of heavy forest machines, their environmental impact has been a constant and contrasting topic. In the past five decades, environmental concerns about forest operation have been increasing due to the development of more productive, sophisticated, and heavy forestry machines (Marchi et al., 2018; Riala et al., 2015). Heavy logs must be transported on the ground in all types of ground-based forest logging. However, even the simplest logging method (i.e., animal logging) has the potential to impact soil (Cambi et al., 2015a; Marchi et al., 2018). Therefore, we must apply methods and technologies to minimize the environmental impact and mitigate the effects of forest operations.

At present, heavy forest vehicles are driven on forest ground during forest operations and may strongly affect soil characteristics and functions (Cambi et al., 2015a). The main negative consequences of ground-based logging operations are compaction and rutting (McNabb et al., 2001). The soil system can suffer substantial, long-lasting, and sometimes irreversible damage from heavy machinery, which negatively affects forest productivity and ecosystem functionality (Hartmann et al., 2014).

The extension and severity of soil disturbances may be affected by several factors related to soil type and condition (Allman et al., 2015; Labelle and Kammermeier, 2019; Naghdi and Solgi, 2014), machine characteristics (Cambi et al., 2016, 2015a; Naghdi et al., 2015; Solgi et al., 2015), forest operators' skills (Marchi et al., 2016), and forest operation planning and design (Picchio et al., 2020; Marchi et al., 2018; Cambi et al., 2016, 2015a; Solgi et al., 2015). The area affected by vehicle trafficking may range between 12 and 70% of the total stand during ground-based logging operations, depending on the system applied (Frey et al., 2009; Grigal, 2000; Picchio et al., 2012). Several studies have investigated the undesired effects of mechanised forest operations on soil and the possible ways to prevent or limit them (Bagheri et al., 2013; Eliasson and Wästerlund, 2007; Greacen and Sands, 1980; Hansson et al., 2018; Jakobsen and Greacen, 1985; Naghdi et al., 2020; Parkhurst et al., 2018; Steinbrenner and Gessel, 1955; Toivio et al., 2017). Nevertheless, studies on the effects of skidding and forwarding on soil showed contrasting results (Cambi et al., 2018; Deconchat, 2001; Gondard et al., 2003; Lanford and Stokes, 1996) and some aspects are still unclear. However, it should be noted that the aforementioned studies were either preliminary investigations or based on methods developed for assessing soil surface disturbance only by the observation of soil conditions after logging. As a result, less visible effects, such as soil compaction, cannot immediately be detected (Spinelli et al., 2010). In addition, neither data nor studies comparing the effects on soil caused by skidding and forwarding (considering a similar operational context) were found, highlighting a gap in the literature.

Wheel ruts have traditionally been measured manually for both research and management purposes (Nugent et al., 2003). This demanding labour, characteristic of traditional methods, make the method trustworthy but costly, and not efficient for dispersed forest logging sites. The high cost and slow nature of such measurements ensure that only a relatively small number of transects can be sampled, making the task well suited for the application of modern geospatial technologies (Koreň et al., 2015).

Research on new methodologies for determining the impact of ground-based logging operations on forest soils is still incomplete. Only a few studies have been carried out on this topic, and there is a recognizable gap in the literature, especially when it comes to comparing new and traditional methods of assessing the impacts of forestry-machine trafficking on soil.

1.2 Soil-machine interaction

The passages of forest vehicles can cause stress components (both vertical and horizontal) and shear forces to the soil (Alakukku et al., 2003). The main consequence of the direct pressure between soil and a portion of the tire or track is soil compaction. This pressure exerted by machines on soil is one of the most important factors affecting soil disturbance, and it depends on the weight and size of the machine as well as the shape of the contact area. The contact area is the portion of the tire or track in contact with the ground. It is difficult to precisely determine the size and shape of the contact area because it depends on tyre characteristics (i.e., inflation pressure, stiffness of the carcass, and distribution of wheel load), soil characteristics (i.e., plasticity and uneven soil surface), and machine movements (i.e., accelerating, braking, and change of direction) (Wong, 2008).

To reduce the risk of soil disturbance, agricultural vehicles can use larger tyres, lower tyre pressure, and bogie-tracks (Alakukku et al. 2003, Chamen et al. 2003). However, the tyre pressure on forest vehicles is usually high due to high wheel loads and uneven terrain, which includes obstacles such as stones and stumps (Eliasson, 2005). Only a few studies have compared the effects of different inflation pressures in tyres of forest vehicles with contrasting results highlight the need for a more in-depth study.

In machine trails, it is possible to identify areas typically affected by machine passages: the wheel tracks area, the area between the two-wheel tracks (also called between-tracks), and the soil close to the wheel tracks (lateral bulges or soil displaced). However, the impacts of machine trafficking on soil may not be limited to the contact area of tyres on terrain; they may also occur in surrounding areas (Solgi et al., 2016).

Many studies have investigated the impacts on soil caused by forestry machines in the wheel tracks area (Bygdén et al., 2004; Eliasson and Wästerlund, 2007). In contrast, few studies have investigated the effects on soil caused by ground-based logging systems in the area surrounding the tracks, highlighting a gap in the literature.

1.3 Impact of forest operations on soil

The main effects on forest soil due to ground-based logging are increased compaction and the creation of rutting, both of which contribute to undesirable effects on soils, vegetation, microorganisms, and water bodies.

1.3.1 Direct impacts on soil

Soil compaction is the densification of soil particles and occurs with an increase in BD or decrease in porosity (Hansson, 2019). In forest operations, soil compaction is the result of pressure exerted by machine tyres or tracks on the ground. When this pressure exceeds the soil's bearing capacity, especially under increasing tractive demand, subsequent wheel slippage can form a shearing rut (Eliasson and Wästerlund, 2007).

The reduction in total porosity by compaction of forest soil may amount to 50–60% (Ampoorter et al., 2012; Ares et al., 2005; Frey et al., 2009; Picchio et al., 2012; Solgi and Najafi, 2014). Higher reduction usually occurs in soil with a low initial BD (Hillel, 1998; Williamson and Neilsen, 2000). However, once compacted, any soil is relatively resistant to further compaction (Ampoorter et al., 2012). In fact, the first forestry machine passage may cause 50-75% of soil compaction (Wasterlund, 2020).

A rut is a manifestation of inelastic soil deformation and the result of the formation of two parallel berms associated with shearing stresses and soil compression in moist or wet soils (Horn et al., 2007). Beyond a critical water content, tyre or track forces cause soil displacement and rut formation rather than simple compaction (Horn et al., 2007, 2004).

The severity of soil compaction and rutting depends on several factors, such as initial soil characteristics, ground slope, number of forest machine passages, tire characteristics, and type of logging operations (Bygdén et al., 2004; Jamshidi et al., 2008). Rut depth and soil compaction may increase with increasing slope, evidently because the vertical component of the force from the load is distributed on a smaller surface. Other factors potentially able to play a role in forest logging damages, such as driving direction (i.e., wood extraction operations uphill and downhill), extraction method (i.e., skidding and forwarding logging operations), and their interaction have not been sufficiently investigated to infer any general rule.

1.3.2 Indirect impacts on soil

Indirect impacts on the soil environment are those that are not a direct result of rutting or the compaction process. These are often produced as secondary or even third-level impacts. Soil disturbance caused by machine traffic can increase soil erosion (Solgi et al., 2015; Wagenbrenner et al., 2016), decrease root penetration and length expansion (Bengough et al., 2011; Picchio et al., 2019), promote the transmission of pathogenic fungi, and inhibit microbiological processes. Moreover, compaction indirectly influences changes relative to the proportion of water and air volume in soil (Brussaard and Van Faassen, 1994), leading to reduced soil aeration, nutrient uptake, and water availability to roots and microorganisms (Bodelier et al., 1996; Frey et al., 2009; Startsev and McNabb, 2000). These changes in the soil environment may influence plant growth and, at the same time, forest productivity and ecosystem functions (Cambi et al., 2015b). Compaction in forest soils can result in positive and negative effects on plant response (Alameda and Villar, 2009; Arvidsson, 1999) depending on plant species (Godefroid and Koedam, 2004), soil texture (Siegel-Issem et al., 2005), and plant age (Blouin et al., 2005).

Several studies, as reported in the above-mentioned literature, have investigated the direct and indirect effects of forest machines on soil. However, since plant response to compaction is complex, the effects of vehicle trafficking cannot be described by individual studies due to small sample size, indicating the need to apply different statistical approaches. (Mariotti et al., 2020).

1.4 Soil recovery and preventing forest soil disturbance

Soil damage seems to persist for around 5 years in areas of less severe disturbance and up to 30 or more years in areas of high disturbance (Jourgholami et al., 2020; Venanzi et al., 2019; Corns, 2011; Reisinger et al., 1992; Froehlich et al., 1985; Wert and Thomas, 1981). However, the amount of time necessary for trafficked forest soils to recover is strictly dependent on several site-related factors, such as terrain slope; soil thickness, texture, and organic matter content; pedoclimate; and biomass and activity of soil biota (Suvinen, 2006; Zenner et al., 2007).

The starting point for limiting the environmental impact of forest machinery traffic is a thorough knowledge of the area involved in order to calibrate interventions based on its susceptibility or resilience to environmental damage. Logging activity should be focused on permanent tracks to reduce the area impacted in the forest.

Negative effects may be reduced if woody residues are left on the ground for topsoil reinforcement, reducing, as much as possible, the contact pressure between machines and soil (Ampoorter et al., 2012; Eliasson and Wästerlund, 2007; Han, 2006; Poltorak et al., 2018). However, the benefits of slash to mitigate soil compaction are limited to their deterioration in a few passages (Agherkakli et al., 2014). Using lighter machinery seems to be the best solution for reducing logging impact on soil. However, machine load capacity needs to be taken into account to avoid a higher number of passages.

Technical solutions designed to reduce the contact pressure of vehicles with the ground, such as using lower tyre pressures, larger tires, and bogie-tracks, may be applied to limit soil compaction (Alakukku et al., 2003; Foltz, 1994). To reduce soil compaction through increased contact area, new machine prototypes with 10-wheel triple-bogie (Starke et al., 2020), or with combi-tracks (Fjeld and Østby-Berntsen, 2020) and additional supportive rollers in the centre of the bogie-axle (Engler et al., 2021), have been performed recently.

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.

1.5 Methodologies for determining impacts on soil

There are many methods for evaluating the soil impact of a forest machine. A very simple method used for assessing the disturbances on soil caused by forest operations is based on visual inspection of soil disturbance (McMahon, 1995). This method may be useful for estimating the ground surface affected by logging but does not give detailed information on disturbance severity (i.e., soil compaction). More accurate traditional methods are usually based on measurements of changes in physical characteristics of soil found within forest-machine tracks. Soil compaction is usually expressed as BD, soil porosity, or indexed by soil strength measurements (soil PR and shear resistance) (Ares et al., 2005).

Several methods have been developed to assess rutting using rut depth and volume (Eliasson, 2005). Traditional methods, such as manual measurements (Jester and Klik, 2005) using a levelled hurdle and ruler or measuring tape can estimate rut depth caused by machine passages by comparing post-trafficking data with data collected before trafficking began (Nugent et al., 2003). These data are usually collected along transects perpendicular to the direction of ruts. The distance between sampling lines is usually several meters (Koreň et al., 2015). The accuracy of the total representation of ruts is not high, and the estimation of rut volume is rough.

To capture and analyse the spatial distribution of soil disturbance more accurately, helpful and innovative tools are available to assess rutting. Rut depths, or moved soil volumes, have been estimated using laser scanning (Giannetti et al., 2017; Koreň et al., 2015; Salmivaara et al., 2018), photogrammetry (Cambi et al., 2018; Haas et al., 2016; Nevalainen et al., 2017; Pierzchała et al., 2016; Talbot et al., 2018), motion and depth sensors (Marinello et al., 2017; Melander and Ritala, 2018), and ultrasonic transducers (Ala-Ilomäki et al., 2012). The above-mentioned methods have been applied in different settings: static and mobile, terrestrial and airborne, and used in real-time and post-operations analysis (Talbot and Astrup, 2021).

A recent study summarized the pioneering approaches and innovative applications of the technologies for rutting estimation (Talbot and Astrup, 2021). However, the use of photogrammetry and terrestrial laser scanning in forestry are considered new methods when used to assess the depth and shape of wheel tracks (Talbot et al., 2018). In reality, little is known about the efficacy of these newer methods in assessing the impact of forestry-machine traffic on soil in comparison to traditional methods. Moreover, even fewer studies have considered the progression of soil changes (i.e., at intervals between passages).

1.6 Aims

The overall aim of this thesis was to assess and discuss, through an emerging methods perspective, how ground-based logging systems affect soil in different working conditions. The thesis is based on four papers (Figure 1.1). The first used a meta-analytic approach to summarize responses of seedlings to machinery-induced soil compaction analysed in previous and different studies. The second and fourth papers developed new methods for estimating soil damage after ground-based logging in Sweden. The third paper used photogrammetry and portable laser scanners to compare soil damage in central Italy caused by skidding and forwarding.

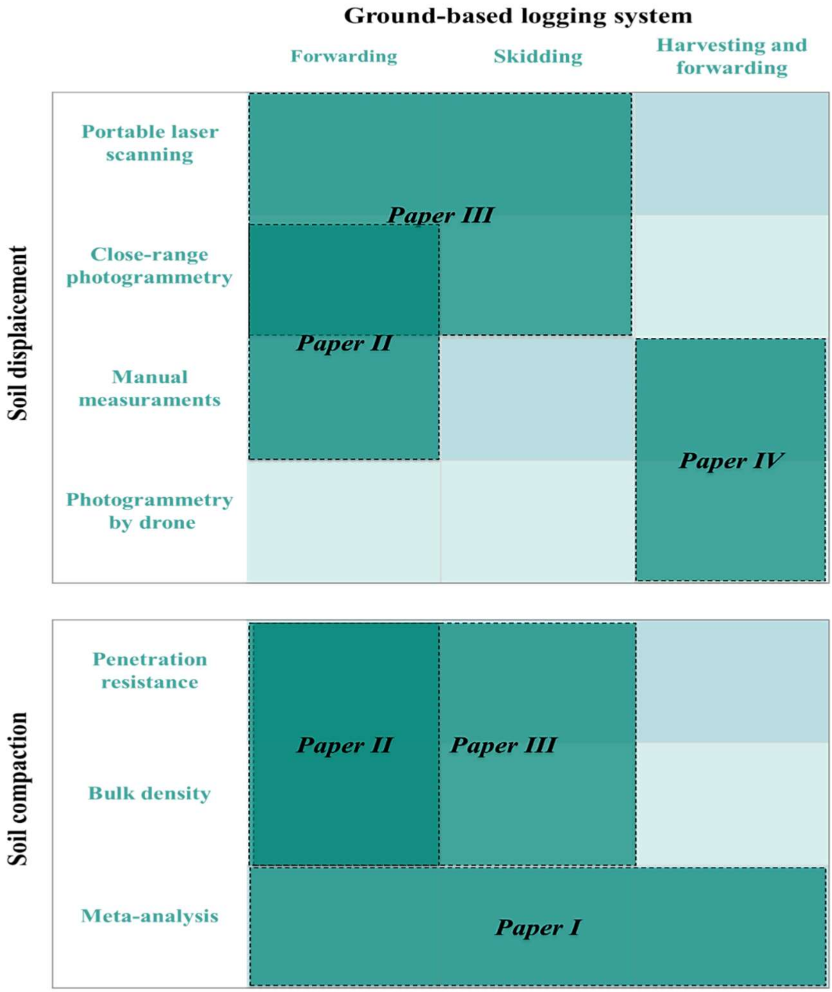

Figure 1.1. Conceptual framework of the thesis and underlying studies (papers).

The specific aims were to assess and/or discuss: i) changes in rutting after forestry operations (Paper II, III, IV); ii) traditional and emerging methods for evaluating rutting (Paper II, III, IV); iii) changes in physical properties of soil caused by forestry operations (Paper I, II, III); vi) the effects of forwarding and skidding on soil under different work conditions (Paper II, III).

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2 Paper I - Vehicle-induced compaction of forest soil affects plant morphological and physiological attributes: A meta-analysis

Abstract

A main disadvantage of heavy machinery in forest operation is soil compaction. Compacted soils may be a barrier to seedling growth, even though the exact mechanisms of action are not clear yet, especially for different soil textures, plant species and ages. Previous meta-analyses did not find significant effects, mostly due to the limited size of their databases. We analyzed 45 articles for above-ground and below-ground morphological traits and 17 articles for physiological traits, and found significant declines following soil compaction. Declines were higher at below-ground than above-ground traits, in younger (< 2-year-old) than older plants (2 to 20-year-old), in pots than in the field, and increased from the coarse-textured Arenic soils to the finer-textured Loamic or Siltic soils. Data from Clayic soils were insufficient for this analysis. More studies on older plants are also recommended. Responses of conifers and broadleaf species were similar. Our findings suggest that the shorter main roots developed due to soil compaction reduce water uptake and thus photosynthesis and the overall plant physiological performance. No significant changes of nitrogen availability to plants were detected. These results could help a successful seedling regeneration after forest operations.

2.1 Introduction

Use of heavy machinery in forest operation implies many advantages, improving work efficiency and production performance (Akay and Sessions, 2001; Montorselli et al., 2010). On the other hand, a main disadvantage is soil compaction, i.e., an increase in the amount of soil particles per volume unit (Kozlowski, 1999; McNabb et al., 2001; Cambi et al., 2015). The extent and severity of soil compaction are affected by several parameters related with soil types and conditions, machine characteristics, and soil/machine interactions. Moreover, in well managed forest operation soil disturbance is confined onto a few selected areas (i.e., skid trails) (Cambi et al., 2015). Soil compaction changes relative proportions of water and air volumes in soil (Brussaard and van Faassen, 1994), leading to reduced oxygen and water availability to roots and microorganisms (Bodelier et al., 1996; Startsev and McNabb, 2000; Frey et al., 2009). Tree physiology and growth may be influenced by these substantial changes of soil environment, so that forest productivity and ecosystem functions are affected (Hartmann et al., 2014; Cambi et al., 2015). A better knowledge about the impact of forest operations by heavy machinery on forest trees is therefore needed for optimizing the use of this machinery (Picchio et al., 2012; Benjamin et al., 2013; Marchi et al., 2014). Compacted soils may be a barrier to seedling establishment and growth (Basset et al., 2005; Cambi et al., 2018; Correa et al., 2019), because the increased soil strength delays penetration of the soil surface by the radicle (Smith et al., 2001; Smith and DuToit, 2005). Kozlowski (1999) mentioned that soil compaction may negatively affect leaf physiology and plant growth by limiting soil water availability and nutrient uptake. However, contrasting hypotheses have been raised to explain the impacts of soil compaction on plant growth. Arvidsson (1999) suggested that soil compaction may facilitate root-soil contact, thus favouring nutrient and water absorption by plants. In fact, several studies found a positive effect on seedling growth (Alameda and Villar, 2009; Bejerano et al., 2010). Meta-analysis has developed rapidly since the late 1990s, and is recognized as a quantitative approach that estimates a mean relative response from individual studies to find general trends and difference (Koricheva et al., 1998; Ainsworth and Long, 2005; Feng et al., 2008; Ampoorter et al., 2011; Haworth et al., 2016). A previous meta-analytic review by Ampoorter et al., (2011) assessed the impacts of soil compaction on height and diameter of seedlings in terms of seedling growth. They reported that those effects of soil compaction were predominantly insignificant, highly variable and changing with soil type. However, in the last decade the amount of studies aimed at assessing the effect of compaction has increased, and includes a wider range of variables, not only morphological and above-ground but also physiological and below-ground traits. A quantitative analysis, with above- below ground interactions and other ecological and physiological traits, is now needed to assess the extent to which compaction affects seedling regeneration (Basset et al., 2005; Cambi et al., 2018). Questions have been raised whether plant response to compaction in forest soils depends on plant species (Godefroid and Koedam, 2004), soil texture (Powers et al., 2005) and plant age (Froehlich et al., 1986; Blouin et al., 2005). However, since the plant response to compaction is really complex, these questions cannot be answered by individual studies due to the small sample size. In this study, according to the meta-analytic approach, our aim was to summarize responses of seedling physiology and morphology, including below-ground traits, to machinery-induced soil compaction. We addressed the following questions: (1) Does soil compaction have a positive or negative effect on seedling growth? (2) To what extent is the plant growth changed by soil compaction, and which parameters are associated with this change? (3) Are plant responses to soil compaction dependent on soil type, taxonomic class, plant age and experiment type (i.e., field vs. pot experiments)?

2.2 Materials and Methods

2.2.1 Database

Target traits were both morphological and physiological. In morphological traits, we included dry biomass (total, shoot, root, and leaf dry biomass), total leaf area, root depth, root-collar diameter (RcD) and seedling height. Concerning physiology, we considered leaf gas exchange (net photosynthesis, transpiration), leaf nitrogen (N) content and midday leaf water potential. Using Web of Science, Scopus and Google scholar, a survey of all peer-reviewed published literature was made on the basis of the keywords "[soil compaction] + [a target trait]", including researches under natural environmental conditions and manipulative experiments. The literature was also cross-checked through the list of references included in review papers. To include an article in this meta-analysis, we examined if it met the following criteria: (1) bulk density (BD) was reported as a metric to quantify soil compaction; (2) plant species were those of forest trees, including cultivars/clones; (3) measured responses included at least one of the target traits; (4) the experimental period was longer than 20 days; (5) the soil data included the information of soil classification according to USDA or FAO classifications; (6) there is a control, (7) the approach is experimental and not observational, and (8) standard deviations and sample sizes are provided. Regarding the first criterion, we decided to include articles that used BD, because it was the most common parameter used in the analyzed literature. The use of other parameters (e.g., total porosity, penetration resistance, shear resistance) would have reduced the number of papers included in our study. We calculated a degree of soil compaction described as the ratio of BD in the compacted treatment to BD in the control (RRBD) as an indicator of soil compaction. Articles were excluded when: (1) the description of experimental design was insufficient to allow an objective assignment, (2) numeric data in results or measurement units were missing, (3) data were collected on sprouts or cuttings, (4) the data were reported in another article. After excluding articles based on these criteria, 45 articles for morphology and 17 for physiology published from 1959 to 2017 were used for the meta-analysis (see the literature list in Appendix S1). The study included trials carried out in Europe (11 articles), North America (31 articles), Asia (4 articles) and Oceania (9 articles).

2.2.2 Sources of variation

Data were analyzed all together to point out the general effect of compaction on each target trait. The dataset was also divided into categories to further investigate the responses to soil compaction according to different factors. The following categories were considered: (1) soil classification, including Arenic, Loamic, Siltic, and Clayic soils (IUSS Working Group WRB, 2015) (2) species taxonomy, including conifers and broadleaf tree species; (3) plant age, including age ≤1, 1–2,

≥2 years; (4) type of experiment, separating experiments in the field, where soil was compacted by vehicles, from trials carried out under controlled conditions (field; no field), such as nursery, greenhouse, growth chamber, where plants were grown in pots and the soil was compacted mechanically by specific tools (e.g. compression-testing machine; details are provided in the original papers). Concerning soil classification, we converted the USDA soil taxonomy into 4 categories according to the FAO (IUSS Working Group WRB, 2015) classification as follows: a) Arenic, which included sand (i.e., fine sand, medium sand and coarse sand), loamy sand and sandy-silt soil; b) Loamic, which included loam (i.e., fine sandy loam, coarse loamy and fine-sandy to silt clay loam), sandy loam, sandy clay loam, clay loam, silt clay loam, loam to clay-loam, sandy loam to loam, sandy loam-clay loam; c) Siltic, which included silt loam, silt loam-loam, and fine silty; d) Clayic, which included clay and silty clay. Concerning plant age, the classes were selected to distinguish the first two growing seasons from the following ones in order to separate the effect on young seedlings from that on more adult stages. Due to the low number of studies carried out on plants older than 2 years, we decided to group them into one class (3–20 years old).

2.2.3 Meta-analysis

The meta-analysis was conducted by using the MetaWin 2.0 statistical software (Rosenberg et al., 2000). To estimate the treatment effect, the natural log of the response ratio (Ln r = Ln [value in the compacted soil/value in the control]) was used as the metric for the analysis (Hedges et al., 1999; Rosenberg et al., 2000) and reported as the percentage change i.e., $(r - 1) \times 100\%$ (Ainsworth et al., 2002; Curtis and Wang, 1998). Negative percentage changes indicate a decrease of the variable in response to soil compaction, whereas positive values indicate an increase. We combined the log response ratios with the mixed effects model on studies, assuming that differences among studies are due to both sampling error and random variation. For net photosynthesis, leaf N content and midday leaf water potential, a weighted parametric analysis was applied because standard deviations or standard errors and sample sizes were available in the original papers. However, for transpiration and all morphological traits, since some studies did not report standard deviations or standard errors with replicate size, we applied an un-weighted non-parametric approach in which 95% confidence intervals of the effect size were calculated by resampling the data using 4999 bootstrap replicates for each analysis. This approach may allow to include a larger number of studies in a meta-analysis (Adams et al., 1997). For those parameters, results by using only the studies providing standard deviations or standard errors with replicate size was also presented in a supplementary file (Appendix Table S2). Estimates of the effect size were assumed to be significant if the 95% confidence intervals (CIs) did not overlap with zero (Curtis and Wang, 1998; Morgan et al., 2003). To compare the effect of compaction between groups in target categories (1. soil classification, 2. species taxonomy, 3. plant age, 4. type of experiment), we conducted a X2 statistical test for target categories (Gurevitch and Hedges, 2001). Meta-analytic methods require individual observations to be statistically independent. Following previous meta-analyses (Curtis and Wang, 1998; Feng et al., 2008, 2010; Feng and Kobayashi, 2009), trait values were considered independent if the study was random effect and if they were obtained from: (i) different plant species and different soil compaction treatments; (ii) when the measurements were made in different seasons or years in the same experiment. The meta-analyses were conducted if there were either at least 10 observations, or two independent articles. In cases where the number of observations of a category did not reach this threshold, it was excluded from the analysis by categories.

2.3 Results

2.3.1 Effects on above- and below-ground morphological traits

2.3.1.1 Overall effects of soil compaction

Across all studies, compaction significantly reduced all target variables except total leaf area (Figure 2.1), with a general decrease both in shoot-and in root-system growth. Soil compaction decreased total dry biomass (-16.9%, ranging from −26.9% to −6.2% [CI ± 95%], with an average RRBD of 1.19). Shoot, root and leaf dry biomasses were also decreased by soil compaction (−14.6%, −17.2% and −13.4%, respectively). The negative effect was remarkable for root depth (−29.0%, 1.24 RRBD). Plant height was also strongly reduced by soil compaction (−22.0%, 1.30 RRBD). Root collar diameter (RcD) was significantly reduced, despite to a lesser extent: −8.3% (1.27 RRBD).

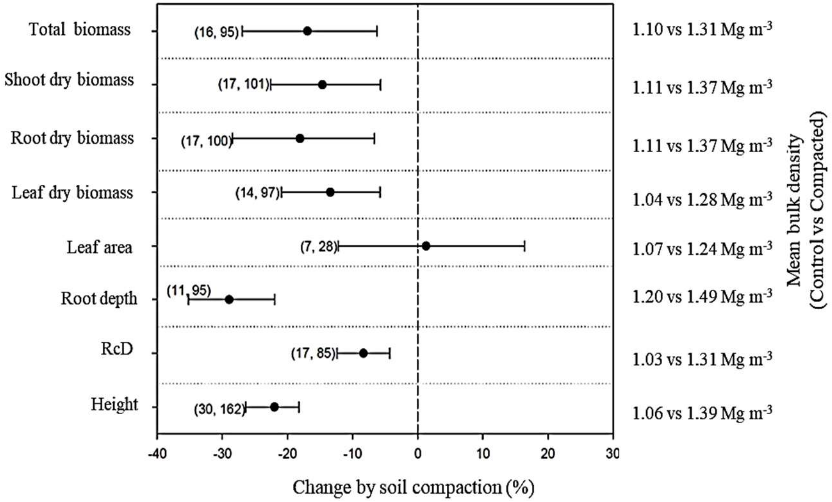

Figure 2.1. Overall effect of soil compaction on morphological parameters (dry biomass [total, shoot, root, and leaf dry biomass], total leaf area, root depth, root-collar diameter [RcD] and seedling height). Symbols represent the overall mean percent change at compacted soil relative to control, and the bars show the effect size (±95% confidence intervals CIs). Number of studies and observations are shown in parentheses, and mean bulk densities in control and compacted soils are given on the y-axis. Effects are significantly different from 0 when 95% CI does not contain zero.

2.3.1.2 Effects of categories

Figure 2.2 shows a comparison of the effect of soil compaction on morphological traits as affected by soil texture. Significant differences between soil categories were found for total dry biomass, root dry biomass, total leaf area, root depth, RcD and height. For total dry biomass, plants growing in Loamic soils showed a significant reduction by soil compaction (−17.9%, 1.20 RRBD) while plants in Arenic soils did not vary significantly (+10.5%, range −6.2 to +30.1%; 1.12 RRBD). Data were insufficient to test the effects of Siltic and Clayic soils. Similar results were found for total leaf area (Arenic: +18.2%, 1.11 RRBD; Loamic: −17.8%, 1.23 RRBD). The negative impacts of soil compaction on root dry biomass and root depth were significantly larger in Siltic soils (root dry biomass: −43.7%, 1.24 RRBD; root depth: −54.7%, 1.28 RRBD) than in Arenic soils (root dry biomass: −8.1%, 1.27 RRBD; root depth: −18.1%, 1.26 RRBD). The decline in root dry biomass in Loamic soils (−11.4%, 1.23 RRBD) did not differ significantly from those in Arenic and Siltic soils, while the decline in Root depth in Loamic soils (−26.9%, 1.23 RRBD) was similar to that in Arenic soil and lower than that in Siltic soil. Plant height was significantly less affected by compaction in Loamic soils (−13.7%, 1.31 RRBD) than in Arenic (−32.3%, 1.26 RRBD) and Clayic soils (−38.9%, 1.45 RRBD). Regarding RcD, plants growing in Loamic soils showed a lower reduction by compaction (−4.9%, RRBD 1.32) than in Arenic soils (−18.5%, RRBD 1.05).

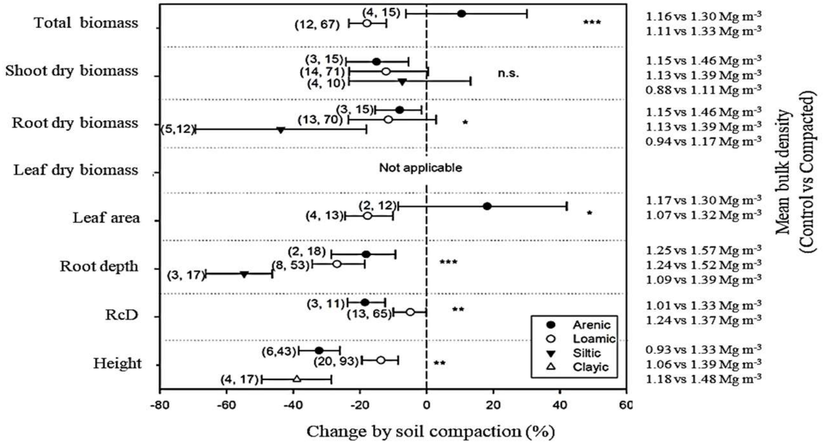

Figure 2.2. Effect of soil compaction on morphological parameters (dry biomass [total, shoot, root, and leaf dry biomass], total leaf area, root depth, root-collar diameter [RcD]

and seedling height) among different soil types (Arenic, Loamic, Siltic, Clayic). Symbols represent the mean percent change of each analyzed category at compacted soil relative to control, and the bars show effect size (±95% confidence intervals CIs). Number of studies and observations are shown in parentheses, and mean bulk densities in control and compacted soils are given on the y-axis. Effects are significantly different from 0 when 95% CI does not contain zero. X2 test was applied for the categorical comparison: ***p < 0.001, **p < 0.01, *p < 0.05, n.s.: not significant.

Figure 2.3 shows a comparison of the effect of soil compaction on morphological traits as affected by plant taxonomy. The only parameter that showed a significant difference between the conifer and broadleaf species was RcD, with broadleaf species more affected (-14.8%, 1.32 RRBD) than conifers (-6.1%, 1.25 RRBD). The traits that showed a significant negative effect of compaction for both broadleaf and conifer species were leaf dry biomass, root depth, RcD and height.

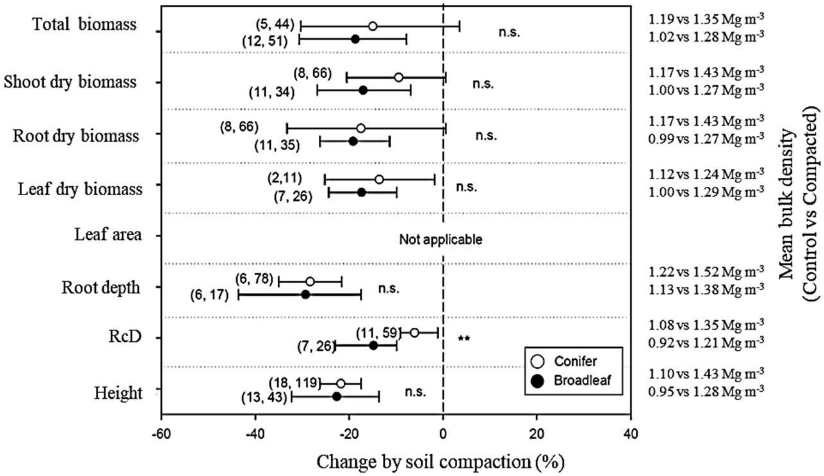

Figure 2.3. Effect of soil compaction on morphological parameters (dry biomass [total, shoot, root, and leaf dry biomass], total leaf area, root depth, root-collar diameter [RcD] and seedling height) between taxonomic classes (conifer, broadleaf). Symbols represent the mean percent change of each analyzed category at compacted soil relative to control, and the bars show effect size (±95% confidence intervals CIs). Number of studies and observations are shown in parentheses, and mean bulk densities in control and compacted soils are given on the y-axis. Effects are significantly different from 0 when 95% CI does not contain zero. X2 test was applied for the categorical comparison: **p < 0.01, n.s.: not significant.

Concerning the response to plant age (Figure 2.4), root depth, RcD and height showed significant differences, with the effects of compaction being more negative in younger seedlings. Root depth in ≤1 years old plants showed a reduction by −52.1% (1.27 RRBD) while 1–2 years old plants showed a reduction by −24.3% (1.23 RRBD). Root collar diameter (RcD) and height showed a significantly larger reduction by soil compaction in ≤1 years (RcD: −10.8%, 1.40 RRBD; height: −27.4%, 1.37 RRBD) and 1–2 years old plants (RcD: −14.0%, 1.14 RRBD; height: −24.9%, 1.21 RRBD) than in>2 years old plants (+0.5%, 1.40 RRBD; height: −7.6%, 1.36 RRBD).

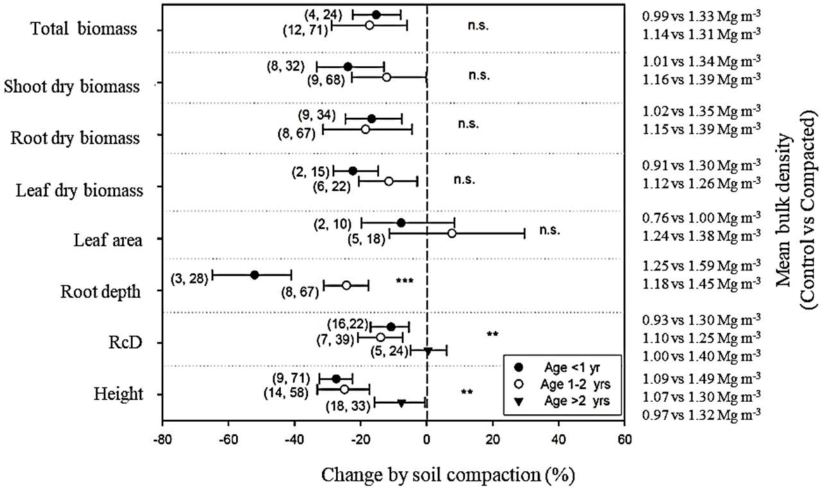

Figure 2.4. Effect of soil compaction on morphological parameters (dry biomass [total, shoot, root, and leaf dry biomass], total leaf area, root depth, root-collar diameter [RcD] and seedling height) among age classes (age ≤1, 1–2, ≥2 years). Symbols represent the mean percent change of each analyzed category at compacted soil relative to control, and the bars show effect size (±95% confidence intervals CIs). Number of studies and observations are shown in parentheses, and mean bulk densities in control and compacted soils are given on the y-axis. Effects are significantly different from 0 when 95% CI does not contain zero. X2 test was applied for the categorical comparison: ***p < 0.001, **p < 0.01, n.s.: not significant.

Most experiments were carried out under controlled conditions. Thus, for most morphological traits, there were not enough data to compare the experiment type categories (field; no field) (Figure 2.5). However, a significant difference was found in RcD and height. Soil compaction reduced RcD in plants growing under controlled conditions (no field) by −26.4% (1.23 RRBD), while those under field condition did not show a significant reduction. Plant height showed a significantly larger reduction by soil compaction under no field (−26.4%, 1.19 RRBD) than under field conditions (−14.0%, 1.36 RRBD).

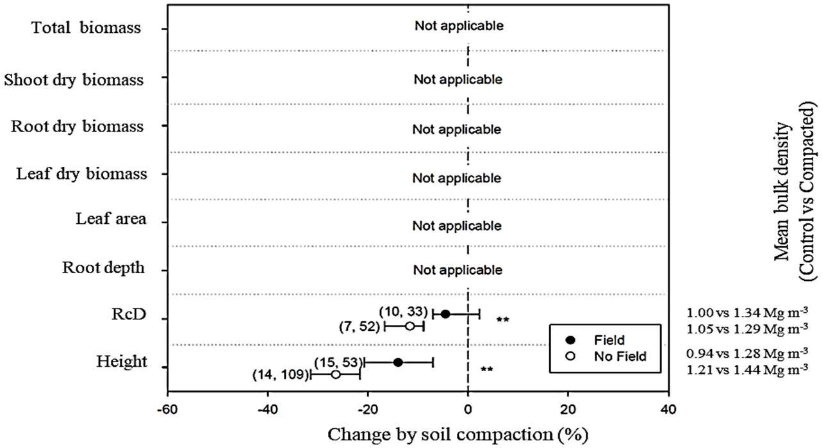

Figure 2.5. Effect of soil compaction on morphological parameters (dry biomass [total, shoot, root, and leaf dry biomass], total leaf area, root depth, root-collar diameter [RcD] and seedling height) between experiment types (field, no Field). Symbols represent the mean percent change of each analyzed category at compacted soil relative to control, and the bars show effect size (±95% confidence intervals CIs). Number of studies and observations are shown in parentheses, and mean bulk densities in control and compacted soils are given on the y-axis. Effects are significantly different from 0 when 95% CI does not contain zero. X2 test was applied for the categorical comparison: **p < 0.01.

2.3.2 Effects on leaf-level physiological traits

2.3.2.1 Overall effects of soil compaction

Across all studies, soil compaction treatments decreased net photosynthesis by −25.6% (range −32.3 to −19.7% with 1.18 RRBD) (Figure 2.6). Transpiration rate was also significantly decreased by soil compaction (−14.8%, 1.16 RRBD). Concurrently with the decline of net photosynthesis and transpiration, leaf water potential significantly decreased (−5.2%, 1.17 RRBD). On the other hand, leaf N content was not significantly affected by soil compaction (−1.4%, 1.19 RRBD).

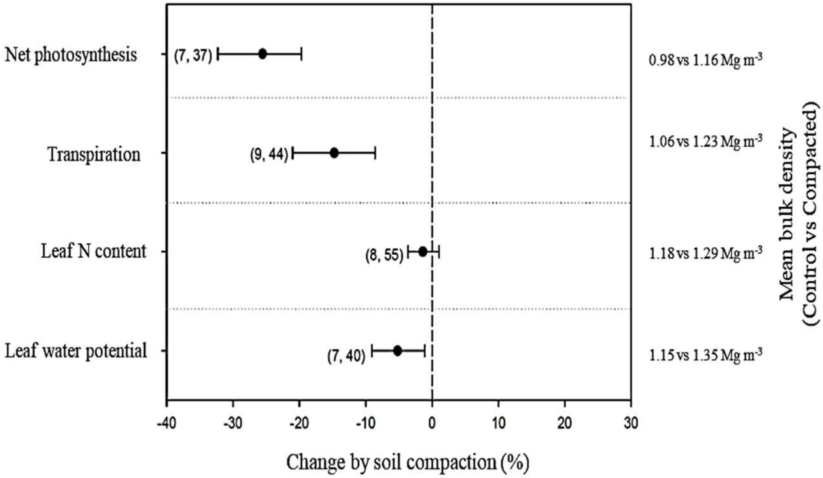

Figure 2.6. Overall effect of soil compaction on leaf physiological parameters (net photosynthesis, transpiration, leaf nitrogen [N] content and leaf water potential). Symbols represent the mean percent change of each analyzed category at compacted soil relative to control, and the bars show effect size (±95% confidence intervals CIs). Number of studies and observations are shown in parentheses, and mean bulk densities in control and compacted soils are given on the y-axis. Effects are significantly different from 0 when 95% CI does not contain zero.

2.3.2.2 Effects of categories

Limitation of data availability affected the analysis of physiological traits. Responses did not differ between species taxonomy, seedling age, and experiment type (data not shown). However, we interestingly found that the effects of soil compaction on net photosynthesis, transpiration and leaf water potential depended on soil type (Figure 2.7). Net photosynthesis decreased in compacted Loamic soils (−36.5%, 1.20 RRBD), while no significant reduction was found in Arenic soils (1.17 RRBD). Similar results were found for transpiration (Arenic: −5.1%, 1.11 RRBD; Loamic: −32.3%, 1.20 RRBD) and leaf water potential (Arenic: +4.6%, 1.15 RRBD; Loamic: −5.8%, 1.18 RRBD).

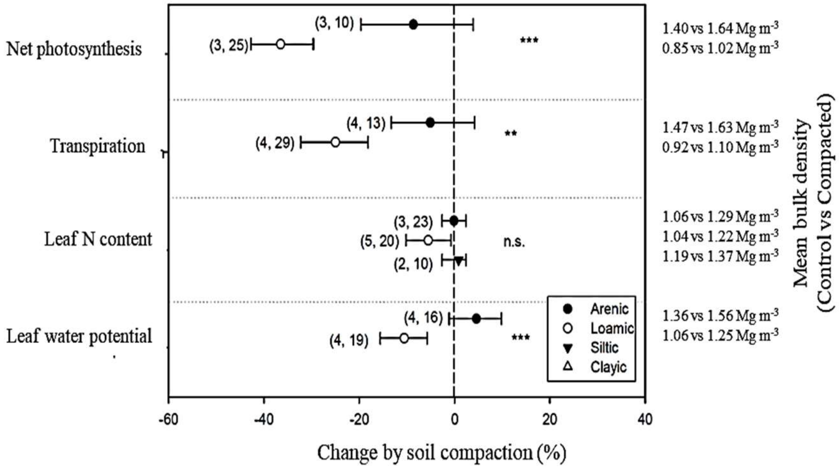

Figure 2.7. Effect of soil compaction on leaf physiological parameters (net photosynthesis, transpiration, leaf nitrogen [N] content and leaf water potential) among different soil types (Arenic, Loamic, Siltic, Clayic). Symbols represent the mean percent change of each analyzed category at compacted soil relative to control, and the bars show effect size (±95% confidence intervals CIs). Number of studies and observations are shown in parentheses, and mean bulk densities in control and compacted soils are given on the y-axis. Effects are significantly different from 0 when 95% CI does not contain zero. X2 test was applied for the categorical comparison: ***p < 0.001, **p < 0.01, n.s.: not significant.

2.4 Discussion

The effects of mechanized harvesting on compaction of forest soils and on sapling growth were previously assessed by meta-analysis in two studies, both by Ampoorter et al., (2011, 2012). International literature related to this topic has increased in the meanwhile. Considering all articles checked for this study, the number has almost doubled from 2000 to 2017. Including only the papers after 2010, the number has increased by about 30%. Unfortunately, many potentially interesting articles (69%) were not included in our final database due to the lack of key details (see criteria for the article selection in Database, Material and Methods).

However, the number of final observations was high and able to provide new reliable information.

2.4.1 Effects on above- and below-ground morphological traits

Soil compaction negatively affected the vast majority of the studied morphological traits related to plant growth. The detrimental effect was particularly evident on root depth, which is an index of the plant capacity of exploring the soil nutrient and water, and on seedling height, which is a key parameter to assess plant growth performance being related to the capacity of successful regeneration (Marshall, 2000; Bekele et al., 2007; Basset et al., 2005; Marchi et al., 2016; Cambi et al., 2017). According to Nadezhdina et al., (2012), roots may be thicker and shorter in compacted soils, because the root depth may be reduced: however, under favourable conditions, the roots may develop mostly in width, for sustaining the above-ground growth and facing the higher penetration resistance (Merotto and Mundstock, 1999; Cambi et al., 2018). As a confirmation, the reduction of RcD was lower than the reduction of the other traits. The effect of compaction on height growth is widely documented, under both field and controlled conditions, being among the first variables to be analyzed in the literature (Youngberg, 1959). Indeed, height was the parameter included in the highest number of case studies in this work. Along with survival and diameter, height was included in the prior meta-analytic study by Ampoorter et al., (2011), although they could not find a clear relationship between any growth trait and compaction due to a general data ambiguity. Both root depth and seedling height in our analysis showed a greater decrease than the other traits, i.e., more than −20% in comparison with the control. According to the literature (Kormanek et al., 2015; Cambi et al., 2018), compaction may start to affect the development of the main root immediately after germination, and our results confirmed that this effect may last at least for the first two growing seasons. This effect is crucial in environments where plant survival and establishment are linked to the root capacity of reaching deeper and moister soil layers, such as in arid or Mediterranean areas (Canadell and Zedler, 1995; Padilla and Pugnaire, 2007; Cubrera et al., 2009), or wherever the occurrence of drought periods during the growing season is harshening due to climate change.

The negative effect of soil compaction depended on soil texture. Studies carried out in Arenic soil may provide contrasting results (Pinard et al., 2000). In coarse-textured Arenic soils, a certain degree of compaction may have a positive effect on available water for plants (Agrawal, 1991; Jakobsen and Greacen, 1985), thus extending the period of plant-available water and reducing water stress (Gomez et al., 2002). Moreover, a high soil porosity in Arenic soil allows to develop lateral roots and thus a wide superficial root system (Bengough and Mullins, 1991). This suggests that above-ground growth can be adequately sustained by the below-ground system in compacted Arenic soils, even though main root depth is reduced by compaction. In fact, some positive effects were found in total dry biomass and leaf area of plants grown in compacted Arenic soils, although the effects were not statistically significant. On the other hand, in compacted Loamic soils, those morphological traits showed a significant reduction. Overall, the negative effects on root dry biomass and root depth were weaker in Arenic soils than in Siltic soils. Fine-textured Loamic or Siltic soils are characterized by a lower porosity than Arenic soils (Foth, 1990). A further compression can lead to a too low aeration or to a reduced water infiltration (Froehlich, 1978; Greacen and Sand, 1980), which challenges plant growth because of limited water absorption and/or aeration (Froehlich and McNabb, 1984). This mechanism of damage, however, seems to contrast with the results in RcD and height, where the negative effects of compaction were even higher in Arenic soils than in Siltic soils. Plant response to soil compaction is considered to be species-specific (Liang et al., 1999), although soil compaction affected almost equally both conifers and broadleaves in the present analysis. Actually, over 90% of the available data with Arenic soils for RcD and height came from the studies carried out for Pinus species in humid boreal regions (e.g. Wästerlund, 1985; Blouin et al., 2008). Compaction in soils of coarse texture may increase the root-water contact area (Arvidsson, 1999). However, it has been also reported that excess water limits productivity of pines on wet soils (Allen et al., 1990). This suggests that the plant response to compacted Arenic soils may also be associated with species adaptation strategies for water. Therefore, further investigations would be required to elucidate this aspect. Most studies on morphological traits were carried out during the first seedling growth stages (≤1 year and 1–2 years); literature on older plants is limited in comparison with the studies available for seedlings, and it basically covers information about the effect on height and diameter. For such variables, our results clearly highlighted less negative effects of compaction after establishment of the seedlings, i.e., when the seedlings were older than two years. Basically, the seedlings are very sensitive to compaction during the first two years, irrespective of soil type, taxonomy, or experiment type. This result confirms the harmful influence of soil compaction, and thus of heavy machinery passages, on the establishment of young seedlings, and more in general of natural regeneration as observed by Kozlowski (1999), Rab (2004) and Cambi et al., (2018). More studies on older plants are needed to identify more detailed age categories and evaluate the significance of soil compaction after seedling establishment. The negative effects were worse in controlled experiments (no field) than in field experiments. According to our analysis, the majority of experiments were performed with pot- or container-grown plants. Constraints of small pots may exacerbate the negative effects of compaction on soil aeration. It was demonstrated that compaction-induced oxygen deficiency is more severe in pots than in the field (Simojoki et al., 1991; Stepniewski et al., 1994). The anaerobic state in compacted soil inhibits essential root functions and thus plant growth (Kozlowski, 1999). However, data were insufficient to compare the experiment type for all target morphological traits. More experiments of soil compaction are needed under field condition.

2.4.2 Effects on leaf-level physiological traits

As mentioned by Ampoorter et al., (2011), soil compaction induces a series of soil structural and physical changes as well as plant physiological consequences. Our meta-analysis indicates that the increase of soil compaction decreased leaf photosynthesis. It has been suggested that the reduction of leaf photosynthesis of plants grown in compacted soils may be attributed to the limitation of both water and nutrient acquisition (Kozlowski, 1999). However, our analysis interestingly found that N acquisition (leaf N content as a proxy) was not significantly inhibited by soil compaction, while water availability (leaf water potential as a proxy) was a primary cause for the observed decrease of photosynthesis for plants in compacted soils. Shorter roots likely contributed to such decreased water availability. In addition, Calvo-Polanco et al., (2008) reported that soil compaction reduced root hydraulic conductivity, which plays a role in water absorption. In parallel with the reduced photosynthesis, a significant decline of transpiration was observed. Cambi et al., (2017) reported that stomatal closure occurred greatly after summer drought in Quercus robur seedlings subject to soil compaction treatments. Komatsu et al., (2007) found that transpiration did not recover after low-precipitation periods in Japanese stone oak (Lithocarpus edulis) trees in compacted soils, while it successfully recovered in the control plants according to a crown-level assessment using sap-flow. These findings suggest that the shorter main roots developed due to soil compaction may reduce physiological performance and tolerance to drought stress in the seedlings. Obviously, stomatal closure in compacted soil condition leads to reduced CO2 availability in the mesophyll (Larcher, 2003). In addition, this may induce excess light energy and production of reactive oxygen species (ROS), which causes a further damage to photosynthetic components (Kitao et al., 2000; Cambi et al., 2017). Several studies confirmed this speculation by a reduction of chlorophyll fluorescence parameters (Philip and Azlin, 2005; Cambi et al., 2017). In general, soil compaction may negatively affect the soil ecosystem (Kozlowski, 1999). However, soil physical changes by compaction may not result in substantial changes of nutritional availability to plants (Arvidsson, 1999; Norris et al., 2014). This is probably because root-to-soil contact may be increased for nutrient uptake (Veen et al., 1992) even though compaction generally restricts lengthening of the main root for absorbing nutrients (Chirino et al., 2008). Soil microbial activity is also related to nutritional availability to plants (Jacoby et al., 2017). Unfavorable soil conditions due to soil compaction may change the total bacterial community structures (Frey et al., 2009). Especially, negative effects on ectomycorrhizal species were found in compacted soils (Hartmann et al., 2014). Hartmann et al., (2014) reported that Clayic soils showed a greater compaction-induced impact on soil microbiomes than Arenic soils. The papers were not sufficient for including soil microbial activity in this meta-analysis. Studies on below-ground ecosystem functions will be a key to elucidate plant-soil interactions in compacted soils. From our analysis of published data on leaf-level physiological parameters, the most important factor determining the variation in plant response to compaction was soil texture. Plants grown in compacted Loamic soils showed significant decreases in physiological parameters and total dry biomass. However, less or no impact of compaction on those parameters was shown in Arenic soils. Leaf-level physiology is essential to explain the behaviour of whole-plant biomass (Baldocchi, 1993). In addition to the leaf-level physiology, the whole-plant growth is also affected by plant-level responses such as respiratory carbon loss, biomass allocation, and plant competition especially in the field (Larcher, 2003). Respiration during daytime was generally higher under water-shortage conditions (Sperlich et al., 2016). If soil compaction limited water availability to plants, the respiratory carbon loss would be also a major cause for the reduction of carbon gain due to soil compaction. However, to the best of our knowledge, there is no study about the effect of soil compaction on plant respiration rate. This may be a next step to fully understand the physiological mechanisms of plant responses to soil compaction.

2.5 Conclusions

This study quantified the magnitude of declines in plant morphological and physiological traits following soil compaction expressed as bulk density increase, such as that due to the passages of heavy machinery in forest operations. We used bulk density as an index to quantify compaction (Cambi et al., 2015); however, bulk density saturates sooner than soil penetration resistance (Da Silva et al., 2016). Declines were higher below-ground than above-ground traits, in younger (< 2 year-old) plants, in pots than in the field, and increased from the coarse-textured Arenic soils to the finer-textured Loamic or Siltic soils. Data from Clayic soils were insufficient for this analysis. Differences between the responses in conifers and broadleaf species were limited to a higher decline of root-collar diameter in conifers. These findings suggest that the shorter main roots developed due to soil compaction reduce water uptake and thus photosynthesis and the overall plant physiological performance and tolerance to drought. Interestingly, no significant changes of N availability to plants were detected, by using foliar N content as a proxy. Our results contrast with the insignificant results reported in previous meta-analyses (Ampoorter et al., 2011, 2012), suggesting that the availability of data has considerably increased. In addition, our results showed that the negative effect of compaction occurs mainly at the seedling stage, suggesting that soil compaction from forest operations is a concern for forest regeneration, and is negligible after seedling establishment. However, more studies with a wider range of variables and plant ages are recommended.

Acknowledgements

We thank Moreno Lazzara for technical support and Yutaka Osada for statistical assistance.

Appendix A

Appendix S1. References included in the database for meta-analysis

Morphology/ Physiology	First Author	Authors	Title	Year	Journal	Volume	Pages	Regions
M P	Abe	Abe, N. and Hashimoto, R.	Effects of micro-meteorological condition and ground treatment by a small sized-excavator on gas-exchange capacity of current-year seedlings of Quercus serrata serminated on a natural reproduction site by mother tree method.	2000	Journal of Japan Forest Society	82	7-14	Asia
M	Alameda	Alameda, D. and Villar, R.	Moderate soil compaction: Implications on growth and architecture in seedlings of 17 woody plant species	2009	Soil and Tillage Research	103	325-331	Europe
M P	Alameda	Alameda, D.	Ecophysiological implications of soil compaction on plant development	2010	Thesis (PhD, Univ. Cordoba)	1	1-165	Europe
P	Alameda	Alameda, D. and Villar, R.	Linking root traits to plant physiology and growth in Fraxinus angustifolia Vahl. seedlings under soil compaction conditions	2012	Environmental and Experimental Botany	79	49-57	Europe
M	Ares	Ares, A., Terry, T.A., Miller, R.E, Anderson, H.W., and Flaming, B.L.	Ground-Based Forest Harvesting Effects on Soil Physical Properties and Douglas-Fir Growth	2005	Soil Science Society of America Journal	69	1822-1831	North America
M	Bejarano	Bejarano, M.D., Villar, R., Murillo, A.M., Quero, J.L.	Effects of soil compaction and light on growth of Quercus pyrenaica Willd.(Fagaceae) seedlings	2010	Soil and Tillage Research	110	108-114	Europe
P	Benigno	Benigno, S.M.	Restoration in a postime environment: using ecophysiological techniques to improve the establishment of framework Bamksia woodland seedlings	2012	Thesis (PhD, Univ. Western Australia)	1	1-139	Oceania
M P	Blouin	Blouin, V.M., Schmidt, M.G., Bulmer, C.E., Krzic, M.	Effects of compaction and water content on lodgepole pine seedling growth	2008	Forest Ecology and Management	255	2444-2452	North America
M	Brais	Brais, S.	Persistence of Soil Compaction and Effects on Seedling Growth in Northwestern Quebec	2001	Soil Science Society of America Journal	65	1263-1271	North America
M	Bulmer	Bulmer, C. E., and Simpson, D. G.	Soil compaction and water content as factors affecting the growth of lodgepole pine seedlings on sandy clay loam soil	2005	Canadian Journal of soil science	85	667-679	North America

M P	Cambi	Cambi, M., Hoshika, Y., Mariotti, B., Paoletti, E., Picchio, R., Venanzi, R., Marchi, E.	Compaction by a forest machine affects soil quality and Quercus robur L. seedling performance in an experimental field	2017	Forest Ecology and Management	384	406-414	Europe
P	Choi	Choi, W., Chang, S.X., Curran, M.P., Ro, H., Kamaluddin, M., and Zwiazek, J.J.	Foliar 13C and 15N Response of Lodgepole Pine and Douglas-Fir Seedlings to Soil Compaction and Forest Floor Removal	2005	Forest Science	51	546-555	North America
M P	Conlin	Conlin, T.S.S., and Driessche, R.V.D.	Short-term effects of soil compaction on growth of Pinus contorta seedlings	1996	Canadian Journal of Forest Research	26	727-739	North America
M	Corns	Corns, I.G.W.	Compaction by forestry equipment and effects on coniferous seedling growth on four soil in the Alberta foothills	1988	Canadian Journal of Forest Research	18	75-84	North America
M	Cubera	Cubera, E., Moreno, G., Solla, A.	Quercus ilex root growth in response to heterogeneous conditions of soil bulk density and soil NH4-N content	2009	Soil and Tillage Research	103	16-22	Europe
M	Dinis	Dinis, C., Surovy´., P., Ribeiro,N., Oliveira, M.R.G.	The effect of soil compaction at different depths on cork oak seedling growth	2014	New Forests	46	235-246	Europe
M	Foil	Foil, R.R., and Ralston, C.W.	The Establishment and Growth of Loblolly Pine Seedlings on Compacted Soils	1967	Soil Science Society of America Proceedings	31	565-568	North America
M	Froehlich	Froehlich, H.A.	The Effect of Soil Compaction by Logging on Forest Productivity	1978	Forest Engineering Department Oregon State University Corvallis, Oregon	-	1-39	North America
P	Gomez	Gomez, G.A., Singer, M.J., Powers, R.F., and Horwath, W.R.	Soil compaction effects on water status of ponderosa pine assessed through 13C/12C composition	2002	Tree Physiology	22	459-467	North America
P	Guo	Guo, Y., Karr, B.L., and Rachal, J.	Effect of soil compaction and the presence or absence of the A soil horizon on water relations of loblolly pine seedlings in north-central Mississippi	1990	Proceedings of the Fifth Biennial Southern Silviculture Research Conference	1	533-538	North America
M	Hatchell	Hatchell, G. E. , Ralston, C. W. , and Foil, R. R.	Soil Disturbances In Logging Effects on Soil Characteristics and Growth Of Loblolly Pine in the Atlantic Coastal Plain	1970	Journal of Forestry	68	772-775	North America
M	Hatchell	Hatchell, G.E.	Soil Compaction and Loosening Treatments Affect Loblolly Pine Growth in Pots	1970	USDA Forest Service Research Paper	SE 72	-	North America

M	Heilman	Heilman, P.	Root penetration of Douglas-fir seedlings into compacted soil	1981	Forest Science	27	660-666	North America
M	Holub	Holub, S.M. , Terry, T.A., Harrington, C.A., Harrison, R.B., Meade, R.	Tree growth ten years after residual biomass removal, soil compaction, tillage, and competing vegetation control in a highly-productive Douglas-fir plantation	2013	Forest Ecology and Management	305	60-66	North America
M	Jordan	Jordan, D., Ponder, F., Jr., Hubbard, V.C.	Effects of soil compaction, forest leaf litter and nitrogen fertilizer on two oak species and microbial activity	2003	Applied Soil Ecology	23	33-41	North America
M	Jourgulami	Jourgholami, M., Khoramizadeh, A., Zenner, E.K.	Effects of soil compaction on seedling morphology, growth, and architecture of chestnut-leaved oak (Quercus castaneifolia)	2016	iForest	10	145-153	Asia
M P	Kamaluddin	Kamaluddin, M., Chang, S.X., Curran, M.P., and Zwiazek, J.J.	Soil Compaction and Forest Floor Removal Affect Early Growth and Physiology of Lodgepole Pine and Douglas-Fir in British Columbia	2005	Forest Science	51	513-521	North America
M	Kormanek	Kormanek, M., Banach, J., and Sowa, P.	Effect of soil bulk density on forest tree seedlings	2015	International Agrophysics	29	67-74	Europe
M	Kormanek	Kormanek, M., Gła, T., Banach, J., Szewczyk, G.	Effects of soil bulk density on sessile oak Quercus petraea Liebl. Seedlings	2015	European Journal of Forest Research	134	969-979	Europe
M	Kormanek	Kormanek, M., and Banach, J.	Influence of soil compaction on the growth of pedunculate oak seedlings bred in laboratory conditions	2011	Utilization of agricultural and forest machinery	-	109–118	Europe
M	Kranabetter	Kranabetter, J.M., Dube, S. , and Lilles, E.B.	An investigation into the contrasting growth response of lodgepole pine and white spruce to harvest-related soil disturbance	2016	Canadian Journal of Forest Research	47	340-348	North America
P	Kranabetter	Kramabetter, J.M., Sanborn, P., Chapman, B.K., Dude, S.	The Contrasting Response to Soil Disturbance between Lodgepole Pine and Hybrid White Spruce in Subboreal Forests	2006	Soil Science Society of America Journal	70	1591-1599	North America
M	Matangaran	Matangaran, J.R., and Kobayashi, H.	The Effect of Tractor Logging on Forest Soil Compaction and Growth of Shorea selanica Seedlings in Indonesia	1999	Journal of Forest Research	4	13-15	Asia

M	Minore	Minore, D., Smith, C.E., and Woollard, R.F.	Effects of high soil density on seedling root growth of seven northwestern tree species	1969	Forest and Range Experiment Station USDA Forest Service Research Note		1-6	North America
M	Misra	Misra, R.K. and Gibbons, A.K.	Growth and morphology of eucalypt seedling-roots, in relation to soil strength arising from compaction	1996	Plant and Soil	182	1-11	Oceania
M	Mitchell	Mitchell, M.L., Hassan, A.E., Davey, C.B., Gregory, J.D.	Loblolly Pine Growth in Compacted Greenhouse Soils	1982	Trans ASAE	25	304-312	North America
M	Naghdi	Naghdi, M., Solgi, A., Labelle, E.R., Zenner, E.K.	Influence of ground-based skidding on physical and chemical properties of forest soils and their effects on maple seedling growth	2016	European Journal of Forest Research	135	949-962	Asia
M P	Nambiar	Nambiar, E.K.S., and Sands, R.	Effects of compaction and simulated root channels in the subsoil on root development, water uptake and growth of radiata pine	1992	Tree Physiology	10	297-306	Oceania
P	Norris	Norris, C.E., Hogg, K.E., Maynard, D.G., and Curran, M.P.	Stumping trials in British Columbia — organic matter removal and compaction effects on tree growth from seedlings to midrotation stands	2014	Canadian Journal of Forest Research	44	1402-1418	North America
M	Polanco	Polanco, M.C., Zwiazek, J.J., Voicu., M.C.	Responses of ectomycorrhizal American elm (Ulmus americana) seedlings to salinity and soil compaction	2008	Plant and Soil	308	189-200	North America
M	Rhoades	Rhoades, C.C., Brosi, S.L., Dattilo, A.J., Vincelli, P.	Effect of soil compaction and moisture on incidence of phytophthora root rot on American chestnut (Castanea dentata) seedlings	2003	Forest Ecology and Management	184	47-54	North America
M	Sands	Sands R., and Bowen G.D.	Compaction of sandy soil in Radiata pine forests II. Effects of compaction on root configuration and growth of Radiata pine seedlings	1978	Australian Journal of Forest Research	8	163-170	Oceania
P	Sheriff	Sheriff, D.W.	Gas Exchange of Field-grown Pinus radiata-Relationships with Foliar Nutrition and Water Potential, and with Climatic Variables	1995	Australian Journal of Plant Physiology	22	1015-1026	Oceania
P	Sheriff	Sheriff, D.W. and Nambiar, E.K.S.	Effect of subsoil compaction and three densities of simulated root channels in the subsoil on growth, carbon gain and water uptake of *Pinus radiata*	1995	Australian Journal of Plant Physiology	22	1001-1013	Oceania

M	Simcock	Simcock, R.C., Parfitt, R.L., Skinner, M.F., Dando, J. , and Graham, J.D.	The effects of soil compaction and fertilizer application on the establishment and growth of Pinus radiata	2006	Canadian Journal of Forest Research	36	1077-1086	Oceania
M	Simmons	Simmons, G.L., and Pope, P.E.	Influence of soil compaction and vesicular-arbuscular mycorrhizae on root growth of yellow poplar and sweet gum seedlings	1987	Canadian Journal of Forest Research	17	970-975	North America
M	Simmons	Simmons, G.L., and Pope, P.E.	Effects of soil compaction on root growth characteristics of yellow-poplar and sweetgum seedlings	1985	Proceedings: Fifth Annual Better Reclamation With Trees Conference	1	227-238	North America
M	Skinner	Skinner, A.K. , Lunt, I.D., Spooner, P., and McIntyre, S.	The effect of soil compaction on germination and early growth of Eucalyptus albens and an exotic annual grass	2009	Austral Ecology	34	698-704	Oceania
P	Tan	Tan, X., Kabzems, R., Chang, S.X.	Response of forest vegetation and foliar δ13C and δ15N to soil compaction and forest floor removal in a boreal aspen forest	2006	Forest Ecology and Management	222	450-458	North America
M	Tuttle	Tuttle, C.L., Golden, M.S., and Meldahl, R.S.	Soil compaction effect on Pinus taeda establishment from seed and early growth	1988	Canadian Journal of Forest Research	27	628-632	North America
M	Tworkoski	Tworkoski, T.J., Burger, J.A., and Smith, D.Wm.	Soil Texture and Bulk Density Affect Early Growth of White Oak Seedlings	1983	Tree Planter's Notes	34	22-25	North America
M	Wästerlund	Wästerlund I.	Compaction of till soils and growth tests with Norway spruce and scots pine	1985	Forest Ecology and Management	11	171-189	Europe
M	Williamson	Williamson, J.R., and Neilsen, W.A.	The effect of soil compaction, profile disturbance and fertilizer application on the growth of eucalypt seedlings in two glasshouse studies	2003	Soil and Tillage Research	71	95-107	Oceania
M	Youngberg	Youngberg, C.T.	The Influence of Soil Conditions, Following Tractor Logging, on the Growth of Planted Douglas-Fir Seedlings	1959	Soil Science Society of America Journal	23	76-78	North America
M	Zisa	Zisa, R.P., Halverson, H.G. and Stout, B.B.	Establishment and early growth of conifers on compact soils in urban areas	1980	USDA Forest Service Research Paper	NE-451	-	North America

Appendix B

Table S2 Effect of soil compaction on morphological and physiological traits by using only the studies providing standard deviations or standard errors with replicate size. We combined the log response ratios with the mixed effects model, assuming that differences among studies are due to both sampling error and random variation. A weighted parametric meta-analysis was applied. Bold indicates statistically significant (i.e., 95% confidence intervals (CIs) did not overlap with zero). In addition to overall effects, the effects of compaction between groups in target categories (1. soil classification, 2. species taxonomy, 3. plant age, 4. type of experiment) were tested. Differences among groups in each categories were tested by X^2 statistical test: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, n.s. denotes not significant. Different letters show significant differences among groups in each categories ($p < 0.05$, X^2 test).

Morphological traits

		Overall effects	**Soil classification**				**Taxonomy**		**Age class**			**Experimental type**	
			Arenic	**Loamic**	**Siltic**	**Clayic**	**Conifer**	**Broadleaf**	**Age < 1 year**	**Age 1 - 2years**	**Age > 2years**	**Field**	**No Field**
Total dry biomass n = 67	mean	**-14.2**	10.4 a	**-12.8 b**	-	-	**-14.6**	**-13.5**	-	-	-	-	-
	95% CI	**[-19.7, -8.3]**	[-5.6, 29.8]	**[-19.5, -6.0]**	-	-	**[-21.5, -7.0]**	**[-22.6, -3.4]**	-	-	-	-	-
				**			n.s.						
Shoot dry biomass n = 75	mean	**-13.3**	-14.9	-8.3	-	-	**-10.1**	**-22.1**	-	-	-	-	-
	95% CI	**[-19.7, -6.4]**	[-29.3, 2.4]	[-16.4, 0.6]	-	-	**[-18.0, -1.5]**	**[-34.0, -8.0]**	-	-	-	-	-
				n.s.			n.s.						
Root dry biomass n = 75	mean	**-19.1**	-8.0	-11.6	-	-	**-16.5**	**-25.0**	**-22.5**	**-18.5**	-	-	-
	95% CI	**[-27.4, -9.7]**	[-18.7, 18.7]	[-22.3, 0.4]	-	-	**[-27.0, -4.5]**	**[-39.8, -6.5]**	**[-32.8, -7.0]**	**[-32.2, -4.8]**	-	-	-
				n.s.			n.s.			n.s.			

Leaf dry biomass **n = 28**	mean	**-14.6**	-	-	-	-	-9.4	**-20.0**	-	-	-	-	-
	95% CI	**[-22.4, -6.1]**	-	-	-	-	[-21.7, 4.8]	**[-30.7, -7.6]**	-	-	-	-	-
							n.s.						
Leaf area **n = 25**	mean	1,3	18.2 a	**-17.7 b**	-	-	-	-	-7.7	7.7	-	-	-
	95% CI	[-12.0, 15.4]	[-8.7, 43.9]	**[-24.4, -10.5]**	-	-	-	-	[-19.2, 9.2]	[-12.3, 30.0]	-	-	-
				*						n.s.			
Root depth **n = 67**	mean	**-19.8**	**-11.8 a**	**-20.9 b**	-	-	-	-	-	-	-	-	-
	95% CI	**[-20.8, -18.7]**	**[-14.1, -9.4]**	**[-22.2, -19.7]**	-	-	-	-	-	-	-	-	-
				***									
RcD **n = 56**	mean	-7.9	-	-	-	-	-5.4	**-16.7**	-	**-15.9 a**	7.8 b	-3.0	**-10.9**
	95% CI	[-13.0, -2.5]	-	-	-	-	[-11.2, 0.9]	**[-27.2, -4.7]**	-	**[-21.7 , -9.7]**	[-3.1, 19.9]	[-11.4, 6.2]	**[-17.0, -4.3]**
							n.s.			***		n.s.	
Height **n = 72**	mean	**-10.8**	-7.7 a	**-7.7 a**	-	**-31.8 b**	**-6.8 a**	**-19.4 b**	-	**-17.9 a**	6.4 b	**-10.1**	**-11.3**
	95% CI	**[-13.4, -8.2]**	[-14.2, 1.3]	**[-9.8, -3.5]**	-	**[-37.1, -26.0]**	**[-9.8, -3.5]**	**[-23.6, -15.0]**	-	**[-20.6, -15.1]**	[0.1, 12.5]	**[-14.0, -5.9]**	**[-14.5, -7.9]**
				***			***			***		n.s.	

Physiological traits													
		Overall effects	Soil classification				Taxonomy		Age class			Experimental type	
			Arenic	Loamic	Siltic	Clayic	Conifer	Broadleaf	Age <1 year	Age 1-2 years	Age >2 years	Field	No Field
Net photosynthesis n = 37	mean	**-25.5**	-8.2 a	**-36.5 b**	-	-	**-28.3**	**-25.5**	-	-	-	-	-
	95% CI	**[-31.4, -19.1]**	[-19.6, 3.9]	**[-42.7, -29.6]**	-	-	**[-40.2, -15.9]**	**[-33.2, -17.0]**	-	-	-	-	-
				***			n.s.						
Transpiration n = 42	mean	**-15.3**	-5.5 a	**-25.0 b**	-	-	-10.4	**-18.2**	-	-	-	-	-
	95% CI	**[-21.7, -8.2]**	[-17.2, 6.6]	**[-32.5, -16.4]**	-	-	[-21.9, 2.9]	**[-26.4, -9.2]**	-	-	-	-	-
				**			n.s.						
Leaf N content n = 55	mean	-1.4	-0.2	**-5.5**	0.9	-	-	-	-	-2.3	-1.2	-	-
	95% CI	[-3.5, 0.8]	[-3.1, 2.9]	**[-9.6, -1.2]**	[-4.8, 6.9]	-	-	-	-	[-7.6, 3.2]	[-3.6, 1.3]	-	-
				n.s.						n.s.			
Leaf water potential n = 30	mean	**-5.2**	4.6 a	**-10.5 b**	-	-	-	-	-	-4.3	-5.3	**-6.3**	-2.4
	95% CI	**[-8.7, -1.8]**	[-1.1, 10.0]	**[-15.5, -5.8]**	-	-	-	-	-	[-11.8, 2.7]	[-10.9, 0.2]	**[-10.6, -2.1]**	[-9.7, 4.4]
				***						n.s.		n.s.	

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3 Paper II - *Photogrammetric estimation of wheel rut dimensions and soil compaction after increasing numbers of forwarder passes*

Abstract

Compaction and rutting on forest soils are consequences of harvesting operations. The traditional methods used to investigate these consequences are time consuming and unable to represent the entire longitudinal profile for a forest trail. New methods based on photogrammetry have been developed. The overall objective was to compare photogrammetry and traditional methods (e.g. cone penetrometer, manual rut depth measurements, bulk density and porosity) used for the evaluation of soil compaction and rutting (i.e., depth and rut volume) after multiple passages of a loaded forwarder using two different tyre pressure levels. The comparison of photogrammetric versus manually measured profiles resulted in R^2 0.93. Both tyre inflation pressure and number of passages had effect on soil disturbance. The rut volumes on 100 m long trails after 60 passages were 8.48 m^3 and 5.74 m^3 for tire pressures of 300 kPa and 150 kPa, respectively. Increased rut volume correlated positively with increased soil compaction and decreased soil porosity. Structure-from-motion photogrammetry is an accurate method for informing the creation of high-resolution digital evolution models and for the morphological description of forest soil disturbance after forest logging. However, a problem with photogrammetry is object reflection (grass, logging residues, and water) that in some cases influence the accuracy of the method.

3.1 Introduction

Soil disturbances are one of the main forms of damage associated with forest operations (Venanzi et al., 2016). Tree harvesting, log dragging and the transportation of heavy machinery over the forest floor results in visible soil compaction and rutting (Eliasson and Wästerlund, 2007; Koreň et al., 2015), thus contributing to soil erosion, reduced porosity and soil aeration, and decreased tree regeneration and growth (Cambi et al., 2015a). Soil compaction is the result of the pressure exerted by the machine tyres or tracks on the ground. When this pressure exceeds the soil bearing capacity, especially under increasing tractive demand, subsequent wheel slippage can result in the development of a shearing rut (Eliasson and Wästerlund, 2007). Soil compaction and rutting are detrimental to tree growth due to both physical root damage and reduced soil porosity, thus decreasing water infiltration and soil aeration (Wästerlund, 1994; Quesnel and Curran, 2000; Sirén et al., 2013). Rutting and other types of soil disturbance caused by machine traffic can also promote the transmission of pathogenic fungi and inhibit microbiological processes (Thor and Stenlid, 2005). Moreover, the increased surface water flow that occurs due to these soil disturbances facilitates the mobilisation of heavy metals (De Wit et al., 2014; Eklöf et al., 2014; Frey et al., 2009). Ruts not only form on flat terrain in areas with high soil moisture, but these conditions also contribute to the depth of the rut, with deeper ruts promoting waterlogging. On steep terrain soil compaction and rutting results in increased canalised runoff and erosion, thus making ruts significantly deeper (Schoenholtz et al., 2000). The extension of the affected area and its impact severity are a function of the type and condition of the soil, climate (i.e., precipitation and temperature), harvesting system and machine characteristics (Cambi et al., 2015b; Frey et al., 2009; Grigal, 2000; Picchio et al., 2012). However, even in the best managed operations with sophisticated harvester/forwarder cut-to-length systems, at least 12% of the site will be subjected to vehicle traffic (Eliasson, 2005).

Forest soil plays a key role in the maintenance and conservation of forest ecosystems, thus highlighting the need to minimise the environmental impact of vehicles during forestry operations (Agherkakli and Najafi, 2010; Heninger et al., 2002; Kimsey et al., 2011). Climate change has resulted in longer periods of soil saturation and soils remaining unfrozen in boreal zones (Soja et al., 2007); therefore, wheel rutting may become a critical issue in the future. In this context, the overall acceptability of operations much depends on quality of harvesting. Methods used to monitor and estimate soil compaction and rutting are usually time consuming and expensive (Bagheri et al., 2013; Koreň et al., 2015; Lotfalian and Parsakhoo, 2009). Several methods and parameters have been developed for measuring both soil compaction and rut depth. Most traditional parameters used to determine soil compaction reflect the physical characteristics of the soil (Ares et al., 2005): bulk density, soil porosity and penetration resistance. These are usually measured or determined within the tracks left by passing machinery. Using a cone penetrometer, a real-time sampling method used for obtaining empirical measurements of soil strength, it is possible to make comparisons between different soil conditions (Kumakura et al., 1993). Measurements of rut depth and width are usually based on data manually collected in the course of developing a cross-sectional and longitudinal profile for a forest trail (Koreň et al., 2015). In these cases, the distance between sampling lines is usually several meters (Koreň et al., 2015), meaning that the accuracy of the total representation of the ruts is low and the estimation of rut volume is usually very rough.

In order to capture and analyse the spatial distribution of soil disturbances more accurately, it may be appropriate to deploy modern technologies, such as terrestrial (Giannetti et al., 2017; Laurent et al., 2012) or airborne laser scanning (Koreň et al., 2015), unmanned aerial vehicles (Pierzchała et al., 2014) and photogrammetry (Haas et al., 2016; Pierzchała et al., 2014) to create a three-dimensional ground reconstruction.

Laser scanning technology uses a laser beam (usually a Faro Focus three-dimensional terrestrial laser scanner with a resolution of 3 mm/10 m) to measure distances and surrounding objects to be captured (Koreň et al., 2015). Modern devices are equipped with an internal camera, which allows for the assignment of colours to points during data post-processing. The resultant point cloud enables the measurements of the position and distance of objects and for the creation of a three-dimensional model (Koren et al., 2015). This method can be applied using fixed terrestrial (TLS) or airborne laser scanner (ALS), the latter may be mounted on unmanned aerial vehicles (UAV) for capturing aerial imagery. A recent study has investigated the spatial analysis of terrain changes caused by forest operations by means of a terrestrial portable laser scanner (PLS) (Giannetti et al., 2017). Ultrasonic transducers were also used for measuring rut depth (Ala-Ilomäki et al., 2012).

Although the use of close-range photogrammetry in mapping the surface structure of soil was demonstrated more than 20 years ago (Warner, 1995), this is still considered a relatively new technology in this area (Haas et al., 2016). Haas et al., (2016), Pierzchała et al., (2016) have shown the usefulness photogrammetric methods for determining rut morphology parameters. In particular, Haas et al., (2016) developed a reference frame for the photogrammetric survey of ruts dimensions caused by forest operation to the skid trail and highlighted as these data may be useful for determining the depression storage capacity.

Pierzchała et al., (2016), applied traditional manual method and photogrammetric method using three software packages and using showed a very good matching among rut depth measurements carried out with the different methods. At a minimum, close-range photogrammetry requires a camera, a standard computer (used to generate a digital elevation model) and a total station or GPS for positioning ground control points (GCP). Nowadays, due to the evolution of low-cost cameras, close-range photogrammetry can be either handheld or mounted on forest machines to estimate rut dimensions. Few studies, however, have been performed with regard to close-range photogrammetry, leaving sizeable knowledge gaps in the literature. In particularly, little is known about the efficacy of these newer methods of assessing the impact of forestry machine traffic on soil in comparison to traditional methods. Moreover, even fewer papers took into consideration the progression of soil changes, i.e., at intervals between passages.

Thus, the objectives of this study were to: compare traditional and photogrammetric methods for evaluating rutting (rut depth and rut volume) and soil compaction after multiple passages of a loaded forwarder with two different tyre pressure levels; and investigate the relationship between soil compaction, rut depth and rut volume.

Based on published studies mentioned above, we hypothesise: (i) the higher the tyre pressure, the greater the effects on the physical characteristics of soil after multiple machine passages; and (ii) photogrammetry will prove to be a promising method to estimate soil disturbances in different and difficult-to-measure soil conditions.

3.2 Materials and Methods

3.2.1 Site description and experimental design

This study was carried out from 27th June to 25th July 2016 on a flat cropland outside Umeå in northern Sweden (N63° 49'; E 20° 18'; 12 m a.s.l.). At this time of year (i.e., June–July), the temperature on average varies 13°C day/2.5°C night with 30 mm in June and 18°C day/7°C night and 18.5 mm in July (Swedish Meteorological and Hydrological Institute). Soil texture was dominated by fine sands (Table 3.1) and determined according to Talme and Almén (1975).

Table 3.1. Soil particle size (% of dry mass) in the fieldwork area. Particle size class terms according to the Swedish Geotechnical Society (2016).

Soil depth (cm)	**Particle size class (mm)**								
	0.0006-0.002	**0.002-0.006**	**0.006-0.02**	**0.02-0.06**	**0.06-0.2**	**0.2-0.6**	**0.6-2**	**2-6**	**6-20**
	clay	**fine silt**	**medium silt**	**coarse silt**	**fine sand**	**medium sand**	**coarse sand**	**fine gravel**	**medium gravel**
0-10	4.0	1.5	8.5	35.0	36.0	11.5	2.0	0.5	1
10-40	5.5	3.5	9.0	30.5	46.5	4.0	1.0	0	0

Note: particle size class terms according to the Swedish Geotechnical Society (2016).

The samples were not pre-treated for removal of humus. Soil moisture was 30% in average and the initial soil bulk density was 1.40 Mg m^3 (measured in the first 10 cm of soil).

The forwarder was a Komatsu 830.3 (Komatsu Forest AB, Sweden), mass 12,415 kg, with bogie on both front and rear axle. The forwarder was loaded with 9,740 kg, giving a total mass of 22,155 kg. The mass distribution was 36% (7,840 kg) on the front axle and 64% (14,315 kg) on the rear axle. The forwarder was equipped with eight 700 mm wide tyres (Trelleborg Twin 423 700/40-22.5 16 P.R). All tyres on the right side of the forwarder were inflated to a pressure of 150 kPa (referred to as low pressure) and all tyres on the left side of the forwarder were inflated to a pressure of 300 kPa (referred to as high pressure). The static contact area of the tyres was measured placing the machine on a flat and hard ground. A rope was placed around the contact area of each tyre to determine the length of the contact area perimeter (Cambi et al., 2015a; Neri et al., 2007). The static contact area was estimated on the assumption of a round shape. Ground contact pressure was calculated on the basis of the mass of the two parts of the forwarder divided by the contact area (Table 3.2).

Table 3.2. Static estimated contact area and pressure on soil per each tyre.

	High Pressure Tyres (300 kPa)	**Low Pressure Tyres (150 kPa)**
Tyre contact area, front axle (cm^2)	2,551	2,696
Tyre contact area, rear axle (cm^2)	3,106	3,265
Tyre contact pressure, front axle (kPa)	76.6	72.8
Tyre contact pressure, rear axle (kPa)	115.3	109.7

Before the trial, the grass was cut and removed from a 6 m wide corridor in the study area. Within the study area, nine rectangular plots (length 3 m, width 6 m) were marked out on the ground, along a straight trail. The forwarder drove on the middle of the defined plots, always in the same direction, for all the passages (Figure 3.1).

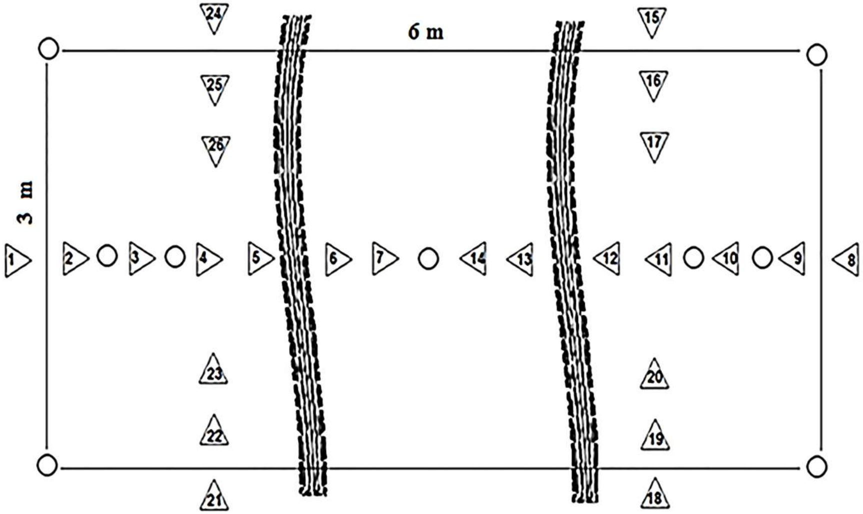

Figure 3.1. Positions of the tripod with the camera and direction of the picture collection for each picture (triangles). GCP are represented by circles.

3.2.2 Rut measurements

Two methods were used to determine the effects of machine passages on soil rutting: manual measurement and structure-from-motion photogrammetry (SfM). Measurements were taken before the first pass and after 1, 3, 5, 7, 10, 20, 30 and 60 forwarder passages. The distance between a horizontally levelled rod and the bottom of the rut was measured manually at three points on each track and plot (Figure 3.2). The final rut depth value was determined as the average of the three measurements. The resolution of the instrument used in rut depth measurement was ± 0.05 cm.

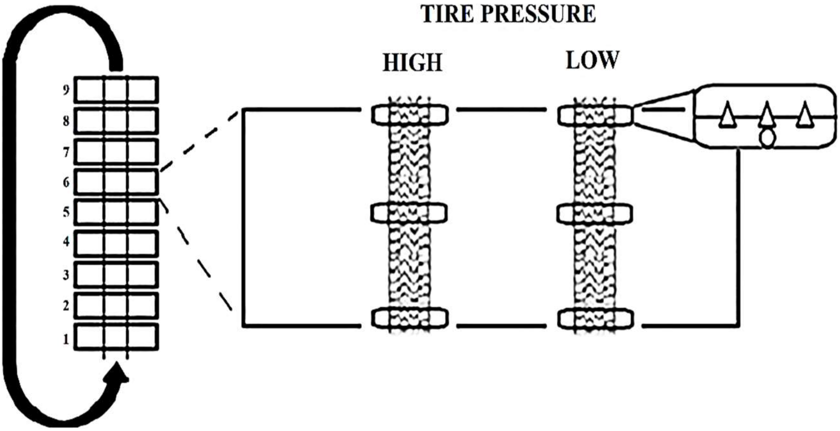

Figure 3.2. Plots position in the field and detail of soil sampling point (circle), penetration resistance measurements (triangles) and rut depth manual measurements (line) within each plot. Arrow show forwarder driving direction.

The SfM method was based on images acquisition in the plots. The images were acquired using a costumer RGB reflex camera (Canon EOS 600D, Table 3.3) mounted on a 3 m height tripod with an angle of 45° and with a focal length of 3 mm. Before the images acquisition nine GCP were positioned in each plot (Figure 3.1). The GCP were used for georeferencing the model in a local three-directional coordinate system and to align the model acquired in different times. The GCP were located far enough from the ruts to ensure that they would not be moved in any direction by forwarder passages (Figure 3.1).

Table 3.3. Camera and sensor details.

Camera Model	Canon EOS 600D
Image resolution	18 MP
Focal length	18 mm
Number of pixel	5184×3456

The image acquisition scheme (Figure 3.1) was designed to collect images at 0.5 m distance. The area covered by images was larger than each plot in order to obtain a robust model of the plots. A total of 26 images per plots were acquired with an overlap and sidelap of 85%. Each image covered an area of approximately 4.7 × 3.2 m. The acquisition scheme was designed to view in all the images the GCP to use in post-processing. We chose to collect several images to ensure a large resampling of all plots surface and avoid shadow zones. The images were acquired in straight lines with a rigid scheme, as usually is done in aerial photogrammetry. All the images acquired were evaluated by visual interpretation to detect eventual problems related to light, saturation and blurriness.

Images were processed using Agisoft PhotoScan (Agisoft LLC, 2017) to create a 3D point cloud and a raster grid Digital Surface Model (DSM). Agisoft PhotoScan combines SfM and photogrammetric stereo-matching algorithms for 3D reconstruction from unordered but overlapping imagery. This software it’s able to align automatically the camera, optimize camera position with GCP and build dense point clouds thanks to the large overlapping among images (Agisoft LLC, 2017).

The workflow of Agisoft PhotoScan was comprised of the following steps: (i) image import, (ii) image alignment, (iii) georeferencing, (iv) optimisation of image alignment, (v) creation of the point cloud and (vi) generation of the DSM. After a rough alignment of camera position, the optimization of the camera positions was done using GCPs as a reference. Thanks to camera optimization, the single dense point cloud was produce to determine the depth information of each point, at each collection time. The dense point clouds were rasterized in a DSM with a pixel resolution of 1 cm. In this study, the DSM derived by Agisoft PhotoScan workflow correspond to the Digital Terrain Model (DTM).

The pre-rutting (i.e., reference cloud) and rutting clouds (i.e., compared clouds) were saved in ‘.las’ file formats and were loaded and co-registered in CloudCompare (CloudCompare, 2017) and analysed using the ‘point pair based alignment tool’. A fast control was carried out for assessing the reliability of the automatic cloud's overlap. The 'cloud distance' function was used to evaluate the depth of the rut, and it evaluates the distance between point-cloud with millimetre accuracy.

Figure 3.3 shows the rut depth (negative values) and bulge heights (positive values). Moreover, in order to estimate the volume of the rut, the DTM with a resolution of 1 cm were used (Giannetti et al., 2017). The difference between the raster grids (reference and compared) were obtained using the map algebra function subtraction implemented in R-cran raster packages (Robert et al., 2012) in order to determine rut (VR) and bulge (VI) volumes. The difference between rut and bulge volumes, in terms of absolute values, was the total missing volume (VT) of the rut (Figure 3.3) (i.e., volume reduction due to compaction).

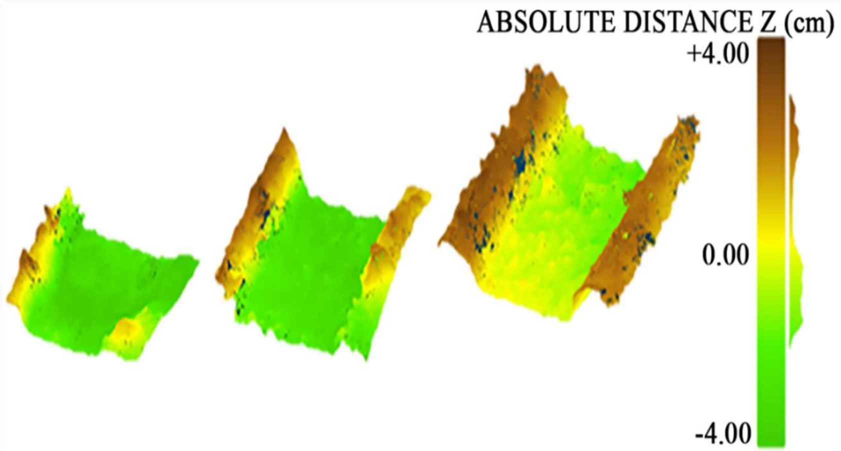

Figure 3.3. examples of bulge height (positive values) and rut depth (negative values).

3.2.3 Comparison of manual and SfM rut measurements

Manually-measured rut depths were compared against the image-based point cloud values in order to estimate the accuracy of structure-for-motion photogrammetry. Two methods were used to compare photogrammetric and manual rut depth measurements. In the first method (M1), manually-measured points were carefully identified on the

RGB images. These manually-measured rut depths were then compared against the rut depths obtained via SfM, which were determined on the basis of their colour values (Figure 3.4).

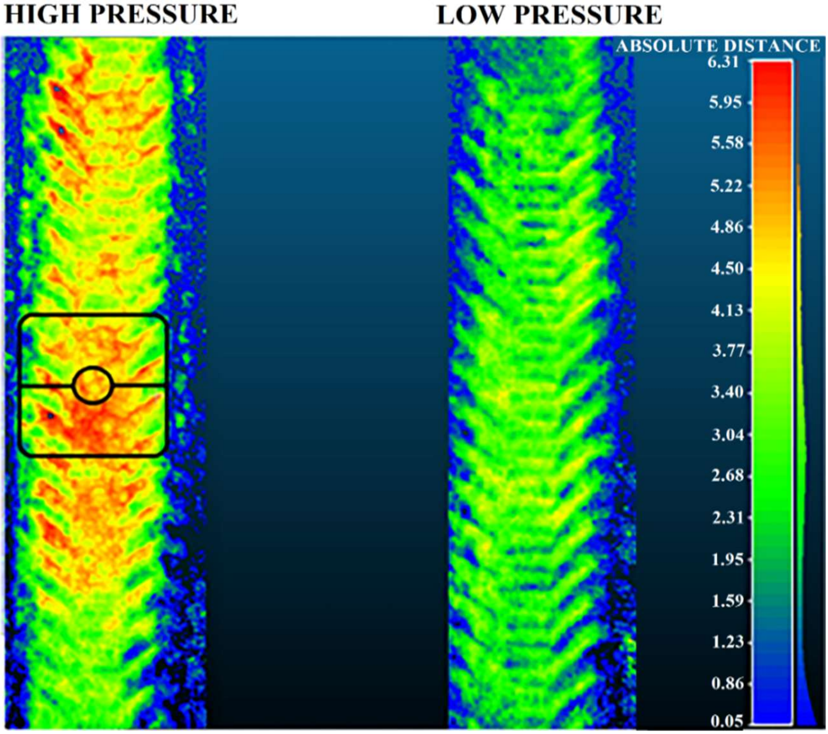

Figure 3.4. Cloud distance determined by CloudCompare classified points after 60 passages. The scale, in the RGB image, show the rut depth in metres (maximum distance 6.31 cm; minimum distance 0.50 cm). The black circle is the estimate location of one point were rut depth was manually measured.

The second method (M2), involved having to determine the average value of rut depth on the basis of all the values detected in the middle line of the ruts using an image-based point cloud derived by SfM photogrammetry (Figure 3.5).

Figure 3.5. Image-based points cloud derived by SfM Photogrammetry by Agisoft PhotoScan software after 60 forwarder passages.

3.2.4 Soil physical parameters

A total of 12 samples were collected from each plot before and after 60 forwarder passages in order to determine soil bulk density (BD), moisture and porosity. Three samples were collected within each track (i.e., for high and low tyre pressure) (Figure 3.2) and three samples were collected 1.5–2.0 m beside each track. After 3, 7 and 20 passages, additional samples were collected in plots 1, 5 and 9 only. All soil samples were collected from the top 10 cm mineral soil layer, using a metal cylinder (7.5 cm inner diameter and 10 cm height) (Picchio et al., 2009). BD was calculated as the dry weight of the soil sample divided by the volume of the sampler (Picchio et al., 2009). The soil moisture content (dry weight basis) was calculated as the weight of water divided by the weight of the dry soil. Soil porosity (n) was determined using Equation 1:

$$n=(Dp-Db)\div Dp\times 100 \qquad (1)$$

where Dp is the particle density (2.65 mg cm^3).

A hand cone penetrometer (Eijkelkamp) was pushed with constant speed into the first 26 cm layer of the soil for measuring the highest value of cone penetration resistance in each test. In order to measure always at the same depth, a sign was made to the instrument. The cone penetrometer followed the American Association of Agricultural Engineers standard design (St. Joseph 1969) for measuring cone index. A cone with a diameter of 11.28 mm and cone angle of 30 degrees was used. Cone resistance was measured inside the rut before and after machine passages. In detail, three cone resistance values were measured in the rut after 3, 7, 10, 20, 30 and 60 passages for the tracks of each plot. Each penetration resistance value was determined as the average of three measurements (centre of rut, 15 cm to the left, 15 cm to the right). The cone resistance value was finally determined as a ratio from the measured resistance and the base cone area.

Statistical analyses were performed using Minitab™ 17 and results were considered significant if p-value <0.05. As a first step, the distribution of the data was plotted and checked for normality and homogeneity of variance (normality test). One-way ANOVA was applied to the manually-measured rut depths, BD, porosity and cone resistance data, in order to test the effects of tyre pressure and number of passages on soil compaction and rutting. A post-hoc HSD test analysed the results. Statistical differences in soil moisture at the time of each machine pass were tested by means of a t-test. In order to check the effects of tyre pressure on soil volume changes (VI, VR and VT), a non-parametric Mann-Whiney U test was applied in light of the asymmetrical distribution of the data. Regression analyses investigated the mathematical relationship between BD and cone penetration resistance, and cone penetration resistance and total volume.

3.3 Results

No significant change was found of the soil moisture content within the study period. Significant changes in soil physical parameters (i.e., BD, cone resistance and porosity) were observed in relation to the number of passages (Table 3.4). In detail: (i) cone penetration resistance increased significant for each data collection (after 3, 7, 10, 20, 30 and 60 passages); (ii) BD and porosity showed significant differences only between 0 and 3 passages and between 20 and 60 passages. The cone penetration resistance increased by 52% after 60 passages, while the soil porosity decreased by 11%. Significant correlations between cone penetration resistance and BD as well as cone penetration resistance and soil porosity were observed (p-value <0.02, R^2=0.81). Changes in soil physical parameters in relation to tire pressure were not significant. Low pressure tyres resulted in the formation of less deep ruts than high pressure tyres. The differences between rut depths at different the tyre pressures was always statistically significant, with the exception of after the first pass. Regardless tyre pressure, the higher the number of passages the greater the rut depth (Table 3.4).

Table 3.4. Average values of soil physics parameters and rut depth before and after increasing machine passages. Standard deviation (SD) in parenthesis.

N. of Passages	Rut Depth High Press. Tyre (cm)	Rut Depth Low Press. Tyre (cm)	Cone Resistance (MPa)	Bulk Density (Mg/m^3)	Soil Porosity (%)
0	-	-	3.00 (0.35)^{a}	1.43 (0.08)^{a}	45.95 (2.13)^{a}
1	1.82 (0.73)^{aA}	1.52 (0.98)^{aA}	-	-	-
3	2.93 (0.81)^{bA}	2.27 (0.90)^{bB}	3.20 (0.32)^{a}	1.48 (0.06)^{b}	43.79 (2.20)^{b}
5	3.35 (0.81)^{bcA}	2.30 (0.98)^{bB}	-	-	-
7	3.62 (0.70)^{cdA}	2.34 (0.10)^{bB}	3.52 (0.41)^{b}	1.51 (0.07)^{b}	43.04 (2.56)^{b}
10	4.17 (0.70)^{deA}	2.79 (0.77)^{bcB}	3.64 (0.29)^{bc}	-	-
20	4.73 (0.75)^{efA}	3.24 (0.86)^{cdB}	3.86 (0.39)^{c}	1.58 (0.05)^{b}	42.42 (1.99)^{b}
30	5.27 (0.69)^{fA}	3.66 (0.94)^{deB}	4.34 (0.37)^{d}	-	-
60	6.05 (0.87)^{gA}	4.31 (0.97)^{eB}	4.56 (0.38)^{e}	1.57 (0.05)^{c}	40.63 (1.75)^{c}

Lowercase letters show statistical significant differences (p-value <0.05) amongst number of machine passages. Uppercase letters show significant statistical differences between rut depths caused by different tyre pressures at the same number of machine passes.

Photogrammetry reconstruction had around 35,070 points for each plot (1,000 points m^{-2}); the errors obtained by Agisoft PhotoScan were always less than 0.03 m. The errors of co-registration were always less than 0.11 mm in x-coordinate, 0.11 mm in y-coordinate and 0.21 mm in z-coordinate (i.e., non-significant for our purpose).

The comparison of manual and photogrammetric M1 measurements of rut depth indicate a significant relationship between manual and SfM rut depth data over 162 observations (R^2 0.93, y = 0.9976x + 0.0133, y manual and x was SfM data).

The difference between manual and photogrammetry measurements were in the range of 0.70–4.61% (average 2.14%) (Table 3.5).

Table 3.5. Average values of rut depths determined by manual measurement and by SfM photogrammetry (method M2) in high pressure tyre (HP) and low pressure tyre (LP). SD in parenthesis.

Number of Passages	Average Rut Depth Manual HP (cm)	Average Rut Depth SfM HP (cm)	Difference Between Manual and SfM HP (%)	Average Rut Depth Manual LP (cm)	Average Rut Depth SfM LP(cm)	Difference Between Manual and SfM LP (%)
1	1.82 (0.73)	1.86 (0.83)	2.20	1.52 (0.98)	1.59 (1.03)	4.61
7	3.62 (0.70)	3.68 (0.73)	1.66	2.34 (0.10)	2.39 (1.03)	2.14
20	4.73 (0.75)	4.79 (0.80)	1.27	3.24 (0.86)	3.35 (0.94)	3.40
60	6.05 (0.87)	6.12 (0.96)	1.16	4.31 (0.97)	4.34 (1.04)	0.70

Significant differences in VI, VR and VT were found in relation to tire inflation pressure (Table 3.6). VI is more than double in high pressure than in low pressure tyre tracks, while VR and VT were 47% and 48% higher in high pressure than in low pressure tyre tracks, respectively. These results allude to a relationship between cone penetration resistance and VT (R^2 = 0.75), thus suggesting a relationship between soil compaction and rutting in low moisture soil condition.

Table 3.6. Average volume of bulges, ruts and total for a forwarder with high (300 kPa) and low (150 kPa) tyre pressure after 60 passages. Values calculated of the based of the point cloud obtained by image-based points derived by SfM photogrammetry. SD in parenthesis.

Tyre pressure	Bulges Volume dm^3/100m strip road	Ruts Volume dm^3/100m strip road	Total Volume* dm^3/100m strip road
High pressure	197.13 (95.44)[a]	-8,287.15 (947.66)[a]	8,484.38 (886.38)[a]
Low pressure	99.99 (82.38)[b]	-5,638.71 (351.42)[b]	5,738.70 (298.73)[b]

Different letters show significant statistical differences between tyre pressures treatments (non-parametric test U Mann-Whitney).

* Sum of the absolute values of Bulges Volume and Ruts Volume

3.4 Discussion and conclusions

Soil compaction and rutting due to forest operations affect soil characteristics and functions. While several investigations of soil compaction and rutting have taken place over the last decade (Cambi et al., 2015a), few studies have investigated the use of modern technologies for monitoring changes in soil caused by forestry operations. This study assessed soil compaction artificially simulated by applying a multiple forwarder passages on a farmland in Sweden.

The physical properties of the soil (i.e., BD, penetration resistances and soil porosity), which are assumed to be the most representative approach to the assessment of soil compaction, were analysed in this study. Consistent with several other studies, our findings confirm that much of the impact on soil, in terms of increased BD and reduced porosity, usually occurs in the first few machine passages (Cambi et al., 2015b; Han, 2006; Wallbrink et al., 2002; Wang, 1997). In this case, significant changes were recorded in BD and soil porosity after the 3 passages, regardless of tyre inflation pressure. Lowering the tyre pressure on one side of the machine would have had a slight impact on the load distribution between the machine sides. Between three to twenty passages, BD and soil porosity did not show any significant variation, despite increasing the number of passages. Significant changes were recorded again increasing the passages number from 20 to 60. The absence of differences due to tire pressure may due to the initial high soil BD due to the previous intensive traffic of agricultural machinery in the study area.

Differences were found in high and low tyre pressure states for cone penetration resistance, which increased significantly with the increasing number of passages, until 60 passages. BD and soil porosity increased rapidly and constantly after 3 passages, while significant increases were recorded in cone resistance even after repeated passages. Jourgholami et al., (2014) described similar results. In a loam to silt loam textured soil, the investigators recorded that most changes in BD and total porosity occurred after five passages, while penetration resistance increased significantly after 10 passages.

Other studies, however, suggest that the progressive effects of machine passages differ significantly according to soil physical properties and depth (Cambi et al., 2015a). According with Sakai et al., (2008), our study clearly highlighted the significant effects of both tyre pressure and the number of passages, while the ANOVA results did not show any significant interaction between these variables. The differences recorded in rut depth between low and high tyre pressures states are the result of the greater stress exerted on the soil by the higher tyre inflation pressure.

Cambi et al., (2015a) recognised that the pressure applied to the ground played a major role in rut formation. Therefore, the machinery with the lowest ground pressure should be used on soils with low bearing capacity. Our finding indicate that the greater the number of passages the deeper the depth of the ruts.

The result of our and previous studies suggest that it might be advisable to reduce the load capacity of forestry machinery in order to reduce the pressure on soil. However, reduced loads or smaller vehicles also mean that the number of vehicle passages has to increase for extracting a certain wood volume, thus meaning that there is a balance between the vehicle size and the number of vehicle passages to take into consideration. Consequently, good design of forest operations design and planning are important for reducing the detrimental impact on soil. In particular, designated extraction trails allow operations to be confined, thereby limiting soil disturbances to a few selected areas (Chamen et al., 2003; Horn et al., 2007; Picchio et al., 2012).

A significant relationship between cone penetration resistance and VT was found, suggesting that it may be possible to develop a model and function for the assessment of soil compaction, in terms of cone penetration resistance, by means of rut depth in soils with low moisture content. In fact, rutting in low moisture soils is primarily the result of soil compaction, with lower quantities of soil being displaced out from the track (Hillel 1998). Above the critical moisture content threshold, machine-induced rut formation is primarily a product of topsoil displacement. In this scenario, the relationship between rut depth and cone penetration resistance becomes non-significant.

The comparison of rut depth determined by manual measurements and photogrammetric methods showed negligible differences (i.e., <5%). Differences in the error distribution were caused by several factors, including manual measurement inaccuracies. Such inaccuracies are possible through various means, for example, by placing the measuring rod in a small hollow, or lugs footprint (Pierzchała et al., 2016). A wrong selection of pixels corresponding to GCP in the reconstruction can also lead to referencing errors.

Using the traditional method, the accuracy of the estimation of rut volume is very rough because it is based on manually collected data from a certain number of cross-sectional and longitudinal profiles of forest trails (Haas et al., 2016; Koren et al., 2015). Moreover, the depth of lugs footprint is usually ignored in manual measurements. On the contrary, photogrammetric methods are based on a complete reconstruction of the ground profile, thus providing a greater degree of accuracy with respect to the identification of rut volumes. A rut generally forms a continuous hull, thus enabling the accurate measurement of both the rut's length and volume (Pierzchała et al., 2016).

Manual methods of measurement are considerably more labour intensive than close-range photogrammetry (Haas et al., 2016; Pierzchała et al., 2016). However, it is important to note that the accuracy and time required for image reconstruction are a function of the quality level chosen in the software by the operator.

One of the main problems related to close-range photogrammetry is object reflection. In the forest, vegetation (grass and/or shrubs), harvesting slash left on the ground and water logging may influence the accurate implementation of the method (Pierzchała et al., 2016). In fact, at the beginning of our study, the first picture alignment could not be automatic due to the presence of high grass (>15 cm), and it made necessary to cut the grass to both facilitate our work and to improve the accuracy of results. Photogrammetry immediately after forestry operations, however, may be more accurate as vegetation should be minimal, thus negating the need for vegetation control (Pierzchała et al., 2016). Nonetheless, logging residues left on the ground should be removed from the sampling area. The use of GCP was essential for ensuring the quality of our results. Without GCP, the assessed rut depth would have been higher than the actual depth. The acquisition of X, Y and Z control point coordinates were obtained using our prior knowledge of the object's position in space. The use of survey equipment, such as a total station, can increase the precision of the soil reconstruction (Pierzchała et al., 2016).

In this study, close-range photogrammetry in soil disturbance assessment was tested in a small area (162 m^2 in total). In larger areas, UAV equipped with a camera could be used instead. However, it must be considered that before logging, forest strip roads may not be clearly visible on aerial images due to the canopy cover, thus reducing the accuracy of the acquired pre-logging DTM. For this reason, Pierzchała et al., (2016) suggested the use a pre-logging DTM derived by LiDAR as reference. Our results highlighted that with close-range photogrammetry it is possible to monitoring soil disturbance also when

LiDAR DTM is not available and when trees cover does not allow the use of UAV images.

In conclusion, soil compaction is a universal concern associated with the use and management of soil. Soil displacement and rut formation often occur concurrently with logging operations. The soil properties directly affected by compaction and rutting include total porosity, pore-size distribution and penetration resistance. Our study investigated an innovative approach to the measurement of certain aspects of soil disturbance. Accordingly, the study results suggest and confirm that:

i) Low tyre pressure may mitigate the effects of forwarder on soil. Specifically, under the test conditions, 150 kPa pressure tyres showed the best performance with respect to rut formation as compared to 300 kPa pressure tyres;

ii) The greater the number of passages, the greater the degree of soil disturbance;

iii) SfM is an accurate and time saving method for the creation of high-resolution DEM and surface morphology description of forest trails.

iv) SfM provides high quantity information and sampling density about the soil surface, thus allowing the creation of accurate images of changes in the terrain.

v) SfM is a promising method compared to traditional methods, in terms of the time necessary for field surveys and data analysis.

While the accuracy of SfM might be high, the output of SfM might be even more accurate with an increase in the number and distribution of GCPs and camera resolution (megapixels). Notwithstanding, the method is not without its weaknesses. The presence of free water in the rut and logging residue or vegetation on the ground can interfere with the results, affecting their accuracy. Further studies are recommended in order to investigate the optimization of the images acquisition and to provide a more comprehensive understanding of soil damage estimation in different conditions (i.e., snow cover, uniform sand surface, etc.).

Our study highlighted interesting results, especially in terms of novelty of the applied methodologies. However, similar studies on different type of forest soils are encouraged in order to confirm our findings.

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4 Paper III - *Impacts of wood extraction on soil: assessing rutting and soil compaction caused by skidding and forwarding*

Abstract

Intensive forestry operations may cause soil compaction, plastic soil disturbances and rutting, which are responsible for undesirable effects on soils, vegetation and water bodies. Despite the numerous studies aimed to identify the main factors affecting soil damages, it still remains unclear whether wood extraction methods and driving direction (uphill or downhill) may affect the impacts of forest machines. This research analyses soil compaction and soil penetration resistance as well as rutting from forwarding and skidding using the same farm tractor in up- and downhill wood extraction. Rutting was estimated by 3D soil reconstruction derived by portable laser scanning (PLS) and close-range photogrammetry using structure for motion (SfM). Our findings showed that the direction of extraction did not affect soil damage severity during forwarding on a 25% slope. On the contrary, in order to reduce soil compaction, downhill skidding is preferable to uphill skidding. The results showed that the pressure on the ground caused by vehicles can be distributed horizontally, thus affecting also the soil between the wheel tracks. The soil bulk density inside the tracks in forwarding increased by 40% and with 23% between the wheel tracks. The soil displacement in skidding trails (7.36 m^3 per 100 m of trail) was significantly higher than in forwarding (1.68 m^3 per 100 m of trail). The rutting estimation showed no significant difference between the PLS and SfM methods, even comparing the two DSMs obtained, even if photogrammetry was preferred for technical and practical reasons.

4.1 Introduction

Soil disturbance is an unavoidable consequence of timber logging, but the severity of its impact is variable and can be managed through good planning and practices (Ares et al., 2005). According to the SFO (sustainable forest operation) concept, the minimization of soil impacts is a key task to improve the environmental efficiency of timber logging (Marchi et al., 2018). Intensive forestry operations may cause soil compaction, plastic soil disturbances and rutting, which are responsible for undesirable effects on soils, vegetation and water bodies (Cambi et al., 2015). Ground-based logging operations can negatively affect soil physical characteristics, reducing porosity while also increasing bulk density and resistance to mechanical penetration (D'Acqui et al., 2020; Lee et al., 2020; Siegel-Issem et al., 2005). Moreover, soil compaction indirectly influences tree growth and regeneration due to both physical root damage and reduced soil permeability (Cambi, et al., 2018a; Jansson and Wasterlund 1999; Mariotti et al., 2020; Sirén et al., 2013; Solgi et al., 2019; Sugai et al., 2020), which may lead to deficiencies of oxygen, water and/or nutrients (Batey, 2009; Lee et al., 2020) with recovery processes that may take several decades (Bottinelli et al., 2014; Jourgholami et al., 2020). Rutting and other soil disturbances can also disperse pathogenic fungi, alter microbiological processes (Cambi et al., 2017; De Wit et al., 2014; Frey et al., 2009) and mobilize heavy metals due to the increase in surface water flow (De Wit et al., 2014; Eklöf et al., 2014; Frey et al., 2009). Depending on logging conditions (e.g., soil condition and type, wood extraction method, machine characteristics and operator skills), the surface affected by disturbance within the logging area may range widely from 10% to 70% (Marchi et al., 2014; Spinelli et al., 2010).

Several studies were published on about the impact of logging on soil in recent years, but the relationships and interactions between compaction/rutting and slope gradient, driving direction (uphill vs. downhill), extraction method (skidding vs. forwarding) remain unclear. Some studies highlighted the effect of slope on soil compaction, finding that the higher the terrain slope, the higher the impact on soil (Jamshidi et al., 2008; Jourgholami et al., 2014; Naghdi et al., 2020). Previous studies have also investigated the impact caused by skidding and forwarding, highlighting that the extent of surface disturbance was higher after skidding, whereas compaction showed contrasting results between the two systems (Cambi et al., 2018a; Deconchat, 2001; Gondard et al., 2003; Lanford and Stokes, 1995). Compared to forwarders, skidders are driven in a denser extraction trail network (Han et al., 2009) with lower loads, thus explaining the greater extent of surface damages. In forwarding, the impacts on soil are related only to the contact of tyres on the ground (rut formation), whereas in skidding, the semi dragged logs also contribute to soil impact (soil displacement). However, the aforementioned studies are to be considered either as preliminary studies on the impact of logging as based on methods developed for assessing soil surface disturbance only by the observation of soil conditions after wood extraction; therefore, less visible effects, such as soil compaction, could not immediately be detected (Spinelli et al., 2010). In general, impacts on soil due to skidding have been more closely studied than forwarding. In addition, neither data nor studies have been found that compare the effects on soil caused by skidding and forwarding considering a similar operational context, which highlights a gap in the literature.

In recent years, innovative tools that are useful in assessing soil surface disturbances have become available. For the measurement of rutting which relied on classical manual measurements (Jester and Klik, 2005), are now available some innovative techniques such as three-dimensional ground reconstruction derived by photogrammetry (Haas et al., 2016; Marra et al., 2018; Pierzchała et al., 2016, 2014; Talbot et al., 2018) or laser scanning (Koreň et al., 2015). In particular, portable laser scanners (PLS) have started to be used in forestry for rutting estimation (Giannetti et al., 2017). However, sizeable knowledge gaps are evident concerning the efficacy of these newer methods (i.e., PLS and close-range photogrammetry) in the impact assessment of forest operations.

The objective of this research was to study the effects of timber extraction on steep terrain by measuring bulk density (BD), penetration resistance (PR) and surface disturbances such as rutting, considering both the extraction system (skidding and forwarding) and driving direction (uphill and downhill). Also, the application of two new methods such as 3D soil reconstructions derived by both portable laser scanner and close-range photogrammetry using Structure for Motion (SfM) were tested for measuring rutting and to identify the most suitable for applications in a forest context.

4.2 Materials and Methods

4.2.1 Site description and experimental design

The field-works for this study were carried out from June 15th to July 5th, 2018 in the Rincine forest, a public forest property located in the north-east part of Florence province, 40 km outside the Florence town (central Italy, N 43°52′; E 11°34′; 400 m above sea level). Considering climate data from the last 30 years, the climate of the study site has been classified as Mediterranean (Köppen-Geiger classification), characterized by a hot, dry summer (with January as the coldest month and August the hottest). In the period 2017–2018, the local mean annual temperature was 9.2 °C (1.5 °C in the coldest months and 17.8 °C in the warmest), and the mean annual precipitation was 924 mm, with the maximum in November and the minimum in July. The soil of the study site developed on Lower Miocene Oligocene sandstone and was classified as Dystric Cambisol based on the World Reference Base for Soil Resources (IUSS Working Group 2014). The study site was identified within a 50-year-old high stand of Douglas fir, located 900 m above sea level. Four trails were designed on the ground in the direction of the slope. Two trails were used for forwarding and two for skidding; in both extraction systems, one trail was used uphill and the other downhill (Figure 4.1).

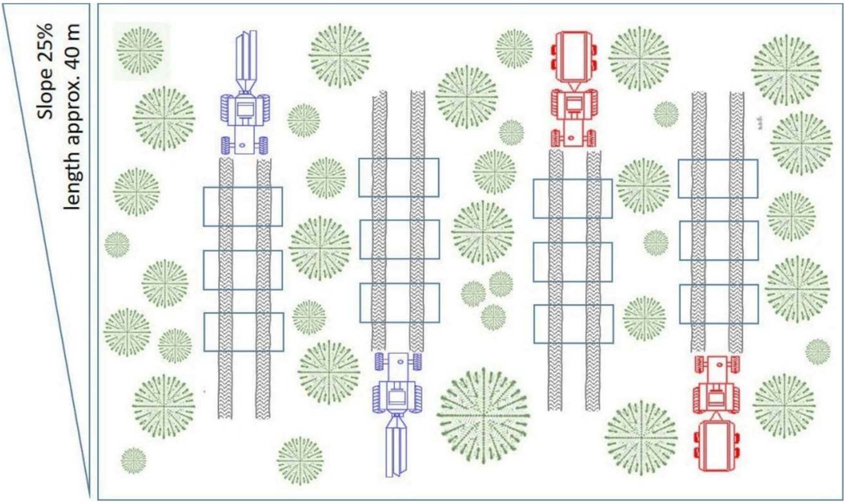

Figure 4.1. A representation of the plots included in the 4 trails. Two directions of extraction – uphill and downhill – were examined for both skidding and forwarding.

All trails had the same slope (25%). On these trails, wood extraction cycles were simulated using a four-wheel driven agricultural tractor adapted to work in forestry for skidding (equipped with a winch) or forwarding (equipped with forest trailer) Douglas fir logs. These machines are very common in forest operations in Italy, especially in peninsular forests, and more generally throughout the Mediterranean area. The tractor was a New Holland T6050, the winch a Farmi JL61 and the trailer a Zaccaria ZAM 140 Forestal TC Super. The trailer had two axles with two wheels each; the front axle was powered by the mechanical transmission from the power take off (PTO) from the tractor, while the rear one was a not powered self-steering axle. The contact areas shown in the table were measured by means of a rope pulled tightly around the portion of the tyre on the ground and assuming a circular contact patch (Cambi et al., 2016). Ground contact pressure was calculated as a ratio between the machine mass and the contact area (Table 4.1).

Table 4.1. Main characteristics of the two vehicles used.

	Tractor		**Trailer**		**Winch**
Model	New Holland T6050		Zaccaria ZAM 140 Forestal TC		Farmi JL61
Tyre model	Michelin TD MULTIBIB		BKT FLOTATION 648		-
	Front axle	**Rear axle**	**Driven front axle**	**Self-steering non driven rear axle**	-
Weight without load (kg)	2,962	3,228	4,750		555
Tyre size	480/65 R28	600/65 R38	385/65 - 22.5	385/65 - 22.5	-
Tyre inflation pressure (kPa)	100	100	375	380	-
Tyre contact area (cm^2)	2,710	5,018	1,473*	1,516*	-
Tyre contact pressure (kPa)	57	32	196*	155*	
Wheels (n)	2	2	2	2	-

* trailer loaded with 7,022 kg of logs

At the time of the study, no logging activities had been conducted within the study area in the last 40 years, thereby avoiding any influence of previous logging operations. The tractor (in both configurations, with trailer or winch) moved on the four new trails designed within the stand to monitor physical parameters and rutting before and after machine trafficking. Three rectangular plots (length 3 m, width 6 m) were selected and marked on the ground along each straight trail section (Figure 4.1).

In skidding, the thickest end of the logs were closest to the tractor and lifted by the winch at least at 0.5 m from the ground. Considering that the load capacity in forwarding was approximately 4.5 times higher than the load capacity in skidding, the comparison of skidding and forwarding was made by taking into consideration both the number of passages and the total volume moved. In detail, during the experimental study, the tractor equipped with a trailer (forwarding) passed 10 times on both the trail driven uphill and the trail driven downhill. The tractor equipped with a winch passed 10 times on each trail and, after an intermediate data collection, made 35 more passages (45 passages in total). In total 38 logs for forwarding and 9 logs for skidding (Table 4.2), with a weights of logs calculated after measuring the density of wood (550 kg·m^{-3}) (Meier E., 2015), were used during wood extraction. In this way, the same volume of wood was moved with the two systems (≃127 m^3) and it was therefore possible to compare the impacts related to both the same number of passages and the same volume of wood transported.

Table 4.2. Characteristics of logs used for loading the winch in skidding and the trailer in forwarding. To simulate the extraction of the same volume of logs, 45 skidding and 10 forwarding passages were made.

	N. logs	**Average log diameter (m)**	**Average log length (m)**	**Load volume (m^3)**	**Load volume after 10 passages (m^3)**	**Load volume after 45 passages (m^3)**
Forwarding	38	0.29	5.09	12.77	127.68	-
Skidding	9	0.27	5.30	2.82	28.17	126.77

4.2.2 Physical soil parameters

Impact on soil physical parameters and rutting were measured on all plots of all trails, before and after 10 and 45 (only for skidding) passages, applying different methodologies. The physical parameters measured for determining soil compaction were bulk density (BD) and penetration resistance (PR). Before machine trafficking, three soil samples were collected approximately one meter from each identified trail, on both the left and right sides, for a total of six samples per plot. After the machine passages (10 passages for forwarding and 10 and 45 for skidding), three soil samples were collected inside both left and right wheel tracks (InR) and three samples were collected between the tracks (BtwR), for a total of nine samples per plot. All soil samples were collected from the top 10 cm of mineral soil layer, using a metal cylinder (7.5 cm inner diameter and 10 cm height). BD was calculated as the dry weight (after a treatment at 105 °C per 48 hours) of the soil sample divided by the volume of the sampler (Picchio et al., 2009). In addition, six soil samples were collected daily from the trails (outside the plots) in order to monitor the soil moisture over time (soil moisture content on a dry-weight basis).

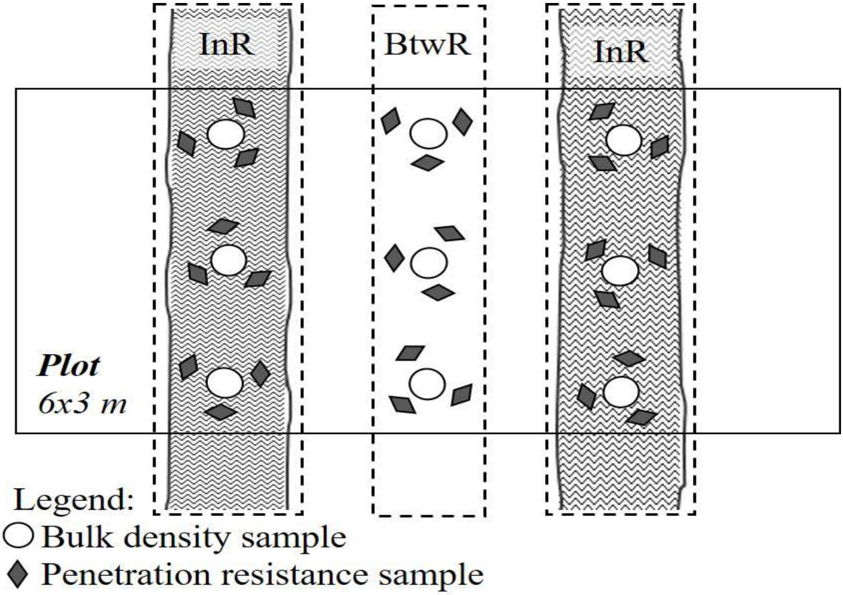

Figure 4.2. Scheme of soil sample and data collection on the trails for physical soil characteristics after machine passages. On each trail, the data were collected within the track (InR) and between the tracks (BtwR). The circles indicate soil samples collected for bulk density; the diamonds indicate penetration resistance measurements.

The PR has been measured by a hand cone penetrometer (Field Scout SC 900). A cone with a diameter of 12.7 mm and cone angle of 30° was used to register the average penetration resistance in the first 10 cm of the soil (at each 2.5 cm of soil depth). In each plot, PR was measured following the same protocol as BD (3 samples each in InR and 3 in BtwR) as an average of 3 values collected in each sample point.

4.2.3 Rut measurements

Two methods to implement a 3D soil reconstruction, derived by both portable laser scanner (hereafter PLS) and close-range photogrammetry using structure for motion (hereafter SfM), were applied to measure rutting caused by machine trafficking on forest soil. Measurements and data acquisition took place in the same plots used for collecting the other soil physical parameter data. Each method may provide accurate information about changes to the ground surface caused by the passage of forest machines by generating 3D representations of the trail section before and after the machine passages. The 3D soil reconstructions derived by both PLS and SfM were used for determining the volume of ruts caused by machine wheels and/or by dragged logs after skidding and forwarding, thereby allowing for the calculation of differences between digging and carryover soil volume.

4.2.4 SfM data collection and pre-elaboration

4.2.4.1 Data collection

The application of SfM is based on a series of images collected in the field. In our study, these images were collected using an RGB reflex camera: a Canon EOS 1300D model with 18 MP of image resolution and 5,184 x 3,456 pixels. The camera, which has a focal length of 18 mm, was mounted on a tripod 3 m in height with an angle of 45°. Image acquisition followed a specific scheme, previously described in Marra et al., (2018), designed to collect several images every half meter in different directions. All the images collected were checked directly in the field, immediately after collection, by visual interpretation to detect eventual problems related to light, saturation and blurriness, recollecting low-quality.

Before the acquisition of the images, 9 ground control points (GCPs) were positioned on each plot for image geolocation (Figure 4.3).

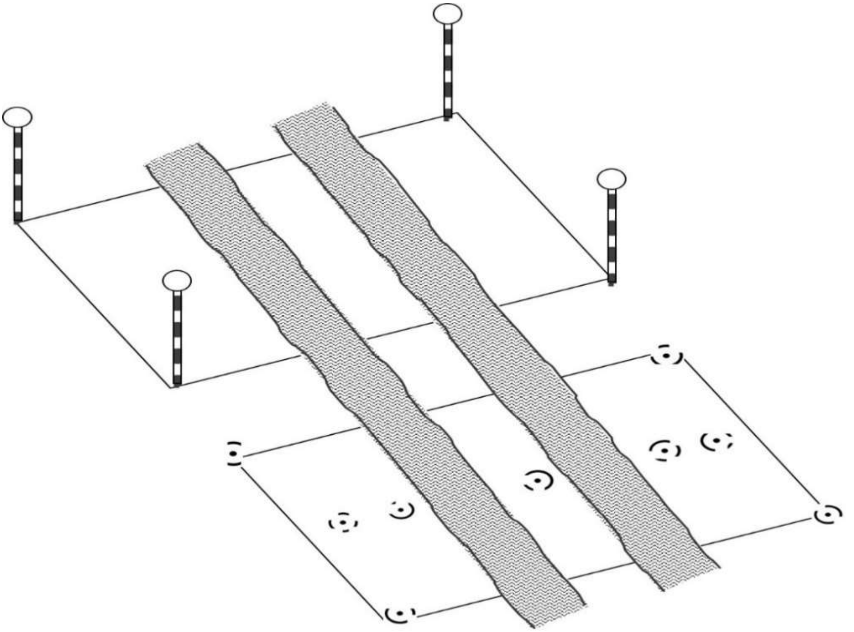

Figure 4.3. Position of the Ground Control Points during laser scanning (above) and close-range photogrammetry (below) data collection.

GCPs were composed of Schneider's coded target (C.T. Schneider, 1991), an automatically recognizable feature generated with Agisoft PhotoScan software (Agisoft, 2016). In detail, each GCP was a 144 cm^2 square aluminium plate with a specific printed image. The image was characterized by a central dot (radius of 15 mm) surrounded by a code band (12-bit pattern) with bit positions at equally spaced angular intervals (black or white).

A local system of coordinates was created and the X, Y and Z coordinates of each GCP were measured and used to align the models acquired at different phases.

4.2.4.2 Pre-elaboration

The SfM technique was applied to photo analyses to obtain 3D georeferenced point clouds. The analysis has been implemented in several steps using the Agisoft PhotoScan photogrammetric software package: (i) image import, (ii) image alignment, (iii) georeferencing, (iv) optimisation of image alignment and (v) creation of the point and dense clouds. After a rough alignment of loaded photos, the camera positions were optimised through the automatic detection and matching of GCPs using a specific functionality of Agisoft PhotoScan. This guaranteed sub-pixel accuracy without the need for human interventions. Thanks to camera optimisation and GCP detection, the single dense point cloud was produced to determine the 3D soil reconstruction of each plot point at each collection time. All workflow was elaborated using Python 3.5 (Van Rossum and Drake, 2020) as a scripting engine and supported by Agisoft PhotoScan.

4.2.5 PLS data collection and pre-elaboration

4.2.5.1 Data collection

A lightweight, portable ZEB1 HMLS consisting of a 2D laser scanner (Geoslam: Ruddington, Nottinghamshire, 2016), combined with an inertial measurement unit (IMU), was used to scan the plots within the study area collecting spatial data (acquisition speed 43,200 points/sec). The reported outdoor operative laser range is 15–20 m around the instrument (Bosse et al., 2012; Giannetti et al., 2017) with a scan ranging noise of ± 30 mm. In each plot, four GCPs were mounted as spherical targets (diameter = 0.14 m) atop 1.5 m poles (Figure 4.3) fixed in the ground at the corners of the plot. The X, Y and Z coordinates of each GCP were measured in the same systems of coordinates implemented for SfM, thereby guaranteeing the correct overlapping of results for comparison. To collect data in the plots (Figure 4.4), the operator walked slowly (approximately 30 cm s^{-1}) holding and oscillating the instrument at breast height (1.40 m above ground). The route inside the plot area was covered by walking the entire plot surface back and forth along straight lines (spaced 0.5 m apart), beginning and ending the survey at the same point (Ryding et al., 2015). In order to avoid shadow zones and to obtain the highest scan density of GCPs, special care was taken to fully scan the spherical targets.

Figure 4.4. Operator during laser scanner survey, holding and oscillating the instrument at breast height (1.30 m above ground) while walking.

4.2.5.2 Pre-elaboration

The 3D georeferenced point cloud was calculated from raw data by an online service (Geoslam: Ruddington, Nottinghamshire, 2016) provided by the producer of the ZEB1 laser scanner. This procedure uses a novel 3D simultaneous localization and mapping algorithm (SLAM) to combine the 2D laser scan data with the IMU data to generate accurate 3D point clouds (Bauwens et al., 2016). The resulting point clouds were loaded in CloudCompare (CloudCompare Version 2.11, 2020) in .las file format and then ‘cleaned’ to detect the plot and remove non-soil objects, such as stumps and trees. This process included the following steps: (i) identifying the plot in the point cloud by visual interpretation of GCPs,

(ii) manually tracking and segmenting the plot, and (iii) georeferenced processing of each GCP.

4.2.6 Quantification of rutting

4.2.6.1 Co-registration of point clouds

The point clouds for both methods used were elaborated by CloudCompare software to obtain the digital surface models (DSM) before and after the passage of forest machines in all plots. First, the soil surface conditions before (i.e., reference cloud) and after (i.e., compared clouds) machine trafficking were co-registered in CloudCompare using the GCPs and analysed using the ‘point pair-based alignment tool’. A fast control was conducted to assess the reliability of the automatic cloud’s overlap. In addition, minimum errors in positioning were eliminated through a calibration of the coordinate system considering the root-mean-square error (approximately 4 cm) for vertical and horizontal displacement. Finally, the point clouds were rasterized considering the average Z coordinate to create high-resolution (pixel = 1 cm) DSMs for each plot.

4.2.6.2 Rut measurement estimations

The differences between the DSMs before and after machine trafficking were implemented in CloudCompare in order to determine the volumes of ruts (volume reduction = VR) and bulges (volume increased = VI) caused by machine wheels or dragged logs. In addition, all the DSMs derived by SfM and PLS had the same resolution (601 x 301 pixels) to compare accuracy, pixel by pixel, with the R-cran raster packages (Hijmans et al., 2020).

4.2.7 Physical parameters and rutting: analysis of data

Statistical analyses were performed using R software (R Development Core Team, 2020). After checking for normality (Pearson chi-square test) and homogeneity of variance (Bartlett test), multi-way ANOVA was applied to the BD in order to test the soil compaction effects by machine type, impacted zone (InR or BtwR), driving direction (uphill or downhill), number of passages and total volume moved. A post hoc LSD test (least significant difference test) was applied to rank the results between dependent significant variables. Statistical differences in soil moisture at the time of each field day were tested by means of a t-test. The Kruskal–Wallis non-parametric multiple-comparison test (Dunn's test) was used to PR data because data distribution was not normal and variances were not homogeneous. Regarding the analysis on rutting, to verify the accuracy of DSMs obtained with SfM and PLS, regression analyses and the root-mean-square-error (RMSE) were performed. Finally, the soil volume changes (VI and VR) were compared by applying a one-way ANOVA in order to understand the effects of the wood extraction methods and to compare the volume estimation with SfM and PLS.

4.3 Results

4.3.1 Physical soil parameters

In the study site, the average soil moisture was 18% throughout the entire study period. BD and PR were significantly affected by machine passages. During forwarding a larger load than skidding was transported in each passage. However, a higher number of skidding passages was required to extract the same wood volume than in forwarding (10 passages in forwarding and 45 in skidding, to obtain 127 m^3 wood volume moved). In detail, the weight of the vehicles and their loads for each passage was 17.962 kg in total for forwarding (7.022 kg of load) and 8.294 kg for skidding (1.549 kg of load). The total weight transported on the ground of the study site after the woos extraction, was higher for skidding (373.246 kg) than for forwarding (179.624 kg) on the study site.

4.3.1.1 Bulk density - BD

The BD measured within the plots (both InR and BtwR) was significantly higher than in the undisturbed soil before the trials (Table 4.3).

4.3.1.1.1 Comparison of BD considering the same number of passages in skidding and forwarding

After 10 passages, in both skidding (28 m^3 of wood volume transported on the trails) and forwarding (127 m^3 of wood volume transported), a significant increase of the BD values was found (Table 4.3). BD was not affected by the driving direction; however, it was significantly affected by the logging method applied and the impacted zone (InR or BtwR). In general, skidding showed significantly lower values of BD in InR than forwarding, while similar BD values were recorded in BtwR. Finally, when forwarding moving both uphill and downhill, the increase of BD InR (40% higher than control on average; range 25%–52%) was significantly higher than the increase of BD BtwR (23% higher than control on average). After skidding operations, an average increase of 30% (range 17%–40%) was recorded in both BD InR and BtwR.

Table 4.3. Mean values of bulk density BD (±SD) after 10 passages by skidding and forwarding in different driving directions (uphill or downhill) measured both inside (InR) and between (BtwR) the tracks. Superscript letters show statistically significant differences (p-value < 0.05).

Bulk Density – BD (g/cm^3)		*Extraction method* *No. passages* *Wood volume transported*	**Skidding** *10 passages* 28 m^3	**Forwarding** *10 passages* 127 m^3
Before machine trafficking			0.86 (0.07)^{a}	
After 10 passages	*Uphill*	InR	1.08 (0.07)^{cd}	1.17 (0.06)^{e}
		BtwR	1.05 (0.06)^{bcd}	1.03 (0.05)^{bc}
	Downhill	InR	1.09 (0.09)^{d}	1.18 (0.07)^{e}
		BtwR	1.06 (0.07)^{bcd}	1.02 (0.03)^{b}

4.3.1.1.2 Comparison of BD considering the same wood volume moved by both skidding and forwarding

Increasing the number of skidding passages to simulate extraction of the same wood volume by forwarding (127 m^3) affected the measured values of BD. Comparing the effects of the two extraction methods, the results showed similar BD values when operating uphill, while when working downhill, skidding showed significantly lower values of BD in InR – and significantly higher values of BD in BtwR – than forwarding (Figure 4.5).

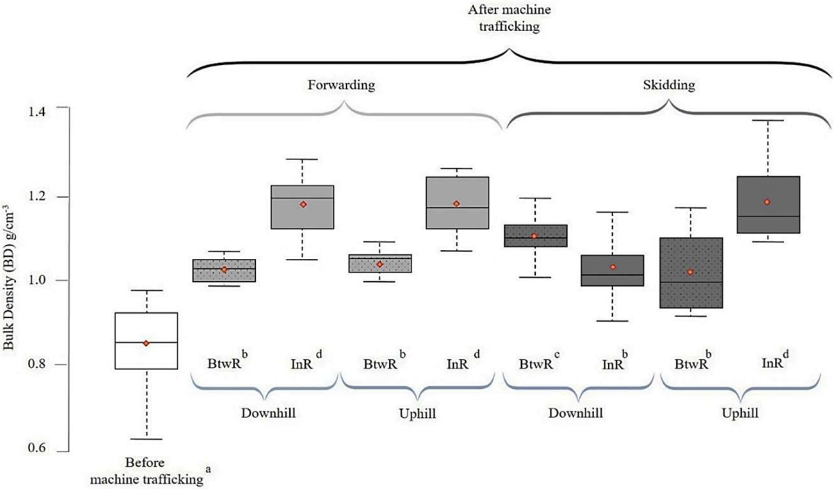

Figure 4.5. Average values of bulk density (red diamonds) after 127 m^3 of wood passed on the trails (including median and spreading range) by 10 and 45 passages for skidding and forwarding, respectively. Data about driving direction (uphill or downhill) and sampling zone (inside tracks – InR – and between tracks – BtwR) are included. Superscript letters show statistically significant differences ($p\text{-value} < 0.05$).

Thus, the highest average values of BD were obtained in InR, in both uphill and downhill directions for forwarding, but only in uphill for skidding (approximately 40% higher than undisturbed soil). On the other hand, the effects on soil in BtwR were lower than in InR, except when using the tractor with winch downhill, in which case the dragged logs caused a greater increase of BD in BtwR than the tyres in InR.

As reported in Table 4.4, the analysis of variance showed a strong influence of both the wood extraction methods and the impacted zone (InR/BtwR) on soil compaction after machine trafficking, in terms of BD. Moreover, a significant effect of driving direction (uphill vs. downhill) was recorded only after 45 passages. The statistical difference between InR and BtwR was strongly significant both after 10 passages and 127 m^3 moved. Analysing multiple interactions for BD, significant ones were found for wood extraction method and driving direction and between driving direction and impacted zone only when considering the same wood volume moved, while those interactions were not-significant when considering the same number of passages (Table 4.5). The interaction between wood extraction method and impacted zone (BtwR vs. InR) was stronger when considering the same number of passages than the same volume moved. Finally, the interaction among wood extraction method, driving direction and impacted zone was strongly significant when considering the same wood volume moved.

Table 4.5. Analysis of variance (p-values) of the effects of wood extraction method (skidding and forwarding), driving direction (uphill and downhill), impacted zone (inside the ruts = InR or between the ruts = BtwR) and the interactions on bulk density (BD) after 10 passages and after 127 m^3 of wood volume moved.

Source of variance	**Bulk density *p*-values**	
	After 10 passages	**After 127 m^3 of wood volume moved**
Wood extraction methods	**	*
Driving directions	-	*
InR vs. BtwR	***	***
Wood extraction method x Driving directions	-	*
Wood extraction method x InR vs. BtwR	***	**
Driving directions x InR vs. BtwR	-	***
Wood extraction methods x Driving directions x InR or BtwR	-	***

Signif. codes: ‘***’ 0.001, ‘**’ 0.01, ‘*’ 0.05, ‘-’ > not significant

4.3.1.2 Penetration resistance - PR

4.3.1.2.1 Comparison of PR considering the same number of passages in skidding and forwarding

After 10 passages of tractor with trailer (i.e., 127 m^3 moved), only the values of PR recorded within the tracks (InR) were significantly higher than the control (untrafficked) (Table 4.6). The PR values between the tracks (BtwR) did not change significantly. When considering the forwarding direction, significant differences were found between InR and BtwR when the tractor with trailer was driven uphill. Any statistical difference was recorded in skidding after 10 passages (i.e., 28 m^3 moved) for both driving direction and within (InR) or between tracks (BtwR). The comparison of skidding and forwarding did not show any significant difference, neither for driving direction nor InR/BtwR. The highest value of PR was recorded in forwarding uphill InR. This value was significantly higher than that recorded in skidding downhill InR and BtwR.

Table 4.6. Mean penetration resistance PR (±SD) after 10 passages by skidding and forwarding in different driving directions (uphill or downhill) measured both inside (InR) and between (BtwR) the tracks. Superscript letters show statistically significant differences (p-value < 0.05) according to Kruskal-Wallis multiple comparison test.

Penetration resistance –PR (kPa)		*Extraction method* *No. passages* *Wood volume moved*	**Skidding** *10 passages* 28 m^3	**Forwarding** *10 passages* 127 m^3
Before machine trafficking			1,048 (280)^{a}	
After 10 passages	*Uphill*	InR	1,676 (368) ^{cd}	2,134 (552) ^{d}
		BtwR	1,551(427) ^{bcd}	1,096 (431) ^{ab}
	Downhill	InR	1,533 (556) ^{bc}	1,621 (437) ^{bcd}
		BtwR	1,394 (421) ^{abc}	1,298 (212) ^{abc}

4.3.1.2.2 Comparison of PR considering the same wood volume moved by both skidding and forwarding

Further increments in PR (both InR and BtwR) were recorded in skidding trails after 45 passages (i.e., 127 m^3 – the same wood volume moved by forwarding). Increasing the number of passages, PR did not show any significant differences among skidding treatments (Figure 4.6). Comparing skidding and forwarding – and considering the same wood volume moved – the results highlighted that the lower PR values were recorded in forwarding BtwR, both in the uphill and downhill directions. The highest values were recorded in InR after forwarding and in all the skidding treatments. The PR value of forwarding BtwR uphill was significantly lower than skidding BtwR, both in the downhill and uphill directions (Figure 4.6).

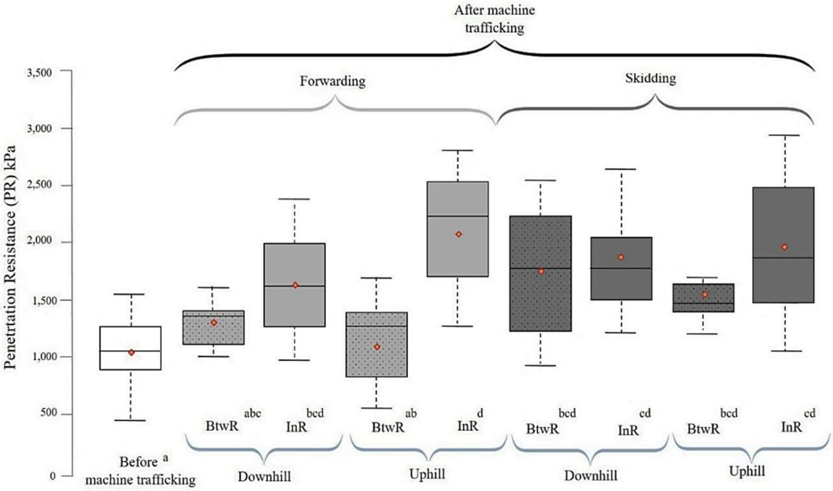

Figure 4.6. Average values of penetration resistance (red diamonds) after 127 m^3 of wood passed on the trails (including median and spreading range) by 10 and 45 passages for skidding and forwarding, respectively. Data about driving direction (uphill or downhill) and sampling zone (inside tracks – InR – and between tracks – BtwR) are included. Superscript letters show statistically significant differences (p-value < 0.05).

4.3.2 Rut measurements

The application of two methods – SfM and PLS – to measure the ruts due to wood extraction produced two different 3D reconstructions for each plot implemented in DSMs.

4.3.2.1 SfM dense cloud

The 3D reconstructions derived by SfM close-range photogrammetry had approximately 2,600,000 points for each plot (144,400 points/m^2). The errors of co-registration were always less than 0.13 mm for both the x and y coordinates, and less than 0.31 mm in the z coordinate thus negligible for our purpose.

4.3.2.2 PLS point cloud

The 3D reconstruction derived by PLS had approximately 1,600,000 points for each plot (88,800 points/m^2). The errors of co-registration were always less than 0.21 mm for both the x and y coordinates, and less than 0.31 mm in the z coordinate thus negligible for our purpose. A total of 10 plots were elaborated with PLS instead of the 12 that had been planned, because two files containing raw data (one forwarding downhill and one skidding uphill – both after 10 passages) revealed corruption during the post-processing phase.

4.3.2.3 DSMs: SfM vs. PLS

The correspondence between the SfM and PLS methods can be easily shown in the pixel-by-pixel comparison of the resulting DSMs obtained by overlapping them. The overlap of each plot showed an RMSE ranging between 2–4 cm; a graphical example representing the gaps between the two methods is reported in Figure 4.7. In addition, this comparison indicates a significant relationship between the 3D reconstruction data of the two methods (R^2 range between 0.97–0.90; p-value < 0.000).

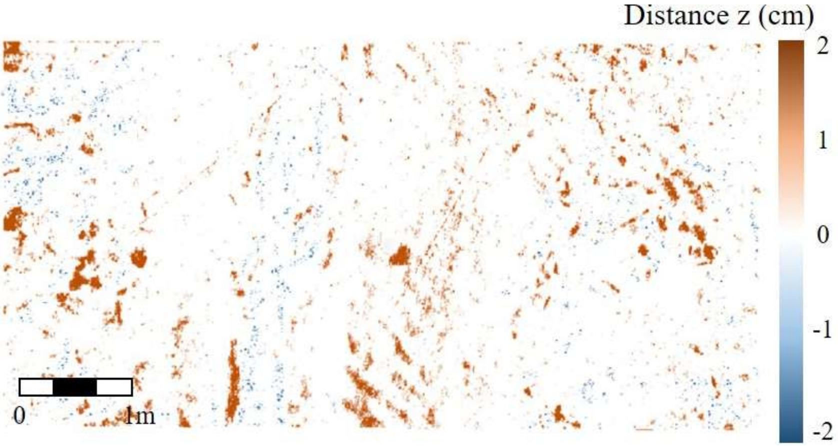

Figure 4.7. Example of pixel-by-pixel comparison of digital surface models (DSM) derived by structure from motion close-range photogrammetry and portable laser scanner.

Moreover, the comparison between these two methodologies focus to measure ruts did not show a significant difference (p-value < 0.001), which reveals a similar quality and reliability of results between both methods with a good correlation (R^2 0.80). Examples of 3D soil reconstructions derived by PLS and SfM are shown in Figure 4.8.

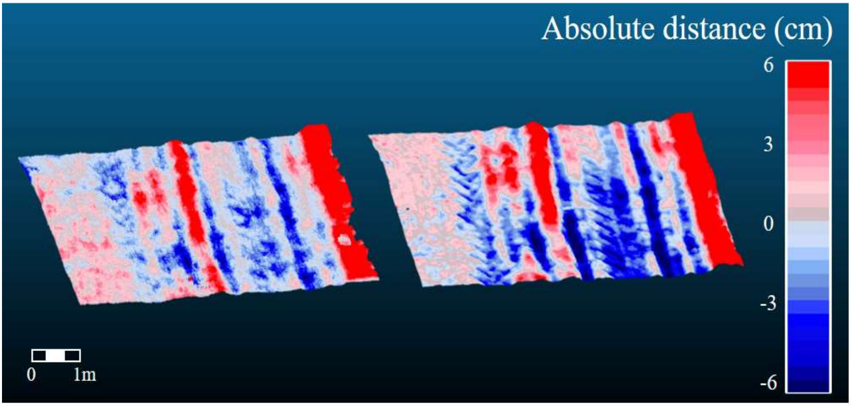

Figure 4.8. Examples of 3D soil reconstructions derived by portable laser scanner (left) and structure from motion (right) showing bulge height (positive values in red) and rut depth (negative values in blue) caused by skidding.

4.3.2.4 Quantification of rutting from DSMs

Because no significant difference was recorded in the estimation of rutting using photogrammetry and PLS (Figure 4.9), only the results deriving from photogrammetry are reported below. However, significant differences in VI were found in relation to wood extraction method when considering the same wood volume moved.

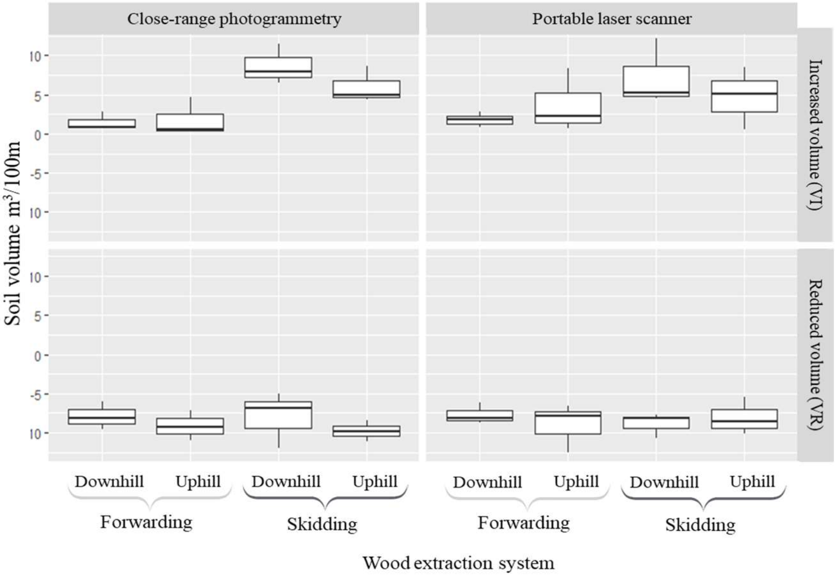

Figure 4.9. Median and spreading range values obtained by digital surface model (DSM) with close-range photogrammetry and portable laser scanner of increased soil volume (VI) and reduced soil volume (VR) per 100 m of trail trafficked by skidding or forwarding after 127 m^3 of wood volume moved.

In detail, VI after skidding (7.36 m^3 /100 m of trail) was almost four times higher than after forwarding (1.68 m^3 /100 m of trail). Conversely, the VR derived by skidding was - 8.88 m^3 /100 m of trail on average, which was similar to VR after forwarding (-8.51 m^3 /100 m of trail). No significant differences were found in VR and VI considering the driving direction in both extraction methods.

A strong and significant positive relationship between VR and soil compaction was found (R^2 0.704; p-value < 0.001) after 127 m^3 of wood volume moved: the higher the VR, the higher the soil compaction. In contrast, the relationship between PR and BD showed a low coefficient of determination (R^2 0.20; p-level < 0.000).

4.4 Discussion

In this study we compared the impacts (compaction and rutting) on forest soil caused by skidding and forwarding, considering both the same number of passages by loaded machine (10 passages for both skidding and forwarding) or the same volume moved (127 m^3 = 10 passages for forwarding and 45 for skidding), due to the different workload capacities of the two extraction systems being examined.

4.4.1 Physical soil parameters: BD and PR

Our findings confirmed the general rule that the passage of a loaded ground-based machine causes soil compaction (in terms of both BD and PR increase) along the trails (Cambi et al., 2015; Han et al., 2009; Williamson and Neilsen, 2003).

Indeed, BD increased for both forwarding and skidding in InR after 10 passages, driving in both uphill and downhill directions. This difference is attributed to the direct (under tyre in InR) effect of the pressure exerted on the soil. Nonetheless, a significant increase of BD was found also between undisturbed area and in BtwR, because of an indirect (between left and right tyres in BtwR) effect of the pressure exerted on the soil. These findings confirm that the impacts of machine trafficking on soil may not be limited only to the contact area of tyres on terrain, but also on the surroundings (Solgi et al., 2016). In fact, Solgi et al., (2016) demonstrated that the soil compaction expressed as BD occurred as far as 1 m from the wheel ruts and increased with slope gradient and traffic intensity, which explains the differences in our results between undisturbed area and BtwR in terms of BD.

In forwarding we found a significant difference between InR and BtwR in terms of BD, with the highest impacts in InR. However, the difference between InR and BtwR is not noticeable in skidding. This distinction between skidding and forwarding may be attributable to the different forces involved in the wheel-soil interaction process and the differences in load distribution for each extraction method. During forwarding, indeed, the load is carried on the trailer and the impact on soil is caused by the pressure exerted by the machine tyres combined with wheel slippage on the ground. During skidding, in contrast, the bottom ends of the logs are lifted and connected to the winch and the top ends are dragged along the ground – thus, the impact on soil is caused by a combination of the pressure exerted by the tyres and the pressure/scratching effect of the top ends of the logs. When the tyre pressure exceeds the soil bearing capacity – especially under increasing tractive demand – subsequent wheel slippage can induce pronounced shearing processes at the soil surface (Edlund et al., 2013), thereby increasing soil compaction (Eliasson and Wästerlund, 2007). Therefore, although this is the case for both skidding and forwarding, during skidding the logs dragged along the skid trail exerted pressure and scratched the soil surface, thus affecting compaction, soil mixing and displacement. The significant difference between InR and BtwR found for forwarding was not recorded in skidding due to the pressure exerted by the top ends of dragged logs in contact with the ground. Accordingly, in BtwR, it was expected that higher BDs and PRs would be found for skidding than for forwarding, due to the effect of the dragged logs on the ground. However, 10 passages of dragged logs were not sufficient to determine a significantly higher compaction in comparison with forwarding, in either downhill or uphill directions. On the contrary, after 127 m^3 of wood volume moved the soil compaction was affected by the driving directions (Table 4.4).

It is interesting to highlight that, although BD values were always higher after machines passage, PR showed no significant differences in BtwR for forwarding – both downhill and uphill – as well as for skidding downhill. However, PR increase for skidding downhill in BtwR became significant increasing the number of passages, i.e., considering the same wood volume moved as that of forwarding (127 m^3).

Considering these results, it appears that PR in BtwR is less affected than BD by the indirect effects of tyre pressure. In fact, the analysis of variance showed a strong influence of the wood extraction methods on BD (Table 4.4), difference that decreases with the increasing number of machine passages (10 forwarding and 45 skidding passages to obtain 127 m^3 wood volume moved). After 127 m^3 transported, similar values of BD between skidding and forwarding were registered in uphill extraction, while in downhill operation the effects of skidding were opposite to those of forwarding considering InR/BtwR; regarding PR, the trend seems similar, but differences were not as strong for BD.

Differences in BD levels of between uphill and downhill skidding may be explained by an uneven load distribution on the machine's axles, depending on slope direction (Jamshidi et al., 2008; Jourgholami et al., 2014) and by the increased wheel slippage and vibration encountered when skidding uphill compared to downhill. In this context, in the downhill direction, the machine's weight is more homogeneously distributed between front and rear axles. Furthermore, the weight of the logs sustained by the winch does not reduce the load on the front axle as occurs in the uphill direction. Therefore, the different distribution of weights between uphill and downhill directions implies a different application of traction force by the tractor on the ground, varying both compaction and shear effects on soils due to the three-dimensional transmission of forces (Horn et al., 2007). For these reasons, in some cases the effect of dragged logs on the ground may be greater than tyre pressure, thus explaining higher BD values in BtwR than in InR in the downhill direction after skidding 127 m^3. On the contrary, in the uphill direction, the tractor weight distribution is mainly on the rear axle, and the weight of logs acting on the winch increases the rear-up effect, thus concentrating the pressure of the rear axle tyres on the ground (McCallum B, 1993). Moreover, the greater the slippage the greater the exposure of mineral subsoil, which naturally has a higher BD than the surface layer (Jourgholami et al., 2014), further underlining the reasons why greater BD resulted in the uphill direction, as also reported by Sidle and Drlica (1981).

Finally, the examined machines -tractor with winch or trailer- may not be the optimal solution available in comparison with machines specifically built for forest operations (i.e., forwarder and skidder). In fact, the ground tire pressure for the loaded trailer, 11,772 kg in total, was high (173 kPa on average per tyre) due to the narrow and small tyres. This could negatively affect the severity of damages on soil, that may be reduced using a skidder or a forwarder, normally equipped with larger tyres with a low pressure of inflation.

4.4.2 Rut measurements

The analysis of rutting after machine trafficking was focused on two main aspects: i) identifying the best method for rutting data collection and processing and ii) assessing the effects of machine passages in terms of soil volume moved.

4.4.2.1 Comparison of DSMs obtained by SfM vs. PLS

The other aspect investigated in this study was rutting formation, analysing in depth the effects of tractors with winch or trailer in terms of both rut (volume reduced: VR) and bulge (increased volume: VI). The two methods applied and compared – PLS and SfM – have not shown significant differences in terms of results. The comparison of DSMs obtained by PLS measurements and SfM methods showed negligible differences (i.e., RMSE 2–4 cm). However, the use of more precise equipment, such as a total station, can further increase the precision of soil reconstruction in both methodologies (Pierzchała et al., 2016). SfM is the preferred method for technical reasons; indeed, in comparison with PLS, photogrammetry has much higher resolution (almost double the point m^{-2} in the dense cloud) and spatial distribution of the point cloud. In fact, the point resolution of laser scanning clouds increases for areas closer to the PLS, whereas it decreases at longer distances, which is one of the main limitations of this technology (Nadal-Romero et al., 2015). It is therefore recommended to minimize the scanning distance when possible (Heritage and Hetherington, 2007). In contrast, the resolution of multiple views with the same shooting height and overlap used in SfM were not affected by object distance (Smith and Vericat, 2015). Moreover, when using PLS, the data check operation must be performed afterward (i.e., not immediately in the field). In photogrammetry, however, it is possible to check on the camera screen if the collected images correctly cover the studied plot, thus easily and promptly identifying and correcting errors during data collection, avoiding further field surveys in case of errors as may happen when using PLS. However, one of the main problems related to SfM is object reflection. In the forest, vegetation (grass and/or shrubs) and water in the rut may compromise the accuracy of the method (Pierzchała et al., 2016), implying the necessity of choosing almost dry conditions for data collection. At the same time, one of the main problems in modelling a terrain based on a point cloud obtained by PLS is distinguishing points reflected by the terrain from those reflected by other objects (Koreň et al., 2015). In our work, we used a simple and effective filtration algorithm that removed all points located at a certain height above the ground (Koreň et al., 2015). However, the DSMs after machine trafficking could be also affected by the presence of harvesting residues on the forest floor or stones overturned by skidding. In this case, a visual detection of such objects is more difficult in PLS point clouds in comparison with coloured photogrammetry point clouds' negative effects on the reliability and accuracy of the method. Nonetheless, logging residues left on the ground should be removed from the sampling area before data collection. In conclusion, both PLS and SfM photogrammetry have increased the capacity to provide large data sets for the estimation of terrain modifications; without these technologies, the common method was manual, which was time-consuming and less reliable than PLS and SfM (Haas et al., 2016; Marra et al., 2018; Pierzchała et al., 2016).

4.4.2.2 Quantification of rutting

Photogrammetry showed interesting results on the effects of skidding and forwarding as causes of rutting. In fact, results showed that after 127 m^3 of wood volume had been moved, the tractor with the winch caused ruts similar to those caused by the tractor with the trailer in terms of soil volume reduced (VR). On the contrary, considering the increased volume (VI: bulges), skidding caused an effect four times greater than that of forwarding, with 7.36 m^3 against 1.68 m^3 of VI, respectively, per 100 m of trail. The reason for this considerable difference is the effect of log heads dragged on the ground, and it is partially explained by what has already been discussed regarding the effects on soil physical parameters (Chapter 4.4.1). In fact, rutting is caused by machine wheels, both in forwarding and skidding – but in skidding, the passing of the end of the dragged logs may change the impacts on soil (Cambi et al., 2018a; Wood et al., 2003). In detail, the ends of the dragged logs scratch and displace a certain quantity of soil in the dragging direction during each extraction trip. In this way, the soil is reshaped after the passage of tractor and the ruts left by the wheels are hidden. This happens especially in slope changes when the logs move and rearrange (Agherkakli et al., 2010; Cambi et al., 2018a; Heninger et al., 2002; Williamson and Neilsen, 2003). Looking at DSMs, rutting values are visually confirmed; in fact, in forwarding, ruts were clearly identifiable, whereas bulges along the trail were not visible. In contrast, ruts were not clearly evident on skidding trails, while bulges were. This difference negatively affected skidding in terms of risk of soil erosion, being the volume of soil moved higher than forwarding. In fact, the soil displaced and disturbed due to the traffic can be very vulnerable to erosion (Bagheri et al., 2013), causing negative indirect impacts on forest ecosystem, water quality and land stability (Frey et al., 2009); in this way, the measured volumes of bulges can be considered as a reference value of the potential entity of short-time erosion along the trail.

4.5 Conclusions

The main aim of this study was to describe the effects of wood extraction on both the physical properties of soil and the rutting caused by tractors with winch or trailer in different wood extraction directions. Our findings highlighted that the use of two different wood extraction methods can affect the soil impact in different driving directions. Within the limits of our experimental conditions, the study results highlighted that:

(i) the role of the driving direction was found to be irrelevant when operating a 4-wheel driven tractor and a trailer with one of its two axles driven. On the contrary, in order to reduce soil compaction, downhill skidding should be preferred to uphill skidding;

(ii) uphill forwarding and skidding (25% soil slope) caused the same soil compaction, an important information in choosing a proper wood extraction technique;

(iii) skidding has a higher effect on soil displacement than forwarding;

In addition, our study applied and compared the performance of portable laser scanning and image based models derived by SfM photogrammetry to evaluate soil rutting. Indeed, the use of both portable laser scanning and image-based models derived via SfM photogrammetry were accurate methods for the creation of high-resolution DEMs and may be very useful to assess the impact of forest operations on soil. However, considering the logistics of data collection in forestry, photogrammetry is likely the best solution.

Finally, negative effects on soil due to ground-based extraction methods in forest operations are recognized worldwide. Following the principles of Sustainable Forest Operations (Marchi et al., 2018), modern logging operations must minimize these impacts. For these reasons, it is fundamental to thoroughly understand the dynamics and factors that affect the extent and severity of the impacts.

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5 Paper IV - *Remote measuring of the depth of wheel ruts in forest terrain using a drone*

Abstract

Even at a well-managed harvesting site, vehicle trafficking occurs on at least 12% of the area and might cause ruts and compaction. The use of drones shows potential to be used for assessing soil disturbances, however there are still difficulties in interpreting images obtained by drones. The purpose of this study was to develop a method for measuring the size and depth of wheel ruts caused by forest machines in harvested areas, using drones and Structure from Motion photogrammetry. In order to investigate the accuracy of drone photogrammetry, measurements from flight altitudes of 60 m and 120 m above ground level were compared with manual measurements. The same methods were used at a control site on farm land, taking into account the rut depth and the location of the sample surface (close to trees or in a fully open area). No statistically significant differences were found between manual measurements and remote measurements from 60 m or 120 m altitude at the harvesting site (R^2 0.77-0.83). At the control site, an underestimation of 2.2 cm of the rut depth was found for remote measurements made from 120 m altitude. The data derived from drone images were able to reproduce the 3D model of surface features, such as bulges and ruts; these measurements were considered to be equivalent to manual measurements. For practical applications, a post-harvest survey using drones could contribute to verifying compliance with international forest certification standards or by private contractors to evaluate rut formation on their harvest sites.

5.1 Introduction

Today, forestry is highly mechanized in many areas of the world. All large-scale logging operations and site preparation are carried out using forestry machinery. In-forest vehicle traffic unavoidably causes soil impacts, especially at the stage of timber extraction (Picchio et al., 2020).

The interaction between a vehicle and soil exerts vertical and horizontal stress components as well as shear forces to the soil (Alakukku et al., 2003; Cambi et al., 2015). Soil damage occurs when the ground pressure from the machine exceeds the soil bearing capacity. With tractive demand increasing, subsequent wheel slippage can result in the development of shearing ruts (Eliasson and Wästerlund 2007). Rutting and soil compaction are the main forms of soil damage caused by forest operations; the soil system can suffer substantial, long-lasting, and sometimes irreversible damage, which negatively affects forest productivity and ecosystem functionality (Hartmann et al., 2014). Soil impacts by vehicle trafficking cause physical, physiological and pathogenic issues for residual trees (Sirén et al., 2013), root systems, and seedlings (Mariotti et al., 2020; Sugai et al., 2020; Cambi et al., 2018b), as well as a reduction of soil conductivity and gaseous exchange capacity (Startsev and McNabb 2009).

The extent of the affected area and the severity of the damage are determined by several factors, such as the type and condition of the soil, harvesting system, and machine characteristics (Picchio et al., 2012). However, even in the best managed operations with sophisticated ground-based logging machines (i.e., harvester and forwarder), at least 12% of the site will be subjected to vehicle traffic (Eliasson 2005). In this context, the overall impact of forestry operations largely depends on the harvesting management. In addition, at present, international forest certification standards issued by the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC), along with national legislation, have recommendations and regulations covering rut formation (Nevalainen et al., 2017). Compliance with legal and standard requirements require rutting and soil disturbance to be monitored.

Wheel track data are traditionally collected using manual measurements from cross-sectional and longitudinal profiles, usually with several meters between the measuring points (Nevalainen et al., 2017), resulting in only a rough estimate of the total rut volume (Koreň et al., 2015). Data collected from manual measurements unfortunately only cover a very small part of the operation site because the method is time-consuming and expensive (Koreň et al., 2015). Recent advances in computers, digital sensors, and digital data processing provide greatly improved methods for collecting and interpreting the required information. Video technology and image processing techniques have been utilized by many disciplines to measure changes in the terrain using photogrammetry (Warner 1995; Taconet and Ciarletti 2007). Indeed, the use of modern technologies can provide more detailed data of the wheel ruts compared to manual methods. Structure from Motion (SfM) is a photogrammetric technique applied over a variety of platforms (drone, pole, tripod or handheld) to provide multiple geospatial data products (i.e. 3D models and orthomosaics) from a single sensor (Iglhaut et al., 2019). Previously, terrestrial laser scanner or close-range photogrammetry (from a low shooting height) had been applied in rutting estimation in relatively small areas (Koreň et al., 2015; Haas et al., 2016; Pierzchała et al., 2016; Giannetti et al., 2017; Marra et al., 2018). Only Talbot et al., (2018) used drones for collecting images to obtain ortomosaics of whole sites and then to visually classify the rutting severity. Compared with other methods, the collection of ultra-high resolution micro-drone (<5 kg) imagery from low altitudes (e.g., 50–120 m) presents a number of advantages, such as collecting image data more cheaply, faster, and more safely than traditional methods. Puliti et al., (2019) showed that creating inventories using drones flying at 110 m above ground level (a.g.l.) took half the time compared to manual inventories of regenerating forest stands. Drones are capable of flying much lower than conventional platforms (such as satellites and manned aircraft), hence can collect much higher resolution images (Scaioni et al., 2009), often at a sub-decimeter resolution, and even as detailed as 1 cm/pixel (Turner et al., 2012). On the other hand, a lower altitude results in increasing flight and working times. However, altitude limitations can vary substantially between countries due to national aviation regulations. For example, in Sweden, the maximum legal flight altitude is 120 m above ground level (a.g.l.). Often, drone imagery has highly variable illumination (i.e., problems with shadow zones), object reflection (i.e. water), occlusions and variations in resolution (Zhang et al., 2011), which are issues frequently found in close-range photogrammetry applications (Turner et al., 2012). The applicability of this technique is limited to the reconstruction of surfaces visible in the image data (Iglhaut et al., 2019), providing only ground or water surface information. Hence, drone photography has the characteristics of both terrestrial and aerial photography, and there are opportunities to use image processing algorithms applicable to both types of imagery (Barazzetti et al., 2010). However, the use of photogrammetry in forestry is considered a new inventory method when applied to the assessment of the depth and shape of wheel tracks (Talbot et al., 2018). A large dataset of rut information would aid not only extensive monitoring of forest standards, but also the modeling and prediction of forest terrain trafficability (Pohjankukka et al., 2016). A post-harvest survey using drones could be an essential part of creating such a dataset.

The overall aim of this study was to develop a method for measuring the depth of ruts caused by forestry machine traffic moving over forest terrain, using SfM applied to images acquired using drones. More specifically, the accuracy of rut depth measurements was compared between:

i) drone flight altitudes of 60 m and 120 m a.g.l.
ii) measurements of a soil surface and where water had pooled

Finally, we compared the accuracy between measurements at an ordinary forest harvesting site with uneven terrain, and on a level agricultural soil surface with short, consistent vegetation. In the latter case, the accuracy was also tested taking into account the rut depth (shallow or deep) and whether there were mature trees close to one side of the ruts or the ruts were in a completely open area.

5.2 Materials and Methods

5.2.1 Site description and experimental design

The study was carried out on a clear-cut area, where logging residues were also extracted, near the town of Ulricehamn, Västra Götaland county, Sweden (57°47′N 13°25′E), in October 2018. The altitude of the site was between 160 and 190 m above sea level. The previous stand was characterized by even-aged Norway spruce (Picea abies) (80%) and Scots pine (Pinus sylvestris) (20%). The mean annual temperature and precipitation in the area are 5.8°C and 772 mm, respectively. Over the period of the study, the average temperature was 7°C and the precipitation 78 mm.

The previous harvest was carried out using ordinary mid-sized harvesters and forwarders equipped with bogie tracks. A sub-area of 4.7 hectare with a high concentration of wheel tracks was selected on the 33 ha clear-cut area. Twenty rectangular plots following the tracks, with lengths between 9.5 and 10 m, were randomly selected (Figure 5.1). Areas where water had pooled within the ruts of some plots were recorded and analyzed. Data collection was also carried out at a 2.4 ha control site on a nearby flat piece of agricultural land with short grass. Four trenches, each with a length of 10 m, were made with a small excavator (Figure 5.1). Two trenches were located about 4.5 to 8 m from a forest stand with a mean height of 20 m. One trench was shallow, 22 cm depth on average (FS) and one trench was deep, 83 cm depth on average (FD). The trenches in the open field consisted of a shallow ditch, 20 cm depth on average (OS), and a deep ditch, 59 cm depth on average (OD). The depth within each trench was made as constant as practically possible. Rut depth measurements from a ground-based manual reference method (hereafter referred to as manual measurement) were compared with the depth calculated using images from a drone flying at 60 m and 120 m a.g.l. using SfM (hereafter referred to as R60 and R120 for remote measurements, respectively).

Figure 5.1. Images draped with 3D triangular irregular network mesh generated from 60 m a.g.l. aerial photography of two harvesting site plots (above) and of the control areas (below): 1. Open field shallow, 2. Open field deep, 3. Near forest shallow and 4. Near forest deep.

5.2.2 Manual rut measurements

The distance between a horizontally leveled rod and the bottom of the rut was measured manually, perpendicular to the driving direction of the track at 1-m intervals on both the left- hand and right-hand sides of the tracks within the plot. The instrument used had a support to the ground about 30 cm on each side of the track, and a vertical sliding scale (resolution of ±0.5 cm) able to measure the rut depth in the middle of the track (Figure 5.2).

Figure 5.2. Manual instrument for rutting measuraments.

5.2.3 Image acquisition for R60 and R120

Imagery for photogrammetric measurement was collected using a DJI Phantom 4 Pro drone (DJI, 2016), equipped with a camera and an on-board global navigation satellite system (GPS/GLONASS) and inertial navigation system. Detailed specifications of the drone equipment are shown in Table 5.1.

Table 5.1. Drone and equipment specifications.

Equipment	Specification	Parameter
Drone	Model	Phantom 4 Pro
	Weight (kg)	1.4
	Flight Speed (m/s)	6
	Max Flight Time (min)	30 Approx.
Camera	Model	FC6310
	Image resolution (pixel)	5,472 x 3,648
	Focal length (mm)	8.8
	Pixel size (µm)	2.41 x 2.41
Satellite Positioning Systems	Type	GPS/GLONASS
	Vertical Accuracy Range (m)	±0.5
	Horizontal Accuracy Range (m)	±1.5
Gimbal	Stabilization	3-axis (pitch, roll, yaw)
	Controllable Pitch Range (°)	-90 to +30

The flight path was prepared on the autopilot software with a georeferenced raster map to set the flight parameters. The PiX4Dcapture software (version 4.0.0) allows for setting of flight parameters such as waypoints, flight altitude, and travel speed. After the assisted take-off by an operator, the drone flew along the defined route at the target altitudes of 60 or 120 m a. g.l., capturing details of the tracks, with a camera view angle of 90 degrees (nadir), acquiring images with 80% forward and side overlap. The resulting flight altitude and the corresponding details of each survey are shown in Table 5.2. During the flight, the operator was able to trigger the camera to acquire imagery. The remote controller also displays, in real-time, flight data such as speed and altitude, as well as other system features such as GPS signal strength. The total time for each flight was recorded. The weather conditions during all the flights were cloudy with a temperature of about + 5°C, without frost on the ground.

Table 5.2. Details of flight data.

Site and flight height	Intended flight altitude (m a.g.l.)	Resulting flight altitude (m a.g.l.)	Number of images (n)	Coverage (ha)	Overlap of aerial photographs (%)
Harvesting site	60	57	229	6.6	80
Harvesting site	120	119	67	9.9	80
Control site	60	60	134	4.0	80
Control site	120	121	40	6.5	80

The images acquired were visually inspected to detect problems relating to light and atmospheric conditions or saturation. Before image capture, 10–12 ground control points (GCPs) were placed on the site and their coordinates recorded with a setting of a 5 cm standard position error target using a Trimble GeoXR 6000 RTK (Real-Time-Kinematic) receiver.

5.2.4 Post-processing of drone images and rut measurements

Dense point clouds were derived from the drone images using the SfM photogrammetry software Agisoftphotoscan Pro (Agisoft LLC 2016). This software allows full automation of the photogrammetric workflow to process aerial images and produce 3D (e.g. image-based point cloud) and 2D (e.g. Digital Surface Model and Orthomosaic) models, using the multi-view stereo matching and SfM algorithm provided. The drone images were processed using the following main steps to obtain the 3D soil reconstructions: (i) image import, (ii) image alignment, (iii) guided marker positioning of GCPs, (iv) optimization of camera alignment by georeferencing using GCPs and by filtering the automatically generated tie points, and (v) generation of dense point clouds. More specifically, after a rough alignment of image positions, the images were optimized using the GCPs as a reference. The GCPs were identified manually in the set of images in which they appeared, and the Agisoftphotoscan Pro software carried out the necessary georeferencing using the images and the GCPs' coordinates as the input. The point clouds thus generated were re-projected onto the SWEREF 99 TM coordinate system projection. To improve the accuracy of the stereo model, pre-processing was carried out on the automatically generated tie point cloud data, consisting of a sequence of operations using the "gradual selection" tool to detect inaccurate points. Tie points with a re-projection error of <0.75 pixel or with a projection accuracy of <10 pixels or derived from fewer than two images were removed from the tie point cloud. The aerial images were oriented and optimized after each adjustment, but the direct and secondary effects of the proximity of the canopy were not eliminated. After this pre-processing, dense point clouds were produced (Figure 5.3) in order to determine the rut depth information. The dense point clouds were rasterized in a Digital Surface Model (DSM) with a pixel resolution of 1 cm. In this study, the DSM derived by Agisoftphotoscan Pro workflow corresponds to the Digital Terrain Model (DTM).

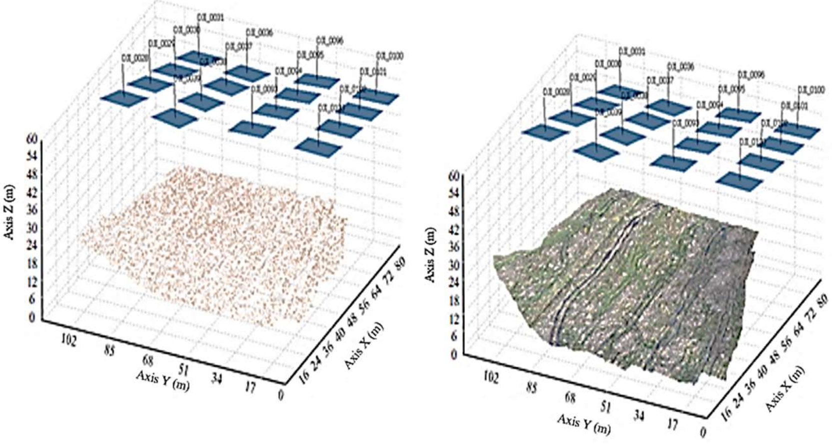

Figure 5.3. 3D view of object tie points are shown in red (left), the 3D soil surface reconstruction (right) of the harvesting site. The blue rectangles represent the location of the camera in relation to the ground.

Rut detection was carried out in three steps: (i) extracting the dense point cloud data and loading them into the Quick Terrain Modeller (version 8.0.7.0), (ii) plot detection and finding the centrelines of the tracks, and (iii) forming the profile model of the ruts. More specifically, in each detected plot in the dense point cloud, the track centreline was found. In order to find the location where the manual measurement was made, the reconstructed plot area was covered using grids of constant pitch. Two grids (1 m width and 10 m length) were generated for each plot at the same distance from the centreline, representing the left and right rut. A cross-sectional analysis was used to evaluate the profile of the track and the depth of the ruts on the grid.

5.2.5 Comparison of manual and remote rut measurements

Manually measured rut depths were compared with the image-based point cloud values. The data obtained in the harvesting site were analyzed separately from the data collected at the control site. Two methods were used to compare photogrammetric and manual rut depth measurements. For the first method, all the manually measured values were compared with the rut depths obtained using SfM applied to images taken at 60 m and 120 m a.g.l. altitude. At the harvesting site, the depth of water-filled wheel tracks was measured from the bottom of the rut to the surface of the water. In the second method, all the rut depths (measured by both manual method and SfM 60 m and 120 m a.g.l.) were split into three classes of depth: Class I all rut depths <20 cm, those between 20 and 40 cm were put in Class II and depths >40 cm were put in Class III. The points with the presence of other features in the rut (i.e., water or vegetation) were treated separately, i.e., all the depths measured for the water-filled wheel tracks were analyzed separately from no-water filled wheel tracks. Furthermore, for the control site, all the rut depths measured in the trenches near vegetation (FS and FD) and in the open field (OS and OD) were analyzed separately. The area of the wheel tracks from vehicular traffic was assessed using the dense cloud derived using SfM (images from 60 m a.g.l. flight). After a visual identification in the dense cloud, the wheel tracks on both sides of the machine were cropped and segmented using Cloud Compare tools. Using the average rut depths, each segment was assigned a rut depth class (i.e., I, II or III). The total length and the wheel area of each rut depth class were calculated. The total length of a rut depth class was the sum of each segment's length recorded as the distance between the two edges of each section. The wheel area was estimated taking into account the width of the tracks detected in the 3D soil reconstruction (around 0.8 m).

5.2.6 Analysis

Statistical analyses were carried out using Minitab™ 18 and results were considered significant for a p-value < 0.05. As a first step, the distribution of the data was plotted and checked for normality (Kolmogorov–Smirnov normality test) and homogeneity of variance (Levene test). Regression analyses and Pearson correlation coefficients were used to calculate the correlation between the results of the different measurement methods. One-way ANOVA was used to compare the manual measurements and the values obtained using SfM reconstructions, in order to test the accuracy of rut depth estimates. A post-hoc HSD test was used to highlight significant statistical differences. In order to identify and exclude any possible interaction effects caused by dependency of the measurement methods on the location of the sample surface, a two- way ANOVA was carried out between the two measurement methods and the control areas (open ground or near forest, shallow or deep).

5.3 Results

5.3.1 General

For the R60 data acquisition, the total flight time and the data computer processing time were twice as long and four times as long as for R120 (Table 5.3). In addition, the number of points in the dense point cloud was almost four times higher for R60 compared with R120 (Table 5.3), providing a higher accuracy in the reconstruction. The ground sampling distance for R60 was almost half as long as for R120 (Table 5.3). The time required for data collection using manual measurements was 8 hours for the harvesting site and 2 hours for the control site.

Table 5.3. General flight and data acquisition parameters.

Site and flight height	Flight time (hour)	Process time (hour)	Points in dense cloud (point/m^2)	Ground sampling distance (cm)	Reprojection error (pixel)
Harvesting site 60 m	0.18	13.55	6,289	1.44	0.43
Harvesting site 120 m	0.08	3.62	1,418	2.97	0.46
Control site 60 m	0.13	5.58	5,635	1.47	0.46
Control site 120 m	0.08	1.40	1,272	3.00	0.40

The root mean square errors (RMSE) for the locations of the control points and checkpoints were calculated (Table 5.4). The mean values of these parameters calculated for all the flights were mx = 1.87 cm, my = 0.97 cm and mz = 1.35 cm, which correspond to an error in the horizontal point position of mxy = 2.20 cm and an error in the spatial position mxyz = 2.65 cm. On this basis, the accuracy of the generated products was initially assessed. The largest RMSE values were obtained for the flight over the harvesting site at 120 m a.g.l. altitude.

Table 5.4. The final root mean square errors for positions of ground control points.

Site and flight height	GCPs (n.)	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total error XYZ (cm)
Harvesting site 60 m	12	0.99	0.99	0.75	1.40	1.59
Harvesting site 120 m	12	4.88	1.19	1.89	5.02	5.37
Control site 60 m	10	0.85	0.88	1.43	1.23	1.88
Control site 120 m	10	0.77	0.84	1.35	1.15	1.77

5.3.2 Rut depth

5.3.2.1 Harvesting site

Overall, there were no statistically significant differences in measured rut depth between the manual measurement and R60 (p-value = 0.2211), as well as R120 (p-value = 0.1674). The comparison of manual measurement and R60 indicate a positive significant correlation over 382 observations (R^2 0.83, y = 0.8976x + 4.0709, where x was a manual measurement and y was the value from R60; p-value < .001) with an RMSE of 4.5 cm (Figure 5.4).

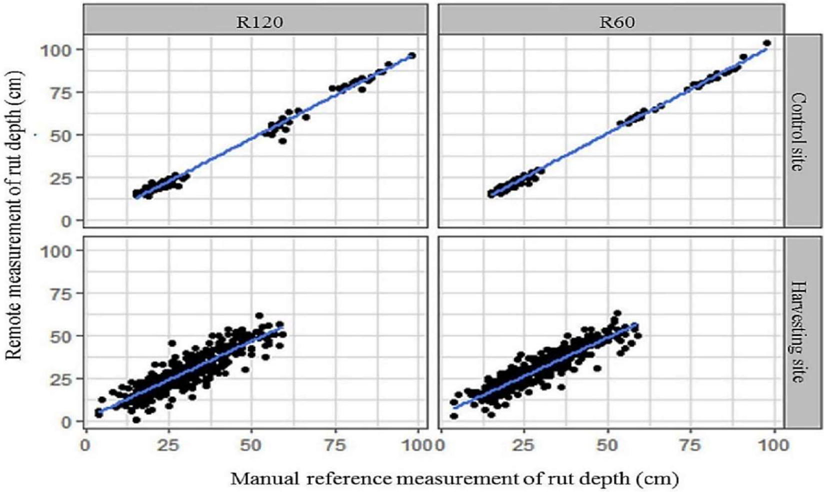

Figure 5.4. Scatterplots of the remote measurement of non-water filled rut depths from 60 m (R60) and 120 m (R120) a.g.l. altitude as a function of the manual reference measurements.

Also, the values of the coefficient of determination (R^2 0.77, y = 0.9049x + 1.7294, where x was a manual measurement and y was the value from R120; p-value < .001) and the RMSE (5.5 cm) revealed a good correlation between the manual measurements and the R120 data. No significant differences were found in the values collected with the three methodologies in non-water filled tracks for all the depth classes. The mean values of rut depths for manual measurements, R60 and R120 were: for Class I 15.9 (±2.5) cm, 16.9 (±4.2) cm and 16.7 (±3.8) cm; for

Class II 29.3 (±5.3) cm, 30.0 (±6.5) cm and 28.9 (±6.8) cm; for Class III 47.3 (±5.6) cm, 46.7 (±6.4) cm and 45.8 (±6.7) cm (Figure 5.5). When measuring non-water filled wheel tracks, the maximum and minimum difference of the mean values between manual measurements, R60 and R120 did not exceed 1 cm. Examination of the measurements of depth in water-filled wheel tracks, where the distance from the ground surface to the water surface was measured, showed that the overall greatest spread in measurement results was for the R60 data, when compared to those of both manual measurement and R120 (Figure 5.5). The mean values of rut depth for manual measurements, R60 and R120 were: for Class I 14.7 (±3.8) cm, 17.5 (±5.7) cm, and 14.4 (±5.6) cm; for Class II 28.6 (±5.3) cm, 29.9 (±5.6) cm and 26.6 (±6.7) cm; for Class III 44.2 (±3.3) cm, 45.8 (±4.6) cm and 41.3 (±5.9) cm (Figure 5.5). Significant differences between the rut depth of water-filled wheel tracks from manual measurements, R60 and R120 were found: for Class I, data from manual measurements and R120 were significantly different from R60, whereas for Class II and Class III, data from manual measurements and R60 were significantly different from R120.

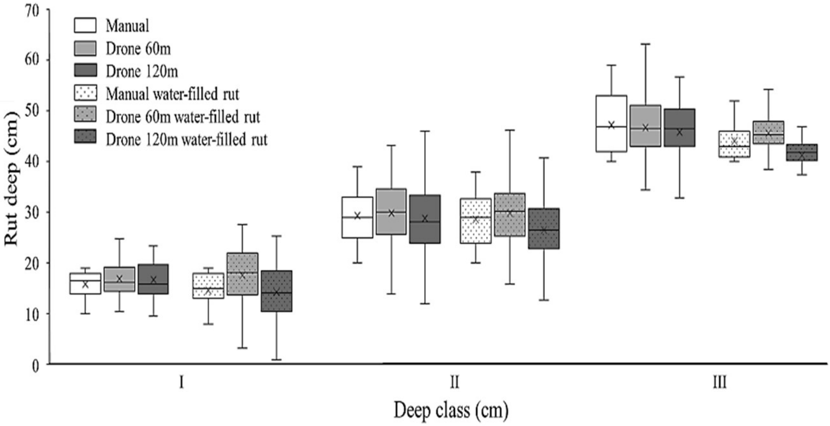

Figure 5.5. Average of wheel rut depth using manual measurements (white), remote measurements 60 m (light grey) and 120 m (dark grey) at harvesting site in non-water filled ruts and the distance to the water's surface for water-filled ruts (filled patters). Data divided by class of rut depth (Class I values < 20 cm, Class II 20 – 40 cm and Class III > 40 cm).

The total machine track length on the site was 1,113 m ha^{-1}, made up of a high percentage of Class I ruts. There were more than double the number of Class 1 ruts than Class III ruts (Table 5.5). The width of the entire area affected by the machine was estimated taking into consideration the tracks measured from the outer edges of the wheel on both sides. The machine track width was 3.2 m, of which almost 50% (0.80 m for each wheel) was in contact with the ground. When considering only the wheels' footprints, the area affected was 18% of the harvest site area.

Table 5.5. The wheel tracks split into rut depth class (Class I < 20 cm, Class II 20 – 40 cm and Class III > 40 cm).

	Machine track		**Wheel track**	
Class	**Length (m ha^{-1})**	**Share of total (%)**	**Area covered (m^2 ha^{-1})**	**Area as share of the total site area (%)**
III	220	19.8	353	3.5
II	406	36.5	650	6.5
I	486	43.7	778	7.8
Total	1,113	100	1,781	17.8

5.3.2.2 Control site

Overall, there were no statistically significant differences between rut depths determined using manual measurements and R60 data (p-value = 0.913), or with R120 data (p-value = 0.586). Between manual measurements and R60 data, there is a positive significant correlation over 83 observations (R^2 0.99, $y = 1.0306x - 0.9248$, where x was a manual measurement and y was R60 data; p-value < .001) (Figure 5.4). In addition, the data for manual measurements and R120 revealed a good correlation (R^2 0.99, $y = 1.00034x - 2.3846$, where x was a manual measurement and y was R120 data; p-value < .001) (Figure 5.4). The measurements of track depth using manual measurements and R60 data, split into their respective test areas, showed no statistically significant differences (p-value = .705). However, the rut depths estimated using manual measurements and R60 data showed a significant difference to R120 data in the OS and FD control areas (Figure 5.6). On average, the R120 data underestimated the rut depth by 2.2 cm (Table 5.6) (ranging from −3.6 cm to −0.8 cm). The measurement accuracy was not affected by the location of the sample surface (located either in a fully open area or near a forest edge) or the depth of the rut (shallow or deep). In fact, the interactions between variables did not show significant differences and, thus, the results of the different measurement methods do not depend on differences between the position of the test surfaces and the surface area.

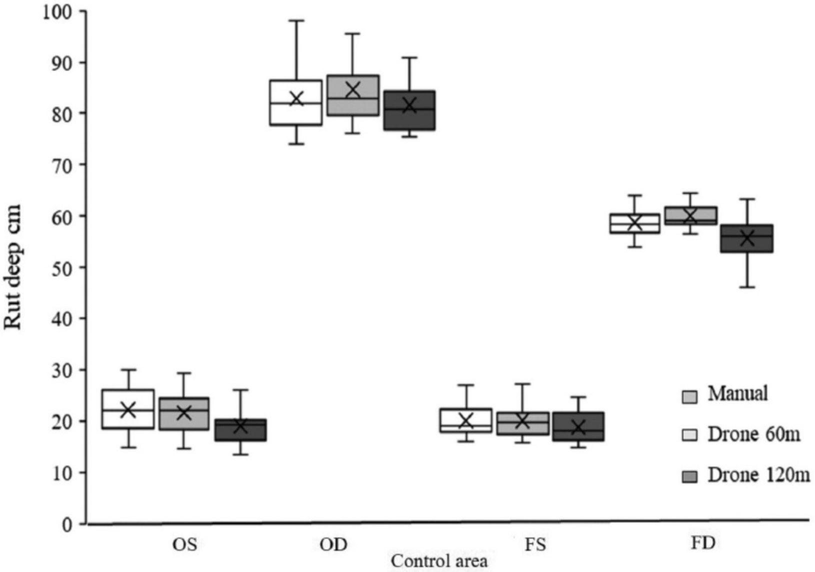

Figure 5.6. Average rut depth including median and spreading range for manual measurements, remote measurements at 60 m and 120 m a.g.l. altitude at control site split into control areas: 1. Open field shallow (OS), 2. Open field deep (OD), 3. Near forest shallow (FS) and 4. Near forest deep (FD).

Comparison of the manual measurements and the R60 data showed that RMSE values were lower than those for the R120 data in each control area (Table 5.6).

Table 5.6. Average of rut depth at control site shown by measurement method: manual measurements, remote measurements from 60 m (R60) and 120 m (R120) a.g.l. altitude, and split into each control area.

	Open field shallow			**Open field deep**			**Near forest shallow**			**Near forest deep**		
	Manual m.	*R 60*	*R 120*	*Manual m.*	*R 60*	*R 120*	*Manual m.*	*R 60*	*R 120*	*Manual m.*	*R 60*	*R 120*
N.	22	25	25	18	18	18	22	22	22	18	18	18
Average rut depth (cm)	22.2 $(4.2)^a$	21.7 $(4.0)^a$	19.0 $(3.2)^b$	82.9 $(5.9)^a$	84.6 $(6.4)^a$	81.7 $(5.3)^a$	20.2 $(2.9)^a$	20.1 $(3.1)^a$	18.9 $(2.9)^a$	58.8 $(2.9)^a$	60.0 $(2.7)^a$	55.8 $(4.3)^b$
RMSE (cm)	-	1.7	3.9	-	2.2	2.5	-	1.4	1.9	-	1.5	4.5

Notes: Standard deviation (SD) in parenthesis. Lowercase letters show statistical significant differences (p-value < 0.05) amongst different measurement method (manual measurements, remote measurements from 60 m and 120m a.g.l. altitude) measured in each control area.

5.4 Discussion

This paper describes a drone-based digital photogrammetry system for acquiring data relating to vehicular wheel ruts. The low-cost, flexible photogrammetry system is easy to operate, and can efficiently capture soil surface imagery fully automatically by shooting photos on the set drone's flight path. The high ground sampling distance of 1.4 cm/pixel obtained allows for identification and detailed evaluation of surface damage. This study focused on one harvesting site which had suffered unusually severe vehicular rutting damage, to compare drone-acquired data with manual measurements. In this context, the characteristics of forestry machines and the soil type, usually important factors in soil compaction or rut formation (Eliasson 2005; Sakai et al., 2008; Talbot et al., 2018), were not relevant.

5.4.1 Research method

At the harvesting site, the high standard deviation of the depths measured made it difficult to identify statistically significant differences between the methods. In fact, a large variation in ground level was found due to the presence of vegetation, logging residues, stumps and differences in soil level. In addition, the variation within measurements can be affected by several factors, including manual measurement inaccuracies (placing the measuring rod in a small hollow or lugs footprint or on a root). However, at the control site, all those issues were less prevalent. This is most likely because the ambient conditions there were more constant, with ruts more even, without bulges or any objects (stones, stumps and high grass), compared to the harvesting site. In fact, the rut depth in a single sample surface was not as variable and thus differences between the measurement methods become more clear. The most accurate and precise measurements were found at the control site in the R60 data, with a high coefficient of determination and low RMSE compared to manual measurements. When the control site's measurements were split by control areas, there was no statistically significant difference between manual measurements and R60 data. Different results were obtained when comparing manual measurements to R120 data, when the control site's measurements were split by control areas. An underestimation of rut depth (average 2.2 cm) was present in the R120 data when compared to manual measurements, high-lighting a statistically significant difference. However, a negative bias of the values obtained from the 3D soil reconstruction using drone data has not been observed in previous studies of soil disturbance in forest tracks or on unpaved roads (Zhang and Elaksher 2012; Nevalainen et al., 2017). That could be explained by taking into account the geometry of the camera positions and GCP positions in relation to flight altitude. In fact, the block of images taken from 120 m altitude covered a 200 m by 200 m area that contained all the trenches, with all the GCPs within 60 m of the center of that block. However, it could be also a random distortion error, as having only one model derived from 120 m data means that it is not possible to compare the reconstruction meaningfully. In all cases, allowing for an average rut depth of 46 cm at the control site, the underestimation of 2.2 cm for our study is an acceptable error. Furthermore, in other cases (i.e., where the rut is shallower) these errors could be an issue in the reconstruction accuracy, highlighting the need for future research. In our study, the correlation between the manual measurement method and data from R60 and R120, shows a good R^2 coupled with a low RMSE. Similar results were obtained using close-range photogrammetry from a few meters at ground level (Pierzchała et al., 2016; Marra et al., 2018). Comparing manual measurements with rut depths obtained using 3D soil reconstruction, Pierzchała et al., (2016) found a RMSE of 2.07 – 3.84 cm, which is within the same range as the results presented here. This value is acceptable when taking into account the manual measurement method precision as well. In addition, our results highlight the fact that drone measurements are at least as accurate as the current manual method. Therefore, our findings suggest that manual measurements should not be considered to be the true rut depth, nor should the manual method be considered as a reference method. The accuracy of the drone measurements can, indeed, be higher compared to manual measurements, especially when flying at low altitudes. Photogrammetric surface can differ from the actual rut surface for stands with a high presence of logging residues. Photogrammetry provides only surface models (Pierzchała et al., 2016) and in some cases, it might be difficult to assess how much damage the brush mat is obscuring (Talbot et al., 2018). These conditions can affect manual measurement accuracy as well. In fact, manual measurement can provide trustable results only if the field worker identifies and removes all the logging residues before the measurements.

5.4.2 Potential for additional rut data collection using drone measurements

A more detailed measurement of the rut depth can be obtained by creating a total profile of the depth of the track. Several studies of soil disturbance after harvesting used systematic sampling designs in the field (Han et al., 2009; Pohjankukka et al., 2016) or a complete 3D reconstruction of the ground profile derived by close-range photogrammetry (Haas et al., 2016; Pierzchała et al., 2016; Marra et al., 2018), terrestrial and portable laser scanning (Koreň et al., 2015; Giannetti et al., 2017), but on relatively small areas. However, extensive field- based soil disturbance monitoring is labor-intensive and cost-prohibitive (Reeves et al., 2012; Talbot et al., 2018). Talbot et al., (2018) reported the use of drones to visually estimate the extent of rutting, based on three severity classes (light, medium and severe), for the whole harvesting site. Manually tracing and categorizing vehicle traffic on the basis of orthomosaic production provides a low-cost method for a more detailed record of site damage (Affek et al., 2017; Talbot et al., 2018). Using drone images, Talbot et al., (2018) applied a line intersect sampling method running on a desktop PC for soil disturbance estimation. Talbot et al., (2018) found a large negative impact on soil condition when the total machine track length exceeded 1,000 m ha^{-1}. The potential of using drone technology for extensive monitoring of forestry post-harvesting was also confirmed by our study. Using a 3D soil reconstruction derived from drone survey data, it was possible to estimate the area affected by the wheel tracks (1,781 m^2 ha^{-1}) and estimate the degree of soil disturbance in the harvesting site. In order to further develop the use of drones in rutting estimation, it is important to investigate the collection of high-resolution 3D point clouds derived by drone photogrammetry. In fact, this method may provide a cost-effective option for producing rut depth maps that cover the whole logging site.

Unlike other methods, the 3D reconstruction using SfM also provides estimates of the volume of ruts and bulges, and volume loss due to compaction, since it is based on a complete reconstruction of the ground profile. The benefits of rut volume calculations have been confirmed in previous studies, when limited to small areas (Cambi et al., 2018a; Koreň et al., 2015; Haas et al., 2016; Pierzchała et al., 2016; Giannetti et al., 2017; Marra et al., 2018). The accuracy of volume estimation with close-range photogrammetry was confirmed by Marra et al., (2018), who showed it was even possible to measure the difference in rut volume caused by different tire pressures of a forwarder. Hence, by using SfM derived from drone data, there is potential to combine the benefits of both, so using the high accuracy of 3D reconstruction obtained by SfM and covering a large area. The total rut volume estimated in the harvesting site (around 732 m^3 ha^{-1}) gives another overview of soil disturbance over a wide area. The process to measure the rut volume from drone data using SfM involves reconstruction of the original terrain surface using Poisson Surface reconstruction (Kazhdan et al., 2006; Pierzchała et al., 2016) and the creation of a DTM with a resolution of 1 cm, using the method described by Marra et al., (2018). The accuracy of drone data-derived SfM was quantified in an estimation of chipped wood volume, where an underestimation of 8–12% was found when using Pix4Dmapper Pro and Agisoftphotoscan Pro (Howell et al., 2018).

5.4.3 Drawbacks of photogrammetric measurements of ruts

Usually, the proximity to low and high densities of vegetation (grass and/or shrubs) may influence the accuracy of the image- based measurement method (Pierzchała et al., 2016). In our results, the accuracy of rut depth measurement was not affected by the presence of a forest on one side (4.5 m). However, different results might be obtained with closer or different distributions of the vegetation (i.e., delimited on two sides or completely surrounded). The SfM method is not without its issues: the presence of free-standing water in the rut can interfere with the results. In non-water filled wheel tracks, the difference of the mean values does not exceed 1 cm. However, significant differences were found in the depths measured in the R60 and R120 data in water-filled ruts. This can be explained by a combination of a high range of values with outliers and poor texture mapping in the 3D reconstruction caused by the surface of the water, with the latter reason causing depth overestimates of up to 15 cm. Reflection from the surface of the water depends on the observation angle and affects the object-matching algorithm. This phenomenon has been found in both the dense cloud data and the cross-sectional profiles of the rut, with noise above and below existing water surfaces only present for the water-filled wheel tracks (Figure 5.7). In fact, photogrammetry generated the model only using the points from the surface and not from the terrain (Pierzchała et al., 2016). However, not even laser scanner methods, usually using beams with wavelengths of 1,064 nm, could provide measurements under the surface of the water leaving room for potential new methodologies in the research field. Measuring the depth of shallow waterbodies is only possible using a bathymetric system (underwater depth research), where its 532 nm beam can penetrate water with far less attenuation than one with a wavelength of 1,064 nm. Due to their weight, the use of traditional bathymetry sensors has been restricted to unmanned airborne platforms (Guenther et al., 2000) or positioning sensors under a boat. A new solution with the sensors attached to a drone has been tried but this is expensive. Overall, to mitigate the problem of water-filled ruts, Pierzchała et al., (2016) suggested taking into account seasonal fluctuations in precipitation before planning the survey.

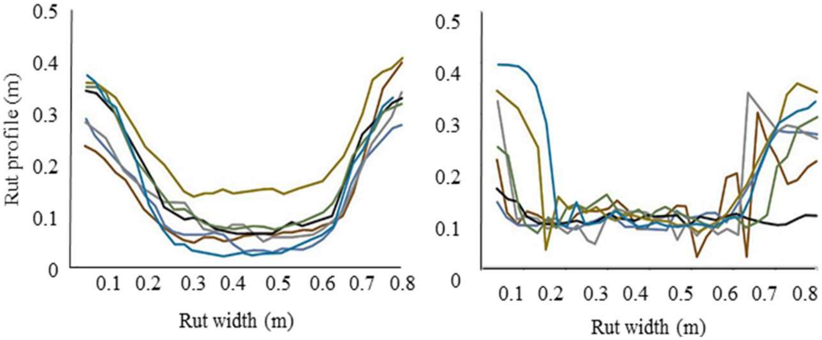

Figure 5.7. Seven cross-sectional profiles derived from 3D point cloud data for 60 m altitude measurements: a plot with measurements on soil surface (left) and of a water-filled rut with measurement on water surface (right).

5.4.4 Implementation

The benefit of using modern drone technology is that it provides a highly accurate 3D reconstruction. The level of accuracy can change according to the specific purposes. Low altitude flights (i.e., 30 m a.g.l.) can collect imagery with extremely high resolution (Scaioni et al., 2009; Hunt et al., 2010), and thus provide interesting data for research purposes. At the same time, higher flight altitudes (i.e., 120 m a.g.l.) with a wide overview might be appropriate for other purposes and prove time-saving. In fact, the high-quality data collected from a height of just 3 m (Marra et al., 2018) were good enough to identify tire tracks after only one pass of the forestry machinery. However, the close-range photogrammetry method was time-consuming when collecting data after forestry operations over a large area; for this reason, this method is only suitable for research purposes. It is true that a drone flying at a low altitude (i.e. 60 m a.g.l.) can provide high-quality data with a reduction in both field and processing times. In fact, a comparison of the man-hours needed for acquiring manual measurement data revealed that the total number of hours required for data acquisition was reduced by almost 90% when carrying out a drone survey. This reduction was due to there being less time needed to walk around the site being surveyed, and the fact that a large area is much more efficiently surveyed from the air. The low time-consumption for post-processing data in manual measurement is an advantage but is limited to estimate a few transects or rutting points. The post-processing with 3D soil reconstruction by drones is longer but able to obtain the depth map in the whole site. Hence, our study confirmed that drone photogrammetry may provide a cost-effective option for collecting high resolution and accurate records of site damage after harvesting (Turner et al., 2012). Given that the new methodologies use algorithms and script-like sequences of commands, it is possible that, in the future, soil disturbance could be automatically detected to reduce the workload and improve applicability. This would significantly reduce the post-processing work and the method shown here could be more efficient and easily usable in practice. Nevalainen et al., (2017) described the first step toward an autonomous rut depth data extraction with a demonstrable reduction in the processing time. After a manual selection of the tracks, Nevalainen et al., (2017) described a workflow for semi-automated analysis of rut depth profile on the basis of given parameters (i.e. rut separation and width). The Pearson correlation coefficient between the remote and reference values was lower ($r = 0.67$) than our study (0.88–0.99). The pre-processing model does require, however, some practical improvements (Nevalainen et al., 2017). However, this suggests possible improvement of the process for automatic estimation of rut dimensions in the future. The development of methods and procedures for correctly utilizing the new source of information provided from drones is overdue (Talbot et al., 2018). The method presented in this study can be implemented for research purposes, for example, a large dataset of rut depths would aid not only extensive monitoring of forest standards, but also the modeling and forecasting of forest terrain traffic-ability (Turner et al., 2012; Pohjankukka et al., 2016). A post-harvest survey using drone technology could be an essential part in creating such a dataset. The original terrain surface can be reconstructed with a good level of accuracy (Pierzchała et al., 2016) but in some cases it may prove essential to carry out a pre-harvest survey to increase the accuracy of the resulting data. It must be acknowledged that, before logging, forest strip roads may not be clearly visible on aerial images due to canopy cover, thus reducing the accuracy of the generated pre-harvest 3D soil reconstruction. In this case, the methodology proposal in this study could be used in conjunction with laser scanning technologies. The use of high- resolution Digital Terrain Models (DTMs) has been described in previous studies of the detection of soil displacement using portable laser scanners (PLSs) (Giannetti et al., 2017), and with terrestrial laser scanners (TLSs) (Jester and Klik 2005). The use of a pre-logging DTM using laser scanners has been suggested to improve the accuracy of the measurements (Pierzchała et al., 2016). However, the equipment is expensive and can be time-consuming when collecting large quantities of rut depth data over a large area (Jester and Klik 2005; Haas et al., 2016). For this reason, using data collected from drones and PLS or TLS is not yet economically feasible at a management level (Talbot 2017). The purpose of this work was to evaluate the efficacy of a method that could easily be integrated into everyday forest management routines. For example, current aerial images or 3D point clouds could be used to evaluate the work of a contractor after harvesting, to allow a discussion of the strengths and weaknesses of the felling strategy, or they could be used to verify compliance with the international forest certification standards issued by the FSC and PEFC concerning rut formation. This study might also help in training machine operators to cause less soil damage in their work.

5.5 Conclusions

This paper describes a drone-based digital photogrammetry system for acquiring data relating to vehicular wheel ruts. The 3D reconstruction method can produce a 3D model of surface features, such as bulges and ruts, which allows for accurate measurement of those features directly on a computer. The accuracy of the method was tested in two cases: in one harvest-ing site which had a large variation in ground level (due to the presence of logging residues and stumps) and in a control site with optimal conditions (without features that could adversely affect remote measurements). Remote measurement of the rut depth using a drone (flying at altitudes of 60 m a.g.l. and 120 m a.g.l.) provided a method of quantifying the size of wheel ruts after harvesting that was equivalent in accuracy to manual measurements and considerably less labor intensive. Therefore, an inventory of the depth of ruts caused by logging vehicles can be carried out using SfM-based processing of drone image data flying at altitudes of 60 m a.g.l. and 120 m a.g.l., obtaining similar results. Nevertheless, at the control site, where the conditions were optimal, the R120 data showed a small error in depth measurements (around 2 cm). The results obtained highlight the method's versatility that could be used in research and especially for operational use where a few centimeters of underestimation is considered an acceptable error. The accuracy of the developed methodology was not affected by the presence of a forest on one side or by the rut depth (shallow or deep), but the presence of free-standing water in the rut can interfere with the results. In conclusion, remote measurement using drones can be considered to be equivalent to manual measurements when measuring rut depth, but with the important limitation that it will not be able to measure the correct rut depth if the rut is water-filled, covered with brush mats, or with a lot of residual brush vegetation.

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6 Conclusions

One of the main topics in forestry in the last 20 years has been the effect of forest operations on the environment. The main priorities for improving sustainable forest management include methods and technologies to minimize and estimate soil impacts. Several studies have investigated the undesired effects of mechanised forest operations on soil. Some aspects, however, are still unclear. Research conducted for this thesis was related to soil impacts (i.e., soil compaction and rutting) caused by ground-based logging systems (i.e., skidding vs. forwarding with adapted farm tractors). To summarize the literature on machinery-induced soil compaction and its effect on forest plant growth, a meta-analytic approach was applied to previous studies. Moreover, emerging technologies were applied to estimate rutting in a controlled environment in order to demonstrate the effectiveness of the technology itself and its potential application in large-scale real-world operations.

Studies have shown that the progressive effects of machine passages affect the formation of rutting in terms of both rut (volume reduced: VR) and bulge (increased volume: VI). The emerging methods studied (i.e., photogrammetry and laser scanning) are reliable methods for measuring rutting. The soil reconstructions derived through photogrammetry and portable laser scanning are based on a complete reconstruction of the ground profile, thus providing more detailed data and a greater degree of accuracy concerning the identification of rut dimensions (i.e., volumes and depth) than traditional manual measurements have done in the past. Moreover, using emerging methods it is also possible to provide detailed measurements over much larger areas (rut-depth maps that cover the whole logging site) than is practically possible with manual measurements. The results obtained highlight the versatility of emerging methods in surface morphology description of forest trails. This data, especially that derived through photogrammetry from images collected by drones, can be used for research and practical purposes. However, only traditional manual methods can measure the depth of a water-filled rut; more research is needed to make it possible to perform these types of measurements using the emerging techniques studied.

Studies have confirmed that much of the impact on soil, in terms of increased BD and reduced porosity, occurs during the first few machine passages. Evaluating the physical parameters of the soil (i.e., BD and PR) and rutting seem to be fundamental for obtaining an overview of soil damage caused by skidding and forwarding, especially for comparing logging methods. Regarding soil compaction estimation, only traditional and well-known methods have been used in this thesis. To some extent, BD and PR are different soil parameters, but both are reliable methods for measuring the hardness and compaction of soil. These methodologies are time-consuming, especially BD. Finding a faster method to measure BD should be an important topic for future studies. In the second paper of this thesis, an interesting correlation between VT and PR was found. This result shows that it might also be possible to estimate PR, and possibly BD, with VT measurements, at least for some types of soils. Further studies are needed to investigate the validity of such a hypothesis. Studies have shown, however, that driving direction during skidding can affect changes in soil compaction. Moreover, the effects on soil (BD) during skidding uphill were similar to the effects of forwarding when the same volume of wood was extracted. However, soil displacement depended on the wood extraction method. Finally, this thesis underlines the importance of measuring soil damages (i.e., soil compaction and rutting) within (InR) and between the ruts (BtwR) after ground-based logging trafficking. This results in important information on soil impact, which can be a useful criterion for choosing a proper wood extraction technique.

Several aspects of the effects of forest machinery on soil conditions were analysed in this work; however, further studies are needed to investigate soil damage under different conditions and to decrease the time necessary to obtain high-quality rutting data. The effect of driving direction on soil caused by ground-based logging operations can be different on lower-degree slopes (i.e., forests in Northern European countries), especially when machines specifically built for forest operations are used (i.e., forwarders and skidders). Moreover, the soil damage that occurs during driving in a curve is larger than driving in a straight line. Specific studies should be implemented to further research this, and further studies should consider short-term effects on soil (i.e., immediately after forestry machine passages) as well as medium- and long-term effects (i.e., each year) until the soil recovers. In order to apply emerging methods on a larger scale, improvements are needed in existing technologies. For example, an automatic rut detection procedure would be welcome, as would a camera or tools mounted to the front of the forest machine that would provide the operator with real-time effects on the soil.