Soil compaction due to mechanized forest harvesting: quantification of ecosystem effects and exploration of recovery potential

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SOIL COMPACTION DUE TO MECHANIZED FOREST HARVESTING: QUANTIFICATION OF ECOSYSTEM EFFECTS AND EXPLORATION OF RECOVERY POTENTIAL

Thesis submitted in fulfillment of the requirements
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Bodemverdichting door gemechaniseerde houtoogst: kwantificeren van ecosysteemeffecten en exploratie van het herstelpotentieel

Illustrations on the cover:
Front: Severe rutting and soil compaction after machine traffic during a harvesting activity in Zoniënwoud (Brussels) [photograph Lotte Van Nevel, March 2007]
Back: Marking on a tree that needs to be thinned, indicating the beginning of a permanent skid trail (Putte) [photograph Robbie Goris, August 2004]

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Woord vooraf

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Contents

Summary

During the last decades, manual felling and logging of forest trees by animals or small tractors evolved towards mechanized harvesting, using heavy tractors or specialized forestry machines with increasing masses. This development may cause soil degradation in forest ecosystems as the resulting soil compaction modifies soil characteristics that are important for the sustained provision of ecosystem services. Consequently, soil conditions may become unfavourable to soil fauna, herb and tree layer and in the long-term it may lead to a loss of biodiversity, soil fertility and stand productivity.

The impacts of site and stand characteristics, machine weight and traffic intensity on the compaction degree were examined in a first field trial, performed in eight Flemish forest stands. If based on bulk density and penetration resistance, we generally found low compaction degrees, even on the vulnerable soil textures. Effects could be explained by high soil water contents in the clayey soils (leading to clear rut formation) and a high precompression stress (as indicated by the high initial bulk densities) on the sandy and loamy to silt loamy soils. Results showed that soil water content and initial compaction status (as an indicator for the precompression stress) should always be taken in consideration when evaluating the influence of texture on the compaction degree. Higher machine masses and traffic intensities increased the compaction degrees. Although compaction degrees remained low, increased carbon dioxide concentrations within tracks on the sandy soils showed that soil aeration was severely affected by machine traffic. These results indicated that quantification of the soil impact based on bulk density and penetration resistance may lead to an underestimation and should take more sensitive soil variables such as soil carbon dioxide concentration into account. The vulnerability to compaction is often regarded as negligible on sandy forest soils and was therefore examined in detail in a second field trial. Significant increases of bulk density and penetration resistance and a positive (logarithmic) relationship with traffic intensity were found. The application of a brash mat reduced the compaction degree. The results of both field trials were combined with international study results to draw general conclusions on the impact of mechanized harvesting. A meta-analysis was performed to examine the effects of soil texture, machine weight and traffic intensity. It showed clear compaction degrees for both clayey as sandy textures and confirmed the significant impact of the initial compaction status and machine mass. A lot of interesting studies could not be implemented due to lack of important information. Recommendations for future research were therefore formulated.

Abiotic changes may yield biotic effects and these were examined in a second meta-analysis, focussing on survival, height and diameter growth of seedlings of mainly light tolerant tree species. The influence of soil compaction on seedling growth and survival was predominantly insignificant, due to strong variation in the datasets. However, they indicated a different response in accordance to soil texture, with negligible to slightly positive impacts on sandy to loamy soils and more negative impacts on silty to clayey soils. Again a lot of the performed studies lacked important information.

As soil compaction induces biotic effects, fast recovery is desired. Compaction status of nine forest stands on three soil textures where the last harvesting activity took place seven to nine years ago was determined by measuring penetration resistance along transects. In all forest stands, traces of former machine traffic were found in the shape of locally increased or overall high penetration resistance. This means that complete recovery of compacted forest soils was certainly not achieved within seven to nine years after the last machine impact. As this is a common period between two harvesting activities, effects will accumulate and expand at subsequent harvests in case machine traffic is not restricted to permanent skid trails. A fourth field trial examined whether stimulating biological activity by means of a manipulation of litter quality, soil acidity and earthworm populations could accelerate recovery. Liming and the application of calcium-rich litter positively influenced the numbers of inoculated anecic earthworms that were retraced, with a positive feedback on soil acidity and litter decomposition. Within the short study period, small reductions of the compaction degree due to anecic worms could only be shown on the non-trafficked soil beside the wheel tracks. Unfavourable soil acidity and nutrient status probably hampered ecological restoration. We hypothesize that ecological restoration of compacted soils is possible though time-consuming, stipulating that soil conditions are favourable, particularly to anecic earthworms. An increase of their survival rate and activity is best achieved through an admixture containing species with high quality litter, which induce lower soil acidity and a better nutrient status.

In this thesis we gained insight into i) the abiotic and biotic effects of soil compaction as influenced by stand, site and harvesting characteristics, ii) the compaction status of Flemish forest soils, and iii) the potential of ecological restoration options for compacted forest soils.

Results showed that the risk for soil compaction should be taken into account for all texture classes when planning and preparing harvesting activities. We recommend performing harvesting activities on sandy soils at intermediate soil water contents, while on medium- to fine-textured soils very dry conditions are optimal for limitation of the soil impact. The machines used should always be tuned to the intensity and the demands of the harvesting activity and the field circumstances. We emphasize to concentrate the traffic on designated skid trails. In this way only a restricted portion of the area is damaged, enabling the soil between trails to recover from the compacted status applied during previous harvesting activities. A brash mat may be very effective to further reduce the degree of soil compaction on these trails. Admixtures with tree species that provide good quality litter, perhaps combined with liming may imply stimulation of biological activity and in the long-term a decrease of the compaction degree.

Samenvatting

Tijdens de laatste decennia hebben manuele vellingen en uitsleepmethoden met dieren of kleine tractoren plaats gemaakt voor gemechaniseerde houtoogst waarbij zware tractoren of gespecialiseerde bosbouwmachines met toenemend gewicht gebruikt worden. Deze evolutie kan bodemdegradatie veroorzaken in bosecosystemen aangezien de resulterende bodemverdichting bodemkarakteristieken wijzigt die van belang zijn voor een duurzame voorziening van ecosysteemdiensten. Hierdoor kunnen bodemcondities ongunstig worden voor bodemfauna, kruid- en boomlaag wat op lange termijn kan leiden tot een verlies van biodiversiteit, bodemvruchtbaarheid en standplaatsproductiviteit.

De invloeden van bodem- en bestandskarakteristieken, machinegewicht en berijdingsintensiteit op de verdichtingsgraad werden onderzocht in een eerste veldproef, uitgevoerd in acht Vlaamse bosbestanden. Op basis van bulkdensiteit en indringingsweerstand vonden we algemeen lage verdichtingsgraden, ook op de gevoelige bodemtexturen. Dit is het gevolg van hoge bodemvochtgehaltes op de *clayey* bodems (resulterend in duidelijke spoorvorming) en sterke precompressie (zoals aangegeven door de hoge initiële bulk densiteiten) op de bodems met *sandy* en *loamy* tot *silt loamy* texturen. De resultaten benadrukten dat bij het evalueren van de invloed van de bodemtextuur op de verdichtingsgraad het bodemvochtgehalte en de initiële verdichtingsgraad (als indicator voor de precompressie) steeds in rekening moeten gebracht worden. Een toename van het machinegewicht en de berijdingsintensiteit verhoogden de verdichtingsgraad. Hoewel de verdichting algemeen beperkt bleef, toonden verhoogde koolstofdioxide concentraties in de wielsporen op zandige bodems aan dat de aëratie van de bodem ernstig gewijzigd was als gevolg van machineverkeer. Dit geeft aan dat het bepalen van de bodemimpact op basis van bulkdensiteit en indringingsweerstand kan leiden tot een onderschatting en dat gevoeligere indicatoren, zoals de bodemconcentratie aan koolstofdioxide, in rekening moeten gebracht worden. De kwetsbaarheid voor verdichting wordt op zandige bodems vaak beschouwd als verwaarloosbaar en werd daarom meer gedetailleerd onderzocht in een tweede veldproef. Significante toenames van bulkdensiteit en indringingsweerstand en een positieve (logaritmische) relatie met berijdingsintensiteit werden vastgesteld. Het gebruik van een

takkenmat reduceerde de verdichtingsgraad. De resultaten van beide veldproeven werden gecombineerd met de resultaten van internationale studies zodoende algemene conclusies te kunnen trekken over de impact van gemechaniseerde houtoogst. Een meta-analyse werd uitgevoerd om de effecten van bodemtextuur, machinegewicht en berijdingsintensiteit te onderzoeken. Resultaten gaven duidelijke verdichtingsgraden aan voor zowel *clayey* als *sandy* texturen en bevestigden de significante invloed van de initiële verdichtingsgraad en het machinegewicht. Gezien heel wat interessante studies niet gebruikt konden worden als gevolg van een gebrek aan belangrijke informatie werden aanbevelingen geformuleerd voor toekomstig onderzoek.

De abiotische wijzigingen kunnen resulteren in biotische effecten, die onderzocht werden in een tweede meta-analyse, waarbij gefocust werd op overleving, hoogte- en diametergroei van zaailingen van voornamelijk lichttolerante boomsoorten. De invloed van bodemverdichting op overleving, hoogte- en diametergroei was overwegend niet-significant als gevolg van sterke variatie tussen de studieresultaten. Ze duidden echter wel op een verschillende respons van overleving naargelang de bodemtextuur, met verwaarloosbare tot licht positieve invloeden op textuurgroepen *sand* en *loam* en eerder negatieve effecten op textuurgroepen *silt* en *clay*. Opnieuw vertoonden heel wat studies een gebrek aan belangrijke informatie.

Aangezien bodemverdichting biotische effecten induceert, is snel herstel gewenst. In negen bosbestanden verspreid over drie texturen, waar de laatste houtoogst zeven tot negen jaar geleden plaats vond, werd de verdichtingsgraad bepaald door het opmeten van de indringingsweerstand langsheen transecten. In alle bestanden werden sporen van vroeger machineverkeer gevonden onder de vorm van lokaal of algemeen verhoogde indringingsweerstanden. Dit betekent dat volledig herstel van verdichte bodems zeker niet bereikt werd zeven tot negen jaar na de laatste berijding. Aangezien dit de normale periode is tussen twee houtoogsten zullen effecten accumuleren en uitbreiden indien het machineverkeer niet beperkt wordt tot vaste ruimingspistes. Een vierde veldproef onderzocht daarom of een stimulans van de biologische activiteit door wijziging van strooiselkwaliteit, bodemzuurtegraad en/of wormpopulaties kon leiden tot versneld herstel van verdichte bodems. Bekalken en de applicatie van calciumrijk strooisel hadden een positieve invloed op het aantal geïnoculeerde anecische wormen dat teruggevonden werd, met een positieve feedback op bodemzuurtegraad en strooiselafbraak. Binnen de korte studieperiode konden enkel lichte dalingen van de verdichtingsgraad door activiteit van anecische wormen worden vastgesteld op de niet-bereden oppervlakte naast de sporen. Ongunstige bodemcondities (zuurtegraad, nutriëntenstatus) hebben wellicht het ecologisch herstelproces vertraagd. We veronderstellen dus dat ecologisch herstel van verdichte bodems mogelijk maar langdurig is, en als voorwaarde stelt dat bodemcondities gunstig zijn voor bodemorganismen, voornamelijk anecische wormen. Een betere overleving en verhoogde activiteit van deze wormen kan verkregen worden door een groter aandeel boomsoorten met een goede strooiselkwaliteit te voorzien, zodat een lagere bodemzuurtegraad en een betere nutriëntenstatus bereikt wordt.

In dit doctoraat verkregen we meer inzicht in i) de biotische en abiotische effecten van bodemverdichting, onder invloed van bestands-, standplaats- en houtoogstkarakteristieken, ii) de verdichtingsgraad van Vlaamse bosbodems, en iii) de opties voor ecologisch herstel van verdichte bodems.

De resultaten tonen aan dat het risico op bodemverdichting in rekening moet gebracht worden voor alle textuurklassen wanneer houtoogsten gepland en voorbereid worden. We raden aan om houtoogsten op zandige bodems uit te voeren bij intermediaire bodemvochtgehaltes, terwijl op intermediaire tot fijne texturen heel droge bodemcondities optimaal zijn voor een beperking van de bodemschade. De machines moeten steeds aangepast zijn aan de intensiteit en de noden van de houtoogst en de terreinomstandigheden. We benadrukken het belang om het machineverkeer te concentreren op vaste ruimingspistes. Op deze manier wordt enkel een beperkt deel van het bestand beïnvloed, zodat de bodem tussen de pistes kan herstellen van de verdichting die veroorzaakt werd tijdens voorgaande houtoogsten. Een takkenmat kan erg efficiënt zijn om de verdichtingsgraad op deze pistes verder te reduceren. Een menging van boomsoorten die een goede strooiselkwaliteit bieden (eventueel gecombineerd met een bekalking) kan de biologische activiteit stimuleren en op lange termijn een daling van de verdichtingsgraad induceren.

List of abbreviations and symbols

Abbreviations

BD	bulk density
CO_2	carbon dioxide
d.f.	degrees of freedom
GLM	General linear model(ling)
HSD	honestly significant difference
O_2	oxygen
PR	penetration resistance
SD	standard deviation
SE	standard error

Symbols

α	significance level
n	number of samples or replications
p	significance of statistical test (p-value)
pH(KCl)	acidity, determined after suspension in a potassium chloride (KCl) solution (the lower the pH values, the more acid is the soil)
τ	weighted Pearson product-moment correlation coefficient

Definition of some terms used in the thesis

(Dry) bulk density	ratio of the dry mass of the soil to its volume
Penetration resistance	measure for the resistance that a soil exerts against the growth of roots (measure for soil strength)
Precompression stress	internal strength of soils, which resulted from pedogenetic processes, anthropogenic effects, or hydraulic site specific conditions. If the soil body is stressed less than the precompression stress, soils react elastic and no additional settlement occurs. Stresses

	exceeding the precompression stress lead to plastic soil behaviour and the soil body becomes deformed and permanently compacted (Horn et al. 2007).
Soil contact pressure	the amount of kg per square cm^2 contact area that is exerted on the soil, or thus the ratio of the machine mass to the contact area of the machine with the soil
Soil strength (or bearing capacity)	the capacity of the soil to withstand forces without experiencing failure
Traffic intensity	the number of machine passes or skidding cycles

1 *Introduction*

The intense deployment of heavy machinery during forest harvesting and their potentially adverse effects on the soil due to soil compaction have received increasingly more attention the last decades. It may lead to overall reduced ecosystem diversity, fertility and functioning in the short or long-term and hamper the sustained provision of ecosystem services. In the following sections, we briefly describe the change of harvesting techniques towards mechanized harvesting (§1.1), the abiotic and biotic effects of soil compaction on the ecosystem (§1.2) and the recovery of compacted forest soils (§1.3).

1.1 Changing of harvesting techniques

For centuries trees have been cut by means of axes and handsaws whereupon small tree logs were removed from the stand by hand or using a barrow. Horses were also frequently brought into action for the hauling of bigger logs or trees because of their high tractive power, speed, intelligence, cheapness and their good performance on rough and stony forest soils. However, their power and thus the dimensions of the logs they can pull are not unlimited. Moreover, the duration of their efforts is restricted by the climate and the terrain slope (Tack et al. 1993). Mechanized forest harvesting started at the beginning of the 20th century, from the moment tractors were brought into action in forest stands for the removal of logs or complete trees. First, agricultural tractors were used and adapted to fit the needs for tree logging (Fig. 1.1). Subsequently, around 1950, specialized forestry machines, such as harvesters, forwarders, skidders, feller-bunchers and knuckleboom loaders, were used for felling and logging (Van Acker 2004). Nowadays, harvests in softwood stands pass off highly mechanized, often deploying harvesters and forwarders.

The former cuts, delimbs and barks trees, cuts the stems at length and piles the logs in one smooth motion, all by means of a processor unit that is attached to a crane arm with a reach of approximately 10 m. Tree logs are removed by a forwarder that loads the logs in its loading space. Cable or grapple skidders are often used for whole-tree logging after chainsaw felling in hardwood stands and drag the trees or logs towards the forest edge. All machine types can be equipped with wheels or tracks but wheeled machines are more often used as they are faster and more movable and they do not induce high soil disturbance to soil or forest roads when turning. Tracked vehicles (and horses) are predominantly applied on sensitive soils as they have a bigger bearing surface and thus lower soil contact pressure, inducing an overall lower soil compaction degree. They can also be used on slopes due to their higher stability. For very steep forests, where the application of the regular forestry machines is no longer possible, special logging techniques have been developed, such as cable or helicopter yarding, although very expensive and only applicable in exceptional situations (e.g., Goris et al. 2005).

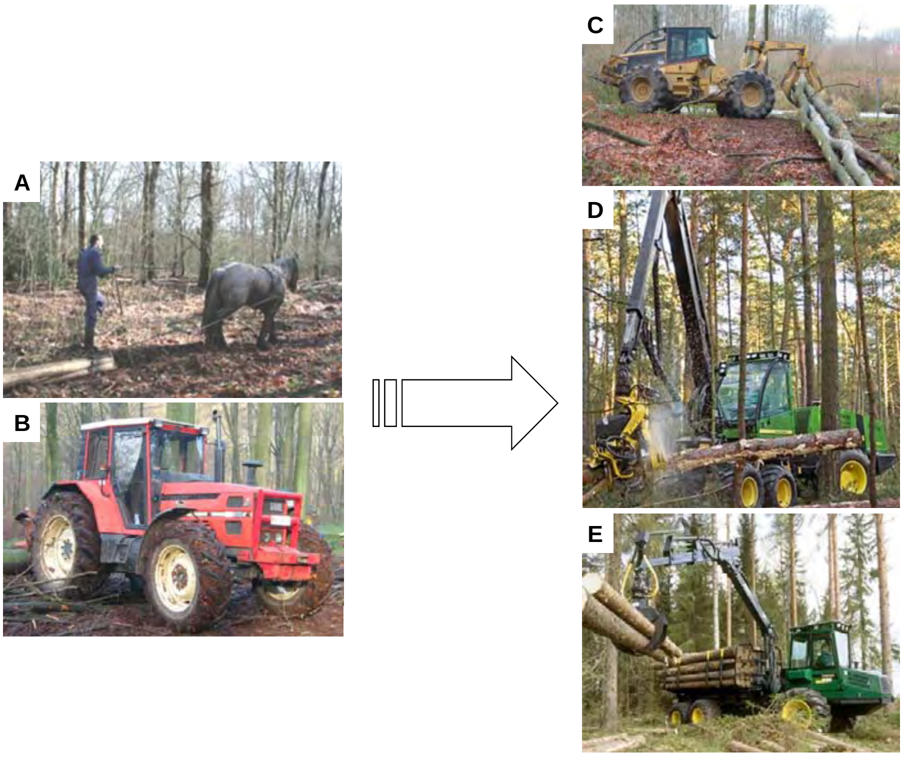


Fig. 1.1 Changing of harvesting techniques from horse (A) and tractor logging (B) to specialized forestry machines such as skidders (C), harvesters (D) and forwarders (E) [photographs: Robbie Goris, www.deere.com].

The trend towards mechanized harvesting and the recently developed techniques (such as remote controlled synthetic cables) brought along several benefits, such as increased productivity, higher safety and a decrease of the physical stress for the forest workers. However, the masses of these machines easily mount up to 12-16 tonnes in unloaded state and to more than 20 tonnes in loaded state (e.g., www.deere.com 2011), possibly inducing adverse soil impacts. As a good soil structure is of great importance to soil fauna, tree, herb and moss layer, serious concern has risen over the short and long-term ecosystem effects of soil compaction induced by mechanized harvesting, within the context of sustainable forest management.

1.2 Ecosystem effects of soil compaction

1.2.1 Definition of soil compaction

Soil compaction, often accompanied by rutting, is a typical process that may result from static and dynamic forces applied by machine traffic, especially with inappropriate use of heavy machinery. Soil compaction refers to the process in which soil pores are compressed or destroyed and surface aggregates are broken down (Fisher & Binkley 2000). Macropores (diameter $d > 50\ \mu m$) are transformed into meso- ($0.2\ \mu m < d < 50\ \mu m$) and micropores ($d < 0.2\ \mu m$). It may imply a reduction of the total porosity by 20% and a 50-60% decrease in the amount of macropores in favour of smaller pores (Herbauts et al. 1996; Teepe et al. 2004).

1.2.2 Abiotic effects

Compression of soil pores results in an increase of bulk density (BD), defined as the proportion of the dry mass of the soil to its volume (Cullen et al. 1991). Alban et al. (1994) noticed a BD increase of 22%, which amounted up to 40% in the study of Miller et al. (1996). As soil deforms when being compacted, the pore continuity is reduced, even when volume reduction is insignificant. This was emphasized by Benthaus & Matthies (1993), Herbauts et al. (1996) and Berli et al. (2003). Together with the decreasing total soil porosity it leads to changes in the soil water retention capacity (Reicosky et al. 1981; Ballard 2000). It may lower the saturated hydraulic conductivity by 80% or more (Benthaus & Matthies 1993) and infiltration rates from 11.4 cm h^{-1} for undisturbed soil to 1.1 cm h^{-1} within wheel tracks (Dickerson 1976). Cullen et al. (1991) and Ballard (2000) made similar findings. In general, gas exchange is also hampered (Gaërtig et al. 2002). Several studies indicated an increase of soil carbon dioxide (CO_2) concentration and decrease of oxygen (O_2) concentration due to an unfavourable influence on soil aeration (e.g., Schäffer 2005; Gebhardt et al. 2009; Startsev & McNabb 2009). The disruption of the air and water balance in the soil may lead to an alteration of chemical processes (Woodward 1996; Arocena 2000; Ballard 2000), such as an increased N_2O emission (Teepe et al. 2004) and reduced mineralization and availability of nitrogen (Van der Linden et al. 1989). Herbauts et al. (1996) found a decrease of redox potential due to temporary waterlogging. Tan & Chang (2007) showed that soil compaction had a negative impact on net nitrification rates, although Blumfield et al. (2005) did not notice a significant effect on nitrogen mineralisation or nitrification. Penetration resistance (PR), which acts as a measure for soil strength (defined as the capacity of the soil to withstand forces without experiencing failure) and indicates the resistance that a soil exerts against the growth of roots, increases as pores become smaller and porosity decreases (Shetron et al. 1988; Alban et al. 1994). Aust et al. (1998) and Nugent et al. (2003) found a 30-50% increase of PR, due to machine traffic.

1.2.3 Biotic effects

A good soil structure is of great importance to soil fauna (Jordan et al. 1999), herb and moss layer (Buckley et al. 2003) and tree roots (Greacen & Sands 1980). Soil compaction has an important influence on soil structural characteristics, soil aeration and the soil water balance, and may considerably affect root development and soil organisms, possibly inducing a reduction of ecosystem diversity and functioning. Since soil fauna have an important role in ecosystem processes as decomposition, release of nutrients and the creation of a good soil structure (Gobat et al. 1998), soil compaction may directly and indirectly change the fertility and the productivity of the site.

1.2.3.1 Growth and survival in herb and tree layer

Root tips have to overcome soil strength to be able to elongate and penetrate through the soil. Moreover, they need pores and do not penetrate compact soil volumes since their O_2 demand limits their ability to enter these soil aggregates. Root growth may thus be hampered in compacted soil (Greacen & Sands 1980; Heilman 1981) due to the lower pore space, reduced oxygen supply and the high soil strength, possibly inducing a lower uptake of nutrients and water (Heilman 1981; Kozlowski 1999; Jordan et al. 2003). Hampered gas exchange possibly affects growth and activity of roots (Schumacher & Smucker 1981; Bathke et al. 1992). Arshad et al. (1996) stated that BD is growth-limiting when the value exceeds 1470 kg m^{-3} on clay, 1750 kg m^{-3} on silt and 1800 kg m^{-3} on loam and sand. The USDA Forest Service determined that a BD increase of more than 15% is in general detrimental for the soil ecosystem (Powers et al. 1998). Whalley et al. (1995) found that root growth slowed down at a PR of 2 MPa and stopped when PR values exceeded 3 MPa. Seedling root growth is also reduced when O_2 concentration drops beneath the 6-10% range (Grant 1993). Macroporosity should be at least 10% in order to keep good air diffusion, microbial activity and root development (Koorevaar et al. 1983; De Bruycker 1984). It should be mentioned that the impact of soil compaction on growth differs among species (cf Godefroid & Koedam 2004) and that thresholds for BD, PR and macroporosity provide no direct link to the ecological processes that accompany soil compaction. For example, even though the obtained BD may be much lower than stated above, soil aeration may already be influenced and induce negative effects on root growth due to decreased O_2 concentration in the soil.

When critical limits are crossed, soil compaction may lead to higher seedling mortality (Cheatle 1991; Simcock et al. 2006) and reduced tree growth (Maynard & Senyk 2004; Bulmer & Simpson 2005; Gebauer & Martinková 2005). Cheatle (1991) found that tree survival and basal areas of *Terminalia brasii* were much lower on compacted areas. Detrimental effects on growth of *Pinus contorta* on a sandy clay loam soil were observed by Bulmer & Simpson (2005). Rhoades et al. (2003) showed that the mortality of *Castanea dentata* seedlings due to the incidence of *Phytophthora* root rot was largest in wet, compacted soils. However, the impacts of compaction on growth and survival are not unequivocal and depend on soil type, water regime and species (Jones 1983; Gomez et al. 2002; Heninger et al. 2002; Dexter 2004). Compaction on sandy soils decreases sizes and continuity of pores that are normally too wide to hold water against gravitational forces. Therefore, water availability increases and this may positively influence root and seedling growth (Agrawal 1991; Brais 2001; Gomez et al. 2002). Moreover, several studies indicated that roots may still grow in compacted soils in case sufficient zones of weakness (e.g., soil cracks, channels of dead roots…) are available (Greacen & Sands 1980; Jones 1983). Sanchez et al. (2006) found that severe soil compaction had an insignificant impact on mean stand volume of *Pinus taeda*. Nabe-Nielsen et al. (2007) showed that the regeneration of *Ficus boliviana* and *Terminalia oblonga* even increased on compacted soils and Alameda & Villar (2009) found a higher total biomass at higher compaction degrees possibly due to a greater root-soil contact. According to Fleming et al. (2006), conifer survival and growth benefited from soil compaction, regardless of climate and species.

The combination of soil churning, compaction and altered light availability that accompanies traffic during harvests leads to higher habitat variation over the whole forest stand and brings about a change of the diversity and composition of the herb layer (Small & McCarthy 2002; Decocq et al. 2004), due to species-dependent sensitivity to disturbances as soil compaction (Zwaenepoel 1989). On the skid trails particularly non-forest species are favoured at the expense of interior forest species (Roberts & Zhu 2002; Buckley et al. 2003; Ebrecht & Schmidt 2003, 2005; Zenner & Berger 2008), partially because of their higher tolerance to soil compaction (Godefroid & Koedam 2004).

1.2.3.2 Soil fauna

As a result of soil compaction, soil fauna may be damaged physically, their movements may be impeded and/or their food and O_2 supply may be changed (Smeltzer et al. 1982; Radford et al. 2001; Battigelli et al. 2004). Boström (1986) found lower earthworm biomass and lower ratio of juveniles to adults of *Allolobophora caliginosa* on compacted soil. The results of Jordan et al. (1999) suggest that the degree of compaction was restrictive to *Diplocardia ornata* but it affected *D. smithii* favourably. Pupin et al. (2009) found shifts from nitrifying bacteria to fungal populations and denitrifying bacteria. The study of Schnurr-Pütz et al. (2006) revealed that soil compaction favoured the occurrence of prokaryotes that are capable of profiting from anoxic conditions. However, Busse et al. (2006) did not state an effect on microbial community size or activity and Kara & Bolat (2007) also found that the examined microfungal soil communities, which are significant for nutrient bioavailability together with the microbial community, tolerated compaction.

1.2.4 Factors influencing the compaction degree

1.2.4.1 Characteristics of the forest site

It is generally assumed that medium- to fine-textured soils (clay, loam, silt and intermediate textures) are more vulnerable to soil compaction from machine traffic than coarse-textured soils (sand, sandy loam, loamy sand) (Larson et al. 1980; Hillel 1998; Fisher & Binkley 2000; Smith 2003). Gomez et al. (2002) stated that the highest BD and the lowest porosities after machine traffic were located on clay soils and Smith (2003) emphasized the important influence of the clay content on the PR increase after machine traffic. However, Brais & Camiré (1998) concluded that mechanized harvesting also increased soil BD in forest stands on sandy soils. Soil porosity, and the average pore radius in particular, has a great influence in this process as smaller pores exert a greater resistance to deformation in comparison with large pores (Greacen & Sands 1980).

When assessing the influence of soil texture on the degree of compaction, one should certainly take the soil moisture content into account, as it determines the proportion between soil compaction and plastic deformation (in the form of rutting) after the application of machine forces (Abeels 1989). Hillel (1998) showed a graph, relating soil water content to the maximum BD obtainable when applying a certain force with the Proctor test (Proctor 1933) (Fig. 1.2), of which the shape applies to both **medium- and fine-textured** soils (e.g., clay, clay loam, silt loam, loam). Howard et al. (1981), Smith et al. (1997) and Williamson & Neilsen (2000) came to the same conclusion. The pore volume of a medium- to fine-textured soil consists mainly of meso- and micropores that easily hold water against gravitational forces. The smaller the pore diameter, the more the adhesion of water molecules to soil colloids exceeds the force of gravitational capillarity. So in a saturated state, all pores are filled with water that cannot be compressed (Froehlich & McNabb 1984) and thus the soil is rather prevented from compaction in this case (Reicosky et al. 1981). However, cohesion between particles is minimal (Al-Shayea 2001) and the soil has only a very small ability to withstand applied machine forces. Therefore plastic deformation is the dominant process (Howard et al. 1981; Williamson & Neilsen 2000), resulting in profile disturbance and rut formation (Greacen & Sands 1980; Hillel 1998). Ruts may be deep and show bulges at the edges that more or less compensate for the loss of soil within the ruts (rut type 1; Fig. 1.3). Although almost no compaction takes place in these conditions, machines may still impose a serious threat for the soil ecosystem as soil pores are closed off and pore continuity is destroyed, leading to a hampered gas exchange and water infiltration. A dry medium- to fine-textured soil typically resists compaction due to its stiff matrix and high degree of particle-to-particle bonding, interlocking and frictional resistance to deformation (Hillel 1998). This limits the compaction degree and more or less prevents plastic deformation (McNabb & Boersma 1993). BD increases to a small extent and small ruts are formed, without bulges at the edges (rut type 3; Fig. 1.3). At intermediate soil water contents (*optimum soil water content*), the cohesion between the soil particles is smaller, making the soil more sensitive and a combination of compaction and plastic deformation takes place (Berli et al. 2003). BD increase may be large and intermediate ruts are formed with small bulges at the edge that do not compensate for soil loss in the ruts (Howard et al.

1981; Williamson & Neilsen 2000) (rut type 2; Fig. 1.3). The function that relates attainable bulk density to soil moisture (Fig. 1.2) does not constitute a single characteristic curve for a given soil but a family of curves, depending amongst others on the compactive effort (Hillel 1998) or the initial compaction status of the soil. It should also be remarked that especially fine-textured soils can exhibit a high biological activity that leads to a second pore system (earthworm tunnels, root canals) with wide soil pores that are easy to compact. This makes the soils more prone to compaction than already mentioned above.

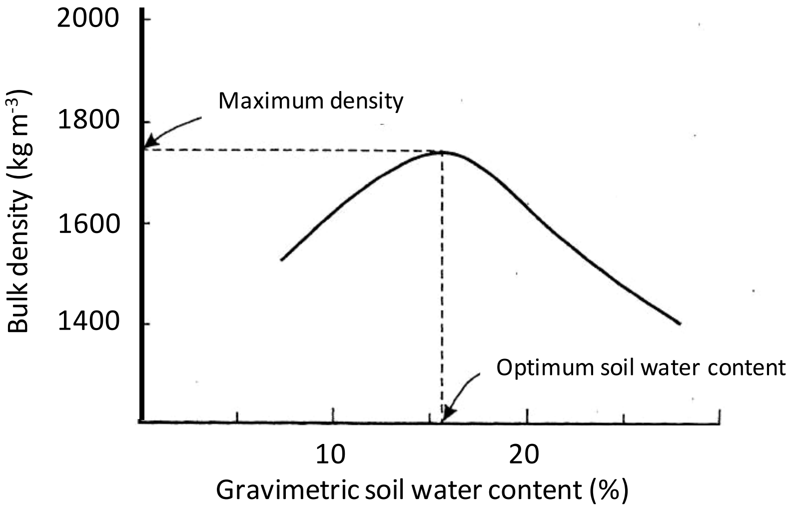


Fig. 1.2 Typical relationship between gravimetric soil water content and maximum bulk density obtainable after application of a certain compactive force for a medium-textured soil. The shape applies to both fine- to medium-textured soils (Hillel 1998).

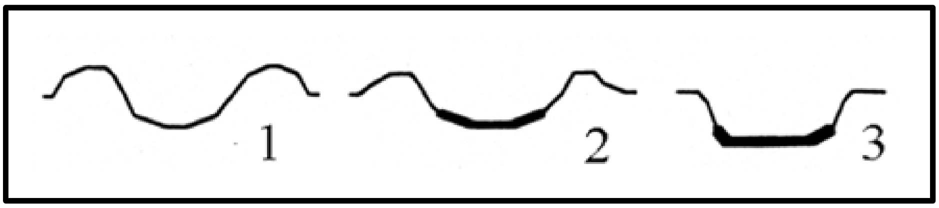


Fig. 1.3 Rut types (Abeels 1989): rut type 1 is caused by plastic deformation, rut type 2 by a combination of plastic deformation and soil compaction and rut type 3 by soil compaction only.

Findings of Hillel (1998) do not apply to **coarse-textured soils** as these soil textures behave differently in relation to soil water content. These soils have a lot of large pores which are easily drained of gravitational water (Fisher & Binkley 2000) and thus are prone to compaction. According to Langohr & Ampe (2004) cohesion is maximal at intermediate soil water contents (*critical soil water content*), leading to minimal compaction degrees and restricted rut formation. At very dry or very wet conditions cohesion between sandy soil particles is much smaller and a combination of compaction and rutting may occur. Results of

Smith et al. (1997) confirmed the presence of a local minimum in the compactibility of a loamy sand soil. Panayiotopolous & Mullins (1985) suggested that the more closed packing under a given load at air-dry and nearly saturated sands compared to intermediate water contents was related to bridges being formed between sand particles. These bridges act like elastic bonds when the soil is moist but are lost when the soil is saturated or air-dry and hence the soil at these two extremes collapses. In contrast with medium- to fine-textured soils compaction of sandy soils is still possible at high water contents. Namely, sandy textures contain a lot of macropores that cannot hold water against gravitational forces, even at very high soil water contents, and these are thus filled with air that can be compacted (Fisher & Binkley 2000).

The precompression stress of the soil is another very important determinant for the vulnerability of a certain soil. The precompression stress defines the internal soil strength, which resulted from pedogenetic processes, anthropogenic effects (such as former machine traffic) or hydraulic site specific conditions. When a soil is compacted, soil particles are piled closer together and the mean pore size decreases. As smaller pores are less prone to compaction it leads to higher soil strength and thus an increased precompression stress, which (partially) protects the soil from further compaction (Shetron et al. 1988; Williamson & Neilsen 2000). If the soil body is stressed less than the precompression stress at the next machine pass, soils react elastic and no additional settlement occurs. Stresses exceeding the precompression stress lead to plastic soil behaviour and the soil body deforms and compacts further (Horn et al. 2007). This explains why loose soils, which are characterized by a high amount of large pores and thus low soil strength and precompression stress, are very vulnerable to soil compaction. However, machine traffic on a vulnerable soil type may result in negligible compaction degrees in case this soil is initially characterized by a high precompression stress. It must be remarked that other soil variables (such as soil aeration) may still be influenced by machine traffic in this situation.

Soil organic matter content also influences the sensitivity of the soil to compaction. Several studies indicate that the addition of organic matter to soil improved structure and reduced compaction (Sands et al. 1979; Greacen & Sands 1980; Howard et al. 1981). Moreover, it is suggested that soils are most susceptible to compaction in a pH-range of 4.5-5.5. Above and below this threshold soil structure is stabilized by calcium, respectively aluminium (von Wilpert K, *personal communication*).

1.2.4.2 Characteristics of the harvesting activity

As mentioned above, there is an ongoing trend to use large sized logging machines with high loads. Machine impact can be quantified using the soil contact pressure, defined as the amount of kg per cm^2 contact area that is exerted on the soil by equipment, or thus the ratio of the machine mass to the contact area of the machine with the soil (Febo et al. 2000). It indicates the vertical or normal pressure and consequently the potential compaction. With increasing soil contact pressure, the compaction process intensifies (McDonald et al. 1996). It is determined by the axle weight and the size of the footprint (the area of the tyres or tracks in contact with the soil). The soil contact pressure of a light machine standing on very small tyres (small footprint) may be as high as a heavy machine, standing on very wide tyres (big footprint). It is not clear, however, whether the relationship between soil contact pressure and degree of soil damage is linear or rather logarithmic. In the latter case the damage degree will stabilize from a specific soil contact pressure onwards. It must be remarked that the real exerted pressure (dynamic load) often differs from the pressure that is calculated using the theoretical contact area (static load), such as when the machine drives over a stump (Chancellor 1994) or during felling and processing (Wehner 2003). This can be attributed to the tree mass during processing, machine vibrations (Kairiukstis & Sakunas 1989; Athanassiadis 1997) and shear stress (Kozlowski, 2000). The impact may be reduced as some machine characteristics change the footprint. At a constant machine mass the compaction degree is negatively correlated with the number of tyres (Alakukku et al. 2003) and tyre dimensions (Benthaus & Matthies 1993), and positively correlated with tyre pressure (Abu-Hamdeh et al. 2000). At constant tyre characteristics, damage increases with increasing machine mass (McDonald et al. 1996). Concerning the benefits of tracks over normal tyres, no general conclusions can be drawn (Alakukku et al. 2003; Sheridan 2003). In case of tracks, the contact area with the soil is in theory larger which could lead to less compaction in comparison with normal tyres (Murosky & Hassan 1991), provided that the whole track makes contact with the forest floor.

The first pass of a machine exerts a pressure on the soil surface, affecting soil structure and porosity in case the applied stress encompasses the precompression stress of the soils (Horn et al. 2007). As pores become smaller, they exert a higher resistance to compaction (Shetron et al. 1988; Williamson & Neilsen 2000), increasing soil strength and thus precompression stress. The following passes of this machine will have a diminishing influence on the soil structure until the applied stress no longer exceeds the constantly increasing precompression stress (Horn et al 2007). Brais & Camiré (1998) and Seixas et al. (2003) confirmed that the relationship between traffic intensity (number of machine passes or skidding cycles) and the response of BD is logarithmic, with a high extra increase per pass at low traffic intensities, approaching zero when the number of passes increases. The traffic intensity at which the extra response starts to decrease depends amongst others on soil texture. The cycle of half impact, defined as the number of passes at which half of the potential impact has been reached, is lower for fine-textured soils in comparison with coarse-textured soils (Brais & Camiré 1998).

Results on the impact of site and harvesting characteristics on compaction degrees were not always unequivocal. Soil water content and precompression stress should always be taken into account while evaluating the impact of soil texture on the compaction degree. Research is needed to examine if the assumed higher vulnerability to soil compaction of medium- to fine-textured soils compared to rough-textured soils is independent of the prevailing soil water content and precompression stress. The strong variation between the results on the biotic impact of soil compaction also shows that further research is necessary to be able to draw more general conclusions. Moreover, studies seldom had an integrated approach, examining several characteristics simultaneously. Further research should therefore be extensive and integrated.

1.3 Recovery of compacted forest soils

1.3.1 Recovery rate

Harvesting activities are normally performed at regular time intervals. In Flanders a common period between two harvesting activities is about eight years. In case soil compaction, induced by a forest operation, persists beyond this period, effects may accumulate at trails that experience traffic at subsequent harvesting activities. Expansion of the compacted area may also occur if machines do not follow the same tracks as in the previous forest operation.

Rab (2004) found no significant recovery of macroporosity and BD on a clay to silty loam soil over a period of ten years. According to Tiarks et al. (1997) and Croke et al. (2001), complete recovery is reached after a period of at least 20-30 years, provided that meanwhile no disturbance takes place. Jakobsen (1983) and Anderson et al. (1992) found that BD on the skid trails still differed significantly from the undisturbed soil 25-32 years after logging. Hakansson & Reeder (1994) concluded that compaction at depths of more than 40 cm is very persistent and virtually permanent even in clay soils in regions with annual freezing. Greacen & Sands (1980) also stated that compaction of deeper layers may persist for 50-100 years.

As soil compaction may negatively influence soil biota, herbs and trees, fast recovery is desired. However, only in exceptional cases, heavily compacted forest soils can be mechanically loosened, for example by using a winged subsoiler (McNabb 1994) or a ripper (Sinnett et al. 2008). These methods may induce severe direct damage to tree roots and soil fauna and may also bring about a thorough churning of the upper soil layers, a disturbance of the seed bank and a destruction of the present herb layer, possibly leading to shifts in the composition of the herb layer. They should thus only be applied in case the forest soil is heavily damaged, natural recovery processes work insufficient and fast recovery by mechanical loosening is essential to preserve diversity and functioning of the forest ecosystem. On all other forest soils, recovery depends on natural processes.

1.3.2 Natural processes controlling recovery rate

In the absence of additional machine traffic, soil compaction may disappear under the influence of natural processes. The recovery process starts at the soil surface and then spreads gradually deeper into the soil (von Wilpert & Schäffer 2006). In soils with an adequate water holding capacity, the freezing and melting of soil water helps to increase pore sizes and brings the total pore volume back to its undisturbed status (Alban et al. 1994; Startsev & McNabb 2000). On soils with high clay content, the swelling and shrinking of clay particles under the influence of soil water takes an important part in the recovery process (Fisher & Binkley 2000; Cornelis et al. 2006). Biological activity may add greatly to the recovery process. The penetration of roots increases total pore volume and leads to a higher pore continuity (Brais & Camiré 1998). Lister et al. (2004) found a better soil quality, i.e. better aeration, lower BD, and higher aggregate stability, with increasing levels of vegetation biomass. Soil fauna, especially anecic earthworms, are important ecosystem engineers that contribute to the formation and stability of soil aggregates (Jastrow & Miller 1991). Earthworms may induce a better soil structure by their burrowing activities, fragmentation and burial of litter and their contribution in soil aggregation (Jones et al. 1994; Herbauts et al. 1996; Jordan et al. 1999, Ponder et al. 2000; Jones et al. 2010). Capowiez et al. (2009) provided experimental evidence that earthworm-mediated regeneration of compacted zones is possible. A stimulation of biological activity by improvement of the soil conditions, for example by manipulating litter quality, soil acidity and earthworm populations, could result in an overall acceleration of the recovery of compacted forest soils.

Alluvial systems, characterized by a relatively low acidity and a large biological activity, should recover relatively fast from soil compaction. However, a lot of forests are characterized by soil conditions that are unfavourable to soil organisms and often even prevent the survival of anecic earthworms (high acidity, poor litter quality). Moreover, sandy soils have low nutrient, clay and water contents, which further reduce the diversity of soil fauna and the herbaceous layer (Hansen & Rotella 1999). Recovery of such forest soils is thus expected to pass off very slowly (Greacen & Sands 1980; Fisher & Binkley 2000). In contrast, Page-Dumroese et al. (2006) found that five years after forest harvesting, recovery of coarse-textured soils (in terms of BD) was higher compared to fine-textured soils. Froehlich & McNabb (1984) and Croke et al. (2001) found no significant impact of soil type on the recovery rate.

The available research results on recovery rate of compacted forest soil show strong variation, perhaps due to differences in stand and site characteristics. It is interesting to examine whether soil compaction may completely recover in the period between two harvesting activities as effects will otherwise accumulate. Moreover, by our knowledge, no study has yet been performed that unravelled the impacts of soil acidity, litter quality and earthworm populations on the elimination of soil compaction. The potential of ecological restoration of compacted forest soils should thus be examined in detail.

1.4 Objectives and thesis outline

During the last decades, manual felling and logging by animals or small tractors have given way to heavy tractors or specialized felling (harvester) and logging (skidder, forwarder) machines with increasing masses. As mentioned previously, this evolution may cause soil degradation in forest ecosystems as the passes of these machines modify soil characteristics that are of critical importance for the sustained provision of ecosystem services. Due to soil compaction, soil conditions may thus become unfavourable to soil fauna, herb and tree layer and in the long-term it may lead to a loss of biodiversity, soil fertility and stand productivity. Despite possible careful planning of field operations, concern remains over the potential adverse impacts of mechanized forest harvesting on the forest ecosystem.

The main objective of this thesis is to quantify the ecological consequences of soil compaction, induced by machine traffic, on the forest ecosystem. The focus lies on common Flemish forest types that experience frequent harvesting activities, such as softwood stands on sandy soils and beech forests on loamy soils. In accordance to the worldwide trend, during the last decades the mass of the machines used in Flanders also gradually increased, leading to concerns about the ecological impact. Moreover, in contrast to many other countries the system of permanent skid trails is not yet well established in Flanders and other rigorous instructions that aim to reduce soil compaction mostly lack, leading to a large amount of potentially compacted forest areas. Harvests in vulnerable forest types, for example forest stands on marshland, are delicate, stipulating exceptional harvesting techniques, and were therefore not selected. As the use of tracked machines is predominantly restricted to these vulnerable situations, the research was focussed on the impact of widespread wheeled machinery.

Through the thesis, the impact of texture, overall known to influence compaction, was examined in detail together with the effects of machine weight and traffic intensity which are easy to control for by the forest management. Based on the previously mentioned research gaps, the specific objectives of this thesis were:

1) To quantify the compaction degree (abiotic impact) after mechanized forest harvesting in function of stand and site characteristics, machine weight and traffic intensity;

2) To examine to what extent compaction influences tree seedlings (biotic impact);
3) To gain more insight into the compaction status of Flemish forest soils and the potential of ecological restoration options for compacted forest soils.

The first part of the thesis deals with the quantification of the compaction degree or the abiotic impact after mechanized harvesting (Fig. 1.4). **Chapter 2** describes the results of a field trial, performed in eight forest stands. This trial was intended to examine the impacts of stand and site characteristics (especially texture), machine weight and traffic intensity on the compaction degree after controlled machine traffic. **Chapter 3** investigates the impact on sandy forest soils in detail, based on the results of a field trial. The vulnerability of this soil texture is generally regarded as negligible, although some studies provided evidence to the contrary. The beneficial use of a brash mat in order to lower the soil impact was also examined in this study. The obtained abiotic impacts of Chapters 2 and 3 were combined with the results of international studies in a meta-analysis (**Chapter 4**) in order to draw general conclusions on the abiotic impact of mechanized forest harvesting. We again focussed on the influences of texture, machine weight and traffic intensity.

In a second part of the thesis a meta-analysis was performed to discuss the biotic consequences of soil compaction on forest soils, as compaction may impose a threat to the biodiversity and productivity of the forest stand. More specific the impacts on survival, diameter and height growth of tree seedlings were examined (**Chapter 5**).

A third part considered the recovery of compacted forest soils. The field trial in **Chapter 6** intended to retrace old skid trails by measuring penetration resistance along transects. **Chapter 7** discusses the results of a second field trail in which the impact of litter quality, soil acidity and earthworm population on recovery of compacted soils was quantified, in the view of ecological restoration of compacted forest soils.

The results of all field trials and meta-analyses are summarized and discussed in **Chapter 8**, leading to general recommendations for forest management.

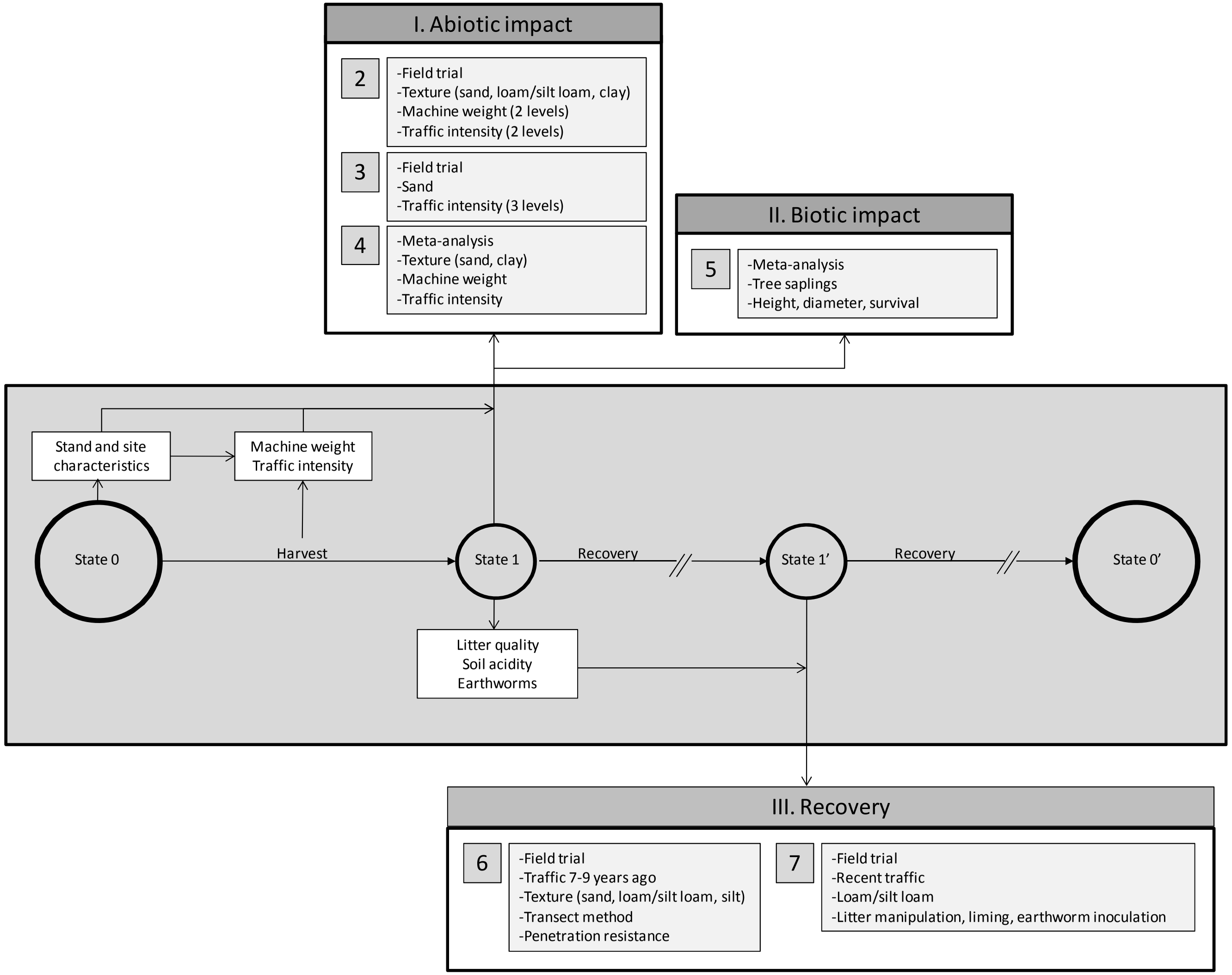


Fig. 1.4 Outline of the thesis. The three parts of the thesis are indicated with Roman numerals (I-III), the Arabic numerals represent the chapters (2-7). The grey zone represents the state of a forest ecosystem (with specific stand and site characteristics). A harvesting activity (characterized by machine weight and traffic intensity) induces abiotic and biotic impacts, resulting in a shift from state 0 to state 1. Starting from this state 1 (characterized by a certain litter quality, soil acidity and earthworm population), gradual recovery takes place, resulting in an intermediate state 1'. Provided that the forest ecosystem is not disturbed again, a new steady state 0' is eventually achieved.

Painted sticks indicated the centres of the experimental skid trails at the field trial in Meerdaal forest (Leuven) (Chapter 2), in order that the machines would follow the same tracks at subsequent passes. The photograph shows the skid trail where a John Deere grapple skidder JD 640 made five passes back and forth in February [photograph: Lotte Van Nevel, February 2007].

2 *The effects of soil characteristics, machine mass and traffic intensity on forest soil compaction: a field trial*

After: Ampoorter E, Van Nevel L, De Vos B, Hermy M, Verheyen K (2010) Assessing the effects of initial soil characteristics, machine mass and traffic intensity on forest soil compaction. Forest Ecology & Management 260, 1664-1676

2.1 Abstract

An extensive field trial was set up in eight forest stands to examine the influence of soil texture (two stands on sandy soils, four on loam to silt loam soils, two on clayey soils), machine mass (light, heavy) and traffic intensity (one and five skidding cycles) (i.e. pass back and forth on the skid trail) on soil compaction after mechanized harvesting. Dry bulk density, penetration resistance, micro-topography and soil carbon dioxide concentration were applied as response variables for soil compaction. Significant effects were nearly absent for bulk density (<7% increase) and occurred occasionally for penetration resistance (60-70% increase, up to 150% on clay soils). Especially for loam to silt loam and clay, this was in contrast with the expectation. The negligible compaction degrees for loam to silt loam were probably due to high initial compaction levels (leading to high precompression stress) that prevented further compaction, as was found by General Linear Modelling for both bulk density as penetration resistance. For clayey soils the small compaction degrees can be explained by the high water contents that resulted in plastic deformation instead of strong compaction degrees, as was confirmed by the micro-topographical measurements. General Linear Modelling also revealed a significant impact of machine mass (bulk density) and soil water content (bulk density, penetration resistance) on the compaction degree. Soil texture, traffic intensity and position in relation to the wheel tracks generally turned out to have an insignificant influence. With regard to clear interactions the influence of traffic intensity depended on the position in relation to the wheel tracks and the machine that was used (penetration resistance). Although soil compaction degrees were small to negligible, machine passes apparently had a strong impact on soil carbon dioxide concentration measured in a forest stand on sand. Values showed significant increases within and between wheel tracks, even after one skidding cycle. Results showed that carbon dioxide concentration is a more sensitive and thus better indicator to quantify machine impacts on the soil.

2.2 Introduction

In the last decades, manual felling and logging by animals or small tractors have given way to mechanized harvesting, using heavy tractors or specialized felling (harvester) and logging (skidder, forwarder) machines. Soil compaction, often accompanied by rutting, is a typical process that may appear as a result of this machine traffic, especially when used inappropriately. It involves the compression of pores, leading to a decreased porosity, decreased pore continuity (Herbauts et al. 1996; Berli et al. 2003; Teepe et al. 2004), an increase of dry BD (e.g., Alban et al. 1994; Miller et al. 1996), a reduction of the saturated hydraulic conductivity (Benthaus & Matthies 1993), a hampered gas exchange (Gaërtig et al. 2002) and an alteration of chemical processes (Herbauts et al. 1996; Woodward 1996; Arocena 2000; Ballard 2000). As pores become smaller, soil strength (Shetron et al. 1988) and thus PR increase (Aust et al. 1998; Nugent et al. 2003). As a result, root growth may be hampered (Greacen & Sands 1980; Heilman 1981), the species composition of the herb layer may experience changes (Buckley et al. 2003), and soil fauna may be negatively influenced (Smeltzer et al. 1982; Radford et al. 2001; Battigelli et al. 2004). Since soil fauna contributes to such processes as decomposition, release of nutrients and the creation of a good soil structure (Gobat et al. 1998), soil compaction may result in a reduced ecosystem diversity, fertility and functioning.

The degree to which a forest soil is compacted by mechanized harvesting, depends on several variables and characteristics, typical of the forest site (soil texture, soil organic matter content, slope), season (soil water content, soil temperature) or the harvesting activity itself (machine type, machine mass, number of trees to be felled, traffic intensity:

1) Soil characteristics: medium- to fine-textured soils (loam, silt, clay and intermediate textures) are assumed to be more sensitive to soil compaction than sandy soils (Fisher & Binkley 2000; Gomez et al. 2002). Brais & Camiré (1998) and Ampoorter et al. (2007, Chapter 3) however found that sandy soils may also be prone to compaction. When assessing the influence of soil texture on the degree of compaction, one should certainly take the soil precompression stress (indicated by initial BD or PR) and the soil water content into account. A machine pass will induce soil compaction on condition that the applied stress exceeds the precompression stress (Horn et al. 2007). On medium- to fine-textured soils, the compaction degree

is maximal at an optimum intermediate soil water content (Smith et al. 1997; Hillel 1998). On coarse-textured soils the soil impact shows a local minimum at a critical intermediate soil water content and compaction degrees are higher at lower or higher soil water contents (e.g., Smith et al. 1997; Langohr & Ampe 2004). The function that relates attainable bulk density to soil moisture does not constitute a single characteristic curve for a given soil but a family of curves, depending amongst others on the compactive effort (Hillel 1998) and the precompression stress of the soil. Soil organic matter content also influences the sensitivity of the soil to compaction as it improves soil structure (Sands et al. 1979; Greacen & Sands 1980; Howard et al. 1981).

2) Machine mass: the mean soil contact pressure of a machine indicates the vertical pressure and consequently the potential compaction. The higher the soil contact pressure, the higher the impact on the soil (McDonald et al. 1996).

3) Traffic intensity (referring to the number of machine passes or skidding cycles): at successive passes, soil particles are piled closer together and the pore size decreases through soil compaction, resulting in a higher soil BD. As smaller pores are less prone to compaction, soil strength and consequently precompression stress are increased, limiting the additional damage with future passes (Shetron et al. 1988; Williamson & Neilsen 2000). Amongst others, Brais & Camiré (1998) found that the relationship between traffic intensity and BD increase is logarithmic. Bearing this in mind, two hypotheses can be formulated: (a) the initial BD (and thus precompression stress) influences the potential damage degree, in general leading to smaller responses when initial BD is higher; (b) the relationship between the number of passes (or traffic intensity) and the response of BD is logarithmic, with a high extra increase per pass at low traffic intensities, approaching zero when the number of passes increases. The cycle of half impact, defined as the number of passes at which half of the potential impact has been reached, is lower for fine-textured soils in comparison with coarse-textured soils (Brais & Camiré 1998).

Numerous studies have already focussed on forest soil compaction after mechanized harvesting. The added value of this research is that it had an extensive and integrated approach. It was executed in various forest stands, examining different factors (texture, machine mass, traffic intensity) and looking at the impact on several soil variables. In this way, an overall view was obtained concerning the impact of mechanized harvesting on the soil ecosystem. It was therefore possible to assess the influence of each factor on the compaction degree. The aims of this study were:

a) To measure the extent to which selected key variables (BD, PR, micro-topography, CO_2 concentration) are influenced by the treatments;
b) To determine which factors (site and harvesting characteristics) contribute to this extent.

2.3 Materials and methods

2.3.1 Experimental design

Eight forest stands, distributed over the Flemish region of Belgium, were selected for this field trial. Four (*Sperwer, Goden, Havik, Renissart*) are located in the Meerdaal forest (N 50.8040°, E 4.7013°) and Heverlee forest (N 50.8393°, E 4.6903°) close to Leuven on Luvisols(-cambisols) (IUSS Working Group WRB 2006) with textures ranging from loam to silt loam *(loam to silt loam)* (Soil Survey Staff 1999) (Table 2.1). The two (gleyic) Podzols in Kapellen (*Kapellen 1, Kapellen 2*) have sandy textures (*sand*). Two other forest stands are situated in an alluvial area in Walem on Gleysols (*Walem 1, Walem 2*) with clay loam and sandy loam to sandy clay loam textures (*clay)* (Table 2.1). All forest stands were located on loose soils. Rocks or rocky substrates were absent. Small stony fragments were occasionally present but not at all to the extent that they could have buffered the impact of the machines nor that they would have influenced the measurements. Therefore, stony fragment content was not measured or taken into account to correct the measurements as this content was negligible. Mean temperature for the region (1961-1990) is 2.5 °C in the coldest month (January) and 17.2 °C for the warmest month (July) while mean annual temperature and precipitation is 9.7 °C, respectively 821 mm (weather station Uccle at about 30 km from Leuven). In all forest stands the previous mechanized harvesting dates back from at least 8 years ago. None of the selected stands has a history of permanent skid trails, so machines had access to the whole stand during past harvesting activities.

Table 2.1 Characteristics of forest stands in field trial. Laser diffraction was applied to determine amounts of sand, silt and clay in the upper 50 cm (sand > 50 µm, 50 > silt > 2 µm, 2 µm > clay); soils were divided into soil types according to IUSS Working Group WRB (2006) and classified into texture groups according to the USDA soil classification system (Soil Survey Staff 1999); SWC = gravimetric soil water content, averaged over all skid trails).

Location	**Leuven**				**Kapellen**		**Walem**	
Forest stand	**Sperwer**	**Goden**	**Havik**	**Renissart**	**Kapellen 1**	**Kapellen 2**	**Walem 1**	**Walem 2**
Dominant tree species	*Fagus sylvatica*	*Pinus sylvestris, Quercus rubra, Quercus petraea*	*Pinus nigra* var. *corsicana*	*Quercus robur, Acer pseudoplatanus*	*Fagus sylvatica, Pinus sylvestris, Quercus rubra*	*Fagus sylvatica, Pinus sylvestris*	*Fraxinus excelsior, Quercus robur, Acer pseudoplatanus, Prunus avium*	*Populus sp.*
Soil type	Luvisol-cambisol	Luvisol-cambisol	Luvisol	Luvisol	Podzol	Gleyic podzol	Gleysol	Gleysol
% sand	31	18	19	7	90	84	36	62
% silt	48	59	59	69	6	10	36	19
% clay	21	23	22	24	4	6	28	19
Texture group	loam	silt loam	silt loam	silt loam	sand	loamy sand	clay loam	sandy (clay) loam
SWC September (10-20 cm, %)	12.8	14.3	12.8	23.3	10.8	14.1	37.7	29.6
SWC February (10-20 cm, %)	22.2	22.4	25.8	31.4	13.4	20.7	44.1	35.0

Table 2.2 Dates when the treatments were applied and the measurements were carried out on trails of the experiment in February and September.

	Variable	**Trails February**	**Trails September**
Before	**Bulk density**	January 2007	January 2007
	Penetration resistance	February 2007	February 2007
	Micro-topography	14-16 February 2007	29 August 2007
Experiment		19-20 February 2007	24-25 September 2007
After	**Bulk density**	February-March 2007	November 2007
	Penetration resistance	March 2007	March 2008
	Micro-topography	26-28 February 2007	10 October 2007
	CO_2	June 2008	/

In each forest stand eight straight trails, approximately 40 m long and 5 m wide, were marked (Fig. 2.1). These trails were used to examine the impact of machine mass and traffic intensity in a 2x2 design, replicated at two different points in time. The experiment was performed on half of the trails in summer conditions in *September* on normally dry soils and on the other half in winter conditions in *February* when soils are normally wet but not frozen (Table 2.2). However, winter conditions were drier than expected so that the difference in soil water content (while performing the experiment) between the two points in time was rather small (Table 2.1). In Walem, soils are capable of capillary rise of soil water, further decreasing the difference in soil water content between February and September. The two experiments were therefore considered as semi-replicates. Treatments were applied, using two machines (Fig. 2.2): a New Holland TCE 50 tractor, weighted with a winch (0.420 tonnes) to 1.88 tonnes to simulate typical Flemish small-scale fire wood harvest (*light*) (tyres front: 28 cm wide, tyre pressure 1.7 bar; tyres back: 36 cm wide, tyre pressure 1.9 bar), and a John Deere grapple skidder JD 640, loaded to 14.3 tonnes by using a concrete block (2.5 tonnes), hanging in the grapple, representative for Flemish machinery that is used to drag trees to forest roads (*heavy*) (tyres front and back: 77.47 cm wide, tyre pressure 3.5 bar). These machine types are also commonly used in other countries. Neither machine had information on soil contact pressure (ratio of machine mass to contact area) available in the brochure. However, roughly estimated, the soil contact pressure was around 65 kPa for the heavy machine and 40 kPa for the light machine. The two levels for traffic intensity (or number of skidding cycles) were *one* and *five* skidding cycles, with a skidding cycle defined as a pass back and forth on the skid trail. The first level mimics traffic intensity deeper in the forest stand. The second level represents intensity of machine traffic on the area close to the log landing. Machines drove at walking pace. Four of the eight trails were used per experiment (February and September), of which two were driven by the light machine and two by the heavy machine (first skid trail: one skidding cycle; second skid trail: five skidding cycles). Tree interdistance on the examined area was large enough to allow forest machines to follow the marked trails during the experiment without the necessity of cutting extra trees. The trail centre was marked with painted sticks to make sure the same wheel tracks were used as much as possible, while making the subsequent skidding cycles.

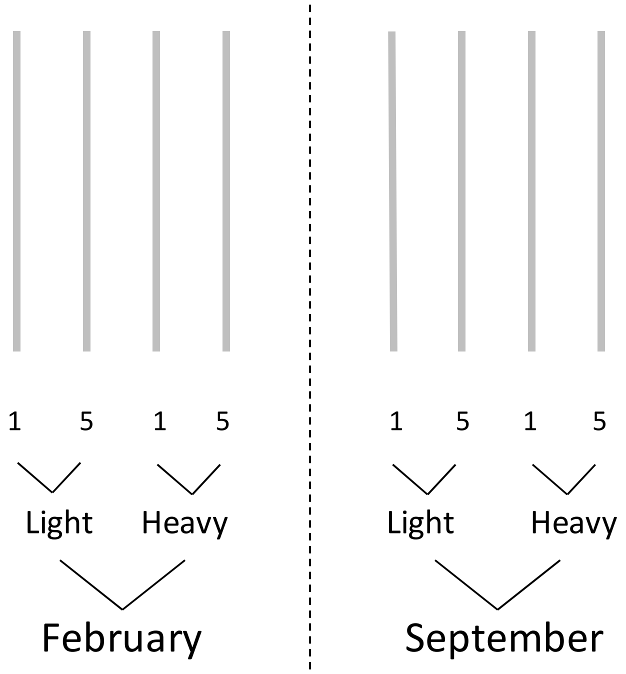


Fig. 2.1 Experimental design of the field trial. Eight skid trails were marked (grey lines) of which four were used in the February experiment and four in the September experiment. At each experiment, both the light and the heavy machine made one pass back and forth on one skid trail and five passes on another.

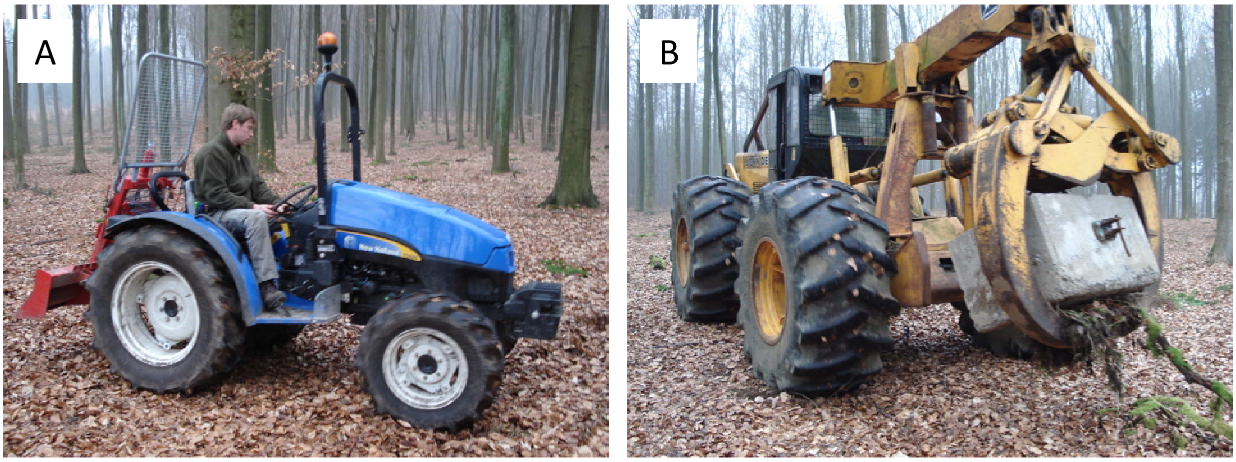


Fig. 2.2 Machines used during the field trial: (A) New Holland TCE 50 tractor, (B) John Deere grapple skidder JD 640 [photographs: Evy Ampoorter, Feburay 2007].

2.3.2 Data collection

Several soil variables were measured to quantify the impact of each machine on the forest soil. BD was sampled using Kopecky soil cores (100 cm^3) (Fig. 2.3A) from depth intervals 0-10, 10-20 and 20-30 cm. Namely, several study results showed that the strongest soil impacts appear in these upper soil layers (Greacen & Sands 1980; Ampoorter et al. 2007, Chapter 3). Before treatments were applied, samples were taken on locations where future wheel tracks would approximately be situated (n = number of replications = 6 per skid trail, thus n = 48 per stand). After applying treatments, they were taken *within* (n = 6 per skid trail) and *between* (n = 6 per skid trail) the two wheel tracks, close to the locations of the initial measurements. Samples were oven dried (105 °C) for 48 h prior to weighing to evaporate all water in the sample. The moment of soil sampling for the quantification of bulk density was thus independent of weather conditions and the current soil water content.

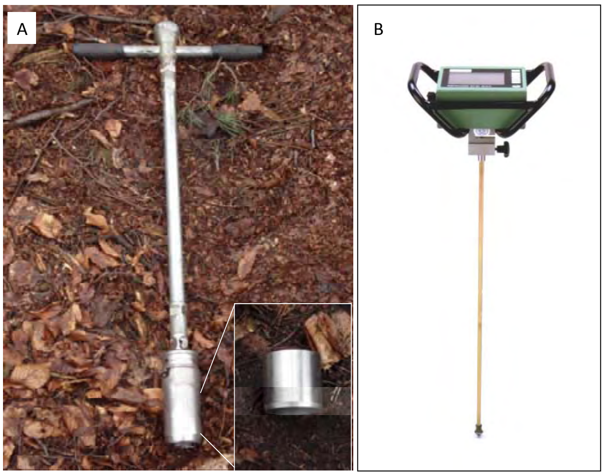


Fig. 2.3 Devices used for quantification of soil compaction: (A) Kopecky soil core sampler [photograph: Evy Ampoorter, February 2007], (B) penetrologger [photograph: www.eijkelkamp.com].

PR was determined using a penetrologger (Eijkelkamp Agrisearch Equipment, the Netherlands) (Fig. 2.3B), that measures to a maximum depth of 80 cm in depth intervals of 1 cm. Cones have an apical angle of sixty degrees, a basal area surface of 1 cm² and a nominal diameter of 11.28 mm. Measurements of PR had to be carried out when soils were at or near field capacity, because of the soil moisture dependence of the measurements (Smith et al. 1997; §3.5.3). Current soil water content was determined as a routine check each time measurements were made. Therefore, soil was sampled at about 10 locations spread over the measurement area with a soil drill on depths 0-10, 10-20, 20-30,…, 60-70 cm. The samples were weighed, then dried (100 °C) for 48 h and reweighed. Before treatments were applied, PR was determined on each skid trail (12 measurements on each trail, thus n = 96 per stand) and on the area between all the trails (n = 120 per stand). After applying treatments, measurements were made within (n = 12 per skid trail) and between the two wheel tracks (n = 12 per skid trail) again in the neighbourhood of the initial measurements. BD and PR were measured in all eight forest stands. The ratio of the BD and PR values after applying treatments to the corresponding values before treatments were applied (semi-paired samples) indicated the soil compaction degree (further called *ratio* or *compaction degree*) at each measurement point. Average ratios per treatment (Tables 2.3 and 2.4) were calculated by averaging the ratios of all measurement points for that specific treatment. In Figs. 2.5 and 2.6 and Tables 2.3 and 2.4, treatment *mean reference* is an average of all values before applying treatments on all treatments for that specific stand.

Coarse- and medium- to fine-textured soils are contrasting texture groups concerning vulnerability to soil compaction (Larson et al. 1980; Hillel 1998; Fisher & Binkley 2000). Therefore, analysis of micro-topography was examined in Kapellen 1 (sand) and Walem 1 (clay). Loam to silt loam soils are also vulnerable to soil compaction. But results of the mean reference for BD (see further) indicated that the forest stands on this texture were already compacted to a considerable extent before the experiment took place, leading to small to negligible compaction degrees. The micro-topography of the loam to silt loam soils was therefore not discussed. To quantify rut depth, a horizontal slat (4 m wide) was placed across the skid trails before and after treatments were applied at exactly the same place and height (marks on the poles to which the slat was attached). The slat was centered over the skid trail in order to enclose the area between and within wheel tracks and a part of the area next to the wheel tracks that was not driven by the machines. PR and the distance between soil and horizontal slat were measured at 10 cm intervals. These measurements were taken before and after applying treatments on each skid trail for one clay loam (Walem 1) and one sand stand (Kapellen 1) (n = 1 per skid trail). As with the other penetrologger measurements, micro-topography was measured in very wet periods and soil samples were collected to ensure comparable soil water content.

Finally, CO_2 concentration was measured 10 cm beneath the soil surface, using a portable gas chromatograph (Gaertig et al. 2000; Gaertig 2001) (Fig. 2.4). This analysis is based on the extraction of soil air through a perforated needle. The application of the device is not advisable in wet conditions or on fine-textured soils, as water or small soil particles may be sucked into the device, rendering it unserviceable. Whether these conditions are met or not, has to be examined in the field, observing if water or soil particles are sucked out of the soil and appear in the connecting pipe. As the soils in Leuven (loam to silt loam) were too wet and the soils in Walem (clay) too wet and fine-textured, measurements were only performed in Kapellen 2, a forest stand on a sandy soil. Measurements were conducted after applying treatments on the skid trails where the heavy machine made one and five skidding cycles during the experiment in February. Across both trails, two blocks of five parallel transects (30 cm interspace, width 5 m) were placed (n = 5 per block). As with micro-topography, transects were centered over the skid trail, so that both trafficked and non-trafficked soil were included in the measurement area. Along each transect, measurements of CO_2 concentrations were carried out at 25 cm intervals.

Fig. 2.4 Quantification of soil CO_2 concentration: (A) portable gas chromatograph, (B) detail of needle [photographs: Evy Ampoorter, June 2008].

In addition to these measurements, on the days of the experiment in February and September the water content in the soil profile was determined. Therefore, in each forest stand soil samples were taken on depths 0-10, 10-20, 20-30,…, 60-70 cm with a soil drill at both ends of each skid trail (n = 2 per skid trail) (*soil water content*). Soil water contents on the loam to silt loam soils and the sandy soils were clearly lower than in Walem on clay (Table 2.1).

Table 2.2 summarizes the dates when measurements were performed. Before applying treatments measurements were predominantly executed at the beginning of 2007. After applying treatments, most variables were quantified within two months after the experiment, except for CO_2 (16 months) and PR after the September experiment (6 months).

2.3.3 Data analysis

Measurements made on the skid trails prior to the experiment or in the neighbourhood of the trails are considered as 'reference'. As there was no tradition of permanent skid trails in any of the forest stands, previous harvesting activities may have influenced the forest soil in a way that the impact is still (partially) detectable (as was the case in all stands in Leuven and Kapellen; see further). Thus the term 'reference' does not mean that the soil is totally undisturbed but that the soil was not driven by machines during the experiment, nor during at least 8 years before the experiment. The 'reference' values for BD and PR indicate the precompression stress at the start of the experiment.

For dry BD and PR, data analysis involved a comparison of the impact of every treatment within and between all forest stands. Depth intervals 0-10, 10-20 and 20-30 cm for BD and depths 5, 15 and 25 cm for PR were analysed separately. Results of PR contained some extreme outliers (points beyond 3 times the interquartile range from percentile 25 or 75). There were in total 78, 37 and 36 outliers for depths 5, 15 and 25 cm respectively (<5% of all measurements). As these values were due to roots, rare coarse fragments or other soil irregularities, they were omitted from the dataset. Outliers in BD were scarce, rather due to normal soil variability, and were therefore retained. As mentioned in §2.3.2, due to the contrasting vulnerability to soil compaction and the low to negligible compaction degrees on loam to silt loam, the relationship between depth and BD or PR was examined more closely for Kapellen 1 (sand) and Walem 1 (clay) in Figs. 2.5 and 2.6. As BD and PR are both indicators of soil compaction, a Pearson correlation coefficient between the reference values of the two variables (measured at the same measurement points) was determined.

Statistical analysis was started with a One-Way ANOVA comparison of the mean reference values between the textures. Further, for each forest stand differences in absolute BD and PR values between the treatments (combination of position in relation to the tracks, machine mass, traffic intensity, time) were analysed applying One-Way ANOVA. Pair-wise comparisons were conducted using Tukey's honestly significant difference (HSD) test with $\alpha = 0.05$. GLM was then applied, based on the ratios of the values after applying treatments to the values before applying treatments. The aim of GLM was to explore in detail the contribution (alone or combined) of texture, machine mass, traffic intensity, forest stand, position in relation to the wheel tracks, time, soil water content and initial compaction status to the soil impact. *Texture* (clay - loam to silt loam - sand), *machine mass* (light - heavy) and *traffic intensity* (1-5 skidding cycles) were considered as fixed factors, whereas *forest stand* (nested in texture), *position* (within wheel tracks - between wheel tracks) and *time* (February and September) were random factors. *Soil water content* (during the experiments) and *reference values* (BD and PR values before applying treatments) were covariables in the model. The model has been limited to the main effects of all the factors and all two-way interactions between texture, machine mass, traffic intensity and position. As a normal distributed dataset is a prerequisite for ANOVA and GLM, data of PR had to be log transformed prior to both analyses. Data analyses were performed using SPSS 15.0.

Concerning the results of the micro-topography, distance and PR results were processed graphically using Surfer 7.0. This was examined for Kapellen 1 (sand) and Walem 1 (clay) in Fig. 2.7. Data were not analysed statistically, as there were no replicates. The CO_2

concentrations were also processed graphically. For the statistical analysis, a distinction was made between the measurements beside the wheel tracks, within the wheel tracks and between the wheel tracks. For each of these three zones, data were averaged over all five transects per block. Next, per block average values for the three zones were compared using One-Way ANOVA. Pair-wise comparisons were conducted using Tukey's HSD test with $\alpha = 0.05$.

2.4 Results

2.4.1 Dry bulk density

Mean BD values were higher for stands in Leuven (loam to silt loam) and Kapellen (sand) in comparison with Walem (clay), as well for the reference as for the treatments (Table 2.3). Moreover, except for Walem, mean references of all forest stands exceeded 1300 kg m^{-3}. One-Way ANOVA concerning the difference in reference values between the soil textures indicated significantly lower values for the forest stands on clay (p-values <0.001 for all three depth intervals). However, looking at the ratios, the impact of the treatments was similar for all forest stands. Ratios were overall low and did not exceed 1.07, meaning that the BD increase was never higher than 7% of the initial value. Two thirds of all ratios did not differ significantly from 1, meaning that no significant effect took place. In some cases ratios were significantly lower than 1. There was no clear difference between the ratios between or within wheel tracks.

The relationship between soil depth and BD within wheel tracks was examined more closely for Kapellen 1 (sand) and Walem 1 (clay) (Fig. 2.5). Reference BD values were significantly higher ($p < 0.001$) for the sandy soil (1481 ± 74 kg m^{-3}, 10-20 cm) than for the clay soil (1008 ± 72 kg m^{-3}, 10-20 cm) (Table 2.3). For Kapellen 1 (Fig. 2.5A), September treatments induced similar BD increases with the heavy and the light machine (0-7% in the first two depth intervals). In February, most BDs after applying treatments are somewhat lower than before applying treatments. For the heavy machine, the impact after five skidding cycles in February was higher than the impact after one skidding cycle (21%, 0-10 cm). In Walem 1 (Fig. 2.5B), values of all treatments were similar to the reference values (<6% increase), except for the September values in the third interval that were smaller than the reference.

Table 2.3 Mean bulk density (kg m^{-3}, upper value) and mean bulk density ratios (mean of ratios of bulk density after applying treatments to bulk density before application, lower value) (± 95% confidence interval) of soil interval 10-20 cm as influenced by treatments: position (between/within wheel tracks), machine weight (light/heavy), traffic intensity (1/5 skidding cycles), time (Febr/Sept). Values for treatment *Mean reference* are obtained by averaging values before treatments were applied (reference values) on all treatments per forest stand.

Forest stand					**Sperwer**	**Goden**	**Havik**	**Renissart**	**Kapellen 1**	**Kapellen 2**	**Walem 1**	**Walem 2**
Treatments				**n**	**p <0.001**	**p <0.001**	**p <0.001**	**p <0.001**	**p <0.001**	**p = 0.017**	**p <0.001**	**p <0.001**
Between wheel tracks	**Light**	**1**	**Sept**	**6**	1440 ± 102 abc	1271 ± 155 abc	1163 ± 87 abc	1203 ± 150 bcd	1453 ± 100 abc	1183 ± 146 a	924 ± 98 ab	1029 ± 50 ab
					0.95 ± 0.07	0.89 ± 0.11	**0.91 ± 0.04** *	**0.89 ± 0.08** *	0.99 ± 0.06	0.91 ± 0.12	**0.89 ± 0.06** *	**0.95 ± 0.03** *
			Febr	**6**	1304 ± 99 ab	1384 ± 76 abc	1253 ± 166 bc	1198 ± 52 abcd	1436 ± 114 abc	1319 ± 66 a	891 ± 77 ab	1046 ± 76 ab
					0.89 ± 0.09	**0.94 ± 0.05** *	0.99 ± 0.13	0.97 ± 0.05	1.00 ± 0.07	1.00 ± 0.10	**0.89 ± 0.09** *	**0.90 ± 0.09** *
		5	**Sept**	**6**	1304 ± 169 ab	1206 ± 263 abc	1164 ± 149 abc	1076 ± 96 ab	1568 ± 71 c	1168 ± 181 a	868 ± 112 a	1086 ± 41 ab
					0.96 ± 0.10 *	**0.81 ± 0.16** *	**0.85 ± 0.08** *	**0.82 ± 0.09** *	1.02 ± 0.05	**0.84 ± 0.12** *	**0.84 ± 0.10** *	0.96 ± 0.06
			Febr	**6**	1370 ± 124 abc	1384 ± 158 abc	1276 ± 31 bc	1209 ± 91 bcd	1378 ± 95 abc	1116 ± 242 a	932 ± 88 ab	1108 ± 90 ab
					0.92 ± 0.12	**0.93 ± 0.06** *	0.94 ± 0.06	**0.92 ± 0.05** *	0.94 ± 0.06	0.87 ± 0.16	0.95 ± 0.07	0.92 ± 0.11
	Heavy	**1**	**Sept**	**6**	1335 ± 152 abc	1220 ± 174 abc	1188 ± 147 abc	1353 ± 61 cd	1517 ± 68 bc	1253 ± 162 a	913 ± 68 ab	1118 ± 111 ab
					0.92 ± 0.07 *	0.83 ± 0.10 *	0.91 ± 0.09	1.00 ± 0.03	1.02 ± 0.04	0.99 ± 0.13	**0.89 ± 0.07** *	0.98 ± 0.13
			Febr	**6**	1384 ± 82 abc	1271 ± 89 abc	1335 ± 96 c	1204 ± 140 bcd	1343 ± 199 ab	1310 ± 56 a	983 ± 47 ab	1004 ± 114 ab
					0.95 ± 0.03	0.87 ± 0.07 *	1.00 ± 0.05	0.96 ± 0.08	0.91 ± 0.11	1.04 ± 0.09	1.01 ± 0.07	1.03 ± 0.09
		5	**Sept**	**6**	1352 ± 96 abc	1144 ± 283 ab	1061 ± 126 ab	1354 ± 139 cd	1506 ± 149 bc	1272 ± 81 a	870 ± 123 a	1037 ± 38 ab
					0.88 ± 0.06 *	0.83 ± 0.17	**0.76 ± 0.10** *	1.00 ± 0.17	1.02 ± 0.10	0.99 ± 0.08	0.88 ± 0.15	**0.89 ± 0.03** *
			Febr	**6**	1352 ± 60 abc	1463 ± 93 bc	1414 ± 81 c	1176 ± 99 abc	1412 ± 124 abc	1272 ± 69 a	916 ± 98 ab	929 ± 82 a
					0.95 ± 0.02 *	0.97 ± 0.05	0.99 ± 0.07	0.94 ± 0.07	0.96 ± 0.11	0.96 ± 0.04	**0.92 ± 0.07** *	0.97 ± 0.12
Within wheel tracks	**Light**	**1**	**Sept**	**6**	1596 ± 129 c	1308 ± 163 abc	1188 ± 178 abc	1150 ± 161 abc	1571 ± 44 c	1106 ± 301 a	964 ± 86 ab	968 ± 134 ab
					1.05 ± 0.03 *	**0.91 ± 0.05** *	0.94 ± 0.12	**0.86 ± 0.12** *	**1.07 ± 0.05** *	0.88 ± 0.20	**0.93 ± 0.06** *	**0.89 ± 0.08** *
			Febr	**6**	1399 ± 121 abc	1324 ± 47 abc	1279 ± 128 bc	955 ± 113 a	1473 ± 89 abc	1380 ± 65 a	991 ± 83 ab	1149 ± 37 ab
					0.97 ± 0.11	**0.88 ± 0.02** *	1.01 ± 0.10	**0.78 ± 0.06** *	1.03 ± 0.03	1.00 ± 0.04	1.01 ± 0.10	0.99 ± 0.08
		5	**Sept**	**6**	1320 ± 57 abc	1070 ± 189 a	1193 ± 223 abc	1215 ± 159 bcd	1538 ± 35 bc	1164 ± 208 a	1013 ± 86 ab	1103 ± 75 ab
					0.96 ± 0.06	**0.71 ± 0.12** *	**0.87 ± 0.12** *	0.92 ± 0.09	1.01 ± 0.03	**0.84 ± 0.14** *	0.98 ± 0.08	0.98 ± 0.08
			Febr	**6**	1265 ± 103 a	1371 ± 80 abc	1361 ± 104 c	1210 ± 124 bcd	1357 ± 120 abc	1223 ± 71 a	1041 ± 20 ab	1132 ± 83 ab
					0.85 ± 0.05 *	0.93 ± 0.11	0.98 ± 0.08	**0.90 ± 0.07** *	**0.92 ± 0.06** *	0.96 ± 0.05	**1.06 ± 0.05** *	**0.93 ± 0.05** *
	Heavy	**1**	**Sept**	**6**	1358 ± 49 abc	1305 ± 291 abc	1014 ± 229 ab	1298 ± 105 bcd	1536 ± 88 bc	1257 ± 179 a	1021 ± 118 ab	1155 ± 56 b
					0.95 ± 0.04 *	0.88 ± 0.13	**0.78 ± 0.11** *	0.98 ± 0.06	1.03 ± 0.05	0.98 ± 0.05	1.00 ± 0.10	1.01 ± 0.12
			Febr	**6**	1401 ± 130 abc	1146 ± 500 abc	1300 ± 70 bc	1205 ± 60 bcd	1239 ± 361 a	1281 ± 78 a	1028 ± 77 ab	906 ± 119 a
					0.97 ± 0.08	0.94 ± 0.14	0.98 ± 0.09	0.96 ± 0.07	0.86 ± 0.21	1.02 ± 0.12	1.05 ± 0.09	**0.94 ± 0.04** *
		5	**Sept**	**6**	1395 ± 163 abc	1235 ± 269 abc	938 ± 228 a	1426 ± 79 d	1537 ± 28 bc	1217 ± 108 a	897 ± 191 ab	1119 ± 68 ab
					0.93 ± 0.10	0.90 ± 0.17	**0.66 ± 0.11** *	1.00 ± 0.11	1.04 ± 0.06	0.95 ± 0.05	0.89 ± 0.11	**0.96 ± 0.03** *
			Febr	**6**	1418 ± 157 abc	1383 ± 303 abc	1409 ± 89 c	1328 ± 21 cd	1355 ± 126 abc	1289 ± 131 a	1038 ± 83 ab	1020 ± 82 ab
					1.10 ± 0.19	0.92 ± 0.18	0.99 ± 0.08	1.05 ± 0.07	**0.93 ± 0.04** *	0.96 ± 0.04	1.06 ± 0.11	1.06 ± 0.15
Mean reference				**48**	1463 ± 93 bc	1471 ± 104 c	1346 ± 98 c	1308 ± 99 cd	1481 ± 74 bc	1312 ± 116 a	1008 ± 72 b	1111 ± 126 b

For each forest stand, means are compared against each other after ANOVA using Tukey's HSD test (p-values are mentioned). Mean bulk density values within a column that differ significantly are marked with different letters. Ratios that differ significantly from 1 (thus indicating a significant effect; $p < 0.05$) are marked in bold with *.

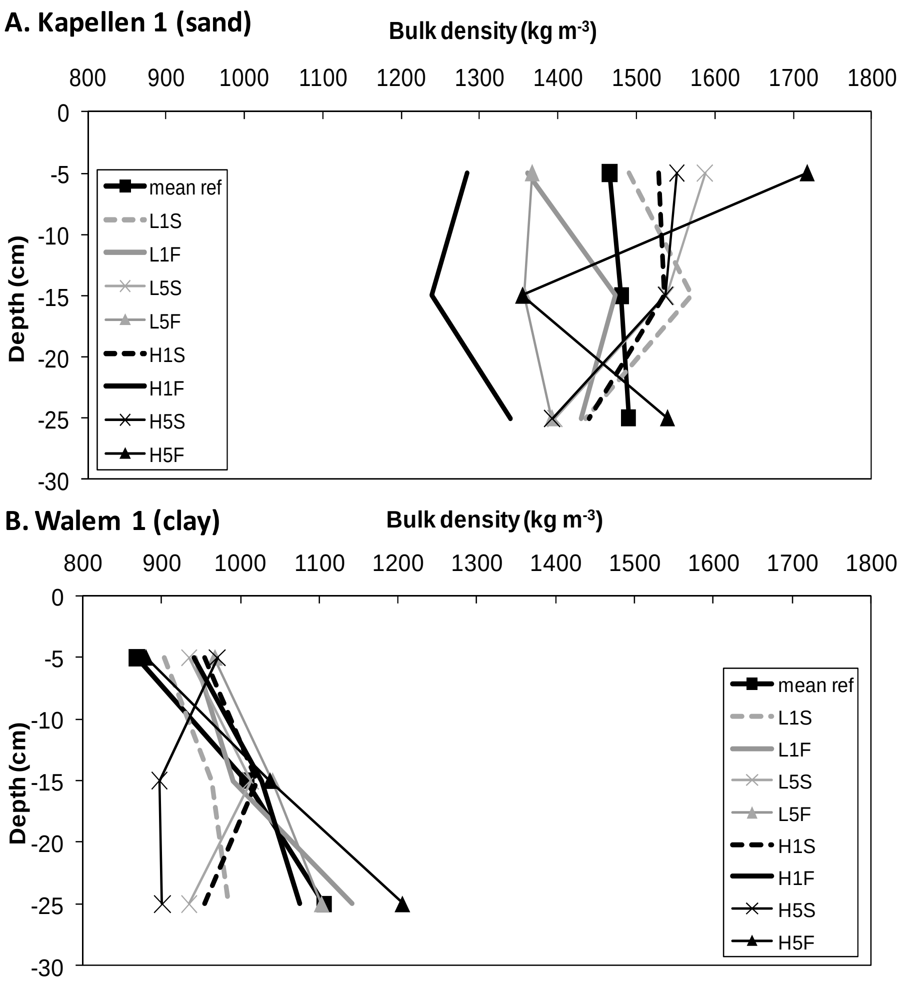


Fig. 2.5 Treatment effect on bulk density within wheel tracks, as a function of depth in Kapellen 1 (A) on sand and Walem 1 (B) on clay (mean ref = reference values for all treatments averaged, L.. = light machine, H.. = heavy machine, .1. = one skidding cycle, .5. = five skidding cycles, ..S = September, ..F = February); n = 6, except for mean reference where n = 48.

Results of ANOVA for depth interval 10-20 cm (Table 2.3) showed for all stands that almost no treatment induced a clear increase of BD with the mean reference, neither within wheel tracks, nor between wheel tracks. Although comparison with the mean reference showed no significant difference, L1S in Sperwer and Kapellen 1 seemed to induce a significant increase, based on the ratio. In Walem 1, L5F induced a significant increase in BD. The remaining significant ratios were due to lower BD values after the treatments in comparison with the initial BD values.

According to GLM results, machine mass had a significant influence in the second ($p < 0.001$) and third ($p = 0.036$) depth interval (Table 2.5). Higher BD values were recorded using the heavy machine compared to the light machine. Compaction degrees depended only in the first depth interval on the traffic intensity ($p = 0.018$). The higher the traffic intensity, the more severe the compaction was. Two other factors determining the compaction degree considerably in all three soil intervals were forest stand ($p < 0.001$ for all intervals) and time (p = 0.019, p <0.001 and p = 0.004 respectively at intervals 0-10, 10-20 and 20-30 cm). Therefore, forest stands within the same texture group and the results of the two experiments (replicated in time) should not be seen as pure replicates. Reference values (or BD before applying treatments) also influenced vulnerability of the soil to compaction to a great extent (p <0.001 for all soil intervals). Pearson correlation coefficients between reference values and BD ratios were -0.414, -0.253 and -0.276 for the first, second and third depth intervals respectively, with all three corresponding p-values <0.001. As the coefficients are negative, it seems that the higher BD before applying treatments was the lower the compaction degree was. Soil water content had also in the second depth interval a significant influence on BD ratios (p <0.001). Pearson correlation coefficients between soil water contents and BD ratios (all three texture groups and the two positions analysed together) were 0.002, 0.108 and 0.063 for the first, second and third depth intervals respectively, with only the second corresponding p-value being significant (p = 0.004). It appeared that the ratio or compaction degree increased with increasing soil water content. Looking at this relationship only for the results within tracks of each texture group separately, it shows that most of the correlation coefficients were negative but insignificant. Texture and position in relation to the wheel tracks did not influence BD in a significant way. Apart from a small significant interaction between texture and position in the first (p = 0.050) and second (p = 0.035) depth interval, no strong significant interactions could be discerned for BD.

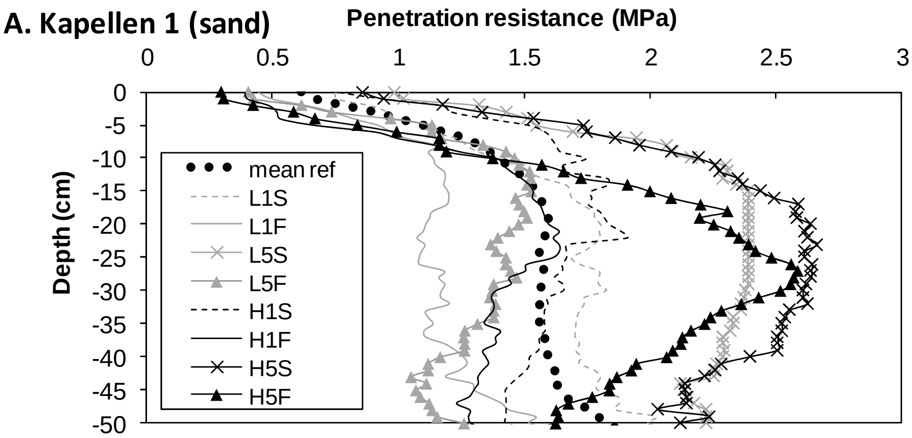
2.4.2 Penetration resistance

As with BD, One-way ANOVA analysis indicated significantly lower mean reference values for clay compared to the other soil textures (p <0.001 for all three depth intervals) (Table 2.4). Based on the absolute PR values after applying treatments, it was not possible to distinguish among the different soil textures. As with BD, the relationship between soil depth and PR within wheel tracks was examined more closely for Kapellen 1 (sand) and Walem 1 (clay) (Fig. 2.6). Only the first 50 cm of the soil profile is shown, as this interval is most important to plant roots and animals and the impact is maximal in the upper soil layer. Reference values in the whole soil profile were lower for clay (± 1 MPa) than for sand (± 1.5 MPa), as was already concluded from the results in Table 2.4. At Kapellen 1 (Fig. 2.6A), treatments executed in September (somewhat drier soils), especially L5S and H5S, led to an increase of

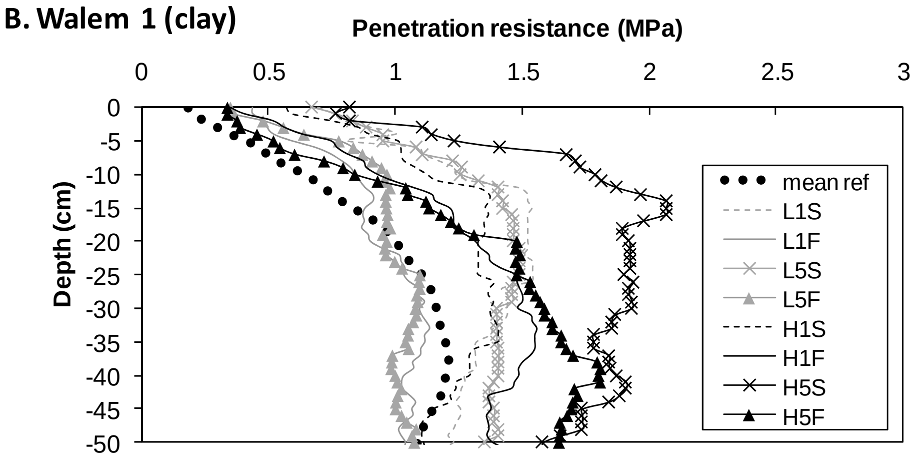
Table 2.4 Mean penetration resistance values (MPa, upper value) and mean resistance ratios (mean of ratios of resistance after applying treatments to resistance before application, lower value) (± 95% confidence interval) of soil depth 15 cm as influenced by treatments: position (between/within wheel tracks), machine weight (light/heavy), traffic intensity (1/5 skidding cycles), time (Febr/Sept). Values for *Mean reference* are obtained by averaging values before treatments were applied (reference values) on all treatments per forest stand.

Forest stand					Sperwer	Goden	Havik	Renissart	Kapellen 1	Kapellen 2	Walem 1	Walem 2
Treatments				n	p <0.001	p <0.001	p <0.001	p <0.001	p <0.001	p = 0.017	p <0.001	p <0.001
Between wheel tracks	Light	1	Sept	12	1.83 ± 0.84 abc	1.35 ± 0.32 ab	1.45 ± 0.41 abc	1.16 ± 0.42 abc	1.74 ± 0.60 abcd	1.59 ± 0.25 bcde	1.42 ± 0.28 Cdef	1.51 ± 0.24 de
					0.76 ± 0.27	1.50 ± 0.76	1.35 ± 0.52	0.92 ± 0.25	**1.89 ± 0.66** *	**1.31 ± 0.20** *	**2.00 ± 0.50** *	**1.96 ± 0.35** *
			Febr	12	1.66 ± 0.54 ab	1.67 ± 1.34 ab	1.22 ± 0.60 abc	1.39 ± 0.75 ab	1.23 ± 0.33 ab	1.12 ± 0.32 ab	0.90 ± 0.37 a	0.76 ± 0.35 ab
					1.32 ± 0.29 *	1.27 ± 0.56	1.10 ± 0.25	1.64 ± 0.74	**1.34 ± 0.33** *	1.01 ± 0.35	1.03 ± 0.35	1.27 ± 0.38
		5	Sept	12	1.64 ± 1.15 ab	1.76 ± 0.58 ab	1.33 ± 0.60 abc	1.24 ± 0.50 abcd	2.33 ± 0.57 cd	1.36 ± 0.48 abcd	1.31 ± 0.35 abcdef	1.40 ± 0.21 cde
					1.20 ± 0.31	1.04 ± 0.22	1.35 ± 0.80	**1.79 ± 0.75** *	1.06 ± 0.13	1.20 ± 0.27	**1.84 ± 0.55** *	**2.21 ± 0.37** *
			Febr	12	2.20 ± 1.12 bc	1.52 ± 1.18 ab	1.74 ± 0.66 abc	0.88 ± 0.25 abcde	1.78 ± 0.67 abcd	1.12 ± 0.27 ab	0.90 ± 0.19 abc	0.76 ± 0.24 ab
					1.44 ± 0.61	0.82 ± 0.35	1.08 ± 0.39	1.35 ± 0.45	1.34 ± 0.35	0.96 ± 0.14	1.17 ± 0.33	1.53 ± 0.73
	Heavy	1	Sept	12	1.70 ± 1.65 ab	1.60 ± 0.61 ab	1.35 ± 0.35 abc	2.36 ± 1.30 bcde	1.62 ± 0.49 abcd	1.43 ± 0.57 bcd	1.47 ± 0.23 def	1.64 ± 0.37 e
					1.57 ± 0.73	1.36 ± 0.54	0.95 ± 0.17	0.92 ± 0.26	1.19 ± 0.29	**1.63 ± 0.56** *	**1.77 ± 0.32** *	**2.16 ± 0.49** *
			Febr	12	1.37 ± 0.44 ab	2.10 ± 0.85 b	1.20 ± 0.41 abc	0.87 ± 0.26 abc	1.54 ± 0.40 abcd	1.25 ± 0.47 abc	0.89 ± 0.26 abc	0.94 ± 0.44 abc
					0.90 ± 0.28	1.28 ± 0.32	**0.61 ± 0.18** *	0.96 ± 0.31	0.96 ± 0.23	1.05 ± 0.29	1.19 ± 0.30	1.71 ± 0.72
		5	Sept	12	1.56 ± 0.74 ab	1.60 ± 0.72 ab	1.94 ± 1.31 abc	0.82 ± 0.21 de	2.29 ± 0.57 cd	2.14 ± 1.12 de	1.79 ± 0.31 ef	1.25 ± 0.46 bcde
					0.68 ± 0.30 *	1.44 ± 0.49	**1.65 ± 0.55** *	1.24 ± 0.34	**1.40 ± 0.28** *	**1.95 ± 0.66** *	**1.57 ± 0.25** *	**1.45 ± 0.26** *
			Febr	12	1.53 ± 0.55 ab	2.11 ± 0.83 b	3.02 ± 1.80 C	0.87 ± 0.26 abc	1.99 ± 0.72 abcd	0.88 ± 0.32 a	0.88 ± 0.34 a	0.74 ± 0.33 a
					1.08 ± 0.33	1.00 ± 0.23	1.30 ± 0.41	0.84 ± 0.27	1.05 ± 0.36	1.03 ± 0.31	1.49 ± 0.74	1.00 ± 0.35
Within wheel tracks	Light	1	Sept	12	2.34 ± 1.17 bc	2.14 ± 0.81 b	1.40 ± 0.50 abc	0.99 ± 0.36 abc	2.39 ± 0.51 abcd	1.82 ± 0.42 cde	1.54 ± 0.51 def	1.51 ± 0.36 de
					0.96 ± 0.29	**1.66 ± 0.44** *	1.24 ± 0.38	0.80 ± 0.20	**1.80 ± 0.58** *	**1.50 ± 0.26** *	**2.12 ± 0.49** *	**2.04 ± 0.52** *
			Febr	12	2.13 ± 0.81 bc	1.64 ± 0.86 ab	1.03 ± 0.42 a	0.79 ± 0.31 a	1.20 ± 0.27 a	1.19 ± 0.37 e	0.88 ± 0.33 ab	0.94 ± 0.26 abcd
					1.74 ± 0.57 *	1.28 ± 0.36	0.94 ± 0.25	1.23 ± 0.45	**1.29 ± 0.28** *	1.03 ± 0.31	1.00 ± 0.39	**1.51 ± 0.31** *
		5	Sept	12	1.34 ± 0.59 ab	2.18 ± 0.91 B	1.57 ± 0.88 abc	1.29 ± 0.50 abcd	1.68 ± 0.42 cd	1.60 ± 0.39 bcde	1.43 ± 0.23 def	1.70 ± 0.27 e
					1.16 ± 0.48	1.41 ± 0.45	1.17 ± 0.50	**1.44 ± 0.42** *	1.14 ± 0.27	**1.43 ± 0.17** *	2.11 ± 0.56	**2.65 ± 0.33** *
			Febr	12	1.96 ± 0.82 bc	1.54 ± 1.25 ab	1.52 ± 0.54 abc	1.13 ± 0.44 abc	1.53 ± 0.21 abcd	1.25 ± 0.24 abc	0.97 ± 0.15 abcd	0.94 ± 0.25 abcd
					1.36 ± 0.53	1.03 ± 0.37	0.97 ± 0.23	1.04 ± 0.30	1.16 ± 0.16	1.32 ± 0.41	1.25 ± 0.32	1.50 ± 0.55
	Heavy	1	Sept	12	1.87 ± 0.81 abc	1.74 ± 0.61 ab	1.28 ± 0.33 abc	1.87 ± 0.54 cde	1.76 ± 0.68 abcd	1.70 ± 0.45 bcde	1.36 ± 0.36 bcdef	1.36 ± 0.34 cde
					1.13 ± 0.35	1.56 ± 0.60	0.87 ± 0.14	1.03 ± 0.29	1.40 ± 0.49	**1.90 ± 0.52** *	**1.62 ± 0.36** *	**1.83 ± 0.42** *
			Febr	12	1.12 ± 0.43 a	1.58 ± 0.54 ab	1.62 ± 0.39 abc	0.85 ± 0.20 ab	1.54 ± 0.51 abc	1.29 ± 0.16 abcd	1.22 ± 0.32 abcde	0.89 ± 0.33 abc
					0.74 ± 0.30	0.93 ± 0.18	**0.79 ± 0.10** *	1.08 ± 0.26	0.98 ± 0.26	1.10 ± 0.19	**1.65 ± 0.44** *	**1.42 ± 0.33** *
		5	Sept	12	3.28 ± 0.98 c	1.95 ± 0.80 ab	2.26 ± 0.75 bc	2.45 ± 0.51 e	2.44 ± 0.35 d	2.44 ± 0.38 bcde	2.07 ± 0.58 f	1.77 ± 0.55 e
					1.41 ± 0.47	**1.71 ± 0.66** *	1.75 ± 0.49	1.22 ± 0.25	**1.48 ± 0.24** *	**2.18 ± 0.33** *	**1.87 ± 0.49** *	**2.52 ± 0.70** *
			Febr	12	1.67 ± 0.5 ab	0.98 ± 0.25 a	2.38 ± 0.78 c	0.99 ± 0.38 abc	2.00 ± 0.47 bcd	1.70 ± 0.27 abcd	1.13 ± 0.26 acde	0.89 ± 0.15 abc
					1.20 ± 0.35	**0.50 ± 0.15** *	1.03 ± 0.25	1.03 ± 0.32	1.06 ± 0.28	**1.94 ± 0.30** *	**1.67 ± 0.47** *	1.14 ± 0.26
Mean reference				216	1.82 ± 0.89 bc	1.75 ± 0.84 ab	1.46 ± 0.64 abc	1.28 ± 0.73 abc	1.55 ± 0.56 abcd	1.17 ± 0.47 ab	0.85 ± 0.31 ab	0.73 ± 0.28 ab

For each forest stand, means are compared against each other after ANOVA using Tukey's HSD test (p-values are mentioned). Mean penetration resistance values within a column that differ significantly are marked with different letters. Ratios that differ significantly from 1 (thus indicating a significant effect; p <0.05) are marked in bold with *.



A. Kapellen 1 (sand)



B. Walem 1 (clay)

Fig. 2.6 Treatment effect on penetration resistance within wheel tracks, as a function of depth in Kapellen 1 (A) and Walem 1 (B) (mean ref = reference values for all treatments and area between trails averaged, L.. = light machine, H.. = heavy machine, .1. = one skidding cycle, .5. = five skidding cycles, ..S = September, ..F = February); n = 12, except for mean reference where n = 216.

PR values with 60-70%, and this is similar to the increase of BD. In February conditions, five skidding cycles of the heavy machine (H5F) resulted in a steep increase in PR around 25 cm depth. However, the impact of the other February treatments, especially L1F, was negligible. It can be deduced for the February treatments that the light machine had a smaller impact than the heavy machine. Additionally, both February and September treatments showed that both machines induced higher PR values after five skidding cycles than after one skidding cycle. At Walem 1 (Fig. 2.6B), all treatments increased PR values to a certain extent. The September treatment H5S yielded a circa 90% increase of PR at 15 cm depth and reached the highest values for the whole depth range. In the upper 20 cm, the impacts of the other September treatments were similar (70-100% increase at 15 cm) and exceeded the results of the February treatments to a small extent. Below 20 cm, results of the February treatments H1F and H5F (heavy machine) kept increasing and exceeded the impact of the September treatments L1S, L5S and H1S. The other two February treatments with the light machine (L1F and L5F) had a negligible effect. The results of the February treatments thus showed that the light machine had a smaller impact than the heavy machine. The results of the September treatments showed that the impact of five skidding cycles of the heavy machine was most severe. Results of ANOVA for soil depth 15 cm (Table 2.4) showed almost no significant differences between the absolute values of the treatments and the reference for the forest stands on loam to silt loam (Leuven) and sand (Kapellen). Concerning the ratios, only the forest stands growing on sand and clay showed several ratios that were significantly higher than 1. The highest ratios were found on clay soils. For Walem 1 and 2 on clay, almost all September treatments showed PR after applying treatments that differed significantly from the mean reference values, as well within as between wheel tracks. Moreover, in Walem 1, treatment H5S compacted soil significantly more than all February treatments. For all stands, compaction degrees between wheel tracks were as high as within wheel tracks. Ratios of September treatments are also predominantly higher than ratios of February treatments.

Results of GLM (Table 2.5) showed no significant influences of texture, machine, traffic intensity and position in relation to the wheel tracks. As with BD, forest stand and time have a strong significant impact on the PR results ($p < 0.001$). Results of the different forest stands per texture group and the two different experiments should thus not be considered as pure replicates. Water content has a significant impact in the second and third depth intervals. Pearson correlation coefficients for the relationship between PR ratios (all texture groups and positions analysed together) and soil water content (when treatments were applied) are 0.107 ($p < 0.001$) at 5 cm depth, 0.094 ($p < 0.001$) at 15 cm depth and -0.036 ($p = 0.180$) at 25 cm depth. This relationship indicates that ratios increase as soil water content increases, as was already indicated by BD. However, looking closer at this relationship for the results within tracks of each texture group separately, it shows significant p-values for sand ($p = 0.011$) and clay ($p = 0.013$) at 5 cm, for loam ($p = 0.021$) and clay ($p = 0.007$) at 15 cm and for loam ($p = 0.001$) and sand ($p = 0.010$) at 25 cm. Each of these significant relationships is negative, meaning that the compaction degree decreases with increasing soil water content. At last, the reference values again determined the compaction degree to a large extent in a negative way. Analysis of the correlations between PR ratios and reference values resulted in significant Pearson correlation coefficients of -0.576, -0.598 and -0.579 at 5, 15 and 25 cm depth respectively (p-values <0.001). The impact of traffic intensity seemed to depend on the machine mass for depths 15 and 25 cm (p = 0.005 and p = 0.003 respectively). For the light machine, compaction degrees after one or five skidding cycles were similar, whereas the heavy machine induced a clearly higher impact after five skidding cycles in comparison with one skidding cycle. Position in relation to the wheel tracks was another term interacting with the impact of traffic intensity at 15 (p = 0.020) and 25 cm (p <0.001) depth. Between wheel tracks the compaction ratios after one and five skidding cycles were rather small. However, within wheel tracks the impact after five skidding cycles was significantly higher in comparison with one skidding cycle. As with BD, a small significant interaction existed between texture and position in relation to the wheel tracks for the first (p = 0.032) depth interval.

Table 2.5 Bulk density and penetration resistance as influenced by texture (Te), machine weight (Ma), traffic intensity (Tr), forest stand (St, nested in Texture), position in relation to the wheel tracks (Po), Time (Ti), soil water content (Wa) and reference values (Re): sources of variation, degrees of freedom (d.f.) and p-values, obtained with GLM.

Source	d.f.	Bulk density			Penetration resistance		
		p-value for depth interval (cm)			p-value for depth (cm)		
		0-10	10-20	20-30	5	15	25
Te	2	0.164	0.095	0.156	0.586	0.236	0.105
Ma	1	0.290	**<0.001**	**0.036**	0.773	0.059	0.241
Tr	1	**0.018**	0.762	0.965	0.159	0.304	0.424
St(Te)	5	**<0.001**	**<0.001**	**< 0.001**	**<0.001**	**<0.001**	**<0.001**
Po	1	0.351	0.446		0.229	0.311	0.479
Ti	1	**0.019**	**<0.001**	**0.004**	**<0.001**	**<0.001**	**<0.001**
Wa	1	0.362	**<0.001**	0.369	0.683	**<0.001**	**0.018**
Re	1	**<0.001**	**<0.001**	**< 0.001**	**<0.001**	**<0.001**	**<0.001**
Te*Ma	2	0.135	0.744	0.564	**<0.001**	0.629	0.321
Te*Tr	2	0.171	0.918	0.654	0.283	**0.020**	**0.018**
Te*Po	2	**0.050**	**0.035**	0.921	**0.032**	0.111	0.354
Ma*Tr	1	0.237	0.261	0.548	0.820	**0.005**	**0.003**
Ma*Po	1	0.567	0.849	0.521	0.411	0.390	**0.003**
Tr*Po	1	0.668	0.394	0.936	0.206	**0.020**	**<0.001**

Significant p-values (p <0.05) are marked in bold.

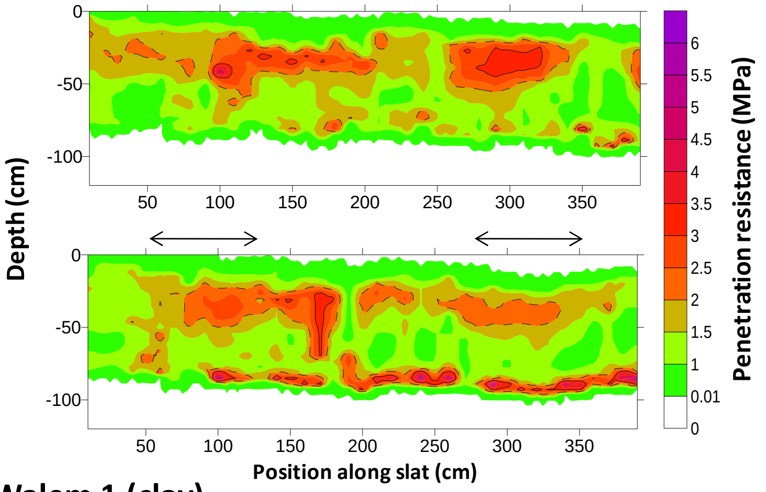
2.4.3 Correlation between bulk density and penetration resistance

BD and PR are both indicators for the extent to which a soil is compacted. A positive relationship existed between these two variables, although the shape (e.g., linear, logarithmic) of the relationship was not clear. Pearson correlation coefficients were 0.469 (p <0.001) at soil depth 0-10 cm, 0.391 (p = 0.001) at soil depth 10-20 cm and 0.226 (p = 0.073) at depth 20-30 cm. As coefficients were significant for the first and second depth intervals, we can conclude for these depths that PR reaches higher values as BD increases.

2.4.4 Micro-topography

The micro-topography of Kapellen 1 (Fig. 2.7A) and Walem 1 (Fig. 2.7B) shows a vertical section of the soil, perpendicular to the direction of the skid trail, before and after five skidding cycles of the heavy machine in February. For Kapellen 1, in several parts of the soil PR before applying treatments already exceeded 2 MPa, or even 3 MPa. However, the load exerted by the machines did not enlarge these areas and rut formation was very restricted. In Walem, before treatments were executed, the soil was loose, with very few areas where PR was larger than 2 MPa. After the treatment, there was a clear formation of deep ruts with bulges on the edges. PR also showed a clear increase under the wheel tracks. Large areas could be detected where values exceeded 2 MPa, but they remained below 3 MPa for the major part.

A. Kapellen 1 (sand)



B. Walem 1 (clay)

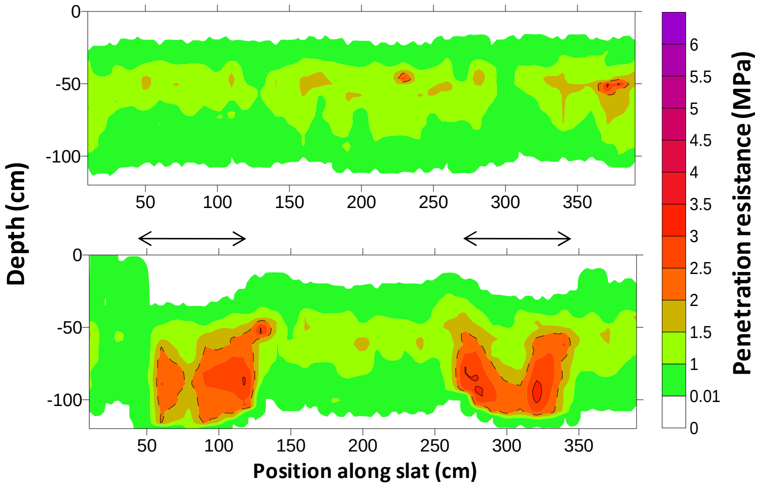


Fig. 2.7 Microrelief (rut depth and penetration resistance) on a sand (A) (Kapellen 1) and clay (B) (Walem 1) texture, before (above) and after (below) five skidding cycles of the heavy machine in the experiment in February (n = 1). The legend indicates values of the penetration resistance; the dotted line shows the isolines for 2 MPa, the full line shows the isoline for 3 MPa. The black arrows indicate the position of the wheel tracks after traffic.

2.4.5 CO_2 concentration

Soil CO_2 concentration was measured in one forest stand on sandy texture (Fig. 2.8). Except for block B, soil CO_2 concentration beside tracks was always higher than 1%. From the results of block A, the location of the wheel tracks could not be deduced as values were generally high (about 3%). These results contrast with block B where values were around 1%. Here, it was easy to discriminate between wheel tracks and the area that was not driven in the experiment, as values had clearly increased within tracks (30-100%). The area between wheel tracks also showed a slight increase of CO_2 concentration. After five skidding cycles of the heavy machine in February, the results were more pronounced. Both blocks C and D showed strong increases of CO_2 concentration within wheel tracks and a somewhat smaller increase between wheel tracks for block C. Traffic intensity obviously had a great influence on the increase of the CO_2 concentration. CO_2 concentrations also clearly differed according to the position in relation to the wheel tracks. In contrast with BD and PR, differences between the locations (area beside wheel tracks, area within wheel tracks and area between wheel tracks) were much more pronounced. This conclusion could be deduced from the results of the ANOVA analysis (Table 2.6). The area beside tracks always had the smallest CO_2 concentrations, mostly followed by the area between wheel tracks. The CO_2 concentration of the area between wheel tracks did not always differ significantly from the area beside tracks and was still significantly lower than the area within wheel tracks. Apart from these measurements along the transects, a few extra measurements have been performed on an area between trees that were standing very close to each other (<2 m). This area has certainly not been disturbed by machines since at least five decades and therefore these measurements can be seen as a true reference for an undisturbed situation. The mean CO_2 concentration here was 0.54%. All blocks showed significantly higher values (except for block B), not only within and between wheel tracks, but also on the area beside the wheel tracks.

Table 2.6 CO_2 concentration in a sandy soil (Kapellen 2) as influenced by the position in relation to the wheel tracks (Kapellen 2) (One-Way ANOVA). Positions with significantly different CO_2 concentrations are marked with different letters.

Block	Treatment	p-value	
A	**One skidding cycle**	<0.001	Beside tracks^a < within tracks^b < between tracks^b
B	**One skidding cycle**	<0.001	Beside tracks^a < between tracks^a < within tracks^b
C	**Five skidding cycles**	<0.001	Beside tracks^a < between tracks^b < within tracks^c
D	**Five skidding cycles**	<0.001	Beside tracks^a < between tracks^a < within tracks^b

For each block, means of all positions are compared against each other after ANOVA using Tukey's HSD test (p-values are mentioned). Positions that have significantly different mean CO_2 concentrations are marked with different letters.

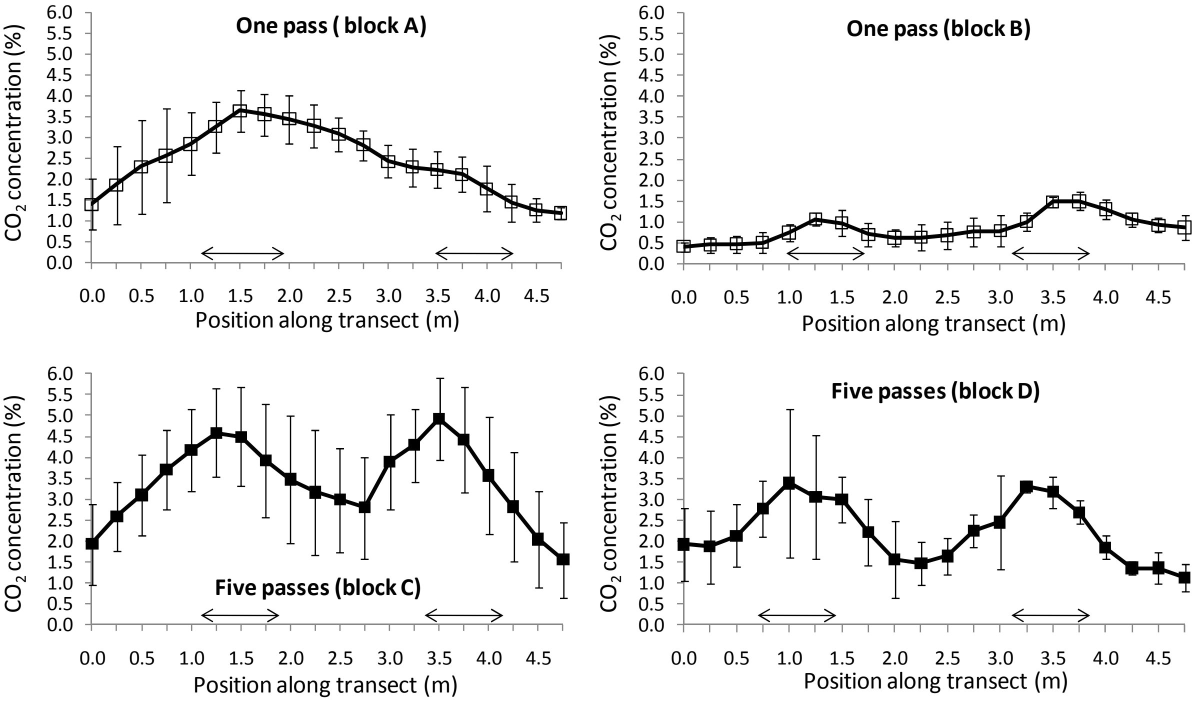


Fig. 2.8 Mean CO_2 concentration in a sandy soil (Kapellen 2) after one (above) and five (below) skidding cycles of the heavy machine in the experiment in February (blocks A and B as replications for one skidding cycle; blocks C and D as replications for five skidding cycles) (within each block n = 5). The black horizontal arrows indicate the position of the wheel tracks after traffic. Error bars represent the 95% percent confidence interval.

2.5 Discussion

2.5.1 Characteristics dominating the impact of traffic on bulk density, penetration resistance and micro-topography

Fine textures, such as clay and silt to loam textures are considered to be more vulnerable to compaction than coarse textures (Larson et al. 1980; Hillel 1998; Fisher & Binkley 2000). However, overall compaction degrees measured with BD were low to negligible, both on clay, loam to silt loam and sand. PR indicated increases after machine traffic of 60-70% on sand and 50-100% on clay, especially after five passes of the heavy machine. Except for H5S on clay, treatments induced similar PR increases for both textures. However, these increases were low compared to the findings of Alban et al. (1998) and Smith & Du Toit (2005) for sandy soils and Brais (2001) for silty clay to sandy loam soils, and PR values remained below the threshold for root growth (3 MPa; Whalley et al. 1995). A possible explanation for the rather low ratios of sandy soils, apart from the naturally lower vulnerability, and loam to silt loam soils follows from the initial BD and PR in Tables 2.3 and 2.4. Mean references of Sperwer, Goden and Kapellen 1 were higher than 1400 kg m^{-3} while Havik, Renissart and

Kapellen 2 had initial BD above 1300 kg m^{-3}. Forest soils where bulk density values exceed 1300 kg m^{-3} can be considered as compacted, especially in case of medium- to fine-textured soils (Von Wilpert K, *personal communication*). Lal & Shukla (2004) also indicated from an agricultural perspective that the optimal range of soil bulk density is lower than 1400 kg m^{-3}. Ampoorter et al. (2008) concluded that the initial BDs of the forest stands on loam to silt loam of this field experiment (especially Sperwer and Goden) are higher than elsewhere in Flanders. Mean reference values for PR in Leuven and Kapellen were all between 1 and 2 MPa, designated as ‘moderate’ according to the Soil Survey Division Staff (1993). The term ‘mean reference’ indicates that this part of the soil was left untrafficked at the last harvesting activity but its high initial BD and moderate initial PR in forest stands in Leuven and Kapellen suggest a strong underlying compaction, due to uncontrolled machine traffic during past harvesting activities. Moreover, GLM and Pearson correlations showed a significant negative influence of the initial BD and PR on the compaction degrees, as was also stated by Powers et al. (2005). Loose soils contain an abundance of macropores that are easy to compact, in contrast with compacted soils where macropores are scarce. Smaller pores exert a higher resistance to compaction (Shetron et al. 1988; Hillel 1998; Berli et al. 2003), leading to higher soil strength and consequently higher precompression stress on compacted soils. A machine pass will only result in soil compaction if the stress applied by the machine exceeds the soil precompression stress (Horn et al. 1997). Machine traffic on an already compacted soil thus results in a small to negligible additional impact (Incerti et al. 1987; Williamson & Neilsen 2000; Page-Dumroese et al. 2006). If the initial precompression stress of the examined forest stands had been less, the soil impact due to the treatments would probably have been much higher and maybe significant. The fact that the values after applying treatments were sometimes significantly lower than those of the mean reference (especially for Kapellen 2) was probably due to a high spatial variation in the topsoil, in part dependent on the pattern of the precompression stress due to former harvesting activities.

The rather low compaction degrees on clay soils can be explained by means of the soil water content. The very high water contents in Walem (Table 2.1) clearly exceeded the optimum water content (Fig. 1.2; Smith et al. 1997; Hillel 1998), and thus most pores are filled with water that cannot be compressed (Froehlich & McNabb 1984). Cohesion between particles is low in this condition (Al-Shayea 2001) and the soil has only a small ability to withstand applied machine forces. Therefore machine traffic resulted in strong plastic deformation (rut type 1) and relatively small compaction degrees as was shown by Tables 2.3 and 2.4 and Figs. 2.6 and 2.7. However, in spite of the low compaction, machines may still have imposed a serious threat for the soil ecosystem as soil pores are closed off and pore continuity is destroyed, leading amongst others to hampered soil aeration.

Looking at all three texture groups together, Pearson correlations showed that compaction degrees seemed to increase with increasing soil water content. Compaction degrees were overall limited and GLM did not show a significant influence of texture. However, the significant correlation between compaction degree and soil water content is rather logic as the forest stands in Walem showed overall slightly higher compaction degrees compared to the other two soil texture groups, combined with overall much higher soil water contents. Looking at the correlation between compaction degree and soil water content for each texture group separately, most of the relationships were negative. As mentioned previously, soil water contents of Walem (clay) were much higher than the optimum soil water content (Hillel 1998) resulting in a decrease of the BD obtained after application of a force at increasing soil water contents. In Leuven (loam to silt loam soils) soil water contents were intermediate (September) to high (February), and probably on average higher than the optimum soil water content for these soil textures, resulting in a negative correlation with the compaction degree. The negative correlation between BD and soil water content at the sandy sites in Kapellen could not be explained as soil water contents were probably higher than the critical soil water content for these textures (Smith et al. 1997; Langohr & Ampe 2004) and thus a positive relationship was rather expected.

Compaction degrees are positively influenced by the machine mass, or rather the soil contact pressure. The estimation of the soil contact pressure showed that the heavy machine induced a higher soil pressure than the light machine and that soil compaction would thus be more severe (McDonald et al. 1996).

The increase of BD was positively related to the traffic intensity in the first depth interval and PR showed a similar effect for the heavy machine. The first pass of a machine exerts a pressure on the soil surface, affecting soil structure and porosity when the applied stress encompasses the precompression stress of the soil (Horn et al. 2007). As pores become smaller, they exert a higher resistance to compaction (Shetron et al. 1988; Williamson & Neilsen 2000), increasing soil strength and thus precompression stress. The following passes of this machine will have a diminishing influence on the soil structure until the applied stress no longer exceeds the constantly increasing precompression stress (Horn et al. 2007). Brais & Camiré (1998) and Seixas et al. (2003) confirmed that this relationship is logarithmic with smaller compaction degrees approaching zero at higher traffic intensities. However, due to a low number of traffic intensity levels, this logarithmic relationship could not be stated here.

When a machine makes a pass, not only is the soil under the tyres influenced, but indirectly machine forces also partially influence the soil around it (both between and next to the wheel tracks) due to lateral movement of soil from beneath the wheel tracks (Wronski 1984) and shear stress caused by rotations of the tyres (Abeels 1989; Vossbrink & Horn 2004). However, as the compaction degrees after most of the treatments were already negligible within wheel tracks (Tables 2.3 and 2.4) due to the high precompression stress before the experiment took place, no significant influence arises from the position in relation to the wheel tracks (Table 2.5). However, GLM showed a significant interaction between position and traffic intensity for PR at 15 and 25 cm. After one skidding cycle, the direct effect within tracks did not differ very much from the indirect effect between tracks. However, after five skidding cycles, the cumulated direct effect showed a significant difference with the cumulated indirect effect.

Within one texture group, compaction degrees seemed to differ significantly between the forest stands (Table 2.5), likely due to differences in organic matter content (Sands et al. 1979), precompression stress (Horn et al. 2007), soil water content (Smith et al. 1997; Hillel 1998;) or bioturbation. Moreover, slightly different soil water contents between September and February may have led to small differences in compaction ratios, explaining the significant impact of time.

2.5.2 Relationship between bulk density and penetration resistance

A positive relationship could be observed between the reference values of BD and PR. As BD increases, the pore space is reduced, significant soil particle rearrangement hence becomes problematic (Whalley et al. 2005) and the friction experienced by the penetrologger cone increases rapidly. Henderson et al. (1988), Vaz et al. (2001) and Ampoorter et al. (2007, Chapter 3) also stated this positive relationship, and reported a logarithmic shape, with stabilization of BD at higher PR. The shape of the relationship between BD and PR in this study was not clear, probably due to high reference BDs at Leuven and Kapellen and high variation.

2.5.3 Impact of mechanized harvesting on soil CO_2 concentration

The mean CO_2 concentration in the superficial layer of an undisturbed part of the forest soil in Kapellen 2 was already more than tenfold higher (0.54%) than the natural atmospheric CO_2 concentration (0.03-0.04%) due to decomposition of organic matter and respiration by fauna and flora (Ameryckx et al. 1995). Soil CO_2 concentration beside tracks was even higher (>1% in blocks A, C and D), indicating traces of the impact of former mechanized harvesting activities on soil aeration, as was stated for BD. In contrast to BD and PR that showed small to negligible impacts, CO_2 concentration was significantly increased by the skidding cycles of the heavy machine. The impact increased with increasing traffic intensity, as was also found by Brais & Camiré (1998) and by Seixas et al. (2003) for other soil variables. CO_2 concentrations within tracks were significantly higher than the soil beside tracks, as was stated by Conlin & van den Driessche (2000), reaching concentration levels over 4%. Between tracks, values were lower but also clearly increased. Namely, as with compression of soil pores destruction of pore continuity is largely realized by direct contact between soil and tyres. The area between wheel tracks is only indirectly influenced by machine traffic and therefore the impact on CO_2 concentration between tracks remained smaller than within tracks. The impact on CO_2 concentration was not a consequence of pore compression, as the impacts on BD and PR were negligible due to high precompression stress on the sandy soil in Kapellen 2. It resulted rather from the destruction of pore continuity, hampering CO_2 efflux towards the free atmosphere (Ponder 2005; Gebhardt et al. 2009) so that CO_2, produced by soil organisms and chemical processes, accumulated in the sealed pores. This may cause problems at higher compaction degrees as root growth of seedlings is reduced when the O_2 concentration drops beneath the 6-10% range (Schumacher & Smucker 1981; Grant 1993; Fisher & Binkley 2000). Qi et al. (1994) and Gaertig et al. (1999) indicated a negative effect on growth when soil CO_2 concentration exceeds 0.6-0.7%, due to a reduction of the root respiration. The precompression stress beside tracks thus already constitutes a hazard that is strongly intensified within and between wheel tracks.

In soils with initially elevated compaction levels, BD and PR are thus not reliable compaction indicators. Results showed that CO_2 concentration seems to be a better, more sensitive indicator of soil damage. It was already used in several studies (e.g., Gaertig et al. 2000). The overall use of soil CO_2 concentration would probably have resulted in a much higher amount of significant differences between treatments in this field trial (and Chapters 3, 6 and 7). However, we do not possess a device that is adapted to measure soil CO_2 concentration accurately and efficiently. For the sandy forest soil in Kapellen 2, we could use the portable gas chromatograph of the Forstliche Versuchs- und Forschungsanstalt (FVA) in Baden-Württemberg. So, although we are fully aware of the importance of CO_2 concentration for the assessment of soil damage, we could not make use of this indicator in the further work. Moreover, we remark that the chapter order does not reflect the chronology in which the field trials were executed. Measurements for Chapters 3 and 6 were already performed before the suitability of the soil CO_2 concentration for quantification of the machine impact became clear at measurements in Kapellen 2.

A Timberjack 1070D harvester, processing a tree, in Putte (Chapter 3) [photograph: Robbie Goris, August 2004].

3 Compaction of sandy forest soils

After: Ampoorter E, Goris R, Cornelis W, Verheyen K (2007) Impact of mechanized logging on compaction status of sandy forest soils. Forest Ecology & Management 241, 162-174

3.1 Abstract

The impact of skidding traffic on bulk density and penetration resistance of two sandy forest soils was examined in Putte (the Netherlands). Different levels of compaction were applied by varying the number of skidding cycles: one pass harvester (H), one pass harvester and forwarder (H+F), multiple passes of both machines (Max). Bulk density and penetration resistance were measured on the undisturbed surface (UD), between the wheel tracks (BT) and within the tracks (WT). For WT, treatment H induced a clear increase of both soil properties in the upper 30 cm of the soil profile compared to the UD. The continuation of the passes to Max only resulted in a limited rise in bulk density. However, penetration resistance was significantly higher for Max compared to H. BT values were situated between UD and WT. Measurements taken within tracks where logging residues were piled up to 40 cm revealed that a brash mat could reduce the compaction level to a considerable extent. The relationship between bulk density and penetration resistance appeared to be non-linear, with bulk density becoming insensitive to penetration resistance changes at higher penetration resistance values. On these sandy soils, we recorded significant increases of bulk density and penetration resistance, but rarely exceeding growth limits for optimal root elongation. However, certain soil characteristics such as soil oxygen concentration may already be influenced at lower compaction levels, inducing negative effects on plants and soil organisms. Moreover, sandy soils are expected to recover very slowly. Designated skid trails should thus also be used on this soil type to minimize the influence on the ecosystem.

3.2 Introduction

In forest harvesting, there is an ongoing trend to increase almost constantly the size, power and load of logging machines, with weights that generally amount up to 12-16 tonnes in unloaded state. This may cause soil degradation in forest ecosystems as the passes of these machines modify important soil structural characteristics. It may imply a reduction of the total porosity (Herbauts et al. 1996; Teepe et al. 2004) and pore continuity (Berli et al. 2003), an increase of BD (Alban et al. 1994; Miller et al. 1996) and PR (Aust et al. 1998; Nugent et al. 2003), restricted gas exchange (Ballard 2000), lowered saturated hydraulic conductivity (Benthaus & Matthies 1993) and infiltration rate (Dickerson 1976). Chemical processes may also be altered, due to a changed air and water balance (Arocena 2000; Ballard 2000). Machine traffic thus changes important soil structural characteristics and may therefore influence root penetration (Heilman 1981), growth (Gebauer & Martinková 2005) and survival of seedlings (Brais 2001; Stone & Kabzems 2002; Maynard & Senyk 2004), diversity of the herb layer (Small & McCarthy 2002; Decocq et al. 2004; Godefroid & Koedam 2004) and soil fauna (Smeltzer et al. 1982; Radford et al. 2001; Battigelli et al. 2004). As soil fauna play an important role in ecosystem processes such as decomposition (Gobat et al. 1998), this may indirectly lead to reduced soil fertility.

It is assumed that traffic effects are most pronounced on clayey or loamy textures (Larson et al. 1980; Fisher & Binkley 2000) and therefore, few studies have focused on compaction of sandy soils until now. Nevertheless, Brais & Camiré (1998) stated compaction on sandy forest soils. McNabb (1995) emphasized that texture has a relatively small impact on the compactibility of forest soils, although texture still is an important factor determining how a plant performs in compacted soil. Moreover, this is a relevant topic given the large surfaces covered by forests on sandy soils, especially in the north-western European lowlands (Bohn & Neuhausl 2000-2003), and the often strong mechanization with an intense use of heavy machinery, like forwarders, harvesters and skidders, in the (pine) plantation forests that are common on these soils (e.g., Larsson 2001). Furthermore, compacted sandy soils will recover slowly (Greacen & Sands 1980; Fisher & Binkley 2000). Freezing and melting of soil water (Alban et al. 1994; Startsev & McNabb 2000), the swelling and shrinking of clay particles (Greacen & Sands 1980; Fisher & Binkley 2000; Cornelis et al. 2006) and biological activity (Brais & Camiré 1998; Jordan et al. 1999; Ponder et al. 2000) generally make a great contribution to the recovery process. However, sandy soils lack the capacity to hold an adequate quantity of water owing to their large amount of wide pores that drain immediately, and a large amount of swelling clay particles is neither present. Moreover, their generally low pH, nutrient and soil water content reduce the diversity of soil fauna and the herbaceous layer (Hansen & Rotella 1999). Therefore, if sandy soils are proved to be prone to critical compaction, particularly during the first pass of logging machines, within-stand traffic should be minimized (Deconchat 2001; Teepe et al. 2004) and/or mitigating measures should be taken, such as the use of brash mats. These are thick layers, made up of tree remnants that are put in front of the machine during logging (Schäfer & Sohns 1993; McDonald & Seixas 1997; Hutchings et al. 2002).

Hence, the aims of this study were:

a) To measure the extent to which the BD and PR of sandy soils are affected by heavyweight logging traffic;
b) To assess the potential of a brash mat to reduce the degree of soil compaction.

Results will be considered in the light of the discussion whether spreading the traffic or concentrating the vehicles on designated skid trails is beneficial in case of sandy soils.

3.3 Materials and methods

3.3.1 Site description

Two ageing pine plantations (~6 ha each), a very common forest type on sandy soils, were selected for this study. The stands are located in Putte, in the south of the Netherlands. In this region, the mean temperature in the coldest month (February) is -0.6 °C and 21.7 °C in the warmest month (July). Mean total annual precipitation is 804 mm. Geomorphologic characteristics of site 1 comprise continental dunes accompanied by plains and depressions. The soil in the area is classified as a Podzol (IUSS Working Group WRB 2006). However, at the time of afforestation of the former heathland on site 1, the podzol was broken by ploughing and hence, no clear horizons could be distinguished now. The texture of the soil is ranging from sand to loamy sand (Soil Survey Staff 1999). The forest stand is composed of a tree layer of first generation 75 years old Scots pine (*Pinus sylvestris* L.) with a shrub layer dominated by the invasic Black cherry (*Prunus serotina* Ehrh.). Site 2 lays on terrace deposition vaults covered with eolian sand deposits. The soil is referred to as a Plaggic Anthrosol (IUSS Working Group WRB 2006). This designation holds soils that were formed or profoundly modified through human activities such as addition of organic materials or household wastes, irrigation or cultivation (FAO 2001). The plaggic horizon is more than 50 cm thick and is the only horizon that could be distinguished. The texture is ranging from sand to loamy sand (Soil Survey Staff 1999). The forest stand at site 2 is composed of a mixed tree layer of first generation 75 years old Scots pine and Corsican pine (*Pinus nigra* Arnold subsp. *laricio* Maire). The shrub layer is dominated by Black cherry with sparsely Silver birch (*Betula pendula* Roth) and European mountain-ash (*Sorbus aucuparia* L.). For both sites the highest groundwater level is always below a depth of 80 cm.

3.3.2 Experimental design and data collection

Careful mechanized thinning, using designated skid trails, took place between August and October 2004. This was the first time ever that a mechanized exploitation was performed in the selected stands. At time of harvesting on site 1, weather conditions had been very dry and warm for over more than three weeks and these conditions remained more or less constant during harvesting. When taking soil samples for BD, soil moisture content varied between 9% at the surface and 3% at 50 cm depth. At site 2 weather conditions had also been very dry for more than three weeks, but it frequently rained during the harvest period. Soil moisture content was therefore higher in comparison with site 1, but data with regard to this are not available.

The machinery consisted of standard cut-to-length equipment, being a middleweight Timberjack 1070D harvester and a Timberjack 1110D forwarder. The tyres of the harvester measured 700/45 x 22.5 on the front axle, 650/60 x 26.5 on the rear axle and were inflated to a pressure of 300 kPa. Its total weight was 16 tonnes in the proportion of 60% on the front to 40% on the rear axle. The forwarder weighed about 15 tonnes in unloaded state, with a maximum of 25 tonnes in loaded state.

Different levels of compaction were applied by varying the levels of machine traffic (Fig. 3.1): one harvester pass (H), one pass of both harvester and forwarder (H+F), and several passes of both machines (at least three with a maximum in the order of seven) (Max). A pass implies a drive back and forth the selected strip, and fully loaded in the case of the forwarder. The measurements for Max took place on the designated skid trails. For H and H+F specific locations in the forest were chosen, where further traffic was prohibited after the treatment. The sampling and measurement positions relative to skid trails were: within the wheel tracks (WT), between the tracks (BT) and in the adjacent undisturbed area (UD). For each site, UD measurements were the same for all treatments, and serve as a reference. They were taken on places where the forest floor and the mineral soil were left undisturbed after logging. In order to assess the influence of a brash mat (BM) on the degree of soil compaction, supplemental measurements were carried out on positions in the wheel tracks of the designated skid trails (Max (WT-BM)) where logging residues were piled up to at least 40 cm.

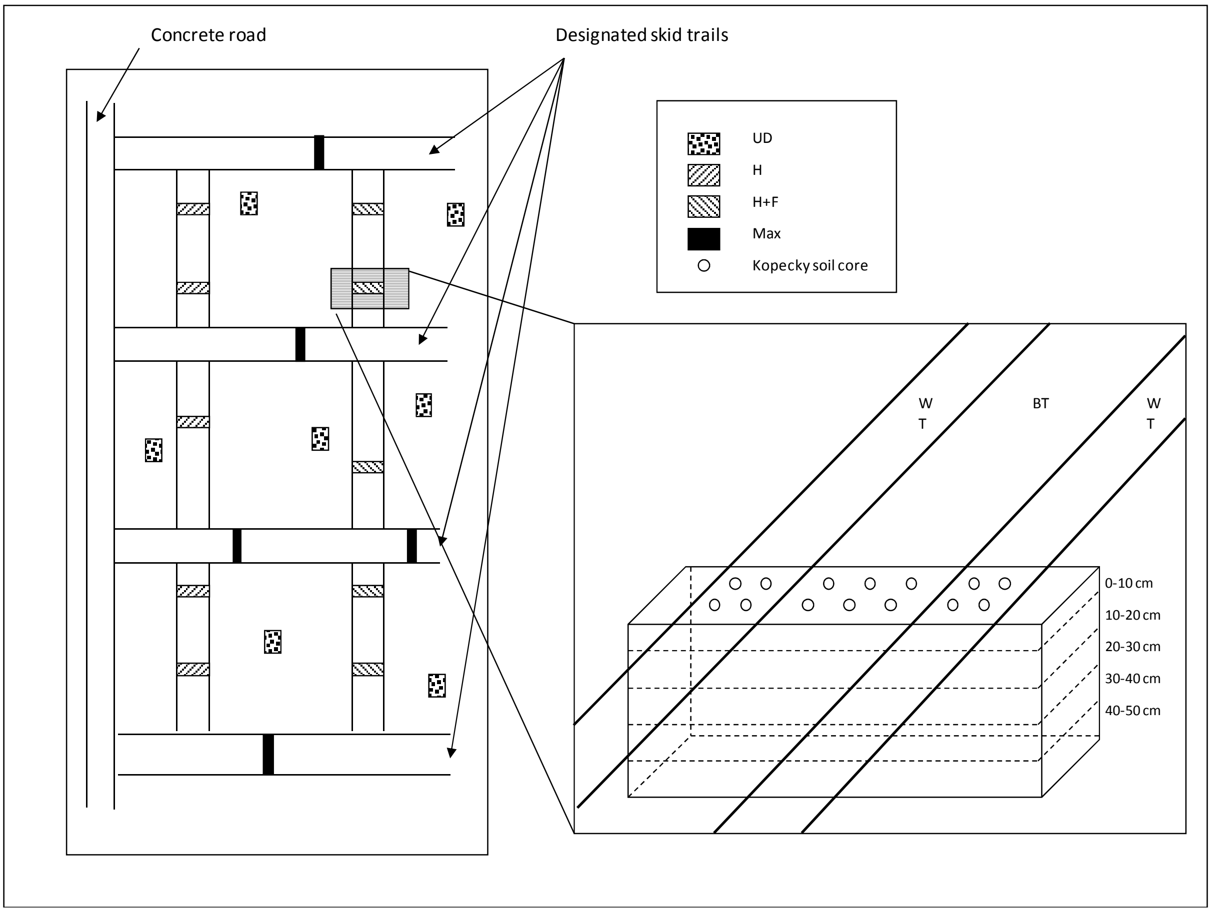


Fig. 3.1 Sketch of the experimental set-up with the location of the pits within the two stands and a close-up of the sampling method for bulk density (for abbreviations, see Table 3.1).

Sampling for dry BD was done by means of Kopecky soil cores (5 cm diameter, 100 cm³). On different locations within the harvested stand, small pits were dug on the undisturbed surface and across the skid trails. In the WT, BT and UD parts of the skid trails, undisturbed mineral soil samples were taken between 0 and 50 cm depth (measured from the surface) at depth intervals of 10 cm (Fig. 3.1), while sampling to study the influence of a brash mat was limited to the upper 30 cm. As wheel rutting was confined to a few centimetres, sampling depth per depth interval was equal in UD, WT and BT. Samples were oven dried (105 °C) for 24 h prior to weighing. PR was measured at 1 cm intervals until a depth of 80 cm using a penetrologger (Eijkelkamp Agrisearch Equipment, the Netherlands). Sixty-degree cones were used with a cone basal area surface of 1 cm² (nominal diameter 11.28 mm). The penetrologger was driven into the soil at equal intervals along the treated area, thereby accounting for the variability of the soil within the stands. Because of the dependency of PR to soil water content (Smith et al. 1997; §3.5.3), measurements were carried out at the same day in December when soil was near field capacity after a long rainy period. Table 3.1 summarizes the number of replications for each treatment for BD and PR. A total of 218 PR measurements were carried out and 2464 soil samples were taken to estimate BD.

Table 3.1 Number of pit locations and n per pit per depth interval for bulk density and n per depth interval for penetration resistance (UD: undisturbed area, H: one pass harvester, H+F: one pass of both harvester and forwarder, Max: many passes of harvester and forwarder, WT: within tracks, BT: between tracks, BM: brash mat present).

Treatment		Dry bulk density				Penetration resistance	
		Site 1		Site 2		Site 1	Site 2
		Pit locations	(n per pit per depth interval) x (number of depth intervals)	Pit locations	(n per pit per depth interval) x (number of depth intervals)	n per depth interval	n per depth interval
UD		7	4 x 5	7	4 x 5	20	28
H	WT	5	8 x 5	5	8 x 5	No sampling	20
	BT	5	6 x 5	5	6 x 5	No sampling	20
H+F	WT	5	8 x 5	5	8 x 5	No sampling	20
	BT	5	6 x 5	5	6 x 5	No sampling	20
Max	WT	5	8 x 5	5	8 x 5	20	20
	BT	5	6 x 5	5	6 x 5	20	20
	WT-BM	No sampling		7	4 x 3	No sampling	10

3.3.3 Data analysis

Since the UD values of the two sites were clearly different and since harvesting was done under different weather conditions, which could have affected the impact of the logging activity, data analysis for sites 1 and 2 was done separately. The purposes of the statistical tests were to search for important increases of BD and PR as a result of harvesting on these two sites and to seek for factors which are important in determining the degree of the increase. The following techniques were applied (using S-Plus and SPSS):

(1) Differences in soil BD between the treatments were analysed for each distinct depth interval using One-way ANOVA. For PR, although measured at 1 cm intervals, analysis was done only for the values at 10 cm depth intervals. Therefore, the average value was calculated for all measurements (replications) at 5 cm depth, at 15 cm depth and so on. Pair-wise comparisons were conducted using Tukey's HSD test with $\alpha = 0.05$.

(2) We further applied GLM to relate BD and PR to pit *location* (only for BD), *depth* (five levels for BD and eight levels for PR), *treatment* (H, H+F, Max, BM) and *position* in relation to the tracks (WT, BT). UD-values were not incorporated in this analysis, in order to obtain a correct interpretation of the importance of the interactions between factors. Moreover, values of the undisturbed surface (UD) were already compared with all other treatments performing ANOVA. *Treatment* and *position* were considered as fixed factors, *depth* as a random factor. *Location* was regarded as a random factor, nested within *treatment*. All two-way interactions, except for combinations with *location*, were included.

(3) As BD and PR are both indicators for the extent to which a soil is compacted (compaction degree), and BD is often used as a parameter to estimate PR (Whalley et al. 2005), the correlation between the two variables was determined by means of a Spearman's rank correlation coefficient.

3.4 Results

3.4.1 Relationship between traffic level, position and compaction degree

3.4.1.1 Bulk density at site 1

In the undisturbed parts (UD) of site 1 (Fig. 3.2A), BD increased from 1309 kg m^{-3} at the soil surface (0-10 cm) to 1422 kg m^{-3} in the interval 10-20 cm. From that depth interval onwards, BD remained constant with depth. Within the tracks (WT), BD increased clearly in comparison with UD, irrespective of the kind of treatment (H, H+F, Max) (Table 3.2). For all treatments, except for H in the interval 0-10 cm, this increase was particularly pronounced and significant ($p < 0.001$) up to 30 cm depth. The UD and Max (WT) values even differed significantly within each depth interval, except for 30-40 cm. Deeper in the soil profile, differences between UD and the treatments became smaller. With respect to H, Max only resulted in a small extra BD increase. The difference increased with depth but remained insignificant. The effect of H+F on BD was rather different compared to H and Max, showing a maximum in the depth interval 20-30 cm. Further, H+F resulted in the highest BD, reaching 1565 kg m^{-3}. With respect to the BD between the tracks (BT), lower values were generally observed compared to WT. For BT, a peak can also be seen in the depth interval 10-20 cm, except for treatment H where values increased until the depth interval 30-40 cm.

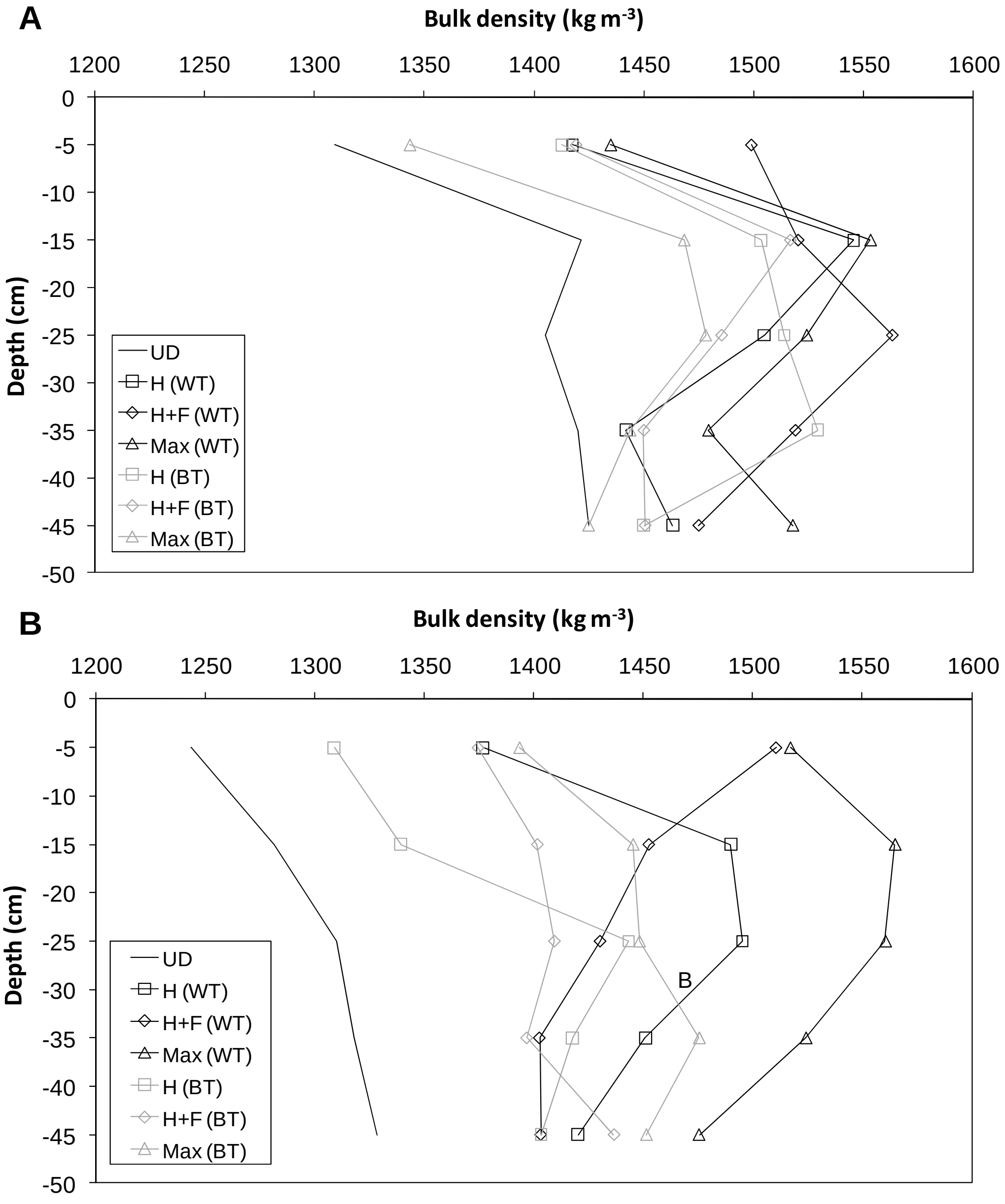


Fig. 3.2 Treatment effect on bulk density in function of depth on site 1 (A) and site 2 (B) (for abbreviations, see Table 3.1).

Table 3.2 Mean bulk density (kg m^{-3}) (± standard deviation) as influenced by depth, treatment and position.

Depth (cm)	F-ratio	p-value	Bulk density (kg m^{-3})						
			UD	WT			BT		
				H	H+F	Max	H	H+F	Max
Site 1									
n			28	40	40	40	30	30	30
0-10	5.153	<0.001	1309 ± 250 a	1417 ± 124 abc	1499 ± 102 c	1435 ± 144 bc	1413 ± 182 abc	1419 ± 100 abc	1344 ± 181 ab
10-20	5.957	<0.001	1422 ± 118 a	1546 ± 100 c	1520 ± 125 bc	1553 ± 93 c	1503 ± 137 abc	1517 ± 71 bc	1468 ± 92 ab
20-30	11.186	<0.001	1405 ± 105 a	1505 ± 76 b	1563 ± 87 c	1524 ± 69 bc	1514 ± 70 bc	1485 ± 107 b	1478 ± 52 b
30-40	4.650	<0.001	1420 ± 122 a	1442 ± 90 a	1519 ± 105 b	1479 ± 124 ab	1529 ± 55 b	1450 ± 117 ab	1444 ± 107 ab
40-50	3.381	0.003	1425 ± 142 a	1463 ± 98 ab	1475 ± 99 ab	1518 ± 86 b	1450 ± 65 ab	1450 ± 115 ab	1425 ± 112 a
Site 2									
n			28	40	40	40	30	30	30
0-10	18.408	<0.001	1244 ± 117 a	1377 ± 143 b	1511 ± 113 c	1517 ± 126 c	1309 ± 105 ab	1375 ± 126 b	1393 ± 196 c
10-20	18.280	<0.001	1281 ± 115 a	1490 ± 101 cd	1453 ± 120 c	1565 ± 119 d	1339 ± 132 ab	1402 ± 113 bc	1445 ± 175 c
20-30	14.416	<0.001	1310 ± 110 a	1495 ± 74 cd	1430 ± 83 b	1560 ± 88 d	1443 ± 77 b	1409 ± 117 b	1448 ± 207 bc
30-40	13.695	<0.001	1318 ± 86 a	1451 ± 73 bc	1403 ± 94 bc	1524 ± 83 d	1418 ± 82 bc	1397 ± 130 b	1475 ± 146 cd
40-50	9.145	<0.001	1329 ± 57 a	1420 ± 68 bc	1403 ± 100 b	1476 ± 80 c	1403 ± 65 b	1436 ± 100 bc	1451 ± 119 bc

For each soil interval, means are compared against each other after ANOVA using Tukey's HSD test (p-values are mentioned). Significant differences between means within a row are marked with different letters (for abbreviations, see Table 3.1).

Table 3.3 Bulk density as influenced by depth, treatment and position: sources of variation, degrees of freedom (d.f.), F-ratio and p-values, obtained with GLM.

Source	Site 1			Site 2		
	d.f.	F-ratio	p-value	d.f.	F-ratio	p-value
Treatment	2	0.259	0.776	2	1.449	0.264
Position	1	21.949	**0.009**	1	9.228	**0.038**
Depth	4	11.427	**0.005**	4	0.454	0.767
Location (Treatment)	12	18.120	**<0.001**	12	30.967	**<0.001**
Treatment x Position	2	12.605	**<0.001**	2	5.759	**0.003**
Treatment x Depth	8	2.059	**0.037**	8	7.167	**<0.001**
Position x Depth	4	1.815	0.124	4	11.428	**<0.001**

Significant terms are depicted in bold.

GLM indicated two significant interaction terms, being treatment x position (p <0.001) and treatment x depth (p = 0.037) (Table 3.3). It can be noticed that BD values of H (WT) and H (BT), summed over the total interval from 0 to 50 cm, are similar, contrary to H+F and Max where WT values are clearly higher than BT values (Fig. 3.2A), which explains the first significant interaction. Regarding the second interaction, values for the different treatments (summed over WT and BT) vary widely in the first depth intervals but converge again towards deeper layers. The interaction between position and depth was insignificant (p = 0.124). This can be attributed to the values of BT being generally lower than the WT values, while the curves run roughly parallel to each other for the whole interval 0-50 cm. The model also showed a strongly significant main effect for the factor location (p <0.001). In other words, the variability of the soil within the stand is, irrespective of depth and treatment, large enough to have an important influence on BD.

3.4.1.2 Bulk density at site 2

At site 2, reference values were lower than at site 1, although the maximum BD was approximately similar (Table 3.2). The change of BD with depth was rather different compared to site 1 (Fig. 3.2B). Again UD had the lowest BD values, which increased linearly with depth from 1244 to 1329 kg m^{-3}. Compared to UD, the increase of BD in terms of percentage owing to Max, measured 22, 22 and 19% in depth intervals 0-10, 10-20 and 20-30 cm respectively. BD at WT differed significantly from those at UD for all treatments within each depth interval. This was also true for BT, except for the treatment H in the first two intervals. BD values of BT were predominantly lower than the corresponding treatment BD values from WT. For most treatments, a local maximum was apparent at depth interval 10-20 or 20-30 cm. An increase in number of machine passes from H to Max resulted in a considerable rise in BD not only for WT but also for BT.

GLM revealed that all twofold interactions treatment x position (p = 0.003), treatment x depth (p <0.001) and position x depth (p < 0.001) are strongly significant (Table 3.3). Unlike site 1, differences between the two positions varied strongly depending on the depth interval. The differences were most pronounced in the surface layers and were markedly reduced towards deeper intervals, which explained the significant interaction between position and depth. With respect to the interaction treatment x position, bulk densities from

WT and BT differed more clearly for Max in comparison with H and H+F. Again soil variability within the stand resulted in a significant main effect of the factor pit location ($p < 0.001$).

3.4.1.3 Penetration resistance at site 1

At site 1, PR was only measured for UD, and for Max at WT and BT. For UD, the value rose steadily from 0.36 at the surface to 2.51 MPa at 80 cm depth, apart from a very local increase between 5 and 15 cm and a small peak from 45 to 60 cm (Fig. 3.3A). Max caused a sharp rise in PR at WT, particularly between the soil surface and 45 cm. The differences between UD and Max (WT) were significant up to 35 cm (Table 3.4). PR reached its maximum between 40 and 60 cm, with values of 3.5-4 MPa. For Max (BT) no significant difference with UD was found. Since on site 1, PR was only measured for Max, GLM contained only the factors position and depth (Table 3.5). A significant interaction existed between the factors position and depth ($p = 0.003$). Measurements from WT and BT differed clearly at 25 and 35 cm but were nearly equal at the surface and at 65 and 75 cm.

3.4.1.4 Penetration resistance at site 2

At site 2, PR was measured at UD, and for all treatments at WT and BT (Fig. 3.3B, Table 3.4). PR at UD was lower than on site 1 and increased gradually from 0.24 to 2.46 MPa. For the position WT, an increase in the number of machine passes resulted in a higher PR. Treatment H caused a clear PR increase compared to UD from 5 to 25 cm, with significant differences at 5 and 15 cm depth. Below 40 cm, no clear distinction could be made between H (WT) and UD. An extra pass of the forwarder (H+F) induced an insignificant PR rise. Max however, led to a strong PR increase, especially between 15 and 35 cm depth. The increase is also apparent in the deeper soil layers. Values of Max (WT) differed significantly from the other treatments from 15 cm to a depth of 65 cm. A local maximum PR of about 2.3 MPa was reached at 15-25 cm depth for Max (WT).

PR from BT was also higher than UD values on site 2, except for H (Fig. 3.3B). The higher the number of machine passes, the higher were the measured PR values. In contrast with BD, H did not increase the PR for BT. Max, however, resulted in higher PR, which were significantly different from UD at 5 and 15 cm depth (Table 3.4). Above 40 cm, values from BT were clearly lower than WT, but below this depth all curves converged towards the UD curve.

Table 3.4 Mean penetration resistance (MPa) (± standard deviation) as influenced by depth, treatment and position.

Depth (cm)	**F-ratio**	**p-value**	**Penetration resistance (MPa)**						
			UD	**WT**			**BT**		
				H	**H+F**	**Max**	**H**	**H+F**	**Max**
Site 1									
n			20			20			20
5	10.001	<0.001	0.99 ± 0.30 a			1.40 ± 0.39 b			0.91 ± 0.41 a
15	71.614	<0.001	1.14 ± 0.34 a			2.58 ± 0.37 b			1.31 ± 0.51 a
25	41.365	<0.001	1.44 ± 0.89 a			3.48 ± 0.85 b			1.42 ± 0.71 a
35	20.158	<0.001	1.68 ± 1.46 a			3.76 ± 1.43 b			1.43 ± 0.82 a
45	3.052	0.055	2.53 ± 2.06 a			3.65 ± 1.87 a			2.21 ± 1.69 a
55	0.737	0.484	2.95 ± 2.05 a			3.54 ± 1.78 a			2.74 ± 1.96 a
65	0.312	0.734	2.75 ± 2.13 a			3.29 ± 1.74 a			3.08 ± 3.08 a
75	0.307	0.737	2.64 ± 2.11 a			3.18 ± 1.74 a			2.92 ± 2.92 a
Site 2									
n			28	20	20	20	20	20	20
5	16.825	<0.001	0.65 ± 0.29 a	1.15 ± 0.40 bc	1.32 ± 0.34 cd	1.61 ± 0.60 d	0.53 ± 0.30 a	0.78 ± 0.25 ab	1.20 ± 0.80 c
15	32.679	<0.001	0.61 ± 0.30 a	1.36 ± 0.33 b	1.52 ± 0.49 b	2.33 ± 0.50 c	0.63 ± 0.40 a	1.13 ± 0.44 b	1.14 ± 0.64 b
25	18.591	<0.001	0.77 ± 0.29 a	1.33 ± 0.47 a	1.36 ± 0.54 a	2.21 ± 0.82 b	0.85 ± 0.44 a	1.08 ± 0.58 a	1.27 ± 0.74 a
35	7.806	<0.001	0.94 ± 0.45 a	1.19 ± 0.43 a	1.21 ± 0.43 a	1.75 ± 0.80 b	0.90 ± 0.27 a	1.12 ± 0.39 a	1.18 ± 0.59 a
45	6.110	<0.001	0.90 ± 0.29 ab	0.84 ± 0.28 a	1.15 ± 0.23 ab	1.59 ± 0.82 c	0.94 ± 0.47 ab	1.16 ± 0.35 ab	1.28 ± 0.91 bc
55	12.293	<0.001	1.18 ± 0.41 ab	0.98 ± 0.33 a	1.47 ± 0.38 ab	2.31 ± 0.99 c	0.95 ± 0.40 a	1.37 ± 0.30 ab	1.74 ± 1.05 b
65	6.555	<0.001	1.40 ± 0.62 a	1.56 ± 0.58 a	1.88 ± 0.50 a	2.78 ± 1.29 b	1.41 ± 0.58 a	1.93 ± 0.32 ab	2.07 ± 1.17 ab
75	1.097	0.368	2.28 ± 1.36 a	2.94 ± 1.45 a	2.28 ± 0.91 a	2.81 ± 1.36 a	2.26 ± 1.48 a	2.16 ± 0.58 a	2.69 ± 1.59 a

For each depth, means are compared against each other after ANOVA using Tukey's HSD test (p-values are mentioned). Significant differences between means within a row are marked with different superscript letters (for abbreviations, see Table 3.1).

Table 3.5 Penetration resistance as influenced by depth, treatment and position: sources of variation, degrees of freedom (d.f.), F-ratio and p-values, obtained with GLM.

Source	**Site 1**			**Site 2**		
	d.f.	**F-ratio**	**p-value**	**d.f.**	**F-ratio**	**p-value**
Treatment	-	-	-	2	31.218	**<0.001**
Position	1	15.149	**0.006**	1	23.287	**0.002**
Depth	7	3.154	0.076	7	13.635	**<0.001**
Treatment x Position	-	-	**-**	2	6.222	**0.002**
Treatment x Depth	-	-	**-**	14	1.978	**0.017**
Position x Depth	7	3.198	**0.003**	7	2.788	**0.007**

Significant terms are depicted in bold.

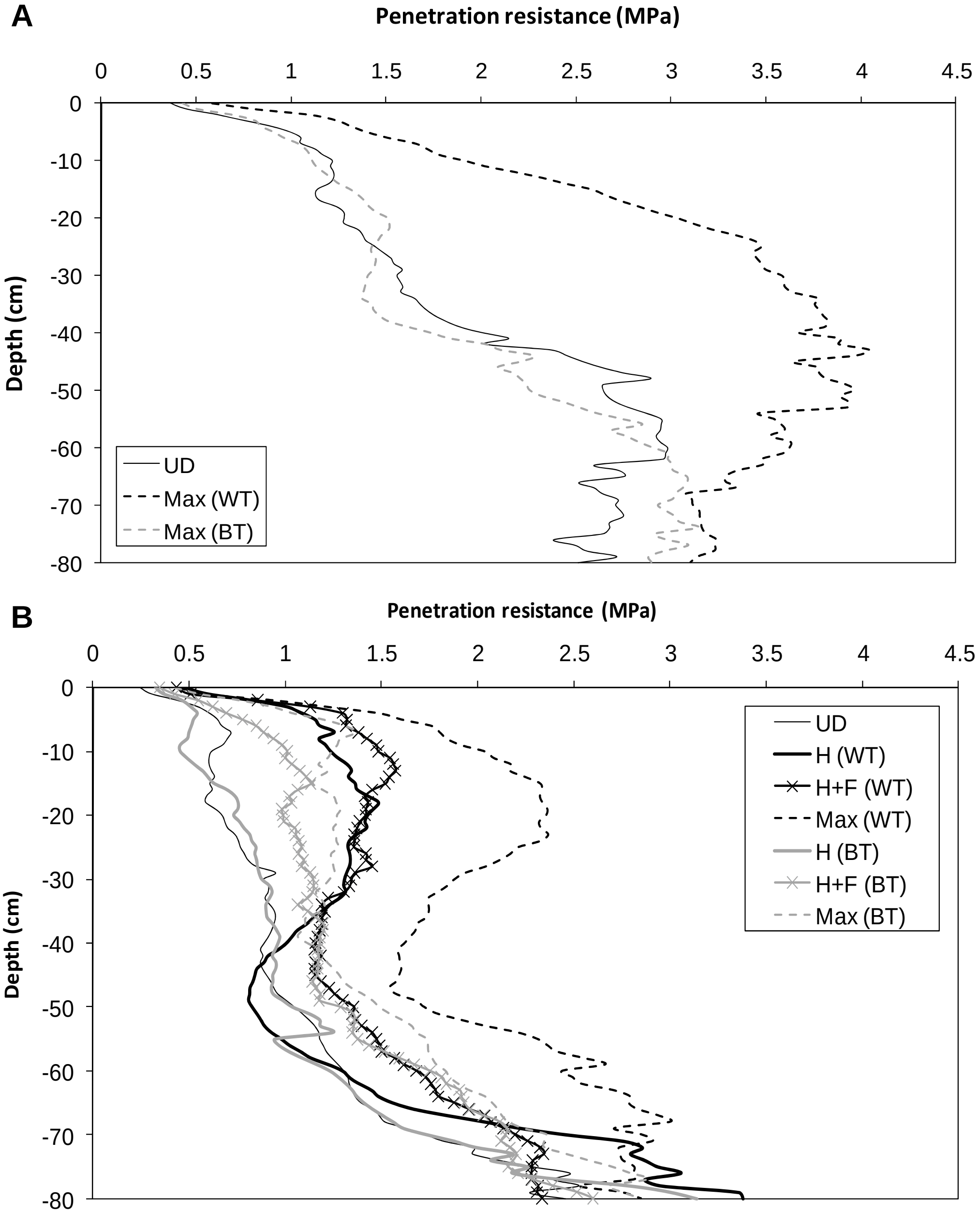


Fig. 3.3 Treatment effect on the penetration resistance in function of depth on site 1(A) and site 2 (B) (for abbreviations, see Table 3.1).

The use of GLM revealed that twofold interactions treatment x position (p = 0.002), treatment x depth (p = 0.017) and position x depth (p = 0.007) were all significant (Table 3.5). Measurements for Max varied greatly between the two positions, whereas the corresponding values for H and H+F were less different. An analysis of the interaction position x depth showed that the position in relation to the wheel tracks had a great influence in the upper 35 cm, whereas differences were minimal in the deeper layers. The significance of the interaction treatment x depth was due to a larger difference in PR between the treatments on 15, 55, 65 cm in comparison with 55 and 65 cm.

3.4.2 Influence of a brash mat on compaction

3.4.2.1 Bulk density

Results on BD and PR emphasized that skid trails that are not covered with sufficient logging residues before they are driven over by logging traffic can be severely compacted. However, a brash mat (Max (WT-BM)) reduced the degree of compaction, expressed in terms of BD, considerably (Fig. 3.4A). Although there still was a significant difference with UD in the intervals 10-20 cm and 20-30 cm (Table 3.6), the protective influence of the brash mat was clearly noticeable over all depths. The brash layer restricted the increase in BD resulting from Max compared to UD, to 1, 7 and 5% in the intervals 0-10 cm, 10-20 cm and 20-30 cm.

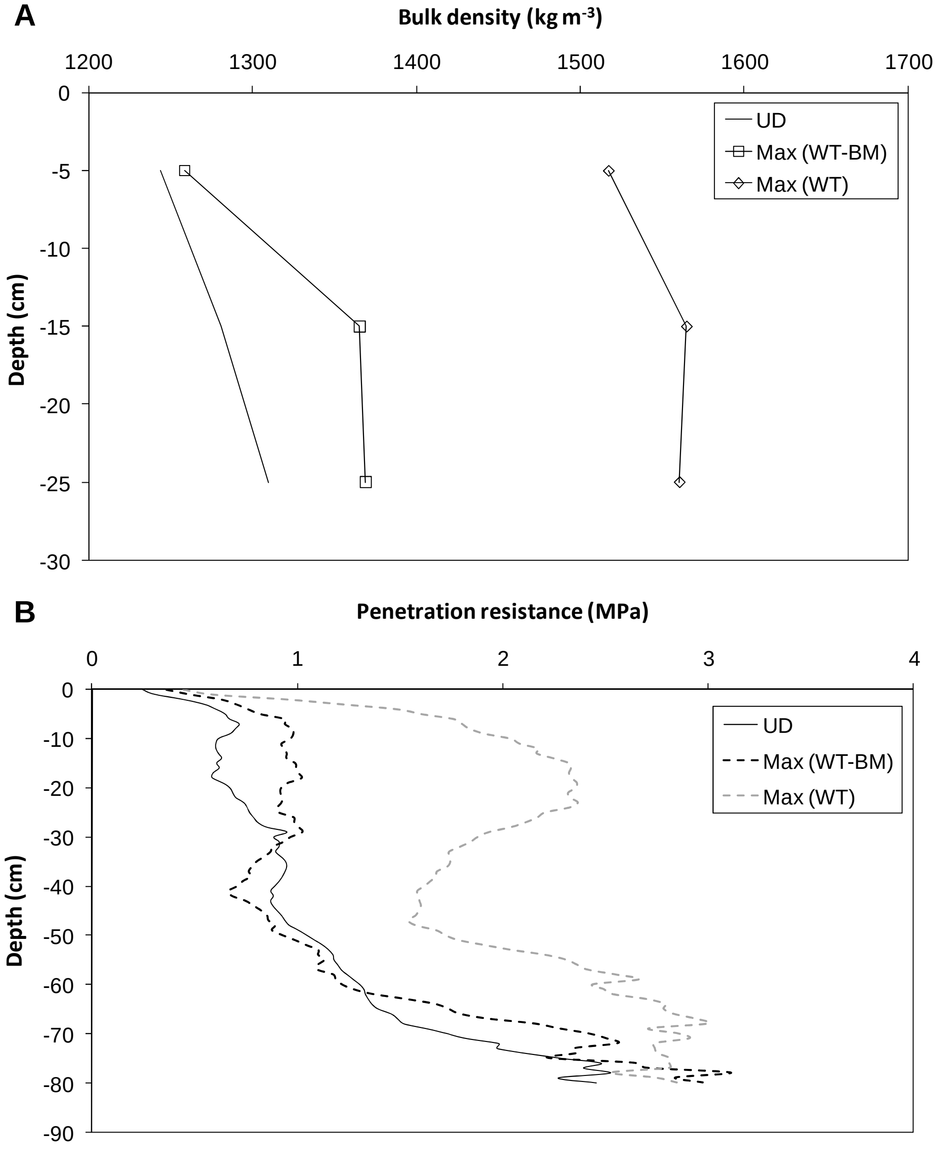


Fig. 3.4 Effect of a brash mat on the degree of compaction, estimated by bulk density (A) and penetration resistance (B) on site 2 (for abbreviations, see Table 3.1).

Table 3.6 Effect of a brash mat on the degree of compaction, estimated by bulk density and penetration resistance (± standard deviation) (site 2).

Depth (cm)	F-ratio	p-value	UD	Max (WT-BM)	Max (WT)
Bulk density (kg m^{-3})					
0-10	44.612	<0.001	1244 ± 117 a	1259 ± 162 a	1517 ± 126 b
10-20	54.287	<0.001	1281 ± 115 a	1365 ± 108 b	1565 ± 119 c
20-30	68.334	<0.001	1310 ± 110 a	1369 ± 76 b	1560 ± 88 c
Penetration resistance (MPa)					
5	31.431	<0.001	0.65 ± 0.29 a	0.82 ± 0.32 a	1.61 ± 0.60 b
15	80.507	<0.001	0.61 ± 0.30 a	0.99 ± 0.40 a	2.33 ± 0.50 b
25	35.807	<0.001	0.77 ± 0.29 a	0.91 ± 0.47 a	2.21 ± 0.82 b
35	16.729	<0.001	0.94 ± 0.45 a	0.80 ± 0.29 a	1.75 ± 0.80 b
45	12.712	<0.001	0.90 ± 0.29 a	0.82 ± 0.19 a	1.59 ± 0.82 b
55	16.052	<0.001	1.18 ± 0.41 a	1.13 ± 0.61 a	2.31 ± 0.99 b
65	10.478	<0.001	1.40 ± 0.62 a	1.74 ± 0.66 a	2.78 ± 1.29 b
75	0.763	0.472	2.28 ± 1.36 a	2.22 ± 1.18 a	2.81 ± 1.36 a

For each soil interval, means are compared against each other after ANOVA using Tukey's HSD test (α = 0.05). Significant differences between means within a row are marked with different superscript letters (for abbreviations, see Table 3.1).

GLM was applied with Max (WT) and Max (WT-BM) as different treatments on the same position WT (Table 3.7). The term treatment x depth was insignificant (p = 0.150) because the difference between the two treatments remained roughly the same across the whole interval 0-30 cm. When the interaction term was removed from the model, the main effects of treatment, depth and location changed to 0.001, <0.001 and <0.001 respectively. In other words, the use of a brash mat significantly decreased the soil compaction degree, with the strongest influence in the upper soil intervals. Again, a significant main effect was calculated for the location of the pits.

Table 3.7 Effect of a brash mat on the degree of compaction on site 2, estimated by bulk density and penetration resistance: sources of variation, degrees of freedom (d.f.), F-ratio and p-values obtained with GLM.

Source	Bulk density			Penetration resistance		
	d.f.	F-ratio	p-	d.f.	F-ratio	p-value
Treatment	1	22.594	**0.001**	1	113.825	**<0.001**
Depth	2	8.047	0.111	7	12.731	**0.002**
Location (Treatment)	10	10.210	**<0.001**	-	-	-
Treatment x Depth	2	1.916	0.150	7	0.618	0.740

Significant terms are depicted in bold.

3.4.2.2 Penetration resistance

As with BD, the positive effect of a brash mat on the degree of compaction was noticed from the PR measurements (Fig. 3.4B, Table 3.6). PR for Max (WT) was clearly higher compared with UD and Max (WT-BM). ANOVA indicated significant differences to a depth of 65 cm. Logging residues, however, seemed to protect the soil. Below 30 cm, differences in PR between Max (WT-BM) and UD, were negligible. The small PR in the depth interval 5-25 cm associated with Max (WT-BM) compared to UD was, further, insignificant. With the protective influence of slash, the increase of the PR in comparison with UD at 5, 15 and 25 cm was reduced from 148, 282 and 187% for Max (WT) to respectively 26, 62 and 18% for Max (WT-BM).

Analysis of the PR data led to the same conclusions as for BD. After removing the insignificant interaction term treatment x depth from GLM ($p = 0.740$), the p-values of the main effects of treatment and depth both became <0.001. The same conclusions could be made as for BD (Table 3.7).

3.4.3 Correlation between bulk density and penetration resistance

When plotting mean PR against mean BD, a non-linear relationship could be observed (Fig. 3.5). At relatively low PR, BD increased rapidly with PR. However, at higher PR values, BD seemed to be insensitive to PR changes and remained more or less constant. The Spearman correlation coefficient was 0.674 and 0.859, respectively for sites 1 and 2, and both were significant at the 0.01 level.

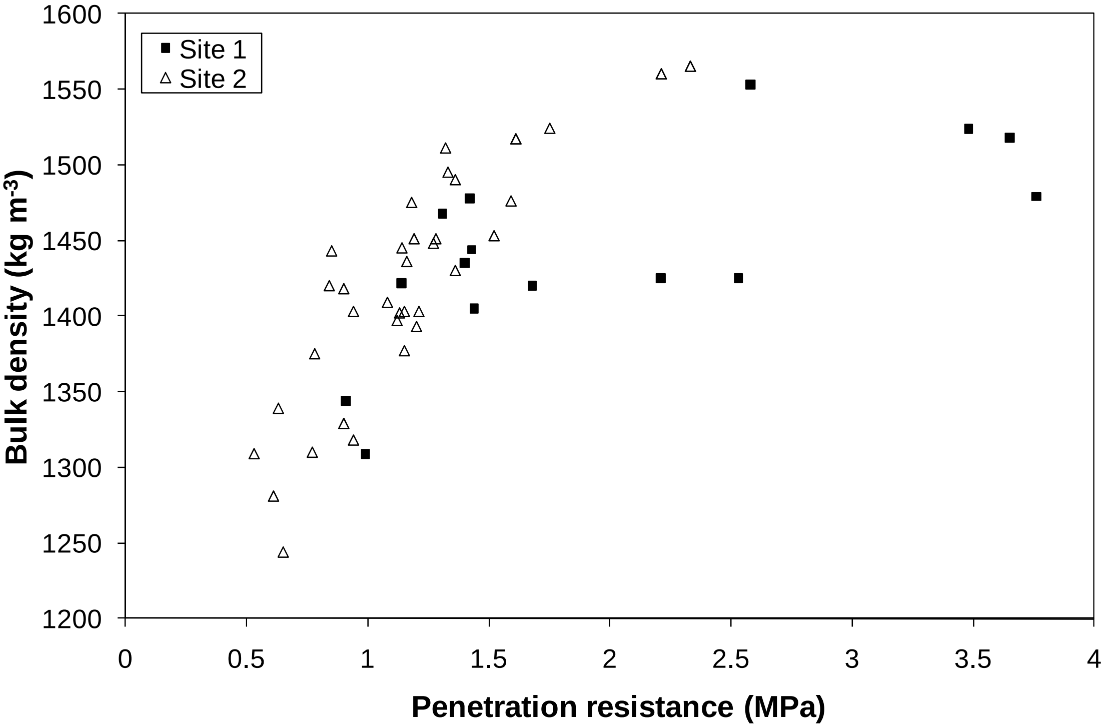


Fig. 3.5 Correlation between bulk density and penetration resistance on sites 1 and 2.

3.5 Discussion

3.5.1 Relationship between traffic, position and compaction

Bulk density (and PR) of UD for site 2 showed lower UD values than site 1, probably due to a higher organic matter content (§3.3.1), but data with regard to the organic matter content were not available. Site 1 had a maximum BD at the interval 10-20 cm instead of a steady linear increase with depth. A local increase of BD or PR in the interval 0-30 cm normally indicates an artificial effect, for example due to machine impact. However, it was the first mechanized harvesting activity in these stands. The local maximum was possibly induced by the partial formation of a new podzolic horizon. Bulk density of UD for site 2 shows a normal gradient, unaffected by former traffic or soil development. Higher BD values for UD at site 1 bring along a higher soil strength and soil precompression stress (Horn et al. 2007), and therefore a higher resistance to soil compaction is expected. Indeed, both the absolute as the relative increases compared to UD were lower at site 1. A similar maximum BD of about 1565 kg m^{-3} was observed. This value probably corresponds to the potential maximum BD value for the sandy soil under study (§4.5.2).

The number of passes had a positive influence on the compaction degree that was measured by means of BD and PR. According to Schäfer & Sohns (1993) and Williamson & Neilsen (2000) this relationship is logarithmic with a strong impact of the first pass(es), approaching zero at higher traffic intensities. As pores are compressed at successive machine passes they exert a higher resistance to the applied forces and thus increase soil strength (Hillel 1998) and precompression stress. Subsequent passes will induce a (diminishing) extra compaction as long as the applied stress exceeds this precompression stress (Horn et al. 2007). This positive logarithmic relationship between traffic intensity and compaction degree was also emphasized by Brais & Camiré (1998). They indicated that on coarse textured soils the increase of the compaction degree is more gradually spread over the first passes, as was stated by the PR results. However, in our study the strongest BD increase within tracks already appeared after one pass of the harvester (H), with limited (site 2) to negligible (site 1) additional BD increments due to the subsequent passes.

While the compacted soil layer is partially protected from further compaction (Incerti et al. 1987; Williamson & Neilsen 2000), an increasing proportion of the applied forces is transmitted to higher depths, as was observed by Shetron et al. (1988) and Balbuena et al. (2002). This explains why differences between the effects of H and Max can normally also be observed at deeper layers. However, BD and PR increased with traffic intensity in the upper 20cm of the soil but in deeper soil layers, the difference between the treatments was less clear, leading to the significant interaction term treatment x depth for BD. Williamson & Neilsen (2000) made similar findings. With increasing depth, the pressure of the machines was dissipated over an enlarging area (Greacen & Sands 1980) and was eventually insufficient to impact physical properties of the underlying higher density materials to a considerable extent (Cullen et al. 1991). Treatment effects were therefore predominantly restricted to the upper 30 cm of the soil, in accordance with Greacen & Sands (1980) with an overall maximum impact at 10-20 cm. In the upper soil layer (0-10 cm), the shear forces, which tend to loosen the soil in direct contact with the wheels, slightly counteract the compactive forces, often leading to smaller compaction degrees compared to the soil interval 10-20 cm.

BD and PR between tracks were also increased, in accordance with Brais & Camiré (1998), also confirming the positive impact of traffic intensity on the compaction degree, though the increase was smaller between the tracks compared to within the wheel tracks. This can be explained by the simultaneous appearance of compaction and loosening of the soil. Wronski (1984) stated that the lateral movement of soil from beneath the wheels induces slight compaction between the wheel tracks on the one hand. On the other hand, rotations of the tyres result in shear forces that tend to loosen the soil (Abeels 1989; Vossbrink & Horn 2004). As treatments all caused significant BD and PR increases within tracks in contrast to the soil between tracks (where increases were small, absent or even negative), a significant interaction between treatment and location was stated.

According to Lacey & Ryan (2000) and the USDA Forest Service, soil compaction becomes harmful if BD rises more than 15%, as was the case on site 2. On site 1, BD increases after Max (WT) in the upper 50 cm were restricted to 10%, in accordance with Alban et al. (1994). Smith & Du Toit (2005) also found a maximal BD increase of 9%, in spite of higher initial BD values. The relative increases of PR after Max (WT) were much higher than for BD at both sites 1 (130% on average) and 2 (up to 280%), again in accordance with Alban et al. (1994) and Smith & Du Toit (2005). According to Greacen & Sands (1980) and Whalley et al. (1995), root growth of many plants becomes restricted when soil PR exceeds 2 MPa and stops at PR greater than 3 MPa. Within the wheel tracks of site 1, plant and tree colonization and growth of roots could thus be hampered. Very high PR values are neither favourable for soil fauna as most of these organisms do not possess a strong capability for burrowing. However, only using thresholds or percentage of BD or PR change is ineffective because changes of BD and PR may vary in its biological significance (Williamson & Neilsen 2000). For example, Gaertig et al. (2002) showed that reduced root growth was rather due to lacking oxygen supply. Hampered soil aeration may already occur at negligible compaction degrees, as was shown in Chapter 2. Even a small increase of BD or PR on a sandy soil may therefore have large consequences, considering the low biological activity that is present in undisturbed conditions.

3.5.2 Influence of a brash mat on the compaction degree

Our results clearly showed a beneficial influence of a brash mat on the reduction of the compaction degree after machine traffic. When enough slash residues are placed on the skid trails, the machine weight is spread over a greater area than the actual footprint of the machine, and hence the mean soil contact pressure declines. Schäfer & Sohns (1993) mentioned a clear relationship between the height of a brash mat and the degree of compaction estimated by PR.

3.5.3 Correlation between bulk density and penetration resistance

Evidence for the non-linear relationship between PR and BD was also found by e.g., Henderson et al. (1988), Smith et al. (1997), Vaz et al. (2001) and Whalley et al. (2005), for a wide variety of textural classes ranging from sand to clay. As BD increases the pore space is being reduced. Eventually, the pore space becomes insufficient to accommodate the rigid particles that are displaced by the intruding penetrologger cone. At high BD significant soil particle rearrangement hence becomes problematic (Whalley et al. 2005) and the friction experienced by the penetrologger cone strongly increases.

This effect was most pronounced on site 1, which can be attributed to the organic matter. Although penetration resistance at both sites was measured during the same day at approximate field capacity conditions, the lower organic matter content observed at site 1, could have resulted in a lower water holding capacity and thus a lower water content. Lower water contents generally result in higher penetration resistances as was observed by many researchers (Henderson et al. 1988; Hernanz et al. 2000; Vaz et al. 2001), due to the dominance of frictional forces over interparticle cohesional forces. At field capacity, lower penetration resistances can be stated as interparticle cohesional forces dominate frictional forces, as was observed by Smith et al. (1997). The critical soil-water content corresponds with the point where individual water wedges at the contact points between soil particles begin to coalescence (Cornelis et al. 2004). Because of the higher frictional forces related to the lower water content at site 1, the latter showed a more pronounced non-linear behaviour of the relationship between bulk density and penetration resistance.

This non-linear relationship has some implications. Beyond a certain PR, BD maintains more or less the same value. In our research, this value did not exceed growth limits for optimal root elongation and so, from this point of view, the measured soil compaction status did not seem to be a threat for the vegetation. PR however, kept increasing and in some cases even exceeded limits for optimal root growth. As these two variables may affect the soil ecosystem in a different way, it implies that it is best to use both BD and PR in order to assess soil compaction. It must be remarked that soil CO_2 concentration is a more sensitive indicator for machine traffic (e.g., Gaertig 2001) but could not be used here due to a lack of appropriate devices.

Four Kopecky cores, brought into the soil for determination of the bulk density of depth interval 0-10cm (Chapter 3) [photograph: Robbie Goris, August 2004].

4 The effects of initial bulk density, machine mass and traffic intensity on forest soil compaction: a meta-analysis

After: Ampoorter E, De Schrijver A, Van Nevel L, Hermy M, Verheyen K (2010) Impact of mechanized harvesting on forest soil compaction: results of a meta-analysis. Forestry, *submitted*

4.1 Abstract

A meta-analysis was performed to draw conclusions concerning the soil impact of mechanized harvesting operations. The influences of initial bulk density, machine mass and traffic intensity were studied, by means of absolute bulk density increases and log response ratios, based on bulk density. In the first depth interval, the impact on clay was highest (18% bulk density increase), but not significantly different from the impact on all textures classes together and on sand (12-13%). For sand, clay and all texture classes together the impact was maximal in the first depth interval, decreasing towards deeper soil layers (10-20 cm, 20-30 cm) and the initial bulk density had a significant negative influence on the absolute bulk density increase ($p < 0.01$). For all texture classes together and for sand, a significant positive relationship existed between the response ratio and the machine mass. No significant relationship between the response ratio and traffic intensity was observed. The mean response ratios for all texture groups (sand, clay, all texture classes together), the compacted initial state of many forest soils and the long recovery period of compacted soils, count in favour of designated skid trails. We also argue for the restriction of machines with a high soil contact pressure and a specific adjustment of the machine type to the job.

4.2 Introduction

In forest harvesting activities, heavy machines are often used, such as harvesters, skidders and forwarders, with masses easily mounting up to 20 tonnes or more in loaded state. Despite eventual careful planning of field operations, concern remains over the potential adverse impacts on the forest ecosystem. Driving on a forest soil may cause soil compaction in addition to soil rutting and churning, as a result of static and dynamic forces. Soil pore volume decrease and a loss of pore continuity (Herbauts et al. 1996; Berli et al. 2003) is obtained, inducing changes in soil aeration (Gaërtig et al. 2002), soil water retention and saturated hydraulic conductivity (Ballard 2000). The proportion of soil to pore space shifts and consequently BD (Cullen et al. 1991; Miller et al. 1996) and PR (Alban et al. 1994; Aust et al. 1998) increase. Heavy compaction may imply a serious risk for the soil ecosystem as a good soil structure is of great importance to soil fauna (Jordan et al. 1999), herb and moss layer (Buckley et al. 2003), tree roots (Greacen & Sands 1980) and their functionalities. It should be mentioned that soil compaction is only detrimental when critical limits (e.g., for BD or O_2 concentration) are crossed (e.g., Powers et al. 1998). A few studies indicate positive effects resulting from soil compaction, mostly on sandy soils (Agrawal 1991; Brais 2001; Gomez et al. 2002).

As mentioned in §2.2 the degree, to which the above-mentioned abiotic and biotic variables are influenced, depends on several factors, such as (1) soil characteristics, (2) machine type, number of tyres and (3) traffic intensity (number of machine passes):

1) It is generally assumed that medium- to fine-textured soils are more vulnerable to soil compaction from machine traffic than coarse-textured soils (e.g., Larson et al. 1980; Hillel 1998), although the sensitivity of sandy forest soils to soil compaction was emphasized by Brais & Camiré (1998) and Ampoorter et al. (2007; Chapter 3). When assessing the influence of soil texture on the degree of compaction, the impact of soil water content (e.g., Smith et al. 1997; Hillel 1998), precompression stress (Horn et al. 2007) and organic matter content (Sands et al. 1979; Greacen & Sands 1980; Howard et al. 1981) may not be underestimated.

2) Machine impact: the higher the soil contact pressure, the more intense the compaction process. At a constant machine mass the compaction degree is

negatively correlated with the number of tyres (Alakukku et al. 2003) and tyre dimensions (Benthaus & Matthies 1993), and positively correlated with tyre pressure (Abu-Hamdeh et al. 2000). At constant tyre characteristics, damage increases with increasing machine mass (McDonald et al. 1996). However, the real exerted pressure (dynamic) often differs from the pressure that is calculated using the theoretical contact area (static), such as when the machine drives over a stump (Chancellor 1994) or during felling and processing (Wehner 2003).

3) The first pass of a machine will affect soil structure and porosity in case the applied stress encompasses the precompression stress of the soil. As a result, pores become smaller and exert a higher resistance to further compaction (Shetron et al. 1988; Williamson & Neilsen 2000), leading to higher soil strength and precompression stress (Horn et al. 2007). Subsequent passes will have a diminishing influence until the applied stresses no longer exceed the constantly increased precompression stress. Brais & Camiré (1998) and Seixas et al. (2003) emphasized that this relationship is logarithmic and that the traffic intensity at which the response starts to mitigate depends amongst others on soil texture.

Soil damage caused by logging machinery has been studied frequently. However, most of the studies only focus on one soil texture, one machine and/or one level of traffic intensity. Seldom different levels of these factors are compared, enabling to make more general and reliable conclusions about the impact of a specific factor on the compaction degree. In this article, a meta-analysis, i.e. a powerful method to conduct an objective review of numerous studies (e.g., Arnqvist & Wooster 1995), was made to examine the impact of logging machinery on forest soils. Available literature was reviewed to address the following specific questions:

a) How strong does machine traffic alter BD of forest soils?
b) Are the results similar for contrasting soil texture classes?
c) To what extent is this relation influenced by initial BD, number of machine passes and machine mass (as an indication of soil contact pressure)?

4.3 Material and methods

4.3.1 Data collection

4.3.1.1 Search strategy and study inclusion criteria

Relevant studies were identified through searches of the bibliographic database ISI Web of Science, and the cited references in these publications, with 1955-2007 as the search period. Search terms used were forest, soil, compact*, machin*, harvest*, disturb*, skidder, forwarder, traffic and effect, used in various combinations with each other. The search was focussed on articles that studied the impact on abiotic soil characteristics, such as BD, PR and hydraulic conductivity. Studies were initially filtered by title and obviously irrelevant articles were not further considered. Subsequently, the abstracts were studied with regard to possible relevance to the research questions. This process yielded 26 articles. Further criteria, used for inclusion into the final stage of the meta-analysis, were:

- Machine type: commonly used logging machines, such as skidder, forwarder, harvester… Experiments with rolling vibrators were, for example, not allowed (2 articles deleted from selection);
- Outcome: as most of the articles examined the impact of traffic on soil BD, and other variables were studied to a much lesser extent, this meta-analysis focused on the BD change (2 articles deleted from selection) and thus on soil compaction. Viscoplastic deformation, which leads to soil rutting, could not be examined using this variable, thus the total soil impact was underestimated;
- Data availability: a good meta-analysis requires three basic statistics: the mean of the response variable (BD before as well as after traffic), a measure of the variance and the number of replicates (Hedges et al. 1999). Despite the importance of detailed information on set-up and results in publications, several articles lacked information on necessary variables and could not be used (11 articles deleted).

Finally, eleven articles, studying 37 different forest stands, contained the needed details and were included in the meta-analysis. More information about this final selection of articles used in the meta-analysis can be found in Table 4.1.

4.3.1.2 Data preparation

Information on soil type, soil texture or particle size distribution allowed to classify each forest stand into a texture class of the USDA soil classification system (Soil Survey Staff 1999). In order to examine differences in response between texture classes, subsets were created consisting of studies on Sand (including sand, loamy sand, sandy loam) and Clay (including clay). An additional subset could not be delimited as textures of the remaining studies were too heterogeneous (sandy clay loam, sandy clay, clay, silty clay, clay loam, silt clay loam, loam, silt loam, silt). It is interesting to analyse differences between Sand and Clay as it is expected that these subsets will have a contrasting response due to different vulnerabilities to soil compaction (Hillel 1998; Fisher & Binkley 2000). Each analysis was performed for all texture classes together (*All*) and for Sand and Clay separately. Table 4.2 shows that about 25% of the forest stands were located on soils with texture classes classified in subsets Sand or Clay, the rest was located on other soil texture classes.

In most articles, measurements were carried out in the upper 30 cm of the soil. For the meta-analysis, this interval was divided into three equal depth classes 0-10, 10-20 and 20-30 cm. Eventual measurements deeper in the soil were not considered as there were not enough replications. In case a paper presented results for BD for different machine types, data for each type were included as an individual study. Likewise, when different levels of traffic intensity (number of passes) were compared, data for each level were treated as individual studies (cf Jactel & Brockerhoff, 2007). Each combination of forest stand, machine type, number of passes and soil depth class is further called a *substudy.* This yielded a total of 98, 102 and 88 substudies for the soil depth classes 0-10 cm, 10-20 cm and 20-30 cm, so 288 substudies for all three depth classes together. Finally, data on measuring precision (standard error (SE), standard deviation (SD), coefficient of variation,…) were all transformed into SD.

Table 4.1 Detailed information concerning articles that were selected for the meta-analysis. 'Other' represents all texture classes apart from the soil texture classes in subsets Sand and Clay.

Authors (publication year)	Location	Texture	Machine(s)	# passes	# replications	# cases
Ampoorter et al. (2007; Chapter 3)	The Netherlands, site 1	Sand	Timberjack 1070D harvester	1	28	3
			Timberjack 1070D harvester (1 pass), Timberjack 1110D forwarder (1 pass)	2	28	3
			Timberjack 1070D harvester (1 pass), TImberjack 1110D forwarder (3 passes)	4	28	3
	The Netherlands, site 2	Sand	Timberjack 1070D harvester	1	28	3
			Timberjack 1070D harvester (1 pass), Timberjack 1110D forwarder (1 pass)	2	28	3
			Timberjack 1070D harvester (1 pass), TImberjack 1110D forwarder (3 passes)	4	28	3
Ampoorter et al. (2010; Chapter 2)	Belgium, Sperwer	Other	New Holland TCE50	1/5	6/6	3/3
			John Deere grapple skidder JD640	1/5	6/6	3/3
	Belgium, Goden	Other	New Holland TCE50	1/5	6/6	3/3
			John Deere grapple skidder JD640	1/5	6/6	3/3
	Belgium, Havik	Other	New Holland TCE50	1/5	6/6	3/3
			John Deere grapple skidder JD640	1/5	6/6	3/3
	Belgium, Renissart	Other	New Holland TCE50	1/5	6/6	3/3
			John Deere grapple skidder JD640	1/5	6/6	3/3
	Belgium, Kapellen 1	Sand	New Holland TCE50	1/5	6/6	3/3
			John Deere grapple skidder JD640	1/5	6/6	3/3
	Belgium, Kapellen 2	Sand	New Holland TCE50	1/5	6/6	3/3
			John Deere grapple skidder JD640	1/5	6/6	3/3
	Belgium, Walem 1	Other	New Holland TCE50	1/5	6/6	3/3
			John Deere grapple skidder JD640	1/5	6/6	3/3
	Belgium, Walem 2	Other	New Holland TCE50	1/5	6/6	3/3
			John Deere grapple skidder JD640	1/5	6/6	3/3
Ares et al. (2005)	Washington (USA)	Other	CAT 330L shovel with 70cm	2	52	3
Block et al. (2002)	Canada	Sand	Feller-buncher, grapple skidder, stroke delimber		29	2
			Feller-buncher, grapple skidder, stroke delimber		30	2
			Feller-buncher, grapple skidder, stroke delimber		30	2
		Other	Line skidder		47	2
			Feller buncher, grapple skidder		42	2
Brais (2001)	Quebec-Ontario (Canada)	Other	Clark 667C	5/15	9/9	1/1
		Sand	Tree Farmer C8E	5/15	9/9	1/1

McNabb et al. (2001)	**Western Alberta (Canada)**	Other	Skidder	3/7/12	16/16/16	3/3/3
		Other	Valmet 540 forwarder	3/7/12	16/16/16	3/3/3
		Other	Skidder	3/7/12	16/16/16	3/3/3
		Other	Skidder	3/7/12	16/16/16	3/3/3
		Sand	Caterpillar D4H TSK	3/7/12	16/16/16	3/3/3
		Other	Skidder	3/7/12	16/16/16	3/3/3
		Other	Skidder	3/7/12	16/16/16	3/3/3
		Other	Skidder	3/7/12	16/16/16	3/3/3
		Other	Skidder	3/7/12	16/16/16	3/3/3
		Other	Skidder	3/7/12	16/16/16	3/3/3
		Other	Skidder	3/7/12	16/16/16	3/3/3
		Other	Skidder	3/7/12	16/16/16	3/3/3
		Other	Timberjack 520A forwarder	3/7/12	16/16/16	3/3/3
		Other	Skidder	3/7/12	16/16/16	3/3/3
Rab (2004)	Victorian Central Highlands (Australia)	Other	Rubber tyre skidder CAT 518 cable		6	3
Schack-Kirchner et al. (2007)	Brazil	Clay	Skidder CAT 528	1/3/9	6/6/6	3/3/3
Seixas & McDonald (1997)	North Carolina (USA)	Sand/other	Forwarder Timberjack 910 (6 tyres), front tyres 700/55-34.00, back tyres 48 x 31.00-20 (wide)	6/6	40/20	2/2
			Forwarder Timberjack 910 (6 tyres), front tyres 700/55-34.00, back tyres 600/55-26.5 (narrow)	6	20	2
			Forwarder Rottne Rapid (8 tyres), front tyres 600/55-26.5, back tyres 48 x 31.00-20	6	40	2
Sheridan (2003)	Victoria (Australia)	Other	Caterpillar Cat 518 Series II	2/4/10	10/10/10	3/3/3
Simcock et al. (2006)	Auckland (New Zealand)	Clay	Rubber-tyred C6E Treefarmer skidder	2	65 (0-10cm) 42 (10-20cm)	2

4.3.2 Data analysis

Statistical analyses to test the impact of machine traffic on forest soils were carried out in accordance with Hedges et al. (1999), using the log response ratio L as an index of effect. For each individual substudy the log response ratio was calculated as the natural logarithm of the ratio of the mean BD after traffic $\left(\overline{X_e}\right)$ to the mean BD before traffic $\left(\overline{X_c}\right)$, thus $L = ln\left(\frac{\left(\overline{X_e}\right)}{\left(\overline{X_c}\right)}\right)$ As the smaller of $\frac{\sqrt{n_c}\left(\overline{X_c}\right)}{SD_c}$ or $\frac{\sqrt{n_e}\left(\overline{X_e}\right)}{SD_e}$ (n = sample size) was larger than 3, the set of L_i had only little bias and the normal approximation to its sampling distribution should have been quite good, with a mean approximately equal to the true log response ratio, a variance v_i approximately equal to $\frac{(SD_e)^2}{n_e\overline{X}_e^{\,2}} + \frac{(SD_c)^2}{n_c\overline{X}_c^{\,2}}$ and a 100(1-α)% confidence interval for the individual log response ratio parameter λ, given by $L - z_{\alpha/2}\sqrt{v} \leq \lambda \leq L + z_{\alpha/2}\sqrt{v}$ with $z_{\alpha/2}$ as the 100(1-α/2)% point of the standard normal distribution.

The first step in the meta-analysis was to check for publication bias. Studies with clear, significant responses according to the expectations were more likely to be published than studies without any significant effects or with a response that contradicted with general assumptions. As a result, literature may have become biased. To approach the problem of publication bias, we produced a funnel plot (Light & Pillemer 1984), in combination with a statistical test (Begg & Mazumdar 1994). The funnel plot shows an index of study size or precision on the vertical axis as a function of effect size (such as the log response ratio) on the horizontal axis. According to Sterne & Egger (2001) the SE is likely to be the best choice at the vertical axis. In this way the funnel plot emphasises smaller studies, being more susceptible to bias. In the absence of bias, the sample points are distributed like a vertical funnel symmetrically round the mean effect size. This means that the individual effect sizes are close to the mean effect size at higher precision levels (generally big studies) but are more spread when the precision level decreases (small studies). In the presence of bias, the wider part of the funnel (small studies) shows a non balanced view. Interpretation of funnel plots is facilitated by inclusion of lines representing the 95% confidence limits around the mean effect size, showing the expected distribution of studies in the absence of bias. To quantify the amount of bias depicted in the funnel plot, a statistical test has been developed by Begg & Mazumdar (1994), based on the rank correlation (Kendall's tau) between the standardized effect size and the variance of this effect. When L_i is the estimated effect size and v_i the sampling variance from the k substudies in the meta-analysis, then, to construct a valid rank correlation test, it was necessary to stabilize the variances by standardizing the effect sizes. The test correlates L_i^* and v_i, where $L_i^* = \frac{(L_i - \overline{L})}{\sqrt{v_i^*}}$, $\overline{L} = \frac{\left(\sum v_i^{-1} L_i\right)}{\sum v_i^{-1}}$ and where $v_i^* = v_i - \left(\sum v_i^{-1}\right)^{-1}$ is the variance of $L_i - \overline{L}$. A value of zero signifies no relationship between effect size and precision, while every departure from zero is indicative of the presence of a relationship, such as publication bias. Namely, if in the publication of smaller studies (smaller precision, larger v_i) greater attention was given to studies with a larger than normal effect size (larger L_i^*), then a positive relationship would be found between effect size and precision.

In order to compare the effect sizes, for example between Sand and Clay, and thus to calculate means and accompanying confidence intervals, the random effect model was used (Gurevitch & Hedges 2001). Differences among these studies in the actual effect size measured were assumed to be due to both sampling error (v_i) and between-study variation in the experiment-specific parameters $\lambda_1,\ldots,\lambda_k$ (σ_λ^2). The cumulated mean effect size or mean response ratio L^* was calculated as a weighted average for All, Clay and Sand per depth class, using following formulas:

$\overline{L}^* = \frac{\sum_{i=1}^{k} w_i^* * L_i}{\sum_{i=1}^{k} w_i^*}$ where k = number of substudies within this group, $w_i^* = \frac{1}{(v_i + \sigma_\lambda^2)}$,

$\sigma_\lambda^2 = \frac{Q-(k-1)}{\sum_{i=1}^{k} w_i - \frac{\sum_{i=1}^{k} w_i^2}{\sum_{i=1}^{k} w_i}}$, $w_i = \frac{1}{v_i}$ and $Q = \sum_{i=1}^{k} w_i * (L_i)^2 - \frac{(\sum_{i=1}^{k} w_i * L_i)^2}{\sum_{i=1}^{k} w_i}$. The corresponding 100(1-α)% confidence interval was given by $\overline{L}^* - z_{\alpha/2} SE\left(\overline{L}^*\right) \le \mu_\lambda \le \overline{L}^* + z_{\alpha/2} SE\left(\overline{L}^*\right)$ where

$SE(\overline{L}^*) = \sqrt{\left(\frac{1}{\sum_{i=1}^{k} w_i^*}\right)\left(1 + 4\sum_{i=1}^{k} \frac{1}{df_i}\left(\frac{w_i^*}{w_i}\right)^2 \frac{w_i^*((\sum_{i=1}^{k} w_i^*) - w_i^*)}{(\sum_{i=1}^{k} w_i^*)}\right)}$ and df_i was the number of degrees of freedom in the *i*th substudies ($n_e + n_c - 2$). As L^* is a weighted mean, significant differences between two groups could not be detected with t-tests using the original response ratios per substudy. Instead, a (double sided) p-value had to be detected with a t-test using the means and SD, calculated as mentioned above (α = 0.05).

The next step was to determine which factors were of influence on the response ratio. For this purpose the correlation was calculated between the response ratio on the one hand and the machine mass, machine mass per tyre (instead of soil contact pressure, see further) and number of passes on the other. The correlation between the initial BD (or BD before traffic) and the absolute BD increase after traffic was also examined. In order to take the size of each study (number of replications) into account, the weighted Pearson product-moment correlation coefficient was used (cf Honnay & Jacquemyn 2008). This number was calculated as follows:

$$\tau_{xy} = \frac{\sum w_i\left(x_i - \overline{x_w}\right)\left(y_i - \overline{y_w}\right)}{\sqrt{\sum w_i\left(x_i - \overline{x_w}\right)^2 \sum w_i\left(y_i - \overline{y_w}\right)^2}}$$

where $\overline{x_w} = \sum w_i x_i / \sum w_i$ and $\overline{y_w} = \sum w_i y_i / \sum w_i$. In these equations w_i and x_i denote the number of replications per response ratio, respectively the response ratio (or the absolute BD increase), and y_i represents the BD before traffic, the machine mass, the machine mass per tyre or the number of passes (Bills & Li 2005). The significance of τ_{xy} was tested by calculating the value of $t = \tau\sqrt{\frac{(n-2)}{1-\tau^2}}$ (with n = number of substudies; d.f. = n-2) and comparing the absolute value with the table of Student’s t for a two-tailed test with α = 0.05 and α = 0.01. More information about the number of substudies for all correlations was summarized in Table 4.3. For each substudy, information was available about the BD before traffic and the absolute BD increase. However, not all studies contained details about the machine mass, number of tyres or number of passes, and this information could not always be found in literature, which explains the differences in *n* between the various characteristics. In case of testing the correlation between the response ratio and the machine mass per tyre, one study was also omitted as it concerned a tracked machine (Ares et al. 2005).

4.4 Results

The funnel plot showed that most of the studies are grouped at rather low SE (Fig. 4.1). A lot of points were not located in the 95% confidence interval, but they were dispersed symmetrical around the mean response ratio. Kendall's tau, calculated for all textures together (tau = -0.018, p = 0.647), was insignificant. However, when looking specifically at subsets Clay (tau = 0.473; p = 0.019) and Sand (tau = -0.191; p = 0.017), Kendall's tau was significantly different from zero.

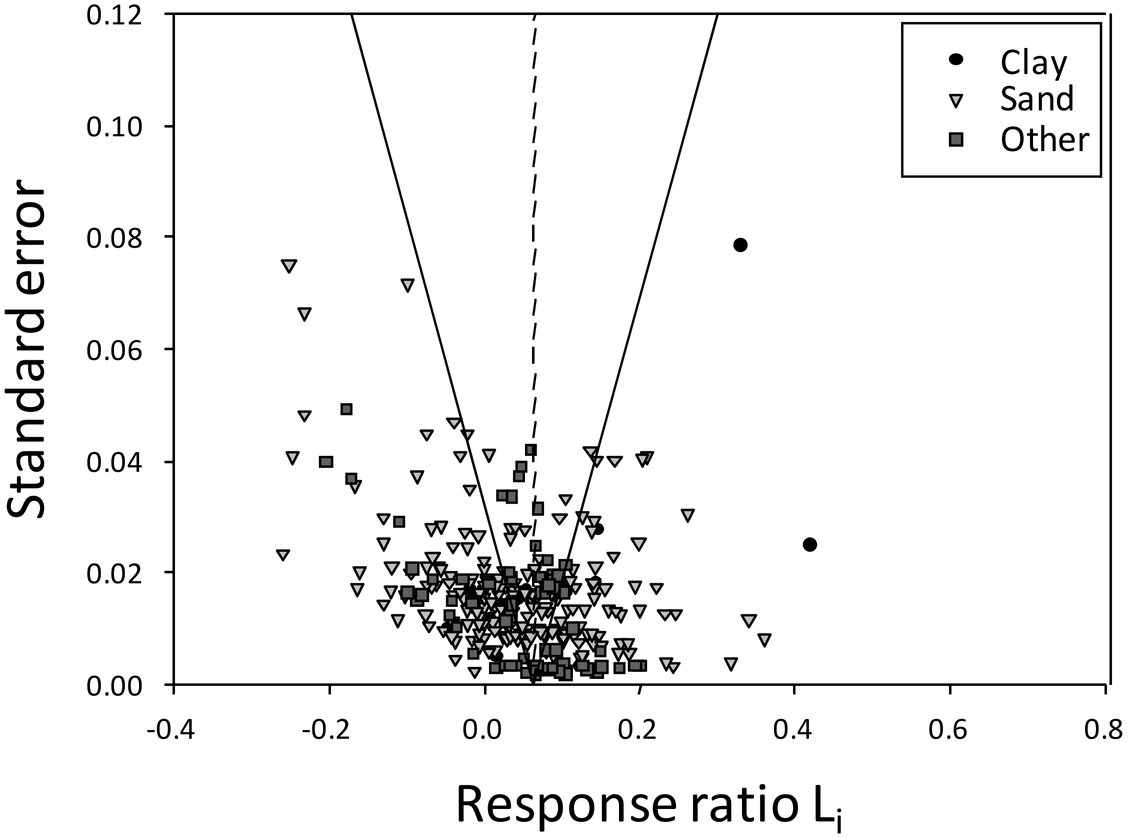


Fig. 4.1 Funnel plot representing SE in function of the response ratio. Dotted vertical line indicates the overall mean response ratio (= 0.0644). The diagonal lines show the expected 95% confidence interval around the mean response ratio. 'Other' represents all textures apart from the soil textures in subsets Sand and Clay.

Most response ratios for depth classes 0-10, 10-20 and 20-30 cm were positive, indicating a larger BD after machine traffic compared to the value before traffic (Fig. 4.2). In other words, in most of the substudies, machine traffic resulted in soil compaction. It seems that all values for Clay and most of the values for Sand were higher than zero. With increasing depth, the positive response ratios decrease, meaning that the machine impact was largest at the surface and decreased with depth.

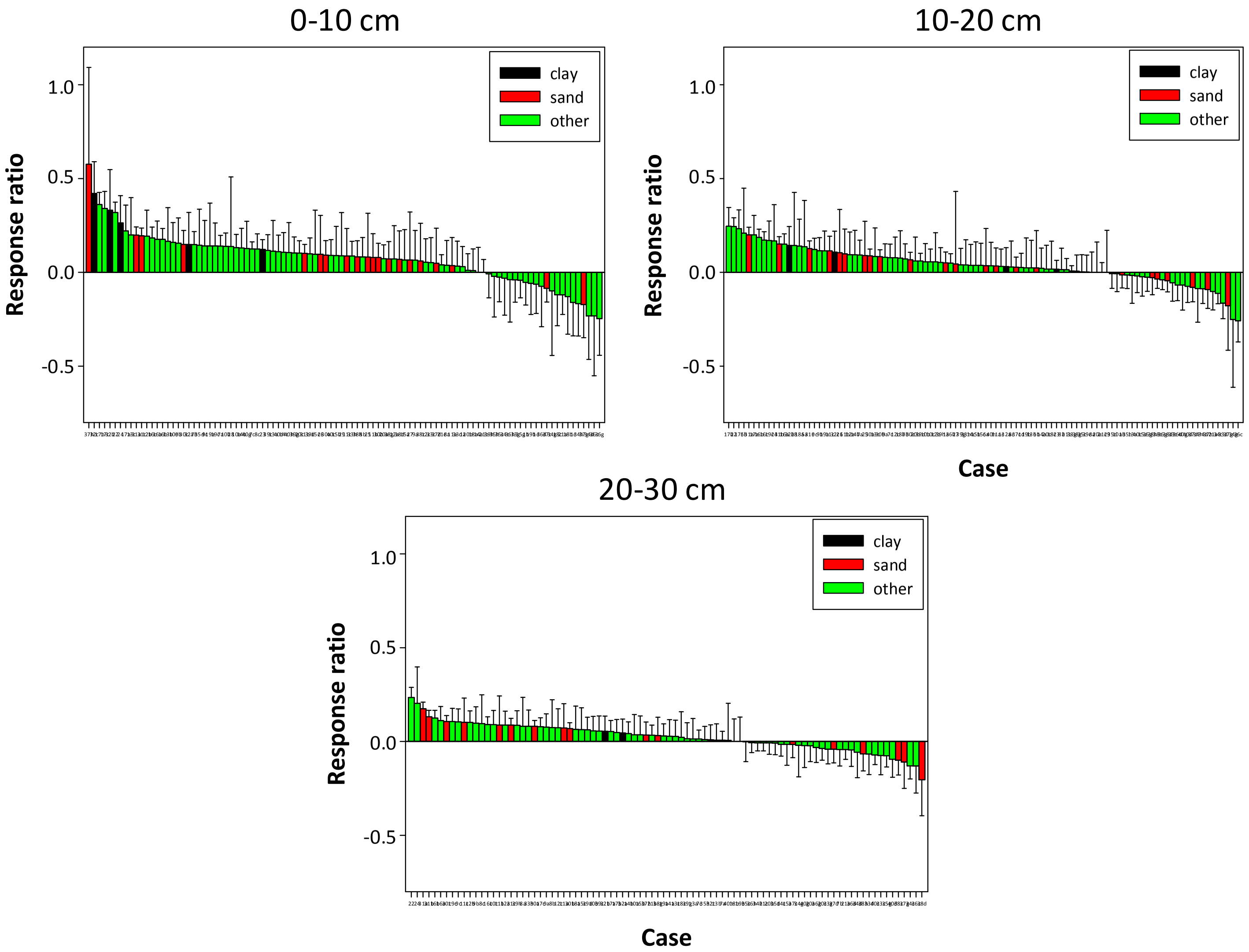


Fig. 4.2 Response ratios for soil depth classes 0-10 cm (98 substudies), 10-20 cm (102 substudies), 20-30 cm (88 substudies). Error bars indicate the 95% confidence interval.

The same conclusions could be drawn when the mean response ratios were calculated per depth class for all texture classes together (All) and for Clay and Sand separately (Fig. 4.3, Table 4.2). All mean response ratios were higher than zero, indicating compaction. For the first depth interval it seems that the impact was highest on Clay soils, but the differences with the mean impact on Sand and All were not significant. The response ratio was 0.16, in terms of percentage equivalent to a BD increase of 18%. Values were similar for All and Sand (0.11 or 12%, respectively 0.12 or 13%; $p > 0.05$). In depth intervals 10-20 cm and 20-30 cm, the mean impact on Sand was highest (0.07-0.08) and significantly different from the mean impact on All ($p < 0.001$ for both depth intervals). The impacts on Clay and All were similar ($p > 0.05$). As could already be concluded from Fig. 4.2, the impact was largest at the surface and decreased with depth and this decrease happened faster for Clay than for Sand and All. For Clay, the differences between impacts in depth intervals 0-10 cm and 10-20 cm on the one hand ($p = 0.009$) and 0-10 cm and 20-30 cm on the other ($p = 0.032$) were significant. For Sand significant differences were stated between 0-10 cm and 10-20 cm ($p < 0.001$), between 0-10 cm and 20-30 cm ($p < 0.001$) and between 10-20 cm and 20-30 cm ($p = 0.004$). For All, all differences between the impacts on the three depth intervals were significant ($p < 0.001$).

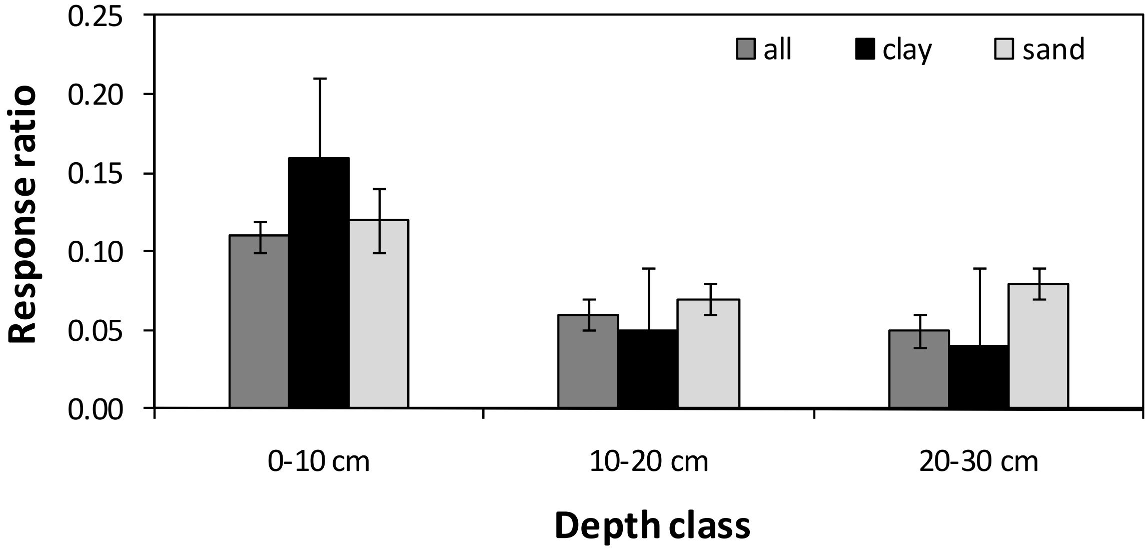


Fig. 4.3 Mean response ratio for All, Clay and Sand per depth class. Error bars indicate 95% confidence interval.

Table 4.2 Number of forest stands, substudies and mean response ratios (with 95% confidence interval) for All, Clay and Sand per depth class.

Depth class	Texture	Forest Stands	Substudies	Mean response ratio
0-10 cm	All	35	98	0.11 ± 0.01
	Clay	2	4	0.16 ± 0.05
	Sand	8	20	0.12 ± 0.02
10-20 cm	All	37	102	0.06 ± 0.01
	Clay	2	4	0.05 ± 0.04
	Sand	10	24	0.07 ± 0.01
20-30 cm	All	28	88	0.05 ± 0.01
	Clay	1	3	0.04 ± 0.05
	Sand	5	17	0.08 ± 0.01

The highest absolute BD increases were found on soils with the lowest bulk densities before traffic (Fig. 4.4, Table 4.3). Looking at all depth classes together, as well for All as Clay the correlation was negative and strongly significant (τ = weighted Pearson product-moment correlation coefficient = -0.23, p <0.01 for All; τ = -0.77, p <0.01 for Clay), what means that the absolute BD increase decreased as the BD before traffic increases. Looking at all texture classes together (All) this significantly negative relationship occurred in the second (τ = -0.29, p <0.01) and third depth interval (τ = -0.39, p <0.01). From a certain limiting value, the absolute BD increases approached zero and were in some substudies negative, indicating that the compaction process stopped and the soil rather seemed to loosen up as a result of machine traffic.

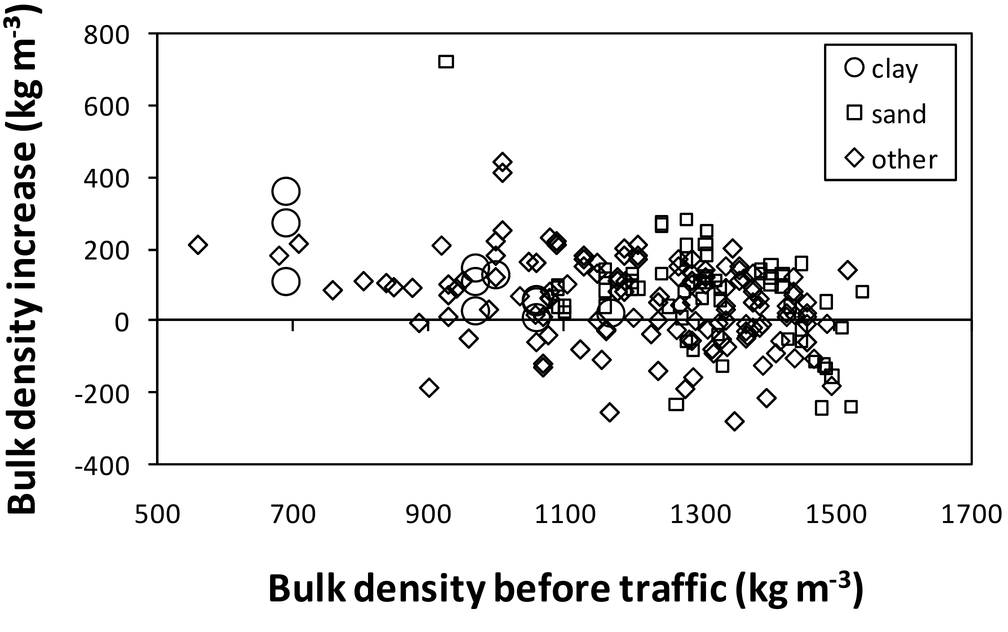


Fig. 4.4 Correlation between the bulk density before traffic and the absolute bulk density increase (kg m^{-3}). 'Other' represents all textures classes apart from the soil texture classes in subsets Sand and Clay.

Table 4.3 Correlation between the response ratio (or absolute bulk density increase) and bulk density before traffic, machine mass, machine mass per tyre, number of machine passes) with n = number of substudies, τ = weighted Pearson product-moment correlation coefficient, * = significant value with α = 0.05, ** = significant value with α = 0.01.

Correlation	Texture	Depth class							
		All depth classes		0-10 cm		10-20 cm		20-30 cm	
		n	τ	n	τ	n	τ	n	τ
Absolute BD increase - BD before traffic	All	288	**-0.23****	98	-0.14	102	**-0.29****	88	**-0.39****
	Clay	11	**-0.77****	4	-0.65	4	-0.75	3	/
	Sand	61	-0.05	20	-0.42	24	-0.29	17	-0.15
Response ratio – machine mass	All	260	**0.48****	87	**0.38****	91	**0.55****	82	**0.63****
	Clay	11	0.19	4	0.77	4	0.77	3	/
	Sand	55	**0.39****	17	0.42	21	0.25	17	**0.66****
Response ratio – machine mass per tyre	All	255	0.11	86	0.09	88	0.11	81	0.17
	Clay	11	-0.19	4	-0.10	4	-0.21	3	/
	Sand	44	**0.57****	14	0.04	16	0.17	14	0.18
Response ratio – number of machine passes	All	275	0.06	92	0.07	96	0.13	87	-0.01
	Clay	11	0.35	4	0.93	4	0.26	3	-0.91
	Sand	55	-0.13	17	0.08	21	-0.13	17	0.05

Significant correlation coefficients are marked in bold (* p <0.05, ** p <0.01).

The machine mass determines, together with a number of other factors such as tyre width, tyre profile and pressure, the soil contact pressure, and thus the extent to which the soil is compacted. However, unfortunately almost all articles lacked information on the soil contact pressure of the machines used, nor was other information available to calculate this pressure, such as weight distribution and tyre characteristics. No correlation could thus be determined between the response ratio and the soil contact pressure. Therefore only machine mass could be used as an indication of soil contact pressure. A significant, positive relationship existed between the machine mass and the response ratio for all textures together (τ = 0.48, p <0.01) and for forest stands on Sand (τ = 0.39, p <0.01), indicating an increased compaction degree with increasing machine mass (Fig. 4.5, Table 4.3). This significantly positive relationship could also be discerned for each depth interval separately for All. It has to be noticed that different machines with the same mass may have a different number of tyres over which the machine mass is distributed, resulting in different soil contact pressures. The machine mass per tyre was therefore correlated with the response ratio. Only for Sand this relationship appeared significant when all depth classes were analysed together (τ = 0.57, p <0.01) (Table 4.3).

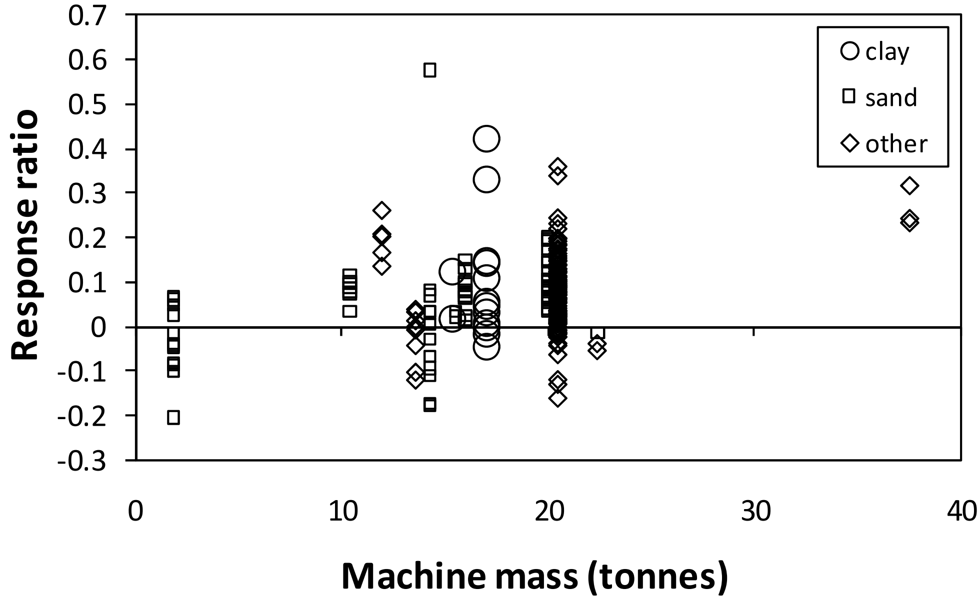


Fig. 4.5 Correlation between the machine mass (tonnes) and the response ratio. 'Other' represents all texture classes apart from the soil texture classes in subsets Sand and Clay.

Looking at the relationship between the response ratio and the number of passes that the machines made (traffic intensity) (Fig. 4.6, Table 4.3), it seemed that for neither All, Sand or Clay the correlation coefficient was significant.

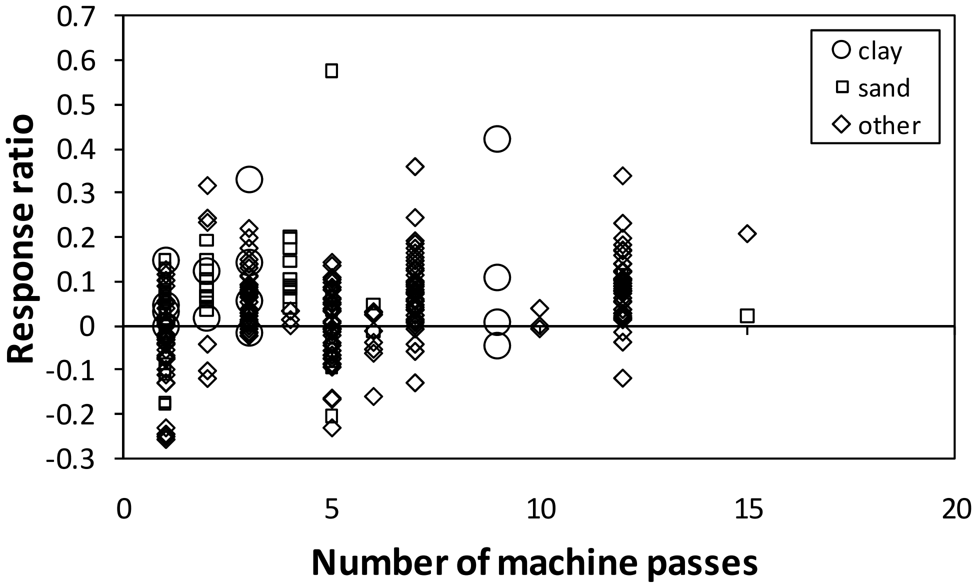


Fig. 4.6 Correlation between the number of machine passes and the response ratio. 'Other' represents all texture classes apart from the soil texture classes in subsets Sand and Clay.

4.5 Discussion

First of all, it should be noted that a lot of the articles found through the literature search lacked necessary basic information and so could not be included in the final dataset. In publications, attention should be given to the record of important characteristics such as number of replications and information about the precision of the measurements. This information is necessary to perform a good and balanced meta-analysis using the method of Hedges et al. (1999). The more study results that can be used in a meta-analysis, the more general are the conclusions that can be drawn. Moreover, soil and machine characteristics, such as soil water contents, soil acidity and the real soil contact pressure of the machines, may influence compaction degrees due to machine traffic. As was stated by Hillel (1998) and Smith et al. (1997) (§1.2.4.1), soil water content has a great influence on the soil compaction degree. Moreover, it is suggested that soils are most susceptible to compaction in a pH-range of 4.5-5.5. Above and below this threshold soil structure is stabilized by Ca, respectively Al (von Wilpert K, *personal communication*). However, the dataset was not further divided based on soil water content or soil acidity, as information on these characteristics lacked in most cases. Therefore, although very interesting, we could not focus on these aspects in the meta-analysis. As cases with completely different soil water content and soil acidity were all present in the same dataset without further subdivision, this may have led to high overall variation. Machines with the same total mass may have a totally different impact due to other tyre dimensions, number of tyres, tyre pressure, or other characteristics that change the contact area between soil and machine and thus the soil contact pressure. The correlation between mean soil contact pressure (disregarding the heterogeneous pressure distribution) and response ratio would already have been more reliable and pronounced in order to evaluate machine impact than the correlation between machine mass and response ratio. However, information to estimate soil contact pressure was unfortunately lacking.

Based on the funnel plot one should conclude that publication bias is present, according to Sterne & Egger (2001). However, looking at the symmetrical distribution around the mean response ratio, it seems that the publication of studies with a larger than normal response was not favoured above the publication of studies with a smaller than normal or even negative response, and thus that publication bias is absent. The large number of points outside the confidence interval could be due to heterogeneity, i.e. studies with similar precision but clearly different response ratios (e.g. due to differences in machine mass, traffic intensity, precompression stress, soil water content, soil acidity). Kendall's tau, calculated for all textures together, confirms the conclusion from the funnel plot that publication bias is absent. However, for subsets Clay and Sand publication bias seems to be present. Conclusions drawn from the funnel plot and Kendall’s tau should be treated carefully. On the one hand, the test has a low power unless there is severe bias or the meta-analysis contains a large number of (sub)studies (more than 25). A non-significant Kendall’s tau is indicative but should not be taken as proof that bias is absent. On the other hand, some studies dealt with several textures, machines, traffic intensities to examine the impact of these factors. In this analysis they were treated as different substudies, although they were not independent from each other. This was necessary to be able to examine the impact of machine, number of passes and texture based on the small number of usable articles. The damage degree that was induced under these diverse conditions was not similar, but showed a range of values. So, from one study as well low impact treatments as high impact treatments could be present in the funnel plot, leading to a rather even distribution. One could then conclude that publication bias is absent and that similar attention has been given to the publication of high and low impact results. However, the even distribution could be largely due to only a few articles, examining diverse conditions and the presence of true publication bias could in this way be masked.

4.5.1 Vulnerability of soils with different texture to soil compaction

USDA Forest Service determined that a BD increase of more than 15%, corresponding to a response ratio of 0.14, leads to detrimental soil compaction (Powers et al. 1998). The individual response ratios per substudy showed that most of the cases had response ratios smaller than 0.14. Looking at the mean response ratios (Table 4.2) it can be deduced that this threshold has been crossed for Clay in the first depth interval, although the difference between this threshold and the mean impact was not significant. For Sand and All, BD increased 12-13% in this interval. If the above threshold is used to evaluate these soil impacts in the first depth interval, it seems that machine traffic may have brought serious threats to the soil ecosystem in some cases. At higher soil depths, BD increases were rather limited for all soil textures. It should be noticed that evaluating the soil impact by means of only the BD increase may lead to a serious underestimation of the real soil impact. Although compaction degrees were rather restricted, machine traffic may have destroyed pore continuity, amongst others leading to hampered gas exchange and water infiltration. This may in turn affect growth and activity of roots and soil organisms (Schumacher & Smucker 1981; Bathke et al. 1992). Therefore, in order to estimate the total soil impact, all aspects of soil damage (such as compaction, rutting and especially the impact on gas exchange) should be evaluated.

Some studies have pointed out that the clay content is positively correlated with the degree of soil damage (Gomez et al. 2002; Smith 2003), explaining the higher positive response ratios for the Clay soils. In general, it is assumed that compaction occurs especially on silty and clayey soils, while sandy soils are often expected to be rather indifferent to traffic with heavy machines (Fisher & Binkley 2000). However, here response ratios for Sand were as high as the overall mean and not significantly different from the impacts on Clay. Brais & Camiré (1998) found that the BD increase in terms of percentage was as high on a soil with a coarse texture in comparison with medium- to fine-textured soils. Ampoorter et al. (2007; Chapter 3) also stated that sandy soils can be compacted to a considerable extent. The assumed higher sensitivity of medium- to fine-textured soils compared to coarse-textured soils is partially true when the soil water content at the medium- to fine-textured soils is close to the optimum soil water content (Smith et al. 1997; Hillel 1998) (§1.2.4.1). In this case, low cohesion exists between clay or silt particles and compaction degrees are maximal. At sandy soils, cohesion between soil particles is minimal at low or high soil water contents and soil impact shows a local minimum at intermediate soil water contents (Smith et al. 1997; Langohr & Ampe 2004). Therefore it is possible that experiments on all textures took place at rather low or rather high soil water contents.

The significant decrease of the compaction degree with depth, as was shown in Chapter 3, was clear for All, Sand and Clay. The forces implied by the machine mass are transformed in the compaction process. Pores are compacted in the first depth interval, in this way intercepting the machine forces and protecting the layers below. However, this initial compaction leads to higher soil strength in the upper soil layers, thereby preventing further compaction in this layer. At the next passes the forces are shifted to deeper soil layers. However, deeper in the soil, compaction passes of more slowly due to a dissipation of the machine forces over a larger area (Shetron et al. 1988; Balbuena et al. 2002).

4.5.2 Impact of initial bulk density on compaction degree

The initial bulk density gives an indication of the precompression stress and influences the absolute BD increase in a significantly negative way for All, Sand and Clay, as was also stated in Chapter 2 and Powers et al. (2005). Soils with a low initial bulk density and thus low precompression stress contain a lot of macropores that are easy to compact. Compacted soils have smaller pores which exert a higher resistance and are thus less prone to compaction (Shetron et al. 1988; Hillel 1998; Berli et al. 2003), protecting the soil from further compaction (Incerti et al. 1987; Williamson & Neilsen 2000). Only when the applied machine stress exceeds this soil precompression stress, then soil structure is influenced (Horn et al. 2007). The impact of a specific machine will this be higher at low precompression stresses compared to high precompression stresses, explaining the negative correlation between initial bulk density and the compaction degree. Results seem to suggest a limiting BD for additional compaction to take place. For clay soils (± 1100 kg m^{-3}) this limit is situated at lower BD values compared to sandy soils (1400-1500 kg m^{-3}). This finding is in accordance with the results of Powers et al. (2005) who saw that soils with an initial BD of 1400 kg m^{-3} or more did not compact anymore. Moreover, through the rotation of the tyres of a heavy machine the compacted superficial soil layer may even churn and break up to a very small extent.

4.5.3 Impact of machine mass on soil compaction

The significant positive correlation between the response ratio and the machine mass for Sand and All should be explained using the mean soil contact pressure. When the machine mass increases strongly and not in proportion to the increase of the contact area with the soil, the soil contact pressure and thus the compaction degree grows. McDonald et al. (1996) came to the same conclusion. A significant relationship between the mass per tyre and the response ratio could only be discerned for Sand. This may partially be due to the fact that for a lot of substudies information about the exact machine type and thus the number of tyres was not available. As this could not always be deduced from literature, these substudies were omitted for this analysis. Moreover, machines often have an uneven mass balance and some axes carry more weight than others. In some cases, the real mass per tyre (and thus also the soil contact pressure) may have been much higher than the value we obtained by dividing the total mass by the number of tyres. Information on tyre pressure, size and profile was for most cases unavailable although these characteristics also have a strong impact on the soil contact pressure and thus the resulting response ratio. The obliged use of total machine mass and machine mass per tyre as a very rough estimation of soil contact pressure instead of the actual contact pressure may have skewed the relationship.

4.5.4 Impact of traffic intensity on soil compaction

For neither All, Sand nor Clay the compaction degree increased significantly with the number of machine passes. This would mean that soil compaction degree is independent of traffic intensity. A rather low number of traffic intensity levels, and a large interstudy variation within each level concerning site and harvest characteristics may have skewed the relationship with traffic intensity. However, several studies (e.g., Brais & Camiré 1998; da Silva et al. 2008) state a logarithmic relationship between traffic intensity and compaction degree with a strong influence of the first passes and a stabilization of the response ratio at higher levels traffic intensities. At subsequent passes pores become smaller and exert more resistance to further compaction, as was mentioned in §4.5.2. This increases the soil strength and thus the precompression stress, partially protecting the soil from further compaction. Subsequent passes will induce a diminishing extra compaction degree until the applied machine stress no longer exceeds the constantly increasing precompression stress.

Water stagnation in deep ruts caused by five passes of the John Deere grapple-skidder JD640 at the field trial in Walem 1 (Chapter 2) [photograph: Evy Ampoorter, February 2007].

5 Impact of forest soil compaction on growth and survival of tree saplings: a meta-analysis

After: Ampoorter E, De Frenne P, Hermy M, Verheyen K (2010) Effects of soil compaction on growth and survival of tree saplings: a meta-analysis. Basic & Applied Ecology, *revised manuscript resubmitted*

5.1 Abstract

Soil compaction due to mechanized harvesting operations in forests can have profound effects on forest soils and, hence, can have a detrimental effect on subsequent forest regeneration. We performed a meta-analysis to quantify the impact of soil compaction on height and diameter growth and survival of tree saplings. The impact of soil compaction on height growth, diameter growth and survival was predominantly insignificant, varied strongly and was thus not unambiguously negative. Only on silty soils (and clayey soils to a minor extent), growth and survival were significantly reduced by soil compaction, which contrasted with sandy and loamy soils, where the impact of soil compaction was negligible or even slightly positive. A weighted analysis revealed an overall decrease of height growth on the compacted area, but this result should be interpreted with caution due to the limited number of observations. Although results did not show an overall negative effect of soil compaction, harvesting activities should focus on minimizing soil compaction degree and extent to prevent a decrease of soil productivity. From a methodological point of view we suggest providing more basic statistics in the articles and to include more shade tolerant tree species in future experimental designs. These species are currently underrepresented.

5.2 Introduction

The use of heavy machinery to perform forestry activities such as logging has increased worldwide during the last decades. However, these machines may seriously influence the soil ecosystem as they induce rutting, churning of the upper soil layers, and soil compaction. The latter implies a decrease of soil pore continuity (Benthaus & Matthies 1993), compression of soil pores, and an increasing soil bulk density (Cullen et al. 1991). Aust et al. (1998) stated an increased penetration resistance after machine traffic, a measure for the resistance that a soil exerts against root growth. Moreover, Ballard (2000) reported changes in soil water retention and saturated hydraulic conductivity. Several studies indicated an increase of soil CO_2 concentration and decrease of O_2 concentration due to an unfavourable influence on soil aeration (e.g., Startsev & McNabb 2009). Tan & Chang (2007) showed that soil compaction also had a negative effect on net nitrification rates, although Blumfield et al. (2005) did not notice a significant effect on nitrogen mineralisation or nitrification.

Heavy soil damage may impose a serious threat to soil ecosystem functioning. Higher PR reduces elongation and penetration of roots and thus lowers the uptake of water and nutrients (Kozlowski 1999). A higher seedling mortality and reduced tree growth was observed by Cheatle (1991), Gebauer & Martinková (2005) and Bulmer & Simpson (2005), in contrast with Fleming et al. (2006), Nabe-Nielsen et al. (2007) and Alameda & Villar (2009) who found a beneficial impact of soil compaction on regeneration, respectively growth. The level of these effects depends on soil type and examined tree species (Gomez et al. 2002; Heninger et al. 2002). Several studies indicated that roots may still grow in compacted soils through soil cracks and channels of dead roots (Greacen & Sands 1980). Apart from the impact on tree growth and survival, soil compaction may also influence the performance and diversity of understory plants (e.g., Zenner & Berger 2008), soil macrofauna such as earthworms (e.g., Jordan et al. 1999), and microbes (e.g., Kara & Bolat 2007).

As shown above, results on the impact of soil compaction on tree growth and survival are not unequivocal. For the most part, studies examined one compaction degree, one species, taxonomic group or one soil type. To date, no general conclusions could be drawn. We performed a meta-analysis to unravel the impact of soil compaction on tree sapling growth and survival in a more general way across an array of climates, compaction degrees, soil types and tree species. We specifically addressed:

(a) Whether machine traffic had a negative impact on sapling growth and survival on average;
(b) Which experimental factors explained the variation in growth and survival responses to soil compaction.

5.3 Materials and methods

5.3.1 Data collection: search strategy and study inclusion criteria

The bibliographic database ISI Web of Science (http://apps.isiknowledge.com) was searched to find relevant studies on the overall biotic effects of soil compaction, published between 1955 and 2009. The Boolean search expression was *compact* AND forest* AND harvest** (* = wildcard). This procedure yielded 207 articles, of which 69 treated the biotic effects of soil compaction. The reference lists as well as citing articles were also examined, resulting in 30 and 10 additional articles on biotic effects respectively. Finally, Google (www.google.com) was used for additional searching but only one new article was found. Of these 110 articles, 65 examined tree growth and survival, 30 studied the herb layer, and 25 looked at the effects on soil biota (microbiota, earthworms, etc). In this meta-analysis we specifically decided to focus on the impact on tree growth and survival. A lot of articles concerning herb layer and soil biota lacked essential information or examined species or diversity indexes were too different to be analysed together. Next, duplicate studies, studies where no clear distinction was made between compacted and uncompacted soil and studies where a combination of soil compaction and litter layer removal was examined, were deleted. Laboratory or pot experiments were also excluded, as in these cases the soil was artificially compacted, root growth was restricted by the pot boundaries, and the soil processes were probably not comparable to the in situ situation. All remaining articles handled the impact of soil compaction on planted seedlings, resprouts, or natural regeneration, further called *saplings*. The effect of soil compaction on established, adult trees could thus not be examined. Height growth, diameter growth and survival of the saplings were selected as response variables as most articles quantified at least one of these variables. This resulted in 22 studies retained in the final dataset. Six were located in Canada, 11 in the USA, two in South America, two in Oceania and one in Africa. Detailed information on the selected studies is summarized in Table 5.1. Local climates were classified according to the Köppen-

Table 5.1 Overview of studies included in this meta-analysis. Local climates were classified according to the Köppen-Geiger classification (Kottek et al. 2006). Local textures were classified in texture subsets (sand, silt, loam, clay) using the USDA classification system (Soil Survey Division Staff 1993). Studies were further classified according to the type of compaction treatment: LTSP (Long-Term Soil Productivity Study), experiment (in which frequently occurring traffic intensities or soil contact pressures were imitated), harvest (compaction due to a true, recent harvest), old wheel tracks (measurements performed in wheel tracks of former harvests). For tree species, information on shade tolerance was indicated (- : intolerant, 0 : intermediate, + : tolerant) (cf USDA & NRCS 2010). All light and dark grey coloured studies were included in the weighted analysis for the calculation of $RR_{height,\ Hedges}$. Dark grey coloured studies were also included in the weighted analysis for the calculation of the weighted Pearson correlation coefficient between $RR_{height,\ Hedges}$ and RR_{dens}.

Article (year of publication)	Location	Köppen-Geiger classification	Texture subset	Type of compaction treatment	Tree species (with shade tolerance)	Type of sapling	Measurement year	Number of substudies			# locations
								Height	Diameter	Survival	
Ares et al. (2005)	Coastal range of Washington State	Csb	Clay	LTSP	*Pseudotsuga menziesii (0)*	planted (at age 2 years)	4 years after planting	1	1		1
Balbuena et al. (2002)	Buenos Aires State, Argentina	Cfa	Clay	experiment	*Populus deltoides (-)*	resprouts	1 year after compaction	3		3	1
Bates et al. (1993)	Northern Minnesota	Dfb (mainly)	silt	harvest	*Populus tremuloides (-)*	natural regeneration	1 year after compaction	4			1
Bockheim et al. (2005)	Northwestern Wisconsin	Dfb	sand	experiment	*Populus tremuloides (-)*	natural regeneration	8 years after compaction		1		1
Brais (2001)	Gulf Coastal Plain of USA	Dfb	Clay	experiment	*Picea glauca (0)*	planted (at age 2 years)	5 years after planting	2			1
			Sand		*Picea mariana (+)*			2			1
			Sand		*Pinus banksiana (-)*			2			
Carter et al. (2006)	Gulf Coastal Plain of USA	Cfa	Sand/silt/clay	LTSP	*Pinus taeda (-)*	planted (at age 1 year)	3-4 years after planting	4	3	3	4
Da silva et al. (2008)	Brazil	Aw	Clay	experiment	*Eucalyptus grandis (-)*	/	1 year after planting		3		1
Heninger et al. (2002)	Western Oregon	Csb	Loam	harvest	*Pseudotsuga menziesii (0)*	planted (at age 2 years)	8 years after planting	1		1	1
Kabzems (2000)	Dawson Creek Forest District, British Columbia	Dfc	Silt	LTSP	*Picea glauca (0)*	/	3 years after planting		1	1	1
Kabzems & Haeussler (2005)	Dawson Creek Forest District, British Columbia	Dfc	Silt	LTSP	*Populus tremuloides (-)*	natural regeneration	5 years after compaction	1			1
Kamaluddin et al. (2005)	Southeastern British Columbia	Dfc	Sand/loam	LTSP	*Pinus contorta (-)*	planted (at age 1 year)	1.5 years after planting	1	1		1
					Pseudotsuga menziesii (0)			1	1		1

Kranabetter et al. (2006)	British Columbia	Dfc	Silt/clay	LTSP	*Pinus contorta (-)* *Picea glauca (0)*	planted (at age 1 year)	12 years after planting	1 1			1 1
Ludovici (2008)	Craven county, Croatan National Forest, North Carolina,	Cfa	loam	LTSP	*Pinus taeda (-)*	planted (at age 1 year)	10 years after planting	1	1		1
Murphy et al. (1997)	New Zealand	Cfb	Clay	experiment	*Pinus radiata (0)*	planted (at age 1 year)	11 years after planting	2	2		1
Perry (1964)	Durham County, North Carolina	Cfa	/	old wheel tracks	*Pinus taeda (-)*	/	at 26 years old	1	1		1
Ponder et al. (1999)	Shannon County, Carr Creek State Forest, Missouri	Cfa	loam	LTSP	*Quercus rubra (0)* *Quercus alba (0)* *Pinus echinata (-)*	planted (at age 1 year)	3 years after planting	1 1 1	1 1 1	1 1 1	1
Puetmann et al. (2008)	Minnesota	Dfb (mainly)	Sand/silt	harvest	*Populus tremuloides (-)/ P. grandidentata (-)*	natural regeneration	4-11 after compaction	4			1
Simcock et al. (2006)	North of Auckland, New Zealand	Cfb	Clay	experiment	*Pinus radiata (0)*	planted (at age <1 year)	3 years after planting	1		1	1
Smith (2003)	Kwazulu Natal, Zululand, South Africa	Cfb-Cwb	Sand	old wheel tracks	*Eucalyptus grandis (-)*	/	at 4-7 years old			5	3
Stone & Elioff (1998)	Minnesota	Dfb	Sand	LTSP	*Populus tremuloides (-)/ Populus grandidentata (-)*	natural regeneration	5 years after compaction	1	1		1
Stone & Kabzems (2002)	Minnesota, British Columbia	Dfb-Dfc	Silt	LTSP	*Populus tremuloides (-)/ Populus grandidentata (-)*	natural regeneration	5 years after compaction	4			2
Tan et al. (2009)	British Columbia	Dfc	Loam-silt/sand/ clay	LTSP	*Pinus contorta (-)* *Pseudotsuga menziesii (0)*	planted (at age 1 year)	3 years after planting			3 3 (1 outlier)	3

Geiger classification (Kottek et al. 2006). Type of compaction treatment refers to the way that soils were compacted. In several studies compaction was experimentally applied with heavy machinery (skidder, loader, bulldozer…), aiming to simulate current traffic intensities or compaction degrees (*experiment*). Other experimental studies were part of the Long-Term Soil Productivity (*LTSP*) Study where nine combinations of organic matter removal and soil compaction were applied. In the LTSP study compaction treatments were also intended to simulate prevailing compaction degrees and were often applied using a compactor head on an excavator or a heavy roller pulled by a tractor. In the remaining studies soils were compacted by virtue of recent (*harvest*) or former (*old wheel tracks*) harvests.

5.3.2 Data preparation and analysis

5.3.2.1 Predictor variables

Because some studies examined the effect of several traffic or disturbance intensities, harvesting regimes, locations or tree species, data for each combination was included as an individual substudy. This yielded a total of 41 substudies for dataset Height, and a number of 19 and 23 substudies for datasets Diameter, respectively Survival. Each substudy was classified in one of four texture subsets using the USDA classification system (Soil Survey Staff 1999): sand (sand, loamy sand, sandy loam), silt (silt, silt loam), loam (loam, sandy clay loam, silt clay loam) and clay (clay, silty clay, sandy clay, clay loam). Due to a lack of detailed information on soil texture, a few substudies were assigned to more than one texture subset. For instance, when soil texture information mentioned sandy loam-silt loam, the soil was classified as both sand and silt. The examined tree species were subdivided into two functional tree groups: deciduous broadleaved species and evergreen coniferous species. Taking the morphological and functional differences between these two groups into account, we hypothesized that there might also be a difference in response to soil compaction. It should be noted that eight of the 14 examined species (around 65% of the substudies for each dataset) were intolerant to shade, five displayed intermediate shade tolerance (around 33% of the substudies) and only one species was shade tolerant (< 5% of the substudies) (cf USDA & NRCS 2010) (Appendix 1).

In each substudy, part of the area was compacted with forestry machines, tractors or a rolling vibrator and another part was left untreated and was thus not influenced by the machines. As an indication of the soil compaction degree, most articles mentioned information on soil bulk density (68%, 79%, 70% of substudies for Height, Diameter, and Survival, respectively). Information on other abiotic variables (e.g., penetration resistance, CO_2 efflux) was not considered due to the limited number of substudies for which these characteristics were available. The response ratio of bulk density (RR_{dens}) of each substudy was determined as the ratio of the mean bulk density on the compacted area for that substudy to the mean bulk density on the uncompacted area for that substudy:

$$RR_{dens} = \frac{bulk\ density\ on\ compacted\ area}{bulk\ density\ on\ uncompacted\ area}$$

The bulk density on the uncompacted area is further in the text mentioned as *Contrdens*. If no compaction took place, RR_{dens} is equal to one, but the ratio increases with the compaction degree. If information on the compaction degree was available for several soil depths, only the results obtained in depth interval 10-20 cm were used in further analyses. This depth interval normally holds relatively high root densities and compaction degrees are often higher compared to depth interval 0-10 cm, thus giving a better indication of the soil impact (e.g., Ampoorter et al. 2007). Finally, the last predictor variable was *period*, representing the number of years between the start of the measurement period (moment of planting for planted seedlings, moment of harvest or compaction treatment for resprouts and natural regeneration) and the end measurements.

5.3.2.2 Response variables

In all substudies, on both the uncompacted and the compacted area, an equal number of saplings with similar initial height and diameter were planted or selected from natural regeneration or resprouts. After a certain period (Table 5.1), various combinations of height, diameter, and survival were measured. In order to evaluate the response of height growth to soil compaction, the response ratio RR_{height} was calculated for each substudy as the ratio of the mean total height on the compacted area for that substudy to the mean total height on the uncompacted area for that substudy:

$$RR_{height} = \frac{total\ height\ on\ compacted\ area}{total\ height\ on\ uncompacted\ area}$$

Response ratios for diameter (RR_{diam}) and survival (RR_{surv}) were calculated in a similar way. One substudy was omitted from the survival dataset (Tan et al. 2009) since it was an extreme outlier (survival rate on the compacted soil 2-3 times survival rate on the uncompacted soil).

5.3.2.3 Analysis

Hedges et al. (1999) stated that a good and balanced meta-analysis requires three basic statistics: the mean of the response variable, a measure of the variance and the number of replicates. Their method determines weighted mean response ratios and correlation coefficients, taking the number of replications and the variance of each substudy into account. Giving greater weights to experiments whose estimates have greater statistical precision (thus with smaller standard error) increases the precision and thus reliability of the combined estimate. A detailed description of these analyses is given in Hedges et al. (1999). In the present study the available information on the number of replicates and variances shows strong variation and the use of the techniques of Hedges et al. (1999) would thus be beneficial. However, a lot of the selected articles lacked information on the above mentioned basis statistics and only for dataset Height an adequate number of studies (7 studies containing 20 substudies in total) contained the necessary information. Hedges' method (Hedges et al. 1999) was used to calculate $RR_{height,\ Hedges}$, defined as the weighted mean of the natural logarithm of RR_{height} (value equals zero in case no difference exists between compacted and uncompacted area). The weighted Pearson correlation coefficient between $RR_{height,\ Hedges}$ and RR_{dens} was based on 4 of these studies (containing 13 substudies) as the rest lacked information on the bulk density increase caused by the compaction treatments. The techniques of Hedges et al. (1999) could thus not be applied to most substudies in the datasets on diameter growth and survival and several substudies in dataset Height. Unweighted analyses are not as accurate as the weighted analysis of Hedges et al. (1999) but may provide an indication of the mean responses to soil compaction. *Resampling Stats v. 4.0* (http://www.resample.com) was used to calculate unweighted mean values and 95 % bootstrapping confidence intervals (dataset resampled 1500 times, randomly and with replacement) of RR_{height}, RR_{diam}, RR_{surv} and RR_{dens} for all substudies together and for the functional tree groups and textures separately.

The relative importance of the predictor variables functional tree group, texture, RR_{dens}, contrdens and period on RR_{height}, RR_{diam} and RR_{surv}, was tested with multilevel models in R 2.11.1 (R Development Core Team 2010). A random effect term s*tudy* was added to the models to address the likelihood that substudies obtained from the same study share autocorrelated characteristics. First, a null model was constructed containing only the random effect term, and the intraclass correlation (% var_{study}) was calculated according to Hox (2002) as the proportion of the grouping level variance (σ^2_{study}) to the total variance ($\sigma^2_{study} + \sigma^2_{residuals}$):

$$\%\ var_{study} = \left(\frac{\sigma^2_{study}}{\sigma^2_{study} + \sigma^2_{residuals}}\right) \times 100$$

Next, the null model was compared with a model that included one of the predictor variables. Based on the -2 log Likelihood information criterion (i.e., deviance; Hox 2002) the significance of each predictor variable was tested (χ^2 test statistic; Zuur et al. 2009). To avoid overfitting and for model simplification, only variables with p-value <0.05 were considered for the final multilevel model. Subsequently, the remaining significant predictors were added one-by-one to the model with the lowest deviance containing only one predictor. If the deviance decreased significantly (χ^2 test statistic with likelihood ratio test), this procedure was repeated.

Finally, we estimated the proportion of the variation explained by adding the predictor variables to the null model. For that purpose, the ratio of the difference in residuals between the null model (σ^2_{null}) and the final model (σ^2_{final}) over the residuals of the null model (Hox 2002) was calculated:

$$\%\ remaining\ var_{final} = \left(\frac{\sigma^2_{null} - \sigma^2_{final}}{\sigma^2_{null}}\right) \times 100$$

5.4 Results

In general, mean RR$_{dens}$ values were significantly larger than one for the three response variables (Table 5.2, Figure 5.1). Some subsets even had a mean RR$_{dens}$ significantly higher than 1.15. Mean RR$_{height}$, RR$_{diam}$ and RR$_{surv}$ and corresponding bootstrapping confidence intervals for all subsets are represented in Table 5.2 and Figure 5.2. Few values, predominantly in dataset Survival, were significantly different from one. Large interstudy variation and thus relatively wide confidence intervals were present.

Table 5.2 Number of substudies (n), unweighted mean RR$_{dens}$ and unweighted mean RR of Height, Diameter and Survival (95% bootstrapping confidence interval in square brackets) for all subsets in datasets Height, Diameter and Survival.

Group	Respons	Height			Diameter			Survival		
		n	Mean		n	Mean		n	Mean	
All	RR$_{dens}$	28	**1.17**	[1.08; 1.27]	15	**1.29**	[1.18; 1.44]	16	**1.12**	[1.06; 1.19]
	RR	41	0.99	[0.92; 1.07]	19	1.05	[0.86; 1.26]	22	0.97	[0.90;1.04]
Broadleaved	RR$_{dens}$	12	1.10	[1.00; 1.21]	7	**1.29**	[1.20; 1.37]	11	**1.11**	[1.04; 1.21]
	RR	20	0.95	[0.82; 1.11]	7	1.06	[0.8; 1.43]	11	0.91	[0.80; 1.01]
Conifer	RR$_{dens}$	16	**1.22**	[1.10; 1.36]	8	**1.30**	[1.10 ;1.54]	5	**1.15**	[1.05; 1.28]
	RR	21	1.03	[0.97; 1.08]	12	1.04	[0.84; 1.34]	11	1.02	[0.95;1.09]
Sand	RR$_{dens}$	9	**1.25**	[1.07; 1.48]	7	**1.32**	[1.09; 1.58]	8	**1.06**	[1.04; 1.07]
	RR	13	1.12	[0.99; 1.33]	7	1.11	[0.84; 1.45]	9	0.98	[0.92;1.03]
Loam	RR$_{dens}$	7	**1.44**	[1.23; 1.64]	6	**1.48**	[1.28; 1.68]	4	**1.35**	[1.24; 1.41]
	RR	7	0.99	[0.93; 1.06]	6	1.21	[0.85; 1.73]	6	**1.12**	[1.06; 1.17]
Silt	RR$_{dens}$	6	0.99	[0.96; 1.02]	0	/	/	0	/	/
	RR	16	**0.87**	[0.76; 0.97]	1	0.61	/	3	**0.47**	[0.11; 0.76]
Clay	RR$_{dens}$	8	**1.15**	[1.03; 1.33]	4	**1.23**	[1.19; 1.30]	4	**1.02**	[1.01; 1.02]
	RR	12	1.03	[0.96; 1.09]	6	0.96	[0.85; 1.03]	6	0.85	[0.66; 1.05]

RR stands for the response ratio or the ratio of the value on the compacted area to the value on the uncompacted area. In case RR equals one, no difference was stated between the two areas. Means that differ significantly from 1 (thus indicating a significant effect) are marked in bold (p <0.05).

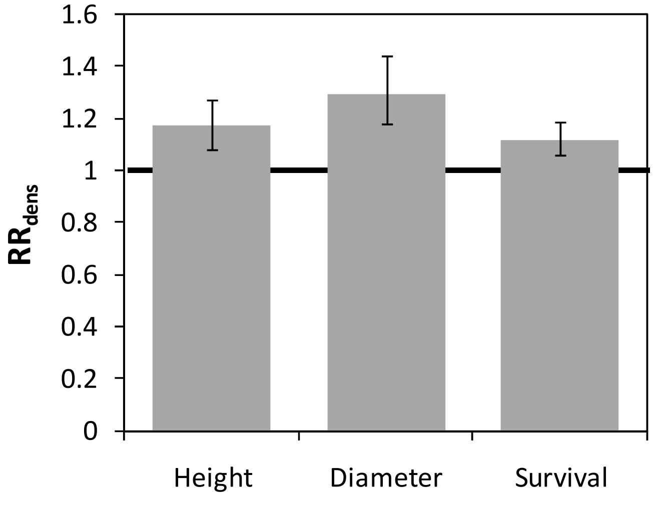


Fig. 5.1 RR of bulk density (RR$_{dens}$) for datasets of height, diameter and survival of tree saplings (and 95% bootstrapping confidence interval). RR stands for the response ratio or the ratio of the value on the compacted area to the value on the uncompacted area. In case RR equals one, no difference was stated between the two areas.

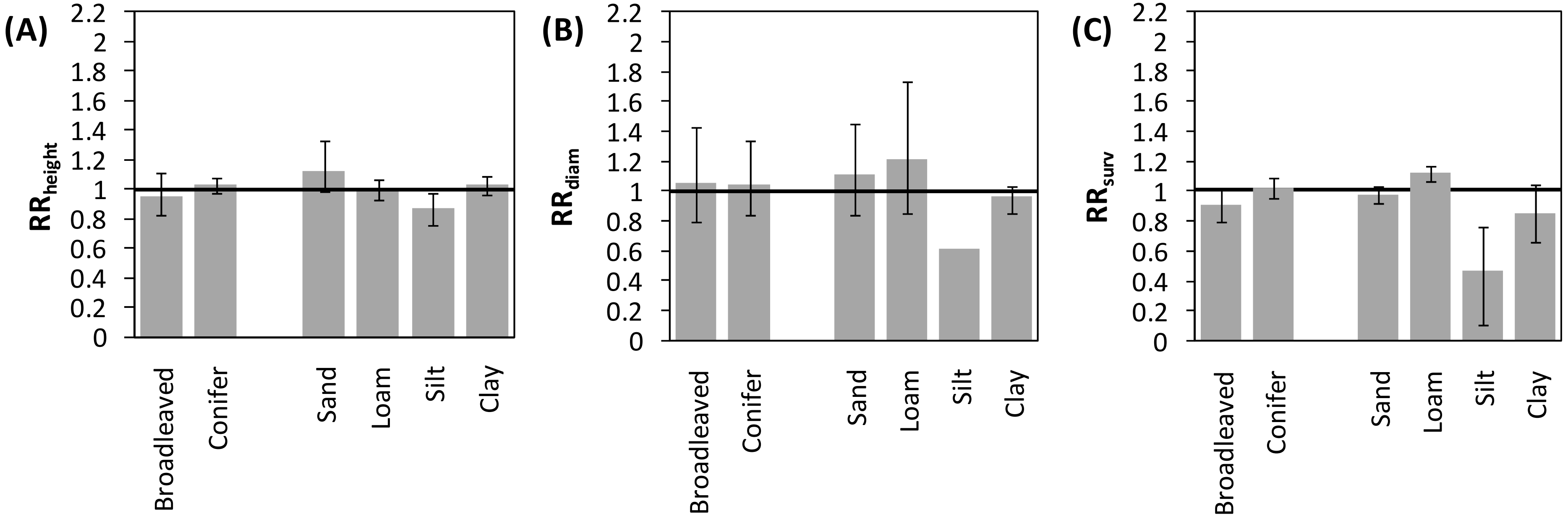


Fig. 5.2 Effects of functional tree group (broadleaved/conifer) and texture (sand, loam, silt, clay) on the mean RR of height (RR_{height}) (A), diameter (RR_{diam}) (B) and survival (RR_{surv}) (C) of tree saplings (95% bootstrapping confidence interval). RR stands for the response ratio or the ratio of the value on the compacted area to the value on the uncompacted area. In case RR equals one, no difference was stated between the two areas.

Looking at RR_{height} (Table 5.2), only the mean value for silty soils was significantly lower than 1, indicating lower height growth following compaction. Comparing texture groups, RR_{height} for silt was significantly lower than for sand that had a mean RR_{height} higher than 1. No significant difference was seen between functional tree groups. Multilevel modelling indicated that the random factor study determined 79.3% of the variance in RR_{height} and that none of the predictor variables significantly influenced RR_{height} (Table 5.3). Seven studies (representing 20 substudies) in the height dataset gave full information on number of replications and a measure of variance, and thus met the requirements of Hedges et al. (1999) for complete analysis. In contrast with the unweighted mean that was not significantly different from 1 and thus indicated that height growth was not changed by soil compaction (Table 5.2), the weighted mean $RR_{height,Hedges}$ for all substudies together was significantly lower than zero (-0.037 ± 0.015) and thus indicated slower growth as a result of compaction. The relationship between $RR_{height,Hedges}$ and RR_{dens} had an insignificant weighted Pearson correlation coefficient of 0.47. This was in accordance with the previous results (i.e., no significant effect of the predictor variables on RR_{height}).

Concerning RR_{diam}, none of the subsets showed a mean value significantly different from 1 (Table 5.2). Although the difference was insignificant, mean RR_{diam} for silt and clay were clearly lower compared to the values for sand and loam. Multilevel modelling indicated that 95.6% of the variance in RR_{diam} was explained by the random factor study and no significant influence of the predictor variables was detected (Table 5.3).

Results for RR_{surv} were predominantly insignificant (Table 5.2). Mean RR_{surv} for silt (and clay to a smaller extent) indicated significantly lower survival on the compacted soil while compaction on loamy soils seemed to be beneficial to survival of tree seedlings. Results of multilevel modelling indicated that 38.4% of the variance in RR_{surv} was determined by the random factor study and that none of the predictor variables had a significant influence on RR_{surv} (Table 5.3).

Table 5.3 Response of height growth (*RR_{height}*) , diameter growth (*RR_{diam}*) and survival (*RR_{surv}*) to five predictor variables: RR of bulk density (*RR_{dens}*), bulk density on the uncompacted area (*contrdens*), *functional tree group* (broadleaved/conifer), *texture* (sand/silt/loam/clay) and the number of years between initial and end measurements (*period*). Reported results are derived from multilevel modelling with one predictor variable and the factor study as a random effect term. The χ^2 values are derived from likelihood ratio tests.

Predictor variable	**RR_{height}**		**RR_{diam}**		**RR_{surv}**	
	χ^2	p-value	χ^2	p-value	χ^2	p-value
RR_{dens}	1.332	0.195	0.001	0.232	3.728	0.054
Contrdens	1.679	0.249	1.428	0.982	0.147	0.701
Functional tree group	0.111	0.739	1.687	0.194	1.418	0.234
Texture	0.647	0.421	1.423	0.233	1.310	0.252
Period	0.005	0.945	1.353	0.245	0.976	0.323

RR stands for the response ratio or the ratio of the value on the compacted area to the value on the uncompacted area. Significant effects are depicted in bold.

5.5 Discussion

The increase in bulk density showed that an overall significant degree of compaction was present. The experimental set-up of the selected articles was thus appropriate to examine the effect of soil compaction on growth and survival. Moreover, for some subsets, bulk density increased with more than 15%. This means that soil compaction degrees could be detrimental for root growth according to Powers et al. (1998).

The application of Hedges' method (Hedges et al. 1999) revealed that, in general, soil compaction significantly hampered height growth. However, this result should be interpreted carefully, as it is based on a small number of study results. Moreover, most unweighted RR were not significantly different from one, except for silt soils, and multilevel modelling did not indicate a significant effect of texture. Results only indicated that height growth, diameter growth, and survival were slightly hampered by soil compaction on silty soils, and survival to a smaller extent also on clay soils. On coarser-textured sandy and loamy soils growth and survival were not affected or rather improved by soil compaction, although compaction degrees were higher than on silt and clay soils. As was mentioned in the introduction, soil compaction induces a lot of soil structural and physical changes, such as decreased soil aeration, higher penetration resistance, lower saturated hydraulic conductivity, and decreasing amount of soil available water. These changes may negatively influence tree saplings, as was stated on the silt and clay soils. However, according to Dexter (2004) and Lacey & Ryan (2000), soil compaction not always implies negative outcomes for soil quality. Undisturbed coarse-textured soils contain many macropores that are too wide to hold water against gravitational forces. This implies a low water retention capacity and thus a low amount of plant available water. Compaction decreases the mean pore size and thus leads to better water retention. As the low amount of plant available water is one of the limiting factors for growth of herbs and trees on coarse-textured soils, this higher water availability may have compensated the negative effects of soil compaction.

A negative correlation was expected between the response ratios of bulk density (RR_{dens}) on the one hand and the response ratios of height, diameter and survival on the other. Higher compaction degrees and thus greater changes in soil chemical and physical characteristics were expected to impose a higher stress on saplings, leading to more retarded growth and survival. However, information on bulk density increase lacked for several substudies. For the remaining substudies with complete information, neither the use of multilevel models nor Hedges' method (in case of height) revealed a significant correlation between the soil compaction degree and responses of growth and survival. At both low as high compaction degrees, RR_{height}, RR_{diam} and RR_{surv} varied strongly around 1, a threshold that indicates no response to soil compaction. These response ratios were also assumed to decrease with increasing value of period. The longer the period in which growth and survival were monitored, the longer compaction could have exerted a negative influence on growth and survival. However, relationships between RR_{height}, RR_{diam} and RR_{surv} on the one hand and period on the other also seemed to be insignificant, again due to high variation and the low number of substudies.

Wide confidence intervals for biotic responses indicated that the effect of soil compaction was ambiguous. Averaged responses of growth and survival predominantly showed no significant effect of soil compaction on saplings. This shows that the impact of soil compaction was not always detrimental for tree saplings but depended, amongst others, on tree species (Miller et al. 1996; Kabzems 2000), compaction degree (Ehlers et al. 1983), and other environmental characteristics. It must be remarked that only a limited number of (sub)studies could be included in the dataset, especially for the weighted analyses. The higher the number of substudies with complete information that are available, the more reliable are the results that are obtained, and the more general are the conclusions that are drawn. It is thus crucial for future publications to give attention to the detailed report of basic statistics so that the results are valuable for meta-analyses.

It is possible that the long-term effect on tree saplings or the effect on adult trees differs from the effect on tree saplings in the first years after soil was compacted. This should be examined through long-term monitoring and examination of the effect of soil compaction on established, adult trees. Moreover, most of the examined tree species are not shade tolerant. This is not surprising as most studies were performed on clearcut areas, with very high light availability, where shade tolerant tree species that are adapted to low light levels are generally not successful. However, this means that no conclusions could be drawn concerning the tolerance to soil compaction of shade tolerant species. It is not certain that the sensitivity to soil compaction is similar for both groups of tree species. For example, compaction is often accompanied by a reduction of the plant available water amount (and thus likely increases drought stress; Ballard 2000). Niinemets & Valladares (2006) examined 806 temperate shrub and tree species and observed significant negative correlations among shade and drought tolerance, with less than 10 % of the examined species being relatively tolerant to both stresses simultaneously. Small & McCarthy (2002) showed severe growth and biomass reductions for *Osmorhiza claytonii*, a shade-tolerant perennial, after soil compaction. Further research is needed to draw general conclusions concerning the effect of soil compaction on seedling performance of shade tolerant tree species.

Detail of the processor head of the Timberjack 1070D harvester, used in Putte (Chapter 3) [photograph: Robbie Goris, August 2004].

6 Compaction status of Flemish forest soils seven to nine years after mechanized harvesting

After: Ampoorter E, Van Nevel L, De Schrijver A, Hermy M, Verheyen K (2010) Compaction status of Flemish forest soils seven to nine years after mechanized harvesting. *In preparation*

6.1 Abstract

We examined whether traces of compaction due to former harvesting activities could still be detected seven to nine years after the last harvest, a common period between two thinning activities. If recovery from soil compaction is not achieved within this period, the effects of successive thinning activities will accumulate at former trails that again experience machine traffic, and may extend when no permanent skid trails are used. In nine Flemish forest stands on three texture classes, where the last mechanized harvest took place seven to nine years ago, compaction measurements were performed along three transects. In most forest stands, old trails could still be detected with penetrologger measurements, especially close to the forest road, where the highest traffic intensities were applied and where wood was piled. Unrestricted machine traffic at former harvesting activities resulted for several forest stands (e.g., Zoniënwoud RII-2 and RII-3) in overall compaction and higher precompression stress. This protects the soil from further compaction and reduces the impact of new machine passes. These sites showed large areas with overall high penetration resistance, exceeding 2-3 MPa, where no separate skid trails could be discerned. Other sites showed a lower influence of former harvesting activities, leading to overall low precompression stress. On these sites old skid trails could be retraced by the presence of locally increased penetration resistances. Each texture group contained forest stands of both types. As effects of former harvests, that took place at least eight years ago, still persist, one can conclude that on all examined textures recovery of soil compaction was incomplete after 7-9 years and effects will accumulate at subsequent harvesting activities with unrestricted machine traffic.

6.2 Introduction

Soil compaction, due to traffic with heavy forestry machines, may affect soil fauna, such as earthworms (e.g., Boström 1986), growth (e.g., Gebauer & Martinkova 2005) and survival of seedlings (e.g., Simcock et al. 2006) and may induce shifts in the composition of the herb layer towards more ruderal species (Roberts & Zhu 2002; Zenner & Berger 2008), due to changed soil characteristics, such as PR (Aust et al. 1998; Nugent et al. 2003), soil aeration (Gebhardt et al. 2009; Startsev & McNabb 2009) and hydraulic properties (e.g., Benthaus & Matthies, 1993; Ballard 2000). As the soil ecosystem diversity and service may eventually be reduced, it is important that recovery takes place relatively fast. Soil compaction may disappear under the influence of natural processes in the absence of additional compaction. The freezing and melting of soil water in soils with an adequate water holding capacity increases pore sizes (Alban et al. 1994), just like the swelling and shrinking of clay particles under the influence of soil water in soil with a high clay content (Fisher & Binkley 2000). Biological activity, such as root growth and penetration (Brais & Camiré 1998; Lister et al. 2004) or earthworm burrowing (Jordan et al. 1999, Ponder et al. 2000; Capowiez et al. 2009), may add greatly to the recovery process. Rich, alluvial systems are characterized by a large biological activity and should thus recover relatively fast from soil compaction. Sandy soils, on the other hand, often lack effective recovery processes as a consequence of their low clay, nutrient and water content and often high acidity, reducing the diversity of the soil fauna and the herbaceous layer (Hansen & Rotella 1999). Froehlich & McNabb (1984) and Croke et al. (2001) found no significant impact of soil type on the recovery rate. Page-Dumroese et al. (2006) even stated faster recovery for coarse textures compared to fine textures.

Rab (2004) found no significant recovery of macroporosity and BD on a clay to silty loam soil over a period of ten years. According to Tiarks et al. (1997) and Croke et al. (2001), complete recovery is reached after a period of at least 20-30 years. Anderson et al. (1992) and Jakobsen (1983) found that BD on the skid trails still differed significantly from the undisturbed soil 25-32 years after logging. Hakansson & Reeder (1994) concluded that compaction at depths of more than 40 cm is very persistent and virtually permanent even in clay soils in regions with annual freezing. Greacen & Sands (1980) also stated that compaction of deeper layers may persist for 50-100 years. It seems therefore that, in general, recovery of compacted soils is slow in the absence of ameliorative treatments, such as ploughing.

When machine traffic is not restricted, in the long run a large part of the forest stand could be disturbed. The latter can be spatially reduced by restricting machines to permanent skid trails. Nevertheless, this system is not yet widely established in certain regions, including Flanders (northern Belgium). Here, a common period between two harvesting activities is about eight years. We performed a study to find out if traces of the last harvesting activity (or former activities) could still be detected seven to nine years after the last harvest. In case soil compaction, induced by a forest operation, persists beyond this period, effects may accumulate at trails that experience traffic at subsequent harvesting activities. Expansion of the compacted area may also occur if machines do not follow exactly the same tracks as in the previous forest operation. We retraced old skid trails along transects in nine stands spread over three different soil textures based on processed data on PR. This sampling method using transects is frequently used for other aspects of forest monitoring (e.g., quantification of dead wood) but to our knowledge was never used before within the framework of soil compaction. Here from we obtained a picture of the compaction status of the examined forest stands, seven to nine years after the last harvest. We hypothesized that traces of former harvesting activities are still detectable at least seven to nine years after the last machine impact, indicating incomplete recovery.

6.3 Materials and methods

6.3.1 Experimental set-up

Nine forest stands were selected in 2008, spread over the Flemish region, where the last mechanized activity took place seven to nine years ago. Three stands were chosen on sand, three on loam to silt loam and three on silt (Soil Survey Staff 1999). Within each soil texture group, characteristics (forest type, mean tree circumference, machines used) were predominantly comparable to each other. The presence of a clear rut pattern was not a determining factor in the selection. This would have skewed the results as in this case, stand selection would be biased in the direction of seriously damaged forest stands or stands with very low recovery potential. In all stands the last harvesting activity was carried out without the use of permanent skid trails as this method was not yet common in Flanders around 1998-2001. Information on the selected stands is summarized in Table 6.1. All sites carried mature forest stands, especially on the sites with loam to silt loam and silt textures. Traces of former harvesting activities may thus also be present in case recovery of the soil impact due to these earlier activities was not yet complete.

Measurements were performed in 2008. A possible approach to quantify the compaction status of forest stands could be to distribute individual measurement points equally over the forest stand (cf Gaertig et al. 2000). However, in that way we would not be able to attribute the compaction on a specific measurement point to the presence of a former skid trail as no information on the compaction degree would be available for the area surrounding that point. Instead, we used a transect design. Positioning of the transects was such that it maximized the discovery rate of former skid trails (Fig. 6.1). Based on information concerning the last harvesting activity, we selected the edge of the forest stand where most of the wood was brought to be transported. A point, centrally situated along the length of this edge, was the starting point for the marking of the transect design. It contained three parallel transects of 37 m. Length was limited due to physical constraints as limited stand dimensions and time needed for performing measurements. At about 10 m in the stand, the first transect was located parallel to the edge and centred in accordance to the starting point. Transects 2 and 3 were placed at about 50 m, respectively 100 m distance from and to the right, respectively left of transect 1. We maximized the chance of crossing old skid trails by i) placing the transects parallel to the forest edge as the main direction of the skid trails is roughly perpendicular to the forest road; ii) subdividing total length into three equal parallel transects that were distributed to the left and to the right to cover a wider area; iii) placing the transects relatively close to the forest edge, as we expected traffic intensity to decrease with distance to the forest edge.

Table 6.1 Characteristics of the forest stands. Soils are classified into soil texture classes according to the USDA soil classification system (Soil Survey Staff 1999) and divided into soil types according to IUSS Working Group WRB (2006).

Location	Forest (stand)	Soil texture class	Soil type	Main tree species	Mean tree circumference	Last harvest	Machine type	Visibility of ruts in 2008
Schilde	**Driehoekbos**	Sand	Anthrosol	*Pinus sylvestris*	70 cm	2000	Harvester + forwarder	Visible
Arendonk	**Hoge vijvers**	Sand	Gleyic podzol	*Pseudotsuga menziesii*	70 cm	2000	Harvester + forwarder	Visible
Lommel	**Riebosserheide**	Sand	Podzol	*Pinus sylvestris,* *Pinus corsicana*	< 70 cm	2000	Harvester + forwarder	Not visible
Overijse	**Zoniënwoud RIII-3**	Loam to silt loam	Luvisol	*Fagus sylvatica*	120-150 cm	2001	Skidder + tractor	Not visible
Opbrakel	**Brakelbos 12**	Loam to silt loam	Luvisol	*Fagus sylvatica*	100-130 cm	2001	Skidder + tractor	Visible
Liedekerke	**Liedekerkebos**	Loam to silt loam	Cambisol	*Quercus robur,* *Fraxinus excelsior,* *Acer pseudoplatanus,* *Populus sp.*	50-100 cm	1998-1999	Skidder	Not visible
Overijse	**Zoniënwoud RII-2**	Silt	Luvisol	*Fagus sylvatica*	150-180 cm	2001	Skidder + tractor	Visible
Opbrakel	**Brakelbos 10**	Silt	Luvisol	*Fagus sylvatica*	100-130 cm	2001	Skidder + tractor	Visible
Halle	**Hallerbos**	Silt	Luvisol	*Fagus sylvatica*	130 cm	1999	Skidder	Visible

6.3.2 Penetration resistance

Along the transects, PR was measured by means of a 06.15 penetrologger of Eijkelkamp Agrisearch Equipment (the Netherlands) to a depth of 80 cm in depth intervals of one cm. The apical angle of the cone was sixty degrees, the basal area surface one cm², and the nominal diameter 11.28 mm. Because of the soil moisture dependence of the measurements (Smith et al. 1997), we chose very wet days (April-May 2008) to ensure soils were at or near field capacity, and performed all measurements within one stand on the same day. Along each transect, measurement points for PR were located at regular intervals of 30 cm (125 measurement points per transect) (Fig. 6.1). At each point, four measurements (n = 4), serving as replications, were performed in line with each other, perpendicular to the transect direction and at a spacing of 30 cm to each other.

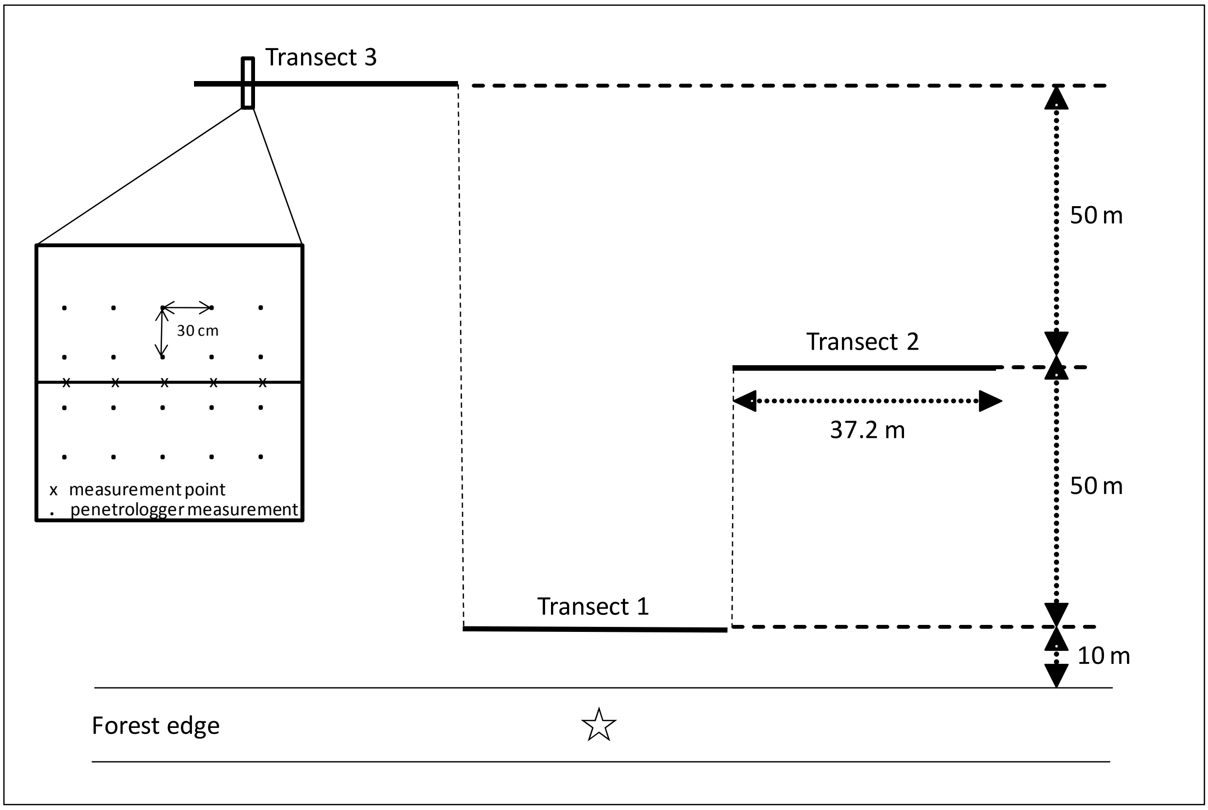


Fig. 6.1 Transect design, used to perform measurements of penetration resistance in the forest stands. The star indicates the starting point (centrally situated along the forest edge) for the positioning of the transects.

The results of the four replicated measurements per measurement point were averaged for each depth interval of one cm, to enable graphical processing of data for each transect with Surfer 7. Kriging was used as gridding method (linear variogram model, slope 1, anisotropy ratio 1, anisotropy angle 0, point kriging type). The mean PR per measurement point (horizontal axis) and per depth interval of 1 cm (vertical axis) were used as input data. This grid was used as input for the creation of a contour plot that was interpreted visually. According to Whalley et al. (1995), root growth of many plants becomes restricted when soil PR exceeds 2 MPa and stops at PR higher than 3 MPa. The percentage of measurement points that crossed limits 2 MPa and 3 MPa per transect at depths 5, 15 and 25 cm were summarized in this respect.

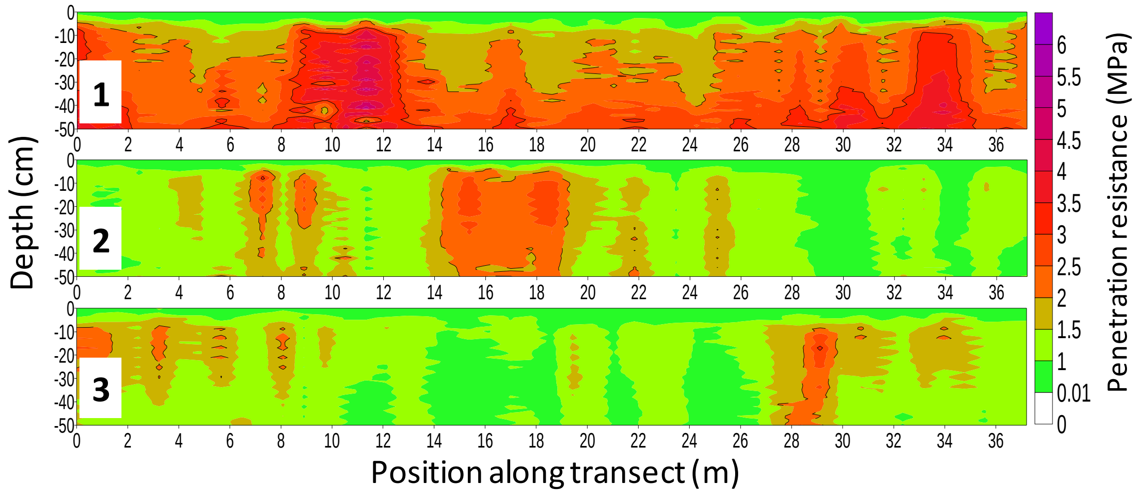
6.4 Results

PR is only considered for the upper 50 cm of the soil profile as artificial compaction due to machine traffic is restricted to the upper soil layers (0-30 cm) and compaction in deep layers (50-80 cm) is related to natural soil profile development rather than machine traffic. The natural gradient of bulk density, i.e. a gradual increase with depth, is taken into account while evaluating the PR values, by only considering clear deviations from this natural gradient. At the forest stand Driehoekbos on a **sandy** soil, PR were highest for the first transect but seldom exceeded 2 MPa at the second and third transect (Fig. 6.3A, Table 6.2). Old skid trails could be located based on PR values for 9-13 m (ruts present) on the first transect and 15-19 m on the second transect. The first transect also showed large areas where PR exceeded 2 MPa in the upper soil layer. The first transect situated on the sandy soil at Hoge Vijvers, had overall relatively high PR in the upper 50 cm of the soil profile (Fig. 6.3B). Almost the whole transect showed values over 2 MPa, in some places exceeding 3 MPa (Table 6.2). Compaction degree appeared to decrease gradually from transect 1 to transect 3. In the upper 25 cm of the soil on transect 3, PR was only in a small area higher than 2 MPa. Patterns of PR indicated traces of old skid trails for 27-31 m and 34-37 m (ruts present) on transect 1. In contrast, at the third forest stand Riebosserheide on sand, transects showed overall high PR and surprisingly the compaction degrees increased towards the third transect (Fig. 6.3C, Table 6.2).

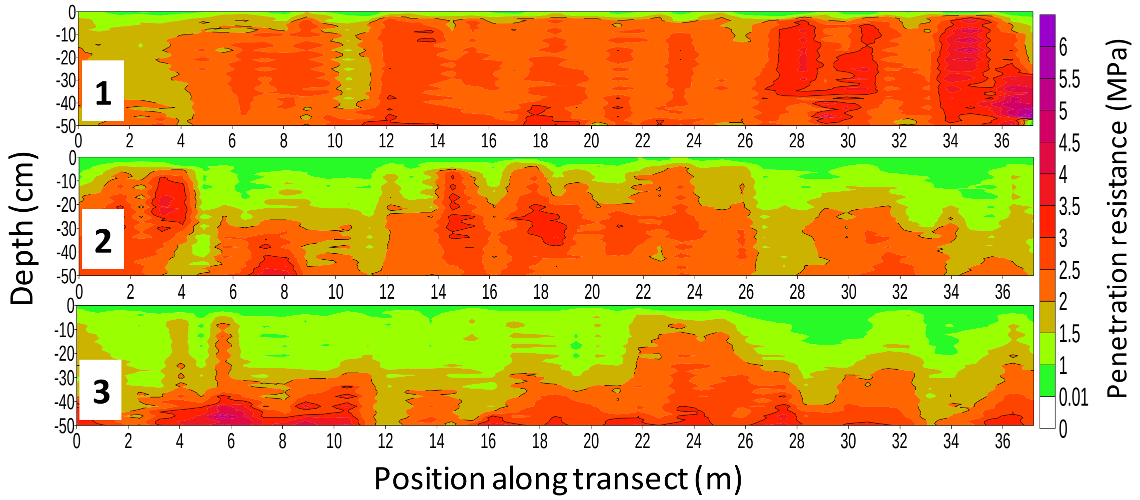
Results for Zoniënwoud RIII-3, on a **loam to silt loam** soil, pointed out that all three transects were compacted (Fig. 6.4A, Table 6.2). Large areas had PR values above 3 MPa. Separate machine tracks could not be discerned. Measurement results of transect 2 were not shown because a locally high concentration of small stones hampered the measurements and skewed the results. For Brakelbos 12, the second forest stand on loam to silt loam, an old skid trail could be discerned on the basis of PR for 0-3 m on the second transect (Fig. 6.4B) but all transects showed areas where PR exceeded 2 MPa. Transects for Liedekerkebos showed similar trends as Hoge Vijvers and Driehoekbos (Fig. 6.4C, Table 6.2). In general, the compaction degree in the upper soil layers was restricted. The number of measurements points where PR exceeded 2 MPa in the upper soil layers decreased from the first towards the third transect. In Liedekerkebos, no skid trails could be discerned on the basis of PR measurements in the superficial layer 0-50 cm. Nevertheless, PR was increased for 27-34 m on transect 1, 33-36 m on transect 3, and several other smaller areas along transects 1 and 2.

Zoniënwoud RII-2 on a **silt** soil also showed severe compaction over the whole depth interval for all three transects (Fig. 6.5A, Table 6.2). PR encompassed 2 MPa for almost the whole transect and 3 MPa for a great part of it. Separate, old trails could not be discerned by analysing penetrologger measurements. The PR values at Brakelbos, the second forest stand on a silt soil, were much lower (Fig. 6.5B, Table 6.2). Here, PR seldom exceeded 3 MPa in the superficial layer (0-25 cm). One machine trail was detected on the first transect for 0-4 m by measuring PR, and this trail was accompanied by visually detectable ruts. The areas 0-7 m, 12-17 m, 32-37 m on the first transect and 10-14 m, 20-24 m and 31-37 m on the third transect showed increased PR in the upper 40 cm. In Hallerbos, the third forest stand located on a silt soil, one machine track was detected with PR for 34-37 m on the first transect (ruts present), while the rest of the transects showed no clear traces of former traffic (Fig. 6.5C, Table 6.2).

A. Driehoekbos



B. Hoge Vijvers



C. Riebosserheide

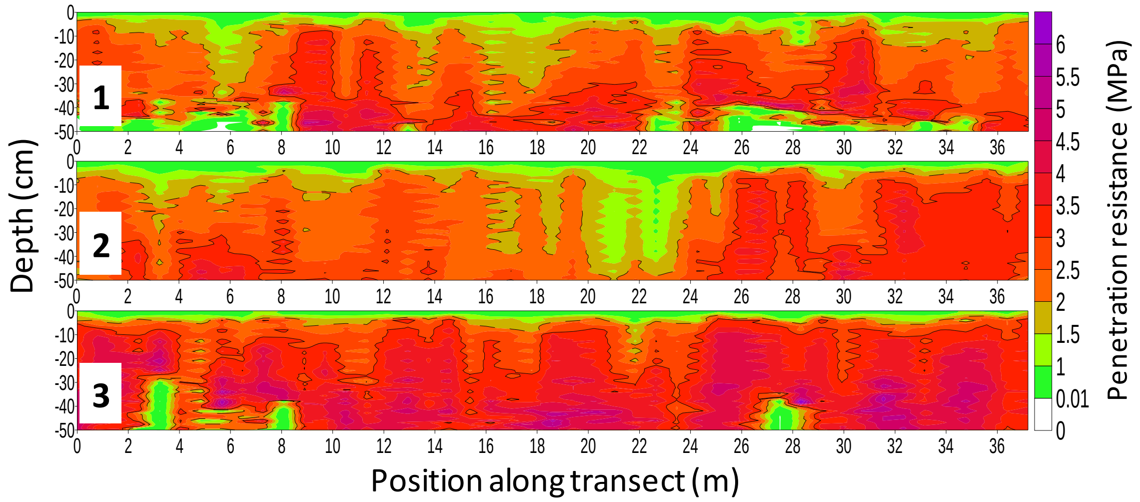


Fig. 6.3 Contour plot of penetration resistance (grayscale, in MPa) in function of depth along transects 1 (10 m from forest road), 2 (60 m from forest road) and 3 (110 m from forest road) for forest stands on sandy soils (A) Driehoekbos, (B) Hoge Vijvers, and (C) Riebosserheide (see Table 6.1 for more information). The dotted line shows the isolines for 2 MPa, the solid line represents the isoline for 3 MPa. The presented penetration resistance values are averages of 4 replications per measurement point (measurement points at 30 cm spacing).

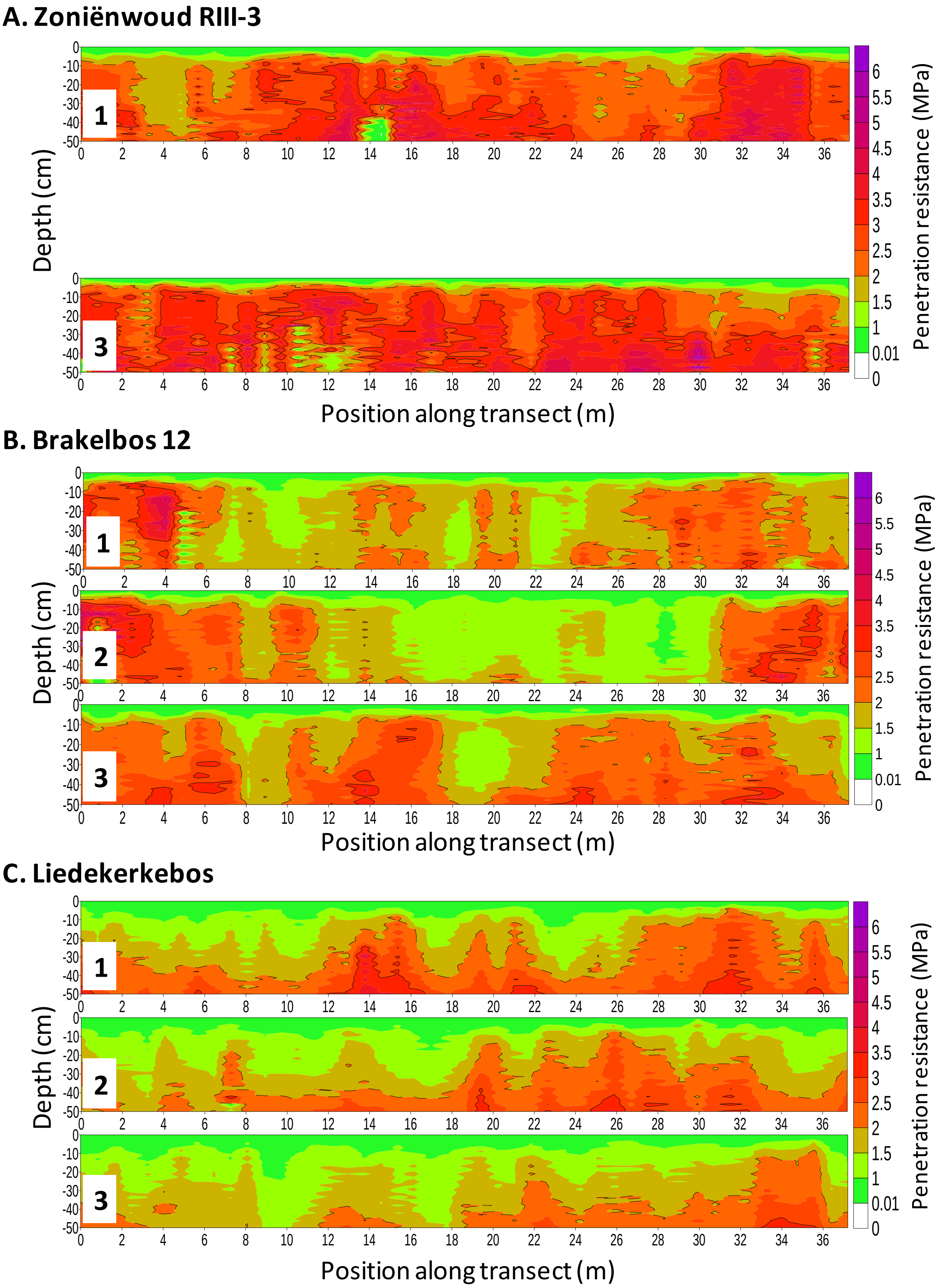
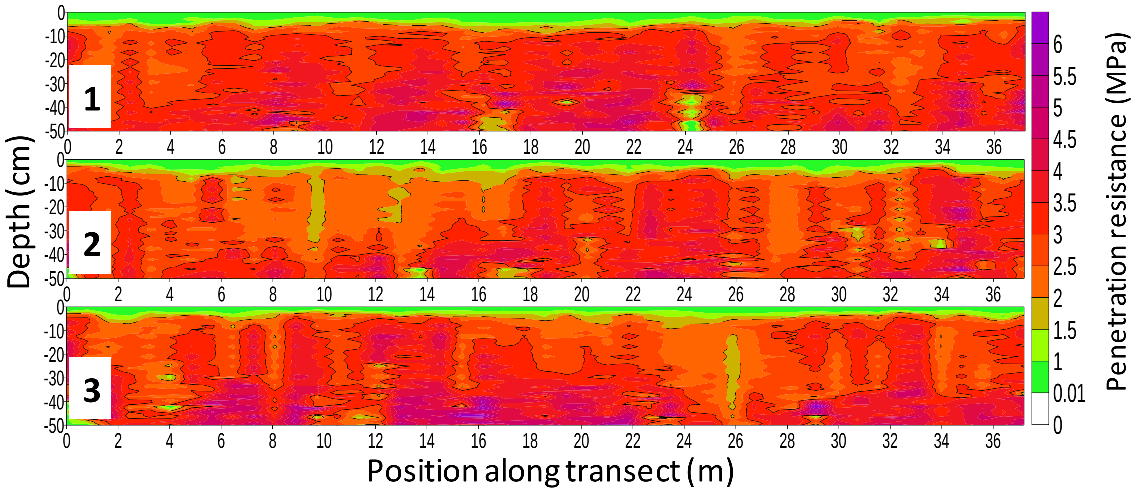
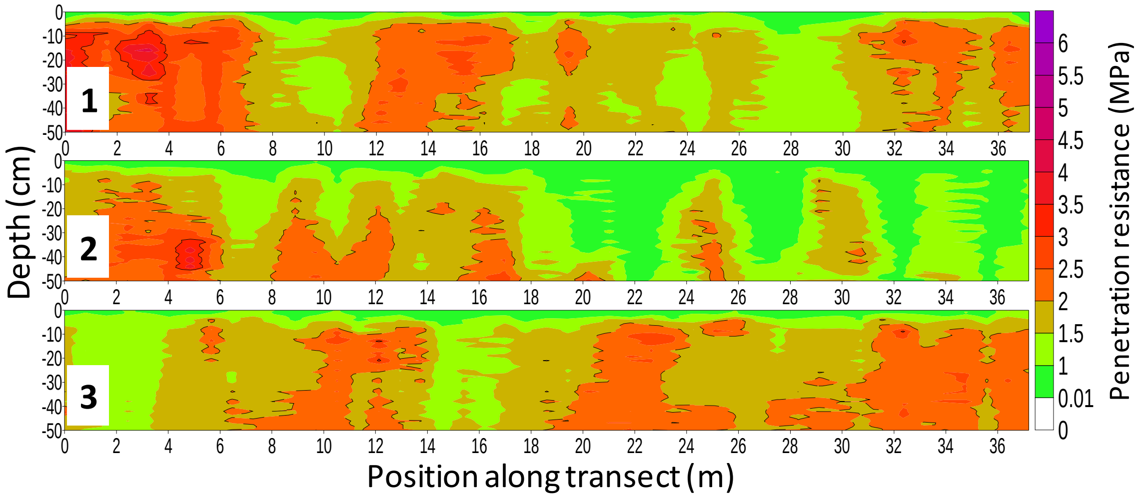


Fig. 6.4 Contour plot of penetration resistance (grayscale, in MPa) in function of depth along transects 1 (10 m from forest road), 2 (60 m from forest road) and 3 (110 m from forest road) for forest stands on loam to silt loam soils (A) Zoniënwoud RIII-3, (B) Brakelbos 12, and (C) Liedekerkebos (see Table 6.1 for more information). The dotted line shows the isolines for 2 MPa, the solid line represents the isoline for 3 MPa. The presented penetration resistance values are averages of 4 replications per measurement point (measurement points at 30 cm spacing).

A. Zoniënwoud RII-2



B. Brakelbos 10



C. Hallerbos

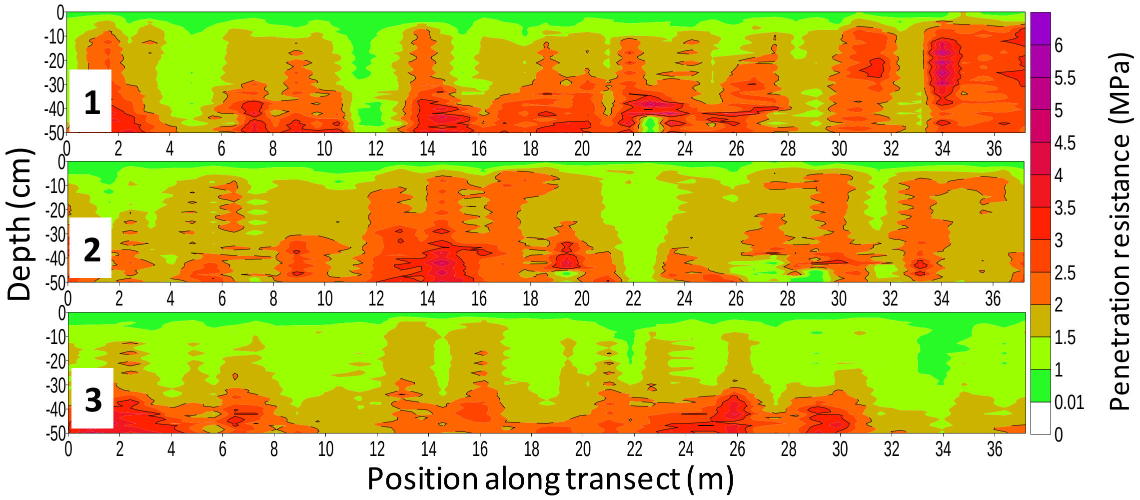


Fig. 6.5 Contour plot of penetration resistance (grayscale, in MPa) in function of depth along transects 1 (10 m from forest road), 2 (60 m from forest road) and 3 (110 m from forest road) for forest stands on silt soils (A) Zoniënwoud RII-2, (B) Brakelbos 10, and (C) Hallerbos (see Table 6.1 for more information). The dotted line shows the isolines for 2 MPa, the solid line represents the isoline for 3 MPa. The presented penetration resistance values are averages of 4 replications per measurement point (measurement points at 30 cm spacing).

Table 6.2 Percentage of measurement points per transect per depth where growth limits 2 MPa and 3 MPa were crossed (125 measurement points per transect) for each forest stand.

Texture class	Forest	Depth (cm)	Transect 1		Transect 2		Transect 3	
			≥2 MPa	≥3 MPa	≥2 MPa	≥3 MPa	≥2 MPa	≥3 MPa
Sand	Driehoekbos	5	13	2	8	2	2	0
		15	63	18	22	6	14	2
		25	74	20	19	2	10	0
	Hoge Vijvers	5	54	10	14	0	3	0
		15	86	19	31	6	10	0
		25	86	23	62	14	25	0
	Reibosserheide	5	29	4	28	5	58	21
		15	72	19	74	25	91	70
		25	82	28	78	26	94	77
Loam-silt loam	Zoniënwoud RIII-3	5	21	3	30	2	40	9
		15	78	32	81	41	84	45
		25	81	38	91	46	85	48
	Brakelbos 12	5	14	2	13	0	8	0
		15	48	15	46	12	57	2
		25	44	14	47	13	57	5
	Liedekerkebos	5	2	1	0	0	1	0
		15	31	2	12	0	11	0
		25	42	4	25	3	18	0
Silt	Zoniënwoud RII-2	5	38	6	37	4	64	15
		15	98	54	85	42	91	45
		25	97	56	87	44	93	47
	Brakelbos 10	5	26	1	2	0	12	0
		15	50	10	11	0	36	2
		25	46	8	24	1	35	1
	Hallerbos	5	7	1	17	0	2	0
		15	33	9	33	2	7	0
		25	39	12	38	2	14	0

6.5 Discussion

6.5.1 Spatial pattern of soil compaction

PR was generally highest for the first transect, thus close to the forest road, and decreased towards the third transect. During a harvest, trees spread over the whole stand are cut and dragged or carried towards the forest road. Machines transporting logs from far within the stand only make one pass or a few passes over the soil deeper in the stand meanwhile influencing the soil close to the forest road that is also affected during the processing of trees standing close to this road. Higher traffic intensities close to the road induce more severe compaction degrees (Brais & Camiré 1998). Moreover, the area next to the forest road is often used to pile stems or logs, again leading to soil compaction. The diverging result at Riebosserheide may be due to the slight slope of the forest stand towards transect 3, resulting in textural dissimilarities in the upper soil layer between transects 1 and 3.

Transect results also showed high compaction degrees in deeper soil layers. This was on the one hand due to the increasing weight of the soil layers above and on the other hand to profile development with the formation of hard, impenetrable layers, such as spodic horizons. The impact of machine traffic is in general restricted to the superficial soil layer between the surface and 30-40 cm depth (Cullen et al. 1991; Nugent et al. 2003; Ampoorter et al. 2007 (Chapter 3)).

6.5.2 Compaction status of Flemish forest soils

In all examined forest stands, traces of old skid trails could still be detected on the basis of the PR pattern, showing locally (3-4 m wide) increased values in the upper soil layers. Moreover, several forest stands, such as Zoniënwoud RII-2 and RIII, showed large areas where PR was overall increased above 2 or even 3 MPa, regarded as critical levels for root growth (Whalley et al. 1995). This widespread soil compaction can be partially due to the last harvest but is predominantly a remainder of the soil compaction induced at former harvesting activities. Before the last harvesting activity took place, the soils in Zoniënwoud RII-2 and RIII-3 were certainly already strongly compacted. Namely, the impacts of intense iron and charcoal extraction in the past, together with long-lasting and non-restricted high recreation pressure (horses, pedestrian) accumulated and resulted in overall soil degradation. Moreover, both forest stands have long been forested with beech with high mean diameter classes implying the use of heavy machines with a high soil contact pressure (McDonald et al. 1996). Compacted soils are characterized by higher precompression stresses which protect the soil from further compaction. Only when the applied stresses at the last harvesting activity exceeded the precompression stress, a small additional compaction was induced (Horn et al. 2007). This explains why in soils with overall high compaction degrees such as Zoniënwoud RII-2 and RIII (and to a smaller extent Hoge Vijvers and Brakelbos 10 and 12), new machine passes resulted in only minor to negligible effects and separate skid trails could therefore hardly be distinguished.

Within each texture group, stands with overall high penetration resistances and overall lower penetration resistances were present. Stand and harvesting characteristics were similar within one texture group and differences in compaction status within one texture group can therefore not be due to different impacts of the last harvesting activity.

Differences in compaction status within a texture group are due to different cumulated impacts of machine traffic in the past. No differences could be stated between the texture groups. Traces of former harvesting activities were still apparent for all texture groups and a similar, high variation in compaction status was stated within each texture group.

Natural soil variability, influencing PR, may have been mistaken for old machine tracks. However, local increases of PR in the soil profile clearly showed the former position of the tyres. Moreover, on several places where old skid trails were assumed to be located due to the PR pattern, visually detectable ruts were also present. The absence of ruts does not mean that the soil surface was levelled out throughout the years. Organic material may have accumulated in the wheel tracks, obscuring the ruts. It should be remarked that in case PR would no longer show traces from former machine traffic, it does not necessarily mean that the soil has completely recovered from the machine impact. Page-Dumroese et al. (2006) emphasized that the examined soil variables (BD, soil strength and macroporosity) recovered at a different rate.

Traces of former machine traffic were apparent in all examined forest stands in the shape of locally increased or overall high penetration resistance. This means that complete recovery of the examined compacted forest soils in all texture groups was not achieved within seven to nine years after the last machine impact. As this is a common period between two harvesting activities, effects will accumulate and expand at subsequent harvests in case machine traffic is not restricted to permanent skid trails.

Inoculated earthworms, at the start of their burrowing activities (Chapter 7) [photograph: Evy Ampoorter, November 2008].

7 *Ecological restoration of compacted forest soils*

After: Ampoorter E, De Schrijver A, De Frenne P, Hermy M, Verheyen K (2011) Experimental assessment of ecological restoration options for compacted forest soils. Ecological Engineering, *submitted*

7.1 Abstract

It is ecologically undesirable to solve forest soil compaction due to mechanized harvesting at large spatial scales using agricultural mechanical soil loosening techniques. We therefore examined whether a stimulation of biological activity through litter manipulation, liming and/or inoculation of the anecic earthworm species *Lumbricus terrestris* could significantly contribute to the ecological restoration of compacted forest soils by comparing the impact of these treatments on soil within and beside compacted wheel tracks. The replacement of native litter by litter with a better quality resulted in a faster litter decomposition, indicating higher biological activity. However, maximal decay rates were obtained only when litter manipulation, earthworm inoculation and liming were combined. Anecic worms were initially absent as soils were probably too acid. Liming as well as litter manipulation had a small positive influence on the numbers of retraced *L. terrestris*, inducing positive feedback mechanisms on soil pH and litter decomposition. None of the treatments, however, induced a significant decrease of the compaction degrees within tracks within the small study period. *Lumbricus terrestris* realized a small decrease of bulk density beside the tracks, where bulk densities were also relatively high. Within the tracks a similar number of *L. terrestris* was retrieved, but effects on the compaction degree were negligible, probably due to a combination of the high acidity, high compaction degrees and the short study period. Liming slightly decreased penetration resistance, but only in the absence of anecic earthworms. We hypothesized that liming stimulates the burrowing activities of earthworms, what strengthens the soil matrix and induces higher penetration resistances. Endogeic worms were overall more abundant than the anecics, especially within tracks where soil water contents and pH values were higher. However, endogeics only had a marginal effect on litter decomposition and although they positively influence soil structure, they could not realize a reduction of the compaction degree, quantified by bulk density and penetration resistance, due to different burrowing habits. Our results indicated that a positive impact of anecic earthworms on the structure of compacted forest soils can be obtained in the long-term, at least in case soil conditions (acidity, nutrient availability and moisture content) are favourable. This can be achieved by conversion of forests towards tree species with high quality litter, which induce lower acidity and a better nutrient status of the soil, increasing the survival chances and activity of the anecic earthworms.

7.2 Introduction

Mechanized harvesting operations may seriously impact soil structure in forests due to the high soil contact pressure of often inappropriately used heavy forest machinery. Numerous studies indicated the negative impact of forest traffic on important soil characteristics such as pore continuity (e.g., Herbauts et al. 1996; Berli et al. 2003; Teepe et al. 2004), PR (e.g., Aust et al. 1998; Nugent et al. 2003) and gas exchange (e.g., Gaertig et al. 2002). These soil changes may affect the herb layer (Buckley et al. 2003; Godefroid & Koedam 2004), tree growth (Bulmer & Simpson 2005; Gebauer & Martinková 2005) and soil fauna (Radford et al. 2001; Battigelli et al. 2004). Altogether, compaction due to mechanized harvesting can have profound effects on forest soils, biodiversity and ecosystem functioning. Heavily compacted forest soils can be mechanically loosened, for example by using a winged subsoiler (McNabb 1994) or a ripper (Sinnett et al. 2008). However, these methods may induce severe damage to the soil ecosystem (fauna, roots, churning of soil layers) and should thus only be applied in exceptional cases.

Soil characteristics such as pore volume and soil aeration can be seen as functional ecosystem attributes that are of critical importance for the sustained provision of ecosystem services (Kardol & Wardle 2010). Callaham et al. (2008) emphasized the central role of the soil in achieving forest ecosystem restoration towards its initial structural and functional condition (e.g., Van Andel & Aronson 2006; Clewel & Aronson 2007). The fast recovery of the above mentioned initial soil characteristics is thus a prerequisite in restoration ecology. Soil compaction is not permanent but disappears gradually over time under the influence of natural processes, as the action of swelling clay particles (Fisher & Binkley 2000) and freezing and thawing cycles of soil water (Alban et al. 1994). Biological activity may also offer a high contribution to the recovery of compacted soils. Vegetation and soil fauna as earthworms can act as ecosystem engineers, modulating the availability of resources to other species, by causing physical state changes in materials such as the litter layer or the soil (e.g., Jones et al. 1994; Jones et al. 2010). According to Jones et al. (2010) the structural changes caused by the engineers (litter supply, litter fragmentation, burrows) induce abiotic changes. Plants are autogenic engineers that may change the environment via root penetration and through the quality and quantity of their litter. The penetration of plant roots opens pores, leading to higher pore continuity (Brais & Camiré 1998), lower BD and higher aeration (Lister et al.

2004). High quality litter, characterised by high nutrient but low carbon and lignin contents, decomposes faster (Reich et al. 2005; Prescott 2010), inducing lower acidity (Neirynck et al. 2000) and consequently stable aggregates (Haynes & Naidu 1998). These structural and abiotic changes may result in biotic changes (Jones et al. 2010). For example, lower soil acidity due to better litter quality stimulates micro-organisms and macrofauna (Aubert et al. 2005), such as earthworms (most anecic and endogeic earthworm species are acid intolerant; Muys & Granval 1997). Earthworms act as allogenic engineers by causing structural changes through their burrowing activities and fragmentation and burial of litter (Jones et al. 1994; Jones et al. 2010). Deep burrowing anecic earthworms feed on fresh litter which is consumed along with soil mineral particles, mixed in the earthworm gut and then egested as surface or subsurface casts (Bardgett 2005). Litter is thus intensely mixed with mineral soil particles and gut secretions (Curry & Schmidt 2007), producing stable casts with higher nutrient concentrations than the surrounding soil (Jordan et al. 1999), leading to better soil aggregation (Herbauts et al. 1996; Ponder et al. 2000; Edwards 2004). Endogeic earthworm species have a geophagous feeding behaviour with high consumption and low assimilation of organic material incorporated in the soil, leading them to burrow continuously to ingest enough soil (Felten & Emmerling 2009). Casts are excreted within their burrows. The burrowing activity of both anecic and endogeic worms creates an extensive and coherent sub-horizontal burrow network until 50 cm soil depth. The presence of these burrows results in a higher macroporosity, better aeration, a faster drainage (Ponder et al. 2000) and lower bulk densities (Binet et al. 1997), especially due to anecic species, as their burrows are free of casts. An increased biological activity may consequently lead to faster restoration of the compacted soil. Eventually, the structural, biotic and abiotic changes may positively feedback to the engineer (Jones et al. 2010).

Most studies indicate that complete recovery of soil compaction may take several decades (e.g., Jakobsen 1983; Anderson et al. 1992; Croke et al. 2001). The compaction degree of deeper layers may even persist for 50 to 100 years (Greacen & Sands 1980) or may in some cases be virtually permanent (Hakansson & Reeder 1994). A slow recovery might be due to the absence of swelling clay particles or deep soil frost in temperate regions, but can in many cases also be related to a poor biological activity.

Many forest soils under tree species with low litter quality as *Picea* ssp, *Pinus* ssp, *Fagus* ssp or *Quercus* ssp are characterized by a relatively high soil acidity and a consequently low base saturation degree and high concentrations of bioavailable potentially toxic aluminium (e.g., Augusto et al. 2002; De Schrijver et al. 2006) lowering biological activity and often even preventing the survival of anecic earthworm species (Muys et al. 1992; Reich et al. 2005).

In the present study, we hypothesize that ecological restoration of compacted forest soils can only be obtained by a combination of the following three factors: (i) a tree species change towards species with higher litter quality (nutrient rich and lignin poor), (ii) a lowering of soil acidity and (iii) the occurrence of anecic earthworm species. To our knowledge it is the first time that the sole and combined impact of the above factors on the compaction degree is quantified in a field trial. Moreover, a lot of the former studies that dealt with recovery of soil compaction only focussed on the quantification of the remaining compaction degree or the recovery rate without knowledge of the initial compaction degree or without focussing on the underlying processes. Our in-situ experiment was also performed in forest stands on real skid trails, making our results more realistic and applicable to management. Here, we assessed:

a) How and to what extent the abiotic and biotic soil characteristics (soil pH, bulk density, penetration resistance, litter decomposition rate, numbers of *L. terrestris* and endogeic earthworms) were stimulated by litter manipulation, liming and/or earthworm inoculation on both compacted and non-compacted zones of the forest;
b) To what extent the compacted forest soils were ecologically restored (quantified as changes in bulk density and penetration resistance) by application of the three factors (sole or in combination).

7.3 Materials and methods

7.3.1 Experimental design

We executed a field trial in four forest stands (*stand*), located in the Meerdaal forest (N 50.8040°, E 4.7013°) and Heverlee forest (N 50.8393°, E 4.6903°) close to Leuven where the experiment of Chapter 2 was performed (Table 2.1). Mean temperature for the region (1961-1990) is 2.5 °C in the coldest month (January) and 17.2 °C in the warmest month (July) while mean annual temperature and precipitation is 9.7 °C, respectively 821 mm (weather station Uccle at about 30 km from Leuven). Soils are Luvisols(-cambisols) (IUSS Working Group WRB 2006) with textures ranging from loam to silt loam (Soil Survey Staff 1999). The contribution of the swelling of clay particles to the recovery process is thus rather low and frost periods are neither severe nor long enough to have a significant impact on the compaction degree. Forest stands 'Sperwer' and 'Havik' were predominantly composed of *Fagus sylvatica* (70 years) and *Pinus nigra* var. *corsicana* (60 years) respectively. Main tree species in 'Goden' were *Pinus sylvestris*, *Quercus rubra* and *Quercus petraea* (50-120 years) and in 'Renissart' *Acer pseudoplatanus* and *Quercus robur* (90-160 years). In 2007, a field trial was performed (Ampoorter et al. 2010) in which a John Deere grapple-skidder JD 640, loaded to 14.3 tonnes (tyres front and back: 77.47 cm wide, tyre pressure 3.5 bar), made 5 passes back and forth on two previously marked skid trails (*trail*), located next to each other (Fig. 7.1). It must be mentioned that the precompression stress was already relatively high before this field trial was performed, restricting the compaction degrees in the field trial (Appendix 7.3; Ampoorter et al. (2010, Chapter 2)). The terms '*compacted'* and '*non-compacted soil*' refer to the soil that was trafficked, respectively not trafficked, during this field trial.

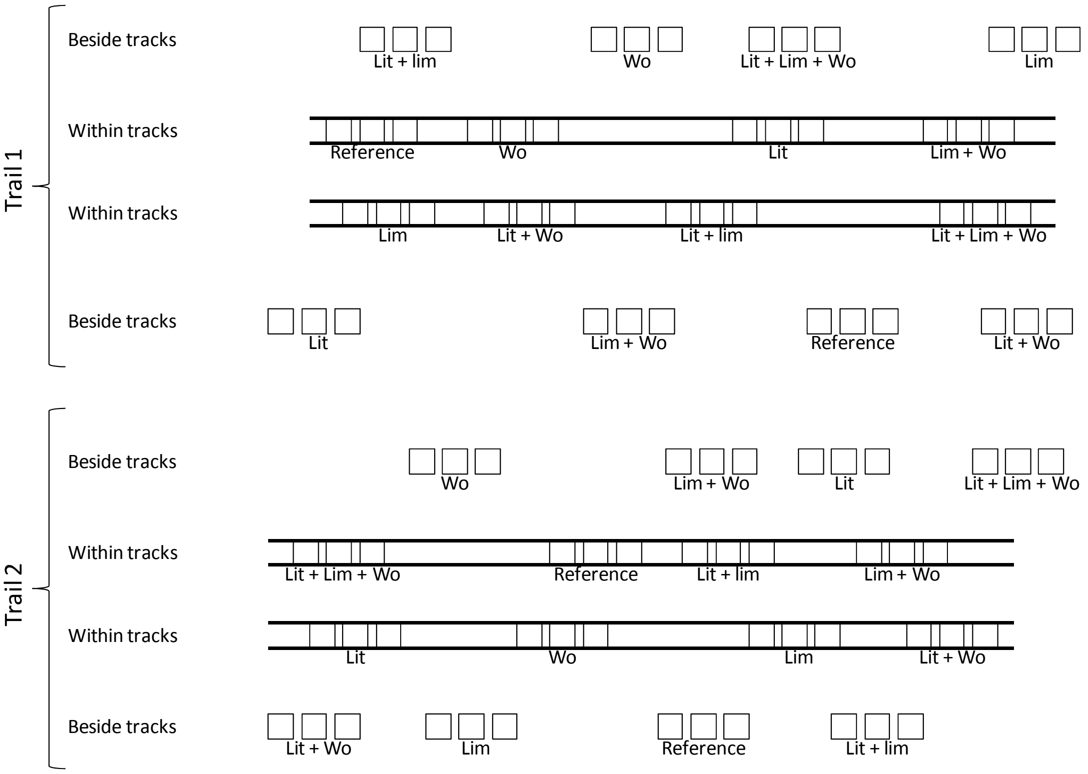


Fig. 7.1 Sketch of the experimental set-up within each stand: 3 frames (squares) per treatment (Lim: lime addition, Lit: litter change, Wo: earthworm inoculation), 8 treatments per location, 2 locations (within/beside tracks) per trail, 2 trails per stand. Frames beside tracks were at least 2m apart from the wheel tracks.

Wooden frames of 0.5 m by 0.5 m and 0.2 m high were constructed to mark out compacted soil areas within the wheel tracks on the one hand and non-compacted soil areas beside the wheel tracks on the other (*track*) (Fig. 7.2). Within the frames, several treatments were applied, alone or in combination with each other. The *lime* treatment consisted of dolomitic lime (60% calcium carbonate, 30% magnesium carbonate, 2-10 mm granules) of which 150 g (equivalent to 6000 kg ha^{-1}) (cf Hultberg et al. 1995; Dulière et al. 2000) was scattered per frame on top of the litter layer. For the *litter* treatment, the existing loose L horizon was replaced by an equal amount of fresh high quality litter of *Populus x Canadensis,* that was collected from a pure *Populus x canadensis* stand (N 50.9721°, E 3.7865°), surrounded by pastures and located close to Ghent*. Populus* sp. litter is known for its high nutrient quality and is easily biodegradable (Muys 1993; Coté & Fyles 1994). Per frame, we placed four litter bags of 10 cm by 10 cm under the loose litter layer. For frames where the litter treatment was applied, litter bags were completely filled with litter of *Populus x canadensis*. For frames where native litter was preserved, litter bags were filled with equal portions of the occurring main tree species. Mesh size of the bags was 6 mm, allowing all macrofauna to contribute to the decomposition process. The bags contained 3.5 g of oven dried litter (25 °C, 48 h) (cf Aneja et al. 2006; Liu et al. 2007). Frames that were selected for the *worm* treatment were inoculated with 20 individuals of the anecic *L. terrestris* (cf Muys et al. 2003). For each worm, a small hole (few cm deep) was made to stimulate digging and to protect the worms from immediate predation by birds. The top of the frames was fenced with a large-meshed gauze (mesh size 1cm) to prevent litter from the surrounding trees to fall into the frames. Leaves or needles that fell on the gauze were removed on a monthly basis(Fig. 7.2).

The frames were installed in February 2008 in series of three (*frame*) (Fig. 7.1). The bottom 5 cm was pressed into the forest floor to prevent inoculated earthworms to immediately disappear out of the frame and to isolate the upper soil layer from the surrounding area. This was performed in a careful way in order to leave the compacted forest soil undisturbed. A first dose of 100 g lime per frame (equivalent to 4000 kg ha^{-1}) was applied in March 2008. All other treatments (litter replacement, a second dose of lime of 150 g lime per frame, earthworm inoculation) were applied at the beginning of November 2008. An extra inoculation of 20 earthworms was performed in May 2009. Earthworms were scattered on top of the litter layer within the frame, in order not to disturb the litter layer. Treatments were applied both alone as in combination, resulting in eight different treatments (Fig. 7.1).

On both skid trails, as well within as beside wheel tracks, each treatment was randomly assigned to one series of three numbered frames (*frame*). For each treatment 6 frames were thus available (n = 2 trails x 3 frames = 6), both within as beside tracks. This set-up resulted in 384 frames spread in the four stands (6 frames x 8 treatments x 2 locations in relation to the tracks x 4 forest stands).

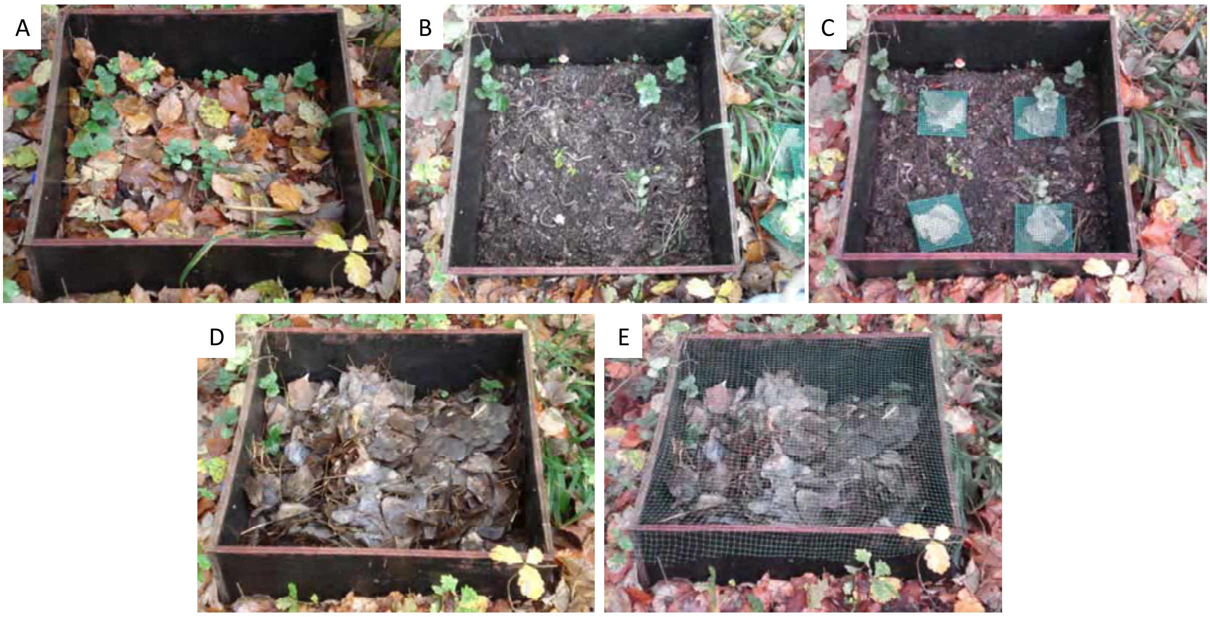


Fig. 7.2 Application of worm + litter treatment (A) frame installed in February 2008, (B) litter removed and worms inoculated, (C) positioning of litter bags, (D) addition of litter of *Populus x canadensis*, (E) installation of a gauze [photographs: Evy Ampoorter, November 2008].

7.3.2 Data collection

Biological activity is of great importance to the formation of a good soil structure (ecological restoration), but depends on a good soil nutrient status and acidity among other things. We examined whether the treatments (alone or combined) could increase the litter decomposition rate (improving the soil nutrient and acidity status), as an indication of biological activity. We assessed the decomposition rate by means of the remaining mass of the litter bags. After 26 and 75 days, one litter bag was removed from all frames (n = 1 x 6 frames = 6). After 147 and 355 days, respectively 236 and 389 days, one litter bag was removed from each frame on the first skid trail, respectively second skid trail (n = 1 x 3 frames). Removed litter bags were oven-dried (25 °C, 48 h) and weighed (accuracy 0.001 g).

From April to June 2010, measurements of BD, PR, earthworm abundance and soil acidity (pH) were performed. PR was quantified by means of a penetrologger (Eijkelkamp Agrisearch Equipment, the Netherlands) that measures to a maximum depth of 80 cm in depth intervals of 1 cm. Cones had an apical angle of 60 °C, a basal area surface of 1 cm² and a nominal diameter of 11.28 mm. Per frame, four PR measurements were performed (n = 4 x 6 frames = 24). All PR measurements within one stand were carried out in one day as changes in soil water content would influence PR (Smith et al. 1997; §3.5.3). After PR measurements, soil samples were taken on three locations within the frame from depth intervals 0-5 cm and 5-10 cm for determination of pH. For each depth interval, the three samples per frame were combined (n = 1 x 6 frames = 6), dried (40 °C, 48 h), grinded and sieved and pH(KCl) was measured using a glass electrode (Orion, model 920A) after suspension of 14 ml soil in a 70 ml KCl (1 M) solution. Next, the litter layer (containing predominantly epigeic worms) was removed. Subsequently, 5 litres mustard solution (7.5 g l^{-1}) was poured out gently on the soil in the frame (cf Lawrence & Bowers 2002; Zaborski 2003), in order to expel endogeic and anecic earthworms by the irritating action of the solution. After 20 minutes, this procedure was repeated. Earthworms coming to the surface were then collected. Subsequently, soil samples were taken from depth intervals 0-10 cm and 10-20 cm on two positions per frame by means of Kopecky soil cores (n = 2 x 6 frames = 12) for the determination of dry soil BD. Finally, the soil in the frame was excavated to a depth of 30cm and hand sorted in search of remaining earthworms (predominantly endogeic). All earthworms that were found were immediately put in a 70% ethanol solution and transferred to a 5% formol solution for fixation at the end of the day. After two weeks, they were transferred back to a fresh 70% ethanol-solution for long-term preservation. Epigeics were (as good as) absent as they were removed with the litter layer. Moreover, results of a presurvey (data not shown) showed that anecic species were absent prior to the inoculation in all forest stands. Worms that were found in the frames, using the mustard method and excavation, thus consisted of the inoculated anecic *L. terrestris* and/or endogeic worm species. Individuals of both groups were counted separately.

7.3.3 Data analysis

First, for each stand the average values were calculated for each combination of location in relation to the tracks and treatment: mean pH-values for depth intervals 0-5 cm and 5-10 cm, mean number of *L. terrestris* and endogeic worms, mean BD of depth intervals 0-10 cm and 10-20 cm, and mean PR at depths 5, 10, 15, 20 and 25 cm. For each stand and depth, pair-wise comparisons between all combinations of treatments and locations were conducted using Tukey's HSD test with $\alpha = 0.05$

Next, to assess the impact of litter manipulation, liming and/or earthworm inoculation on the biological activity, the relative importance of the factors litter, lime, worm and track on the soil pH (0-5 cm and 5-10 cm), the numbers of *L. terrestris* and endogeic earthworms, and the target variables BD (0-10 cm and 10-20 cm) and the PR (5, 10, 15, 20, 25 cm) was tested with mixed models in R 2.11.2, using the lme function of the lme4 library (R Development Core Team 2010). All main effects and twofold interactions between the predictor variables were included in the model. The nested random effect of the terms *stand* and *trail* was added to the models to address the likelihood that results obtained from the same stand and/or trail were autocorrelated. Based on the -2 log Likelihood information criterion (Hox 2002), the significance of each random effect term was tested (χ^2 test statistic; Zuur et al. 2009) and non-significant terms were deleted. For BD and PR, two, respectively four values were obtained per frame and therefore, the nested random effect term consisted of *stand*, *trail* and/or *frame*, that were first checked for significance (-2 log Likelihood information criterion; Hox 2002). Once the optimal random-effects structure was selected, the multilevel model was run and the significances of the main effects and interactions between the predictor variables were interpreted. The proportion of variance explained by the random structure ($\%\ var_{random}$) was then calculated according to Hox (2002):

$$\%\ var_{random} = \left(\frac{\sigma^2_{random}}{\sigma^2_{random} + \sigma^2_{residuals}}\right) * 100$$

The remaining mass of the litter bags after 389 days was divided by the initial mass (3.5 g) to obtain the remaining portion of leaf litter. These results were analysed similarly with the multilevel modelling procedure. Additionally, a double exponential decay model was fit to the portions for each treatment on both locations in relation to the tracks for all four stands. Single exponential decay models use a constant relative decomposition rate (Wieder & Lang 1982). A double exponential decay model assumes that litter can be partitioned into a relatively easily decomposed or labile fraction (A), and a more recalcitrant fraction (1-A) and therefore often fits data better than the single exponential decay model. Each fraction decays exponentially at rates characterized by k_1 and k_2, respectively. Using *SPSS 15.0*, this decay model was fit to the data:

$$X = A * e^{-k_1 * t} + (1 - A) * e^{-k_2 * t}$$

with X as the remaining portion of leaf litter, A as a constant ($0 \leq A \leq 1$), k_1 and k_2 as decay rates (both ≥ 0) and t as number of days (Wieder & Lang 1982; Bird & Torn 2006; Rovira & Rovira 2010). The sequential quadratic programming method was used to estimate parameters A, k_1 and k_2. The adjusted R^2 (R^2_{adj}) accounts for different degrees of freedom and, hence, the extra regression parameters (z), and was used to evaluate the fit. It was calculated as $R^2_{adj} = 1 - \left[\frac{(1-R^2)*(n-1)}{(n-z-1)}\right]$, with n as the sample size (Zuur et al. 2009). Values of R^2_{adj} were predominantly higher than 0.750 and the double exponential model thus provided a good fit for the data. Differences between treatments per stand were analysed visually, based on a plot of the fitted curves that was created with *Sigmaplot 11*.

Finally, for each forest stand, Spearman's rank correlation coefficients were determined for the relations between pH values of depth interval 0-5 cm, remaining portions of litter after 389 days, numbers of *L. terrestris* and endogeic earthworms, BD (depth interval 0-10 cm) and PR (depth 10 cm).

7.4 Results

Mean soil pH(KCl) values at depths 0-5 cm and 5-10 cm varied between 3.0 and 5.0 but were predominantly smaller than 4 (Appendix 7.1). Reference values were similar for all stands, for both compacted as non-compacted soil, with slightly higher values for depth interval 5-10 cm compared to 0-5 cm. Lime addition (sole or in combination) resulted in a clear increase of pH, especially at depth interval 0-5cm (Fig. 7.3). At first sight, none of the other treatments seemed to have a significant influence on soil pH. Although this was not clear from Fig. 7.3 nor Appendix 7.1, the results of our multilevel analysis (Table 7.1) showed that values were significantly higher within tracks compared to beside tracks. It also confirmed the significant positive impact of lime on pH at both soil depths ($p < 0.001$). Worm addition ($p = 0.012$ for 0-5 cm and $p = 0.005$ for 5-10 cm) and track ($p = 0.002$ for 0-5 cm and $p < 0.001$ for 5-10 cm) also influenced pH in a positive way, with significantly higher pH-values after inoculation of worms, respectively within tracks. The significant relation between soil pH at 0-5 cm and abundance of *L. terrestris* is also reflected in the significant, positive correlation coefficient between both variables at three of the four studied forest stands (Sperwer, Goden and Havik: $p < 0.001$) (Table 7.2).

Table 7.1 The effects of earthworm inoculation (*worm*), liming (*lime*), litter change (*litter*) and location in relation to the wheel tracks (*track*) on soil pH(KCl) at depths 0-5 cm and 5-10 cm, numbers of *Lumbricus terrestris* and endogeic earthworms and the remaining portion of litter: sources of variation, F-ratio, p-value and variation due to the random structure. Reported results are derived from multilevel models (see text for more details).

Sources of variation	**pH 0-5 cm**		**pH 5-10 cm**		**# *Lumbricus terrestris***		**# Endogeic worms**		**Remaining portion of litter**	
	F-ratio	**p-value**	**F-ratio**	**p-value**	**F-ratio**	**p-value**	**F-ratio**	**p-value**	**F-ratio**	**p-value**
Litter	0.46	0.496	3.13	0.078	16.00	**<0.001**	3.650	0.057	104.00	**<0.001**
Lime	385.58	**<0.001**	60.31	**<0.001**	36.25	**<0.001**	7.693	**0.006**	0.30	0.584
Worm	6.35	**0.012**	8.15	**0.005**	35.87	**<0.001**	0.219	0.640	20.96	**<0.001**
Track	10.11	**0.002**	24.71	**<0.001**	0.71	0.401	50.368	**<0.001**	0.43	0.513
Litter x lime	1.95	0.163	1.99	**0.026**	1.14	0.285	0.000	0.983	0.11	0.745
Litter x worm	1.22	0.269	0.10	0.749	8.49	**0.004**	1.439	0.231	0.00	0.992
Litter x track	0.15	0.697	0.01	0.946	0.66	0.425	0.012	0.913	4.09	**0.045**
Lime x worm	1.65	0.199	2.56	0.111	9.02	**0.003**	0.245	0.621	0.49	0.485
Lime x track	0.08	0.776	0.00	0.966	0.62	0.432	6.495	**0.011**	0.05	0.820
Worm x track	0.00	0.955	3.02	0.083	2.62	0.107	2.659	0.104	3.89	**0.050**
Variation due to random structure	6.9 %		12.8%		8.1%		38.6%		49.4%	

Significant effects are depicted in bold (p <0.05).

Table 7.2 **Spearman's rank correlation coefficients (*corr. coeff.*) and corresponding p-values (n: number of values) for relations between pH values at depth 0-5 cm (*pH5*), remaining portions of litter (*litter*), number of individuals of *Lumbricus terrestris* (*Lterr*), number of endogeic earthworms (*endog*), bulk density at depth 0-10 cm (*BD10*) and penetration resistance on depth 10 cm (*PR10*) for each forest stand.**

Forest stand	**Sperwer**			**Goden**			**Havik**			**Renissart**		
	n	**Corr. coeff.**	**p-value**	**n**	**Corr. coeff.**	**p-value**	**n**	**Corr. coeff.**	**p-value**	**n**	**Corr. coeff.**	**p-value**
pH5 - litter	184	0.105	0.156	164	0.080	**0.311**	184	**0.243**	**0.001**	184	0.001	0.986
pH5 - Lterr	184	**0.259**	**<0.001**	164	**0.273**	**<0.001**	182	**0.297**	**<0.001**	184	0.098	0.184
pH5 - endog	184	-0.024	0.749	164	**0.219**	**0.005**	182	0.069	0.353	184	**0.393**	**<0.001**
pH5 - BD10	184	0.098	0.187	164	-0.001	0.986	184	**0.226**	**0.002**	182	**0.241**	**0.001**
pH5 - PR10	368	-0.008	0.882	328	**0.183**	**0.001**	368	0.011	0.837	367	**-0.171**	**0.001**
Litter - Lterr	184	**-0.504**	**<0.001**	164	**-0.188**	**0.016**	182	**-0.153**	**0.039**	184	0.034	0.649
Litter - endog	184	-0.015	0.843	164	-0.040	0.614	182	0.063	0.396	184	**-0.186**	**0.011**
Litter - BD10	184	**-0.239**	**0.001**	164	0.100	0.203	184	0.115	0.120	182	0.093	0.212
Litter - PR10	368	-0.075	0.150	332	0.006	0.909	368	0.070	0.183	367	-0.068	0.195
Lterr - endog	184	**-0.203**	**0.006**	164	0.135	0.084	182	**-0.324**	**<0.001**	184	-0.015	0.843
Lterr - BD10	184	0.039	0.595	164	-0.081	0.303	182	0.137	0.065	182	-0.122	0.101
Lterr - PR10	368	**-0.128**	**0.014**	332	**-0.116**	**0.034**	366	-0.081	0.123	367	**-0.114**	**0.029**
Endog - BD10	184	**0.230**	**0.002**	164	0.060	0.442	182	**0.150**	**0.044**	182	**0.234**	**0.001**
Endog - PR10	368	**0.365**	**<0.001**	332	**0.172**	**0.002**	366	**0.345**	**<0.001**	367	**-0.142**	**0.006**

Significant effects are marked in bold ($p < 0.05$).

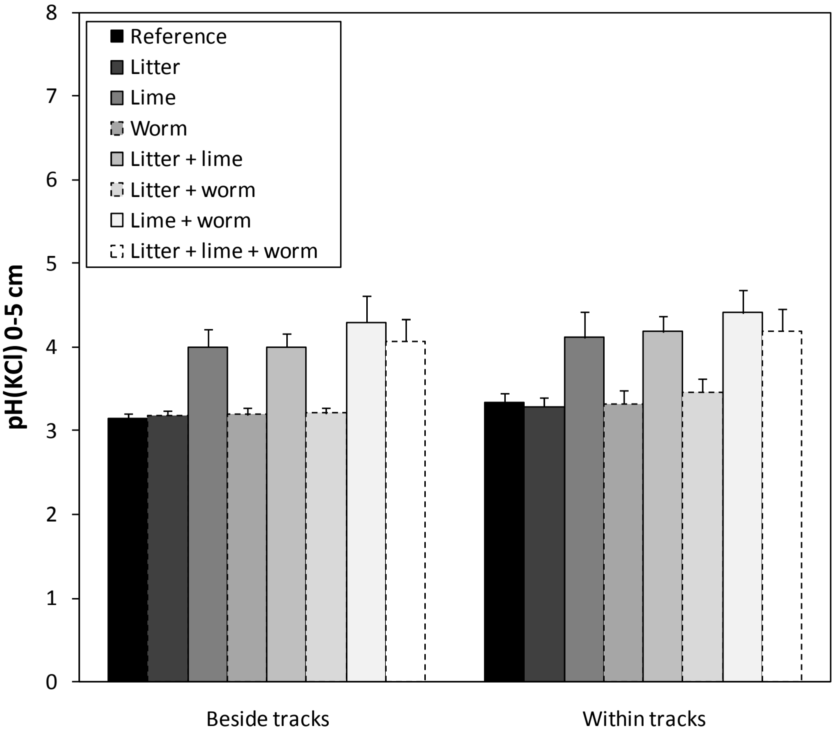


Fig. 7.3 Mean pH(KCl) of depth interval 0-5 cm, averaged over all stands, as influenced by earthworm inoculation (*worm*), liming (*lime*), litter change (*litter*) and location in relation to the wheel tracks. Error bars represent the 95% confidence interval.

Eighteen months after the first earthworm inoculation, almost none of the 2 x 20 inoculated individuals could be retraced (Appendix 7.2), especially when inoculation took place in the absence of another treatment. The treatment combination worm + lime + litter predominantly resulted in the highest anecic earthworm numbers. Measurements before the start of our experiment deduced that *L. terrestris* was absent in all stands before inoculation. However, in frames where no worms were inoculated, individuals of *L. terrestris* were also found. Therefore, there were almost no significant differences between locations in relation to the tracks. Our multilevel modelling revealed a significant positive impact of lime, litter and worm applications on the numbers of *L. terrestris* (Table 7.1: all $p < 0.001$). This also resulted in a significant interaction between worm and lime ($p = 0.003$) on the one hand and worm and litter on the other hand ($p = 0.004$). In the absence of lime or litter, the numbers of *L. terrestris* were only a little higher in inoculated frames compared to non-inoculated frames. However, in the presence of lime or litter, the numbers of *L. terrestris* were clearly higher after inoculation compared to non-inoculated frames. The number of *L. terrestris* was furthermore positively correlated with soil pH at 0-5 cm at Sperwer, Goden and Havik (all $p < 0.001$).

Endogeic species were present in larger numbers, especially at Sperwer and Havik (Appendix 7.2). The endogeic earthworm abundance was generally higher within the tracks compared to beside the tracks (Fig. 7.4, Table 7.1: p <0.001). As the position within tracks is characterized by higher BD (Fig. 7.6) and PR (Fig. 7.7), this also lead to positive correlation coefficients between BD at 0-10 cm and PR at 10 cm on the one hand and the number of endogeic worms on the other (Table 7.2). In contrast with the results on *L. terrestris*, liming seemed to negatively influence endogeic species (p = 0.006). This could also be deduced from the significant interaction between lime and track (p = 0.011). On the non-compacted area, the numbers of endogeic earthworms decreased slightly with liming while on the compacted soil the numbers were much higher than on the non-compacted area without lime, but were almost similar to the non-compacted area in case lime was applied. Here, it must be remarked that 38.61% of the variation in the numbers of endogeics can be explained by the random structure. Moreover, as mentioned above, liming clearly led to higher pH values and the correlation coefficients between pH at depth 0-5 cm and the numbers of endogeic species were clearly positive at Goden (p = 0.005) and Renissart (p <0.001) (Table 7.2).

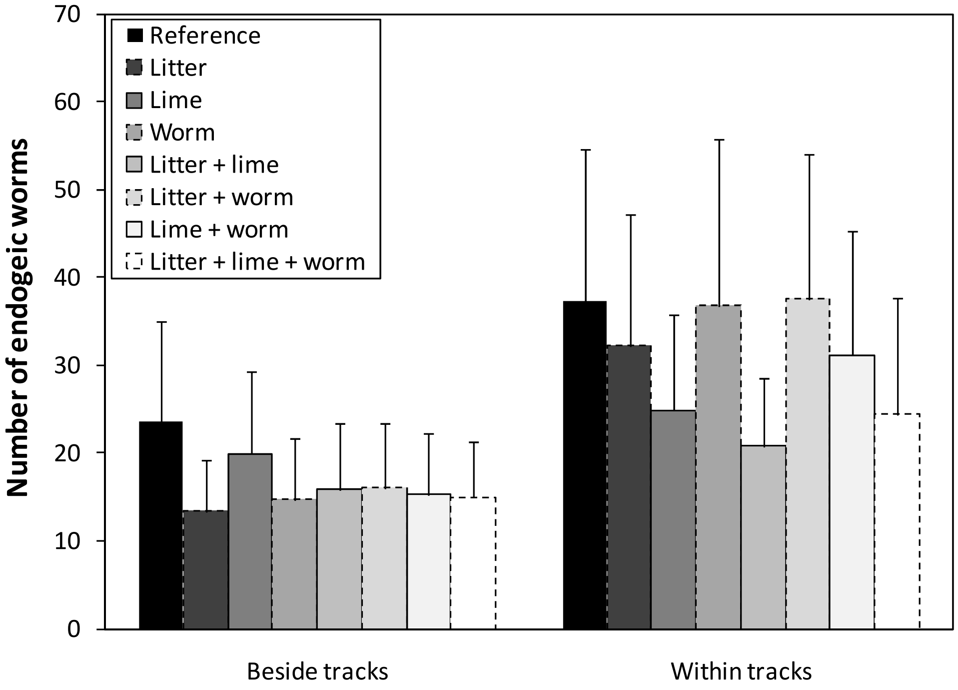


Fig. 7.4 Mean number of endogeic worms averaged over all stands, as influenced by earthworm inoculation (*worm*), liming (*lime*), litter change (*litter*) and location in relation to the wheel tracks. Error bars represent the 95% confidence interval.

The fits of the double exponential decay models for litter decay for all locations in relation to the tracks and treatments were similar for Sperwer, Goden and Havik (Fig. 7.5). Treatments lime (c, k) and worm + lime (e, m) resulted in the slowest decay. In Sperwer, more than 90% of the initial mass in the litter bags remained after 389 days for these treatments. This contrasted strongly with worm + litter (f, n) and worm + litter + lime (h, p) that induced the highest decay rates. The other treatments, including the reference (a, i), showed intermediate decay rates. For most treatments, decay rates were slightly higher on the compacted soil compared to the non-compacted soil. The results of Renissart differed somewhat from the other stands, as the remaining portion of leaf litter after 389 days was lower than 60% for all treatments. In this stand the reference treatments on both locations in relation to the tracks (a, i) resulted in the lowest decay rates, together with the lime treatments (c, k). The influences of the other treatments on the decay rate all led to remaining portions of leaf litter beneath 25% after 389 days.

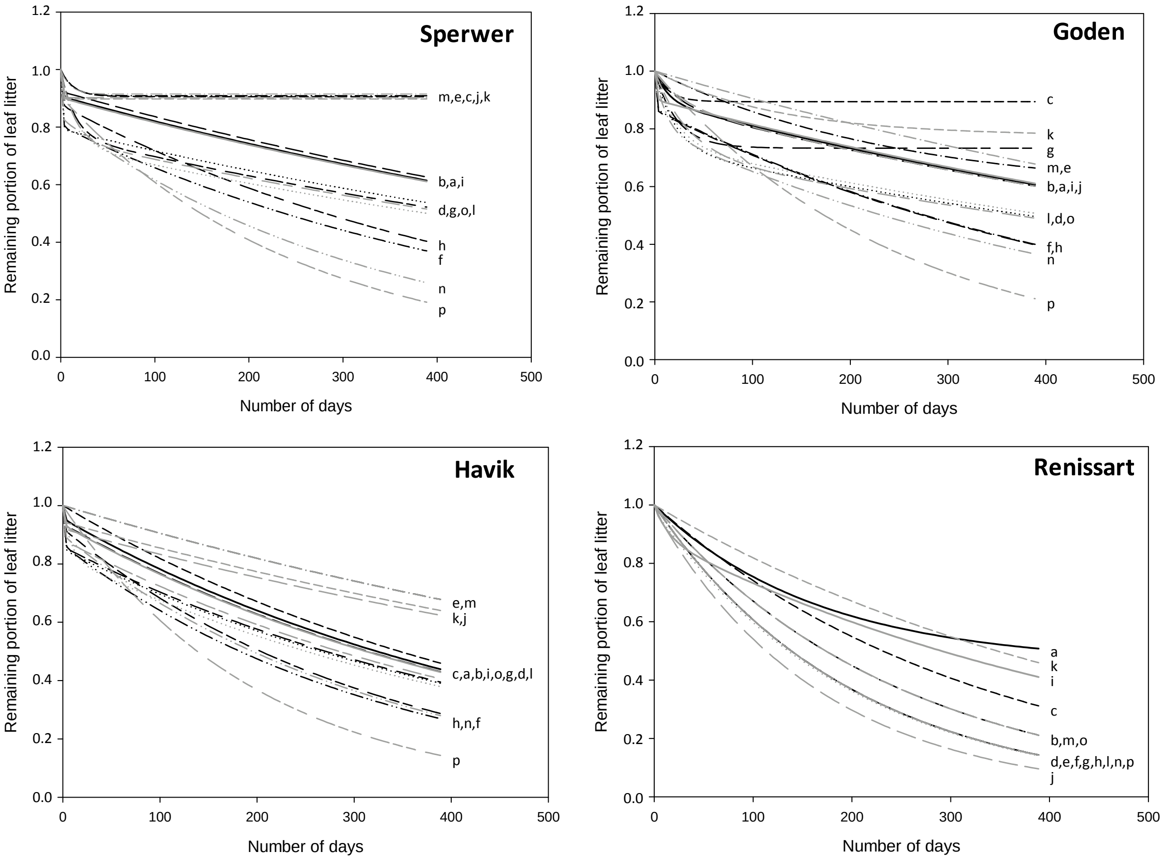


Fig. 7.5 Remaining portion of leaf litter in function of number of days that litter bags lied incorporated in the litter layer. Curves represent double exponential decay models that were fit to the raw data. Characters to the right of the curves indicate treatments (BT = beside tracks, WT = within tracks):

a) BT, reference;
b) BT, worm;
c) BT, lime;
d) BT, litter;
e) BT, worm+lime;
f) BT, worm+litter;
g) BT, lime+litter;
h) BT, worm+lime+litter;
i) WT, reference;
j) WT, worm;
k) WT, lime;
l) WT, litter;
m) WT, worm+lime;
n) WT, worm+litter;
o) WT, lime+litter;
p) WT, worm+lime+litter.

The remaining portions of leaf litter after 389 days (based on the true end masses of the litter bags, not on the model results) showed a strongly significant negative influence of litter

(Table 7.1: p <0.001). The decay of litter of *Populus x canadensis* seemed to pass off faster compared to the native litter, leading to smaller remaining portions. The inoculation of *L. terrestris* also accelerated the decay process (p <0.001). This could also be concluded from the significant negative correlation coefficient between the remaining portions of litter and the numbers of *L. terrestris* at Sperwer (p <0.001), Goden (p = 0.016) and Havik (p = 0.039) (Table 7.2). Again, a large part of the variation in the dataset (49.4%) was due to the random structure. Moreover, for several litter bags that originated from frames that were limed, lime powder was attached to the leaves and could not be removed. This may have led to an underestimation of the decay rate of some limed frames.

In general, soil BD of depth intervals 0-10 cm and 10-20 cm were clearly higher within tracks, compared to the soil beside tracks (Appendix 7.3, Fig. 7.6). None of the treatments induced a clear decrease of the compaction degree, neither within nor beside tracks. Besides the significant impact of track on BD at soil depths 0-10 cm and 10-20 cm (p <0.001), we only found a significant effect of the interaction between worm and track at 0-5 cm soil depth (p = 0.015; Table 7.3). Apparently, the difference in BD between the two locations in relation to the tracks further increased by worm inoculation. BD beside the tracks decreased in the presence of worms in contrast with the location within tracks.

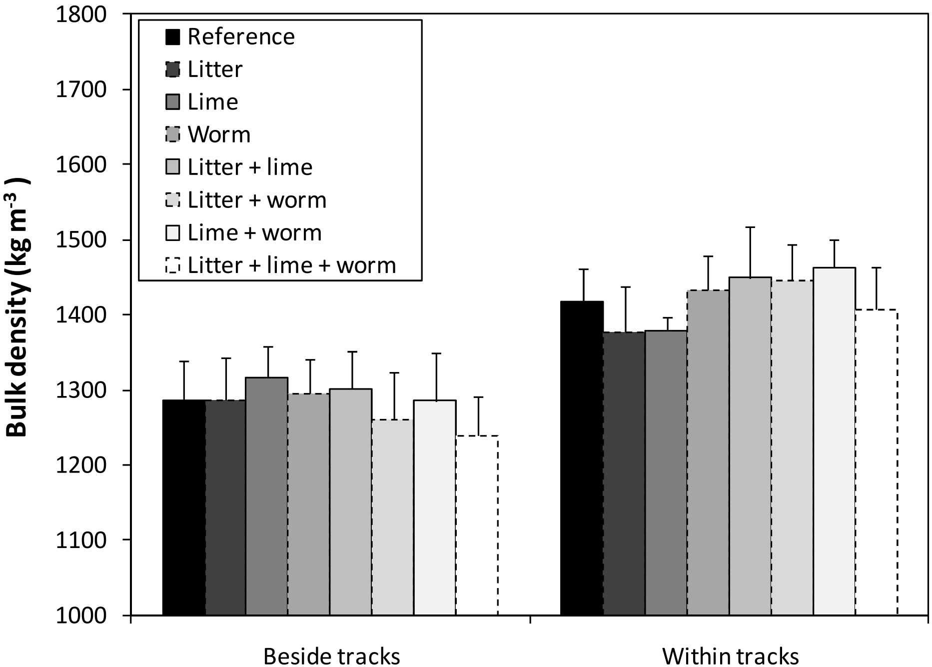


Fig. 7.6 Mean bulk density (kg m^{-3}) of depth interval 0-10 cm, averaged over all stands, as influenced by earthworm inoculation (*worm*), liming (*lime*), litter change (*litter*) and location in relation to the wheel tracks. Error bars represent the 95% confidence interval.

Table 7.3 The effects of earthworm inoculation (*worm*), liming (*lime*), litter change (*litter*) and location in relation to the wheel tracks (*track*) on soil bulk density at depths 0-10 cm and 10-20 cm: sources of variation, F-ratio, p-value and variation due to the random structure. Reported results are derived from multilevel models (see text for more details).

Sources of variation	Bulk density 0-10 cm		Bulk density 10-20 cm	
	F-ratio	p-value	F-ratio	p-value
Litter	0.730	0.393	0.83	0.361
Lime	0.726	0.395	1.09	0.296
Worm	0.045	0.832	0.05	0.828
Track	114.03	**<0.001**	129.69	**<0.001**
Litter x lime	0.04	0.837	0.99	0.319
Litter x worm	2.39	0.122	0.00	0.987
Litter x track	0.73	0.392	1.24	0.266
Lime x worm	1.69	0.194	0.20	0.654
Lime x track	0.09	0.766	0.18	0.669
Worm x track	5.91	**0.015**	0.03	0.871
Variation due to random structure	3.4%		5.3%	

Significant effects are marked in bold (p <0.05).

Results on PR (Fig. 7.7, Table 7.4, Appendix 7.4) confirmed the presence of higher compaction degrees within the tracks compared to beside the tracks and the lack of clear effects after application of the treatments. At 15 cm, 20 cm and 25 cm depth, in the absence of inoculated worms, PR was significantly lower in limed frames compared to unlimed frames. When worms were inoculated, PR were intermediate, with or without lime addition (worm x lime, p = 0.004 at 15 cm, p = 0.001 at 20 cm, p = 0.013 at 25 cm).

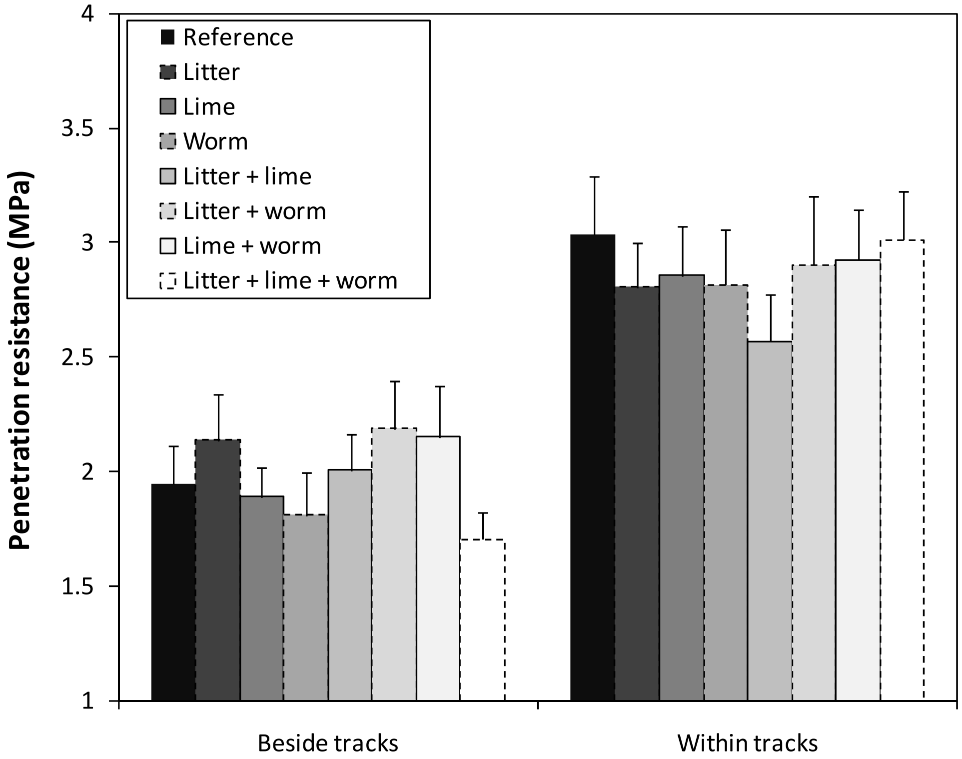


Fig. 7.7 Mean penetration resistance of depth 10 cm (MPa), averaged over all stands, as influenced by earthworm inoculation (*worm*), liming (*lime*), litter change (*litter*) and location in relation to the wheel tracks. Error bars represent the 95% confidence interval.

Table 7.4 The effects of earthworm inoculation (*worm*), liming (*lime*), litter change (*litter*) and location in relation to the wheel tracks (*track*) on penetration resistance (*pen res*) at depths 5 cm, 10 cm, 15 cm, 20 cm and 25 cm: sources of variation, F-ratio, p-value and variation due to the random structure. Reported results are derived from multilevel models (see text for more details).

Sources of variation	**Pen res 5 cm**		**Pen res 10 cm**		**Pen res 15 cm**		**Pen res 20 cm**		**Pen res 25 cm**	
	F-ratio	**p-value**	**F-ratio**	**p-value**	**F-ratio**	**p-value**	**F-ratio**	**p-value**	**F-ratio**	**p-value**
Litter	1.66	0.197	0.04	0.841	0.00	0.954	0.03	0.853	0.05	0.828
Lime	0.14	0.704	0.86	0.353	2.11	0.147	2.50	0.114	1.52	0.218
Worm	0.04	0.835	0.71	0.400	0.00	0.961	0.02	0.889	0.63	0.429
Track	123.78	**<0.001**	326.75	**<0.001**	377.86	**<0.001**	423.49	**<0.001**	452.44	**<0.001**
Litter x lime	0.84	0.361	4.98	**0.026**	4.01	**0.045**	5.82	**0.016**	3.39	0.066
Litter x worm	0.16	0.685	0.36	0.551	1.20	0.273	0.63	0.428	0.18	0.674
Litter x track	0.74	0.389	2.14	0.144	1.74	0.188	2.60	0.107	4.72	**0.030**
Lime x worm	0.11	0.740	3.54	0.060	8.37	**0.004**	10.75	**0.001**	6.23	**0.013**
Lime x track	6.06	**0.014**	0.33	0.568	0.20	0.657	0.01	0.933	0.00	0.980
Worm x track	0.14	0.704	1.33	0.249	0.03	0.867	0.39	0.531	0.12	0.727
Variation due to random structure	16.3%		18.5%		20.3%		20.6%		22.6%	

Significant effects are depicted in bold (p <0.05).

7.5 Discussion

7.5.1 Stimulation of biological activity by manipulation of litter, soil acidity and earthworm populations

As expected, decay rates of litter of *Populus x canadensis* were higher compared to the native litter. Higher calcium concentrations (Reich et al. 2005; Hobbie et al. 2006) as well as low lignin to N ratios (Prescott 2010) were found to be good predictors for litter decay rates. The calcium content of the litter of *Populus x canadensis* (25.8 g kg^{-1}) was at least three times as high as the calcium content of the native litter (3.9-8.2 g kg^{-1}). According to Neirynck et al. (2000) and Aubert et al. (2005), good litter degradability litter stimulates micro-organisms and macrofauna. The higher decay rates in Renissart were probably also due to the better litter quality of *Acer pseudoplatanus* (calcium content = 14.4 g kg^{-1}). Endogeic earthworms were abundant as soil acidity was within their pH-range (2.5 < pH(KCl) < 10) (Sims & Gerard 1999). As these species seldom dwell the soil surface in search of food (Felten & Emmerling 2009), the relationships between numbers of endogeics and the remaining portions of litter were predominantly insignificant (Table 7.2). Conversely, anecic worms intensively fragment litter at the soil surface for immediate digestion or they pull pieces along in their burrows (Bouché 1977; Edwards & Bohlen 1996). However, before the field trial, anecic worm species as *L. terrestris* were absent in all four stands. In frames where no inoculation took place, decomposition was thus due to other macrofauna and micro-organisms, such as epigeic earthworms that live in the litter layer (Sims & Gerard 1999). Moreover, in the inoculated frames only a negligible number of *L. terrestris* was retraced. Sims & Gerard (1999) emphasized that *L. terrestris* prefers a pH(KCl) range of 5.2 to 9. The higher acidity in our forest stands may have resulted in high mortality rates and/or the escape to the surrounding area and frames, as was stated by the results. The application of lime slightly decreased the acidity of the soil, resulting in higher numbers of retrieved anecic worms. Muys et al. (2003) also indicated a negative impact of soil acidity on *L. terrestris*. Although replacement of the native litter by litter of *Populus x canadensis* did not result in a higher soil pH, at least not within the time-span of our study, results showed that *L. terrestris* was positively influenced, leading to a positive feedback on litter decomposition. It has formerly been suggested that individuals of *L. terrestris* have well-developed calciferous glands that produce calcium carbonate to reduce the blood CO_2 level and to regulate blood pH when faced with high soil CO_2 levels (Piearce 1972). Therefore they benefited from the presence of the calcium-rich *Populus x canadensis* litter. Reich et al. (2005) also proved this positive relationship between earthworm abundance, particularly *L. terrestris*, and litter calcium concentration.

The highest decay rates were obtained by an overall synergetic effect between lime application, earthworm inoculation and litter replacement. As the survival and activity of anecic earthworm species was limited due to unfavourable soil conditions as a low pH, liming increased their survival changes and activity and thus entailed an extra boost for decomposition (Wolters et al. 1995; Schack-Kirchner & Hildebrand 1998). Deleporte & Tillier (1999), Theenhaus & Schaefer (1995) and Ammer & Huber (2007) also found an overall positive effect of liming on earthworm biomass. The presence of anecic earthworms also resulted in higher pH-values (Räty 2004), what might be associated with the incorporation of organic matter and the direct alkalinisation due to cutaneous mucus excreted by earthworms (Haimi & Huhta 1990; Schrader 1994). This possibly induced a positive feedback on their activity in accordance to Jones et al. (2010). Endogeic species were also found to be positively influenced by higher pH values in the upper 10 cm of the soil. Several studies already pointed to the beneficial effect of endogeic and anecic species on the dispersal of lime by burrowing activities (e.g., Baker et al. 1999; Chan 2003).

The slightly higher decomposition rates within tracks were probably due to the higher soil pH. The lower acidity may be due to the enhanced anaerobic proton-consuming processes, such as the reduction of iron and sulphate (Schnurr-Pütz et al. 2006). Our results were also consistent to the study of Makineci et al. (2007) who found that, in addition to physical changes in the mineral soil layers, changes in the properties of the H and F forest floor layers due to machine traffic can affect the acidity of the soil. Earthworms are very sensitive to dehydration and are most active at moisture tensions approaching field capacity (Nordström 1975; Baker et al. 1993). Throughout our field trial the weather conditions were relatively dry. As a compacted soil has a higher unsaturated hydraulic conductivity compared to a non-compacted soil, it can sustain the evaporation process longer (Hillel 1998) and it remains longer wet. Endogeic worms may therefore have found better survival probabilities within the wheel tracks. The lower acidity together with the higher soil water contents within tracks, may thus have led to higher endogeic earthworm abundance within the tracks. The drier conditions beside the tracks may have led to migration, mortality or quiescence.

7.5.2 Ecological restoration of compacted soils

Compaction degrees within tracks were still significantly higher compared to the soil beside tracks. Contrary to the soil within the wheel tracks, anecic earthworm inoculation induced a small BD decrease in the upper soil layer beside tracks. This beneficial effect of especially anecic earthworms on BD was also stated by Fonte et al. (2010). *Lumbricus terrestris* is detritivorous and ingests only in rare conditions deliberately large amounts of soil (Buck et al. 2000). In relatively loose soils, this species pushes the soil particles aside in order to construct its burrows, thereby slightly compacting the soil that surrounds the burrows (Kretzschmar 1987). It results in a net increase of macroporosity and a decrease of BD by the construction of their burrows, by mixing mineral soil and organic matter and by excreting casts at the soil surface (constructing middens), containing mineral soil particles of deeper soil layers (e.g., Edwards 2004). The rather small BD decreases after earthworm inoculation in our study were probably due to the overall very low number of retrieved *L. terrestris* and the rather short study period. Moreover, as indicated by Ampoorter et al. (2008), the compaction degrees on the non-compacted soil beside tracks were also relatively high and could have decelerated the burrowing activity. Rushton (1986), Kretzschmar (1991) and Söchtig & Larink (1992) also found a reduced activity of *L. terrestris* as soil became more compressed. As it becomes more and more difficult to push particles aside, *L. terrestris* is forced to ingest a higher amount of soil to burrow in compacted soil (Buck et al. 2000). As this process has high energy requirements, it leads to reduced activity which may stop at high compaction degrees. The loosening effect was not observed for the soil within tracks although no difference in number of individuals of *L. terrestris* between the two locations in relation to the tracks was found. The absence of an effect within the tracks was thus not due to a higher mortality or avoidance of the compacted zones for energy budget reasons, as was stated by Stovold et al. (2004) and Capowiez et al. (2009), but probably also the result of reduced or lacking burrowing activity as compaction degrees were even higher than beside tracks. Despite the reduced activity, Ponder et al. (2000) noticed a significant decrease of BD in compacted pot microcosms after six months. The number of endogeic worms was higher within tracks. Although these worms also intensively burrow and positively influence soil structure (such as macroporosity), their impact on aeration, hydraulic conductivity and certainly BD is probably much smaller compared to anecic species. Namely, endogeics excrete their casts within their burrows, in contrast with anecic species that excrete their casts (an intense mixture of organic material and soil particles from deeper layers) on the surface, in this way keeping their burrows open.

In the absence of inoculated worms, PR showed overall clearly lower values after liming. Also Kirkham et al. (2007) found reduced PR and increased saturated hydraulic conductivity values after lime application. Chan et al. (2007) concluded that BD was decreased by liming, due to reduced dispersion and slaking. Half of this effect was reached by inoculating worms without lime application, as was observed for BD beside the compacted tracks. This relatively smaller effect was in part due to the low number of survived inoculated worms. Moreover, as mentioned above, within the compacted wheel tracks the activity of *L. terrestris* is limited. Beside the tracks, *L. terrestris* compacted the soil surrounding the burrows, in this way strengthening the soil matrix. These processes may have lowered the beneficial effect of *L. terrestris* on PR. The extra application of lime did not result in a further decrease of PR. We hypothesize that liming stimulated the activity of *L. terrestris*, resulting in more burrows but also an extra reinforcement of the soil structure.

The loosening effect of biological activity, stimulated by litter manipulation, liming and earthworm inoculation was thus not as high as expected, deduced from the BD and PR results. This was probably due to the limited number of retrieved worms as anecic earthworms are very important ecological engineers in the restoration process. It must be emphasized that the study period was time limited due to practical reasons and probably too short to be able to detect clear ecosystem responses. The effect of liming, litter manipulation and earthworm inoculation on the examined soil characteristics (pH, BD, PR) is probably only clear in the long-term after sustained application of these treatments for several years. On the other hand the rather low loosening effects could be due to the variables that were used to quantify restoration success. The chance to detect significant BD changes depends on the presence or absence of burrows in the soil samples. As mentioned above, PR is also affected by the compacted soil layer surrounding the burrows. Moreover, by quantifying only BD and PR as indicators of soil restoration success, the overall positive effect of both endogeic and anecic worms on soil structural development was underestimated. While burrowing, both endogeic as anecic earthworm species increase macroporosity (e.g., Edwards 2004), resulting in higher saturated hydraulic conductivity (Joschko et al. 1992) and better aeration (Lee & Foster 1991). The burrows form a preferential pathway for root elongation in compacted soils (Edwards & Lofty 1980; Hirth et al. 1997), as root tips cannot overcome high soil strengths in compacted soils and growth would thus be hampered. Moreover, earthworms realize an intense mixture of mineral soil particles with organic material and microbial organisms, as well on the surface as in their burrows (Devliegher & Verstraete 1997; Binet & Le Bayon 1999). This results on the one hand in high mineralization rates and thus fast nutrient release in the short term in the drilosphere (Brown et al. 2000). On the other hand, it entails the formation of stable macroaggregates (Beare et al. 1994; McInerney et al. 2001). Results of Chapter 2 already showed that soil CO_2 concentration is more sensitive to soil structural changes and may therefore give a better indication of the ecological restoration potential of earthworms.

Appendix 7.1

Mean pH(KCl)-values (± standard deviation) of depth intervals 0-5 cm and 5-10 cm as influenced by earthworm inoculation (*worm*), liming (*lime*), litter change (*litter*), and location in relation to the wheel tracks.

Treatment		Sperwer		Goden		Havik		Renissart	
		0-5 cm	**5-10 cm**	**0-5 cm**	**5-10 cm**	**0-5 cm**	**5-10 cm**	**0-5 cm**	**5-10 cm**
F-ratio		5.573	1.838	10.444	3.511	12.693	5.463	13.142	7.505
p		<0.001	0.044	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Beside tracks	**Reference**	3.2 ± 0.1 a	3.5 ± 0.1 a	3.0 ± 0.1 a	3.3 ± 0.1 a	3.1 ± 0.1 a	3.4 ± 0.1 a	3.3 ± 0.1 a	3.6 ± 0.1 abc
	Litter	3.3 ± 0.1 ab	3.5 ± 0.1 a	3.1 ± 0.1 a	3.5 ± 0.1 a	3.1 ± 0.1 a	3.3 ± 0.0 a	3.2 ± 0.1 a	3.4 ± 0.1 a
	Lime	3.7 ± 0.3 abcd	3.7 ± 0.2 a	3.6 ± 0.5 abc	3.4 ± 0.6 a	4.5 ± 0.6 bc	3.7 ± 0.4 a	4.2 ± 0.3 cdef	3.6 ± 0.1 abcd
	Worm	3.2 ± 0.1 a	3.5 ± 0.1 a	3.1 ± 0.6 a	3.1 ± 0.1 a	3.0 ± 0.1 a	3.2 ± 0.1 a	3.4 ± 0.1 abc	3.5 ± 0.1 abc
	Litter + lime	3.8 ± 0.3 abcd	3.6 ± 0.1 a	3.9 ± 0.5 abcd	3.4 ± 0.5 a	4.2 ± 0.5 bc	3.6 ± 0.2 a	4.1 ± 0.2 bcdef	3.6 ± 0.1 abcd
	Litter + worm	3.2 ± 0.1 ab	3.5 ± 0.1 a	3.1 ± 0.2 a	3.5 ± 0.1 a	3.1 ± 0.1 a	3.4 ± 0.1 a	3.3 ± 0.2 ab	3.5 ± 0.1 ab
	Lime + worm	4.2 ± 0.7 d	3.6 ± 0.1 a	3.8 ± 0.6 abcd	3.4 ± 0.7 a	5.0 ± 0.7 b	4.2 ± 0.7 b	1.2 ± 0.6 cdef	3.6 ± 0.3 abcd
	Worm + lime + litter	4.1 ± 0.8 cd	3.6 ± 0.2 a	3.8 ± 0.4 abcd	3.4 ± 0.7 a	4.1 ± 0.7 bc	3.5 ± 0.1 a	4.5 ± 0.4 efg	3.7 ± 0.1 bcde
Within tracks	**Reference**	3.4 ± 0.2 ab	3.7 ± 0.2 a	3.4 ± 0.0 ab	3.6 ± 0.1 ab	3.0 ± 0.1 a	3.3 ± 0.1 a	3.6 ± 0.1 abcd	3.6 ± 0.1 abcd
	Litter	3.3 ± 0.1 ab	3.6 ± 0.1 a	3.0 ± 0.1 a	3.3 ± 0.1 a	3.1 ± 0.1 a	3.3 ± 0.2 a	3.7 ± 0.1 abcd	3.7 ± 0.0 bcde
	Lime	3.6 ± 0.2 abcd	3.7 ± 0.1 a	4.5 ± 1.1 cd	3.6 ± 0.5 ab	3.9 ± 0.5 ab	3.6 ± 0.2 a	4.5 ± 0.6 efg	3.9 ± 0.2 de
	Worm	3.4 ± 0.2 abc	3.6 ± 0.2 a	3.0 ± 0.2 a	3.4 ± 0.1 a	3.1 ± 0.1 a	3.4 ± 0.1 a	3.9 ± 0.2 abcdef	3.9 ± 0.1 de
	Litter + lime	3.8 ± 0.2 abcd	3.6 ± 0.0 a	4.3 ± 0.4 bcd	3.6 ± 0.7 ab	4.3 ± 0.7 bc	3.6 ± 0.1 a	4.3 ± 0.3 defg	3.8 ± 0.1 cde
	Litter + worm	3.5 ± 0.1 abc	3.7 ± 0.1 a	3.6 ± 0.1 abc	3.7 ± 0.1 ab	3.1 ± 0.1 a	3.5 ± 0.2 a	3.9 ± 0.4 abcde	3.8 ± 0.2 cde
	Lime + worm	3.8 ± 0.2 abcd	3.7 ± 0.2 a	4.7 ± 0.4 d	4.1 ± 0.5 b	4.1 ± 0.5 bc	3.7 ± 0.2 a	5.0 ± 0.6 g	4.0 ± 0.2 e
	Worm + lime + litter	3.6 ± 0.4 bcd	3.7 ± 0.2 a	4.5 ± 0.3 cd	3.8 ± 0.6 ab	3.7 ± 0.6 ab	3.6 ± 0.1 a	4.6 ± 0.5 fg	3.8 ± 0.1 cde

Treatment means were compared against each other after ANOVA using Tukey's HSD test (α = 0.05), for each depth interval per stand (p and F-ratio are indicated). Significant differences between means within a column are marked with different letters; F-ratio and p of each test are indicated.

Appendix 7.2

Mean number of individuals (± standard deviation) of *L. terrestris* and endogeic earthworms as influenced by earthworm inoculation (*worm*), liming (*lime*), litter change (*litter*), and location in relation to the wheel tracks.

Treatment		Sperwer		Goden		Havik		Renissart	
		L. terrestris	**Endogeic**	***L. terrestris***	**Endogeic**	***L. terrestris***	**Endogeic**	***L. terrestris***	**Endogeic**
F-ratio		10.910	4.151	2.369	2.939	2.405	1.023	1.888	3.096
p		<0.001	<0.001	0.008	0.001	0.007	0.442	0.038	0.001
Beside tracks	**Reference**	0.0 ± 0.0 a	47.5 ± 22.7 ab	0.0 ± 0.0 a	0.8 ± 1.0 a	0.0 ± 0.0 a	44.8 ± 27.2 a	0.7 ± 0.8 ab	1.3 ± 2.3 a
	Litter	0.0 ± 0.0 a	25.2 ± 6.3 ab	0.0 ± 0.0 a	1.8 ± 2.1 a	0.2 ± 0.4 a	23.3 ± 17.7 a	0.0 ± 0.0 a	3.2 ± 5.4 a
	Lime	0.0 ± 0.0 a	39.7 ± 30.0 ab	0.0 ± 0.0 a	2.2 ± 2.1 a	0.2 ± 0.4 a	32.8 ± 16.5 a	1.2 ± 1.8 ab	5.0 ± 3.3 a
	Worm	0.0 ± 0.0 a	33.2 ± 15.7 ab	0.0 ± 0.0 a	2.4 ± 3.0 a	0.0 ± 0.0 a	18.0 ± 14.4 a	0.2 ± 0.4 ab	3.8 ± 4.5 a
	Litter + lime	1.2 ± 1.3 ab	26.8 ± 12.5 ab	0.0 ± 0.0 a	0.5 ± 1.0 a	1.8 ± 2.8 a	28.3 ± 22.2 a	0.0 ± 0.0 a	2.5 ± 2.2 a
	Litter + worm	0.6 ± 0.9 a	35.4 ± 16.2 ab	0.5 ± 0.6 a	1.0 ± 1.1 a	0.0 ± 0.0 a	29.6 ± 8.9 a	1.0 ± 1.3 ab	3.7 ± 3.4 a
	Lime + worm	0.4 ± 0.6 a	25.8 ± 14.5 ab	0.3 ± 0.5 a	2.7 ± 2.4 a	1.2 ± 1.0 a	30.1 ± 17.8 a	2.2 ± 2.7 b	2.2 ± 0.8 a
	Worm + Lime + Litter	2.6 ± 1.5 bc	17.2 ± 10.0 a	1.2 ± 0.5 a	3.8 ± 3.3 ab	1.7 ± 1.2 a	28.3 ± 20.1 a	0.6 ± 0.9 ab	10.2 ± 11.2 ab
Within tracks	**Reference**	0.0 ± 0.0 a	82.2 ± 32.7 bc	0.0 ± 0.0 a	0.3 ± 0.6 a	0.3 ± 0.8 a	40.8 ± 34.6 a	0.2 ± 0.4 ab	7.2 ± 4.8 ab
	Litter	0.0 ± 0.0 a	57.3 ± 43.5 abc	0.0 ± 0.0 a	2.0 ± 2.0 a	0.0 ± 0.0 a	54.7 ± 40.5 a	0.0 ± 0.0 a	15.0 ± 2.8 ab
	Lime	0.2 ± 0.4 a	50.5 ± 34.6 abc	0.0 ± 0.0 a	2.6 ± 1.5 a	0.2 ± 0.4 a	31.7 ± 17.8 a	0.0 ± 0.0 a	11.2 ± 6.0 ab
	Worm	0.0 ± 0.0 a	107.4 ± 32.1 c	0.0 ± 0.0 a	0.7 ± 0.8 a	0.0 ± 0.0 a	27.7 ± 25.7 a	0.0 ± 0.0 a	20.4 ± 15.0 b
	Litter + lime	0.0 ± 0.0 a	40.7 ± 8.4 ab	0.0 ± 0.0 a	3.0 ± 2.1 a	0.5 ± 0.6 a	28.8 ± 22.1 a	0.7 ± 1.2 ab	10.7 ± 11.7 ab
	Litter + worm	0.8 ± 1.2 a	66.0 ± 41.5 abc	0.0 ± 0.0 a	8.0 ± 1.4 b	1.4 ± 1.1 a	40.8 ± 27.0 a	1.0 ± 1.2 ab	11.4 ± 14.0 ab
	Lime + worm	0.0 ± 0.0 a	64.2 ± 34.7 abc	1.6 ± 2.1 a	2.8 ± 1.3 a	1.6 ± 2.3 a	48.4 ± 29.5 a	0.3 ± 0.5 ab	7.3 ± 3.6 ab
	Worm + Lime + Litter	3.8 ± 1.9 c	65.3 ± 31.7 abc	0.8 ± 1.8 a	0.4 ± 0.5 a	1.8 ± 1.8 a	19.6 ± 17.1 a	0.8 ± 0.8 ab	7.7 ± 2.4 ab

Means were compared against each other after ANOVA using Tukey's HSD test (α = 0.05), for both *L. terrestris* and other species per stand (p and F-ratio are indicated). Significant differences between means within a column are marked with different letters; F-ratio and p of each test are indicated.

Appendix 7.3

Mean soil bulk density (kg m^{-3}) (± standard deviation) of depth intervals 0-10 cm and 10-20 cm as influenced by earthworm inoculation (*worm*), liming (*lime*), litter change (*litter*), and location in relation to the wheel tracks.

	Treatment	Sperwer		Goden		Havik		Renissart	
		0-10 cm	**10-20 cm**	**0-10 cm**	**10-20 cm**	**0-10 cm**	**10-20 cm**	**0-10 cm**	**10-20 cm**
	F-ratio	5.689	7.193	2.340	2.313	4.531	5.201	8.424	2.791
	p	<0.001	<0.001	0.005	0.006	<0.001	<0.001	<0.001	0.001
Beside tracks	**Reference**	1414 ± 95 abcd	1451 ± 60 abcde	1328 ± 172 ab	1473 ± 117 a	1208 ± 126 a	1303 ± 49 a	1190 ± 141 abc	1455 ± 128 b
	Litter	1321 ± 117 a	1413 ± 69 abcd	1458 ± 161 ab	1521 ± 103 ab	1311 ± 86 abcd	1353 ± 60 ab	1058 ± 166 a	1286 ± 116 a
	Lime	1364 ± 79 ab	1397 ± 58 abc	1445 ± 151 ab	1451 ± 138 a	1247 ± 123 abc	1370 ± 97 ab	1211 ± 121 abc	1410 ± 118 ab
	Worm	1380 ± 141 abc	1364 ± 77 a	1372 ± 168 ab	1475 ± 115 a	1210 ± 137 a	1382 ± 77 abc	1218 ± 98 abc	1393 ± 65 ab
	Litter + lime	1412 ± 102 abcd	142 ± 70 abcde	1320 ± 199 ab	1423 ± 84 a	1312 ± 139 abcd	1369 ± 124ab	1168 ± 147 abc	1390 ± 94 ab
	Litter + worm	1443 ± 153 abcd	1437 ± 77 abcde	1220 ± 270 a	1464 ± 72 a	1231 ± 142 ab	1331 ± 71 ab	1156 ± 128 ab	1348 ± 114 ab
	Lime + worm	1386 ± 97 abc	1386 ± 68 ab	1316 ± 204 ab	1510 ± 82 ab	1403 ± 79 abcd	1428 ± 50 abc	1008 ± 206 a	1346 ± 109 ab
	Worm + Lime + Litter	1365 ± 117 abc	1432 ± 94 abcde	1217 ± 184 a	1452 ± 87 a	1223 ± 193 a	1305 ± 231a	1160 ± 168 ab	1318 ± 154 ab
Within tracks	**Reference**	1450 ± 165 abcd	1536 ± 77 ef	1636 ± 71 b	1653 ± 54 b	1353 ± 73 abcd	1439 ± 149abc	1341 ± 70 bcd	1421 ± 67 ab
	Litter	1528 ± 87 cd	1490 ± 117bcdef	1415 ± 245 ab	1522 ± 138 ab	1279 ± 270 abcd	1499 ± 84 bc	1285 ± 97 bcd	1374 ± 108 ab
	Lime	1487 ± 76 bcd	1494 ± 62 bcdef	1240 ± 301 a	1536 ± 94 ab	1442 ± 182 bcd	1553 ± 79 c	1325 ± 135 bcd	1398 ± 73 ab
	Worm	1496 ± 142 bcd	1526 ± 58 def	1469 ± 153 ab	1525 ± 108 ab	1387 ± 186 abcd	1381 ± 188abc	1381 ± 117 cd	1465 ± 58 b
	Litter + lime	1550 ± 132 d	1540 ± 56 ef	1362 ± 394 ab	1502 ± 166 ab	1412 ± 190 abcd	1500 ± 154bc	1474 ± 124 d	1450 ± 64 b
	Litter + worm	1566 ± 89 d	1568 ± 86 f	1419 ± 140 ab	1593 ± 25 ab	1415 ± 109 abcd	1462 ± 131abc	1351 ± 186 bcd	1462 ± 129 b
	Lime + worm	1515 ± 90 bcd	1499 ± 88 bcdef	1478 ± 120 ab	1523 ± 78 ab	1490 ± 101 d	1549 ± 96 c	1375 ± 152 cd	1444 ± 81 ab
	Worm + Lime + Litter	1557 ± 76 d	1509 ± 92 cdef	1263 ± 306 a	1579 ± 91 ab	1453 ± 68 cd	1468 ± 83 abc	1340 ± 58 bcd	1383 ± 86 ab

Means were compared against each other after ANOVA using Tukey's HSD test (α = 0.05), for each depth interval per stand (p and F-ratio are indicated). Significant differences between means within a column are marked with different letters; F-ratio and p of each test are indicated.

Appendix 7.4

Mean penetration resistance (MPa) (± standard deviation) of depths 10 cm and 20 cm as influenced by stand, depth, location and treatment.

	Treatment	Sperwer		Goden		Havik		Renissart	
		10 cm	20 cm	10 cm	20 cm	10 cm	20 cm	10 cm	20 cm
	F-ratio	19.334	22.262	7.488	9.941	10.291	10.786	3.635	5.257
	p	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Beside tracks	Reference	2.03 ± 0.57 abc	2.38 ± 0.59 bcd	1.50 ± 0.44 ab	1.56 ± 0.46 ab	1.77 ± 0.73 ab	1.83 ± 0.75 ab	2.49 ± 1.10 abcd	2.77 ± 1.36 abc
	Litter	1.56 ± 0.46 a	1.75 ± 0.50 ab	1.97 ± 1.04 abcd	1.98 ± 0.96 abcd	1.83 ± 0.58 ab	1.94 ± 0.65 abc	3.19 ± 1.00 d	3.32 ± 0.85 c
	Lime	2.16 ± 0.68 abc	2.13 ± 0.68 abc	1.86 ± 0.74 abc	1.84 ± 0.67 abcd	1.65 ± 0.57 a	1.77 ± 0.66 a	1.90 ± 0.56 a	2.02 ± 0.54 a
	Worm	1.99 ± 0.66 ab	2.17 ± 0.92 abc	1.26 ± 0.63 a	1.25 ± 0.67 a	1.43 ± 0.75 a	1.63 ± 0.99 a	2.41 ± 0.92 abcd	2.52 ± 0.84 abc
	Litter + lime	1.62 ± 0.39 a	1.87 ± 0.63 ab	1.68 ± 0.64 ab	1.87 ± 0.72 abcd	1.96 ± 0.52 abc	2.14 ± 0.50 abcd	2.66 ± 0.83 abcd	2.80 ± 0.77 abc
	Litter + worm	2.50 ± 0.58 bcd	2.36 ± 0.46 bc	1.32 ± 0.74 a	1.35 ± 0.44 a	2.30 ± 0.96 abcd	2.56 ± 0.99 abcde	2.71 ± 1.05 abcd	2.95 ± 0.91 abc
	Lime + worm	1.50 ± 0.54 a	1.51 ± 0.57 a	1.64 ± 0.46 ab	1.61 ± 0.48 abc	2.80 ± 1.29 bcde	2.87 ± 1.26 bcdef	2.66 ± 1.04 abcd	3.18 ± 1.32 bc
	Worm + Lime + Litter	1.52 ± 0.47 a	1.55 ± 0.55 a	1.59 ± 0.55 ab	1.67 ± 0.66 abc	1.79 ± 0.45 ab	2.03 ± 0.59 abcd	1.93 ± 0.67 ab	2.06 ± 0.52 a
Within tracks	Reference	3.29 ± 1.02 e	3.32 ± 0.92 ef	2.04 ± 0.63 abcd	2.37 ± 0.62 bcde	3.38 ± 1.35 e	3.70 ± 1.25 f	2.94 ± 1.16 cd	3.45 ± 1.24 c
	Litter	3.29 ± 0.53 de	3.55 ± 0.60 f	2.35 ± 0.75 bcd	2.69 ± 0.90 de	2.79 ± 1.26 bcde	3.38 ± 1.20 ef	2.79 ± 1.02 abcd	3.20 ± 0.75 bc
	Lime	3.00 ± 0.79 de	3.14 ± 0.61 def	2.35 ± 1.07 bcd	2.57 ± 1.00 de	3.29 ± 1.42 de	3.59 ± 1.14 ef	2.70 ± 0.56 abcd	3.21 ± 0.55 bc
	Worm	3.05 ± 1.09 de	3.35 ± 0.89 ef	2.32 ± 0.72 bcd	2.32 ± 0.52 bcde	3.54 ± 1.36 e	3.64 ± 1.36 ef	2.32 ± 0.80 abcd	2.69 ± 0.64 abc
	Litter + lime	2.82 ± 1.12 cde	2.71 ± 1.18 cde	2.58 ± 1.07 cd	2.55 ± 1.04 de	2.77 ± 1.04 bcde	3.00 ± 1.02 cdef	2.09 ± 0.70 abc	2.34 ± 0.82 ab
	Litter + worm	3.12 ± 0.93 de	3.32 ± 0.99 ef	1.65 ± 0.25 ab	2.26 ± 0.88 cde	3.10 ± 1.27 de	3.05 ± 1.37 def	2.91 ± 1.81 bcd	3.20 ± 1.54 bc
	Lime + worm	3.38 ± 0.85 e	3.51 ± 0.76 f	2.20 ± 0.83 bcd	2.44 ± 0.78 cde	3.15 ± 1.31 de	3.31 ± 1.29 ef	2.89 ± 0.93 abcd	3.13 ± 0.78 bc
	Worm + Lime + Litter	3.10 ± 1.05 de	3.58 ± 0.86 f	2.83 ± 1.04 d	3.09 ± 1.17 e	3.01 ± 1.12 cde	3.12 ± 1.26 def	3.09 ± 0.94 d	3.25 ± 0.80 bc

Means were compared against each other after ANOVA using Tukey's HSD test (α = 0.05), for each depth interval per stand (p and F-ratio are indicated). Significant differences between means within a column are marked with different letters; F-ratio and p of each test are indicated.

8 General discussion and conclusions

The deployment of forestry machines, such as harvesters and skidders, strongly increased productivity and safety of forest harvests. However, their high masses induce changes of important soil structural characteristics, such as porosity (e.g., Herbauts et al. 1996; Teepe et al. 2004) and pore continuity (e.g., Benthaus & Matthies 1993; Berli et al. 2003). As the activity and diversity of the soil biota, understorey and tree layer depends on the presence of favourable soil conditions, compaction may result in reduced ecosystem functionality. A lot of studies already discussed the problems that arise from mechanized forest harvesting, however seldom integrating the influences of site and stand characteristics, machine weight and traffic intensity on the compaction degree, and rarely focusing on sandy forest soils as these are generally assumed to be insensitive to soil compaction. General conclusions on the biotic impact are lacking, as most studies focus on the impacts on a single species or soil type. Information on the recovery of compacted soils is available but scarce, rarely focusing on factors that influence this process. With this thesis, we aimed to fill some gaps in the knowledge concerning soil compaction after mechanized harvesting. We investigated (1) abiotic effects of soil compaction as influenced by site and stand characteristics, machine weight and traffic intensity in Chapters 2 and 4, paying special attention to sandy forest soils in Chapter 3, (2) consequences of soil compaction for growth and survival of tree seedlings in Chapter 5, and (3) the compaction status of Flemish forest soils (Chapter 6), paying special attention to ecological restoration options in Chapter 7. The results of this study provide more insight i) into the abiotic and biotic effects of soil compaction as influenced by stand, site and harvesting characteristics, ii) into the compaction status of Flemish forest soils, and iii) into the potential of ecological restoration options for compacted forest soils. In addition, the findings allowed us to formulate suggestions for forest management and raised several questions to be addressed in further research.

8.1 Abiotic effects of soil compaction, as influenced by soil and machine characteristics

8.1.1 Impact of soil characteristics

Texture

Several studies indicated that the compaction degree is positively correlated with the clay content (Gomez et al. 2002; Smith 2003), indicating the highest vulnerabilities on medium to fine textures such as silt and clay (Larson et al. 1980; Hillel 1998; Fisher & Binkley 2000). This is confirmed by the higher compaction degrees in depth interval 0-10 cm on the clay soils compared to the sandy soils in Chapter 4.

However, compaction degrees on clay and loam to silt loam soils in Chapter 2 were negligible and comparable to the sandy soils. In Chapter 4 the impact on sand was as high as the impacts on clay in depth intervals 10-20 and 20-30 cm and results on BD and PR of Chapter 3 stated that sandy soils can be compacted to a considerable extent. It must also be remarked that CO_2 concentrations of the sandy soil, examined in Chapter 2, showed a clear impact of machine traffic, in contrast with the negligible impacts on BD and PR. The impact of machine traffic on pore continuity (and soil CO_2 concentration as a result) was independent of the compaction degree and determination of the soil impact solely based on PR and BD seriously underestimated the true impact on the sandy soil. Brais & Camiré (1998) and Smith & Du Toit (2005) also stated clear compaction degrees on sandy soils. While evaluating the impact of texture on soil compaction, soil water content and precompression stress should certainly be taken in account.

Soil water content

The low compaction degrees on clay in Chapter 2 can be explained by the soil water content during traffic, using the findings of Smith et al. (1997) and Hillel (1998) for medium-to fine-textured soils (§1.2.4.1). Water contents in Walem (clay loam and sandy loam to sandy clay loam) clearly exceeded the optimum soil water content for soil compaction for these textures (Table 2.1). A lot of pores were filled with water that cannot be compressed (Froehlich & McNabb 1984). Cohesion between particles is low in this condition (Al-Shayea

2001) and the soil has only a small ability to withstand applied machine forces. Therefore machine traffic resulted in strong plastic deformation (rut type 1) and small compaction degrees as was shown by Tables 2.3 and 2.4. Ruts were deep and showed bulges at the edges that partially compensated for the loss of soil within the ruts (Fig. 2.7). This also explained the negative correlations between soil water contents and compaction degrees in Walem and on the loam to silt loam soils in Leuven. As mentioned, soil water contents of Walem were much higher than the optimum soil water content for clayey soils, while soil water contents in Leuven (loam to silt loam soils) were on average probably also higher than the optimum soil water content for these textures (Smith et al. 1997), resulting in a decrease of the compaction degree with increasing soil water content.

Soil water contents at the sandy soils of Chapter 3, especially at site 2, were probably higher than the critical soil moisture content for this texture (Smith et al. 1997; Langohr & Ampe 2004; §1.2.4.1). As sandy soils lack coherence in these relatively wet conditions (Panayiotopolous & Mullins 1985), they were vulnerable to soil compaction. The negative correlation between BD and soil water content at the sandy sites in Leuven (Chapter 2) could not be explained as soil water contents were probably higher than the critical soil water content for these textures (Smith et al. 1997; Langohr & Ampe 2004) and thus a positive relationship was rather expected.

Precompression stress

High precompression stress (indicated by high initial BD) due to former mechanized harvesting activities or natural profile development, seemed to have a very important influence on the compaction degrees in forest stands in Leuven and Kapellen (Chapter 2). A significant negative influence of the initial compaction status or precompression stress on the absolute BD increase was also found in Chapter 4, confirming the findings of Powers et al. (2005). Loose soils contain an abundance of macropores that are easy to compact. However, compacted soils contain a high amount of smaller pores that exert a higher resistance to soil compaction (Shetron et al. 1988; Hillel 1998; Berli et al. 2003), and therefore increase soil strength and precompression stress. A machine pass will only result in soil structural changes in case the applied stress exceeds the precompression stress (Horn et al. 2007). From a certain precompression stress additional compaction is therefore prevented (Chapter 4), in accordance with the results of Powers et al. (2005) who saw that soils with an initial BD of 1400 kg m^{-3} or more did not compact anymore. If the soils of the examined forest stands on loam to silt loam and sand in Chapter 2 had been less compacted initially, the soil impact due to the treatments would probably have been much higher and significant, as they are regarded as sensitive to soil compaction (e.g., Fisher & Binkley 2000).

We conclude that the assumption of higher sensitivity of medium- to fine-textured soils is too general. The impact of texture on soil compaction degree should be differentiated on the basis of soil water content and precompression stress. Based on the outcomes of our field trials and literature research, we conclude that sandy soils are most vulnerable in dry or wet conditions, while the compaction potential on medium- to fine-textured soils is maximal at intermediate soil water contents. A high precompression stress may restrict the compaction degree of machine traffic on all textures. Though one should keep in mind that even at low compaction degrees some soil structural variables may already be significantly influenced by machine traffic, such as soil aeration (affecting soil O_2 and CO_2 concentrations).

8.1.2 Impact of harvest characteristics

First it should be mentioned that machine traffic not only influences the soil immediately under the tyres, but also partially the soil around it. Our results also showed clear increases of BD, PR (Chapter 3) and soil CO_2 concentrations (Chapter 2) next to the tracks, confirming the findings of Brais & Camiré (1998). The compaction degree between wheel tracks is normally lower than within wheel tracks, as this area is only influenced indirectly. This can be explained by the simultaneous appearance of compaction and loosening of the soil. Compaction between and outside the wheel tracks can be attributed to the lateral movement of soil from beneath the wheel tracks (Wronski 1984). Rotations of the tyres result in shear forces that tend to loosen the soil (Abeels 1989; Vossbrink & Horn 2004).

Machine mass

Results of Chapters 2 and 4 clearly emphasized a positively influence of machine mass on the compaction degree. This positive correlation can be explained using the mean soil contact pressure. When the machine mass increases strongly and not in proportion to the increase of the contact area with the soil (as is the case with the machines in Chapter 2), the soil contact pressure and thus the compaction degree grows, as was stated by McDonald et al. (1996). Several machine characteristics can be changed to increase the contact area and thus to lower the soil contact pressure: number of tyres (Alakukku et al. 2003), tyre dimensions (Benthaus & Matthies 1993), tyre pressure (Abu-Hamdeh et al. 2000) and use of tracks (Murosky & Hassan 1991). However, one should keep in mind that the real exerted pressure can be much higher than the static pressure due to vibration or weight of the processed tree (Kairiukstis & Sakunas 1989; Chancellor 1994; Athanassiadis 1997; Wehner 2003).

Traffic intensity

A positive influence of traffic intensity on the compaction degree was stated in Chapters 2 (CO_2 concentration) and 3 (BD and PR). The impact was insignificant in Chapter 4, probably due to the low number of traffic intensity levels and the high variation that blurred the relationship between compaction degrees and traffic intensity. Results in Chapter 6 also showed that PR was highest close to the forest road where compaction degrees were highest due to higher traffic intensities and the presence of landings. The first machine pass on a loose soil normally has a strong influence on the soil structure. This soil contains a lot of large pores that are easy to compact, leading to a relatively low precompression stress. When the stress, applied by the machine, exceeds this precompression stress, macropores are transformed to meso- and micropores that exert a higher resistance to the applied forces and increase the precompression stress, partially protecting the soil from further compaction (Incerti et al. 1987; Williamson & Neilsen 2000). Subsequent machine passes on this soil will result in diminishing extra compaction degrees until the applied stress becomes lower than the precompression stress. No further compaction will be stated, unless the applied stress is increased (such as heavier machine, higher load) (Horn et al. 2007). This could lead to a logarithmic relationship, indicating a stabilization of the response ratio at higher traffic intensities. This was stated by Brais & Camiré (1998) and Seixas et al. (2003). BD results in Chapter 3 showed that the strongest impact resulted from the first pass, with declining influences of the subsequent passes. However, the logarithmic trend of the relationship could not be deduced from the results in Chapters 2 and 4, probably due to a low number of traffic intensity levels, restricted compaction degrees and strong variation in the dataset. PR results in Chapter 3 also showed a more gradual increase with increasing intensity of machine traffic.

Brash mat

When sufficient slash residues are available on the skid trails, the machine weight is spread over a greater area than the actual footprint of the machine, and hence the mean soil contact pressure declines. In Chapter 3, a clear relationship between the use of a brash mat and the compaction degree was found, confirming the findings of Schäfer & Sohns (1993) and McDonald & Seixas (1997).

Concerning the impact of harvest characteristics, we conclude that the compaction degree increases with increasing traffic intensity (for CO_2 in Chapter 2; Chapter 3) and soil contact pressure (Chapter 2) or mass (Chapter 4) of the machine, while a brash mat reduces the impact (Chapter 3). The first machine pass(es) often exerts the strongest influence, so that unrestricted machine traffic on relatively loose soils may induce overall high compaction degrees in a forest stand.

8.2 Effects of soil compaction on tree saplings

The change of important soil structural characteristics such as PR (Chapter 3), BD (Chapter 4) and soil aeration (Chapter 2) due to soil compaction may influence root growth (e.g., Heilman 1981; Bathke et al. 1992). However, the impact of soil compaction is certainly not unambiguously detrimental for tree saplings but depends, amongst others, on tree species (Miller et al. 1996; Kabzems 2000), compaction degree (Ehlers et al. 1983) and other environmental characteristics. Drawing general conclusions is thus hard, due to strong variation in the available data (Chapter 5). However, our results showed that texture seemed to influence the sensitivity of tree saplings to soil compaction. The rather negative impact of soil compaction on growth and survival of light tolerant tree saplings on silt (and clay) soils contrasted with sandy and loamy soils where growth and survival were unaffected or rather improved by soil compaction (Table 5.2). The soil structural changes accompanying soil compaction, such as higher PR, decreased aeration and lower saturated hydraulic conductivity may negatively influence tree saplings, as was found for the silt (and clay) soils.

However, according to Dexter (2004) and Lacey & Ryan (2000), soil compaction not always implies negative outcomes for soil quality. Undisturbed sandy soils contain a lot of macropores that are too wide to hold water against gravitational forces. This implies a low water retention capacity and thus a low amount of plant available water. Compaction decreases the mean pore size and leads to better water retention. As the low amount of plant available water is one of the limiting factors for growth of herbs and trees on sandy soils, this higher water availability may have compensated the negative effects of soil compaction.

We conclude that soil compaction influenced the growth and survival of tree seedlings, although results were not unequivocal, leading to predominantly insignificant impacts. Results indicated that it is crucial to take the influence of soil texture into account in the evaluation of biotic effects due to soil compaction.

8.3 Recovery of compacted forest soils

8.3.1 Compaction status of Flemish forest soils seven to nine years after the last harvesting activity

In several forest stands, traces of old skid trails could still be detected on the basis of the PR pattern. Moreover, certain sites, such as Zoniënwoud RII-2 and RIII, showed large areas where PR was overall increased above 2 or even 3 MPa, regarded as critical levels for root growth (Whalley et al. 1995). This widespread soil compaction can be partially due to the last harvest but is predominantly a remainder of the soil compaction induced at former harvesting activities. Before the last harvesting activity took place, the soils in Zoniënwoud RII-2 and RIII-3 were already strongly compacted. Namely, the impacts of intense iron and charcoal extraction in the past, together with long-lasting and non-restricted high recreation pressure (horses, pedestrian) accumulated and resulted in overall soil degradation. Moreover, both forest stands have long been forested with beech with high mean diameter classes implying the use of heavy machines with a high soil contact pressure (McDonald et al. 1996). Compacted soils are characterized by higher precompression stresses which protect the soil from further compaction. Only when the applied stresses at the last harvesting activity exceeded the precompression stress, a small additional compaction was induced (Horn et al. 2007). This explains why in soils with overall high compaction degrees such as Zoniënwoud RII-2 and RIII (and to a smaller extent Hoge Vijvers, Brakelbos 10 and 12), new machine passes resulted in only minor to negligible effects and separate skid trails could therefore hardly be distinguished.

No differences could be stated between the texture groups. Traces of former harvesting activities were still apparent for all forest stands on all textures. Moreover, a similar, high variation in compaction status was stated within each texture group, due to different cumulated impacts of machine traffic in the past between the forest stands within each texture group. It should be remarked that in case PR no longer showed traces from former machine traffic, it does not necessarily mean that soil had completely recovered from soil impact. Page-Dumroese et al. (2006) emphasize that the examined soil variables (BD, soil strength, and macroporosity) recovered at a different rate.

Traces of former machine traffic were still apparent in all examined forest stands in the shape of locally increased or overall high penetration resistance. We conclude that complete recovery of compacted forest soils was certainly not achieved within seven to nine years after the last machine impact. As this is a common period between two harvesting activities, effects will accumulate and expand at subsequent harvests in case machine traffic is not restricted to permanent skid trails.

8.3.2 Options for ecological restoration of compacted forest soils

Heavily compacted forest soils can be mechanically loosened but these methods may induce severe damage to the soil ecosystem and should thus only be applied in exceptional cases, where the forest soil is heavily damaged, natural recovery processes work insufficient and fast recovery by mechanical loosening is essential to preserve diversity and functioning of the forest ecosystem. On all other forest soils, recovery depends on natural processes, such as freezing of soil water, swelling of clay particles or biological activity. Only the last process may be altered by forest management and forms the basis of ecological restoration of compacted forest soils. Within this framework, the activity of ecosystem engineers, such as the anecic earthworm *L. terrestris* is very important. However, as many forest soils are acid and most anecic earthworm are acido-intolerant (Edwards 2004; Sims & Gerard 1999), these species are mostly scarce or absent, as was the case in the examined forest stands of Chapter 7 where anecic earthworms had to be inoculated to examine their effect on forest soil compaction.

The composition of the tree layer can be changed to obtain better litter quality and thus a stimulation of biological activity. Decay rates of litter of *Populus x canadensis* were higher compared to the native litter in the examined forest stands of Chapter 7, amongst others due to the higher calcium content (e.g., Hobbie et al. 2006) and low lignin to N ratios (Prescott 2010) that stimulated the activity of micro-organisms and macrofauna (Neirynck et al. 2000; Aubert et al. 2005). Although the replacement of the native litter by litter of *Populus x canadensis* did not (yet) lead to lower soil acidity, results showed that the numbers of retraced inoculated *L. terrestris* were positively influenced, leading to a positive feedback on litter decomposition. Namely, their high calcium requirements (Piearce 1972) are satisfied by the fragmentation and ingestion of the fresh calcium-rich *Populus x canadensis* litter, in this way accelerating decomposition (Bouché 1977; Edwards & Bohlen 1996). A decrease of soil acidity by liming also increased the survival changes and activity of L. *terrestris* (and probably also other soil organisms) and thus entailed an extra boost for decomposition, as was also stated by Wolters et al. (1995) and Schack-Kirchner & Hildebrand (1998). Moreover, the presence of the inoculated anecic worms also resulted in higher pH-values, inducing a positive feedback on their activity.

Liming itself reduced PR due to reduced dispersion and slaking, as was also emphasized by Kirkham et al. (2007) and Chan et al. (2007) for BD. Earthworm inoculation had a small beneficial effect on BD in the upper soil layer beside tracks, as was also stated by Fonte et al. (2010). Litter manipulation and liming increased the survival chances (and probably also the activity) of inoculated anecic worms. However, none of the applied treatments could induce a clear decrease of the compaction degree within tracks during the study period (1.5 years). No significant differences were stated in the numbers of *L. terrestris* within and beside tracks. The number of retraced inoculated L. *terrestris* was overall low, both within and beside tracks, as soil conditions (acidity, nutrient status), even after ameliorating treatments, were probably not favourable to *L. terrestris,* restricting the potential beneficial effect on the compaction degree. Within the wheel tracks the activity of the scarce *L. terrestris* was probably further reduced due to the high energy requirements while burrowing in compacted soil (Rushton 1986; Kretzschmar 1991; Söchtig & Larink 1992). We hypothesize that continued liming and litter manipulation for several years would have had a more thorough positive effect on soil conditions and thus survival and activity of L. *terrestris*. We therefore emphasize that ecological restoration of compacted forest soils is only possible when soil conditions (acidity, nutrient availability) are optimized for anecic earthworms. This can be achieved by conversion of forests towards tree species with high quality litter, which induce lower acidity and a better nutrient status of the soil, increasing the survival chances and activity of the anecic earthworms.

It must be stated that the duration of the study was limited due to practical reasons and probably too short to be able to detect clear ecosystem responses. Moreover, the use of only BD and PR for the quantification of restoration success may have underestimated the total soil impact of the treatments. Litter manipulation and liming had a beneficial effect on anecic earthworms, increasing their burrowing activities, and this probably had a positive influence on macroporosity (e.g., Edwards 2004), saturated hydraulic conductivity (Joschko et al. 1992) and aeration (Lee & Foster 1991). The burrows form a preferential pathway for root elongation in compacted soils (Edwards & Lofty 1980; Hirth et al. 1997), as root tips cannot overcome high soil strengths in compacted soils and root growth would thus be hampered. Earthworms realize an intense mixture of mineral soil particles with organic material and microbial organisms, as well on the surface as in their burrows (Devliegher & Verstraete 1997; Binet & Le Bayon 1999). However, these ameliorating effects on soil structure could not be quantified using BD or PR. Moreover, results showed that endogeics were also positively influenced by higher pH values. It is overall known that their burrowing activities ameliorate soil structure, although this could not be stated by the quantification of BD and PR, further leading to an underestimation of the effect of biological activity on soil restoration.

We conclude that ecological restoration of compacted forest soils is possible though time-consuming, as effects after the short study period were small to negligible. Moreover, it stipulates that soil conditions (acidity, nutrients) are favourable to soil organisms, in particular anecic earthworms, which can be achieved by an admixture containing species that produce high quality litter, inducing a lower soil acidity and a better nutrient status. The real impact of ecological restoration is best quantified by means of an integrated set of soil functional characteristics.

8.4 Recommendations for forest management

Results showed that the risk for soil compaction should be taken into account for all texture classes when planning and preparing harvesting activities. Based on the outcomes of our field trials and literature research, we recommend to perform harvesting activities on sandy soils at intermediate soil water contents for this soil texture (Smith et al. 1997), while on medium- to fine-textured soils very dry conditions are optimal for maximal limitation of the soil compaction degree. Machine traffic on very wet medium- to fine-textured soils would also lead to negligible compaction degrees. However, in these conditions, machine forces are transformed into severe plastic deformation (Hillel 1998), resulting in very deep ruts that may also have detrimental effects on the soil ecosystem (Stone & Elioff 2000; Lindo & Visser 2004) and different soil and climatic conditions may increase plant diversity (Alban et al. 1994; Buckley et al. 2003). One should keep in mind that even at these optimal soil water contents, machine traffic will always have a certain impact on the soil. Independent of soil texture and soil water content of the forest stand, preference should thus be given to harvesting methods and machine characteristics that minimize the impact on the soil. The already compacted status of a certain forest soil (high precompression stress) should not at all be an incentive not to restrict machine dimensions nor to allow machines to drive the whole forest stand. Certain soil characteristics, such as soil CO_2 concentration (due to the sealing of soil pores) might still be significantly influenced even though compaction degrees are small to negligible due to high precompression stress (Chapter 2).

The machines used should always be tuned to the intensity and the demands of the harvesting activity and the field circumstances (soil, weather, slope, tree species…). Chapters 2 and 4 showed that lighter machines or machines with a smaller load (and a smaller soil contact pressure) have a smaller effect than heavier machines. It is thus recommended to use machines with a small soil contact pressure. This may be obtained by using light machines, combined with decreasing tyre pressure, increasing the number of tyres and using wider tyre dimensions (Benthaus & Matthies 1993; Alakukku et al. 2003; Ziesak 2003). Heavy machines with a higher soil contact pressure should only be used in exceptional cases, for example for harvesting or logging of big sized trees on soils with a good bearing capacity. A brash mat may also be very effective to reduce the degree of soil compaction (Chapter 3) as the mean soil contact pressure of the machine declines. The construction of brash mats is predominantly restricted to softwood stands, and is realized by harvesters, dropping the residues of processed trees on the skid trail in front of the machine. A higher cover of dwarf shrubs, possessing a dense root layer can have a similar effect.

Several studies indicated a logarithmic relationship between soil compaction degree and number of machine passes, with the highest impacts resulting from the first passes (e.g., Nugent et al. 2003; Seixas et al. 2003), especially on fine-textured soils, and this logarithmic effect was also observed for BD of sandy soils in Chapter 3. We therefore emphasize to concentrate the traffic on designated skid trails. In this way only a restricted portion of the area is damaged, leaving the rest undisturbed. Moreover, results in Chapter 6 showed that traces of former machine traffic were still detectable on all soil textures eight years after the last mechanized harvesting activity. Recovery of the compacted soils thus lasted longer than the normal period of eight years between two harvesting activities. In case at future harvesting operations machine traffic is not restricted, effects will accumulate and an increasingly large area could be impacted. The use of permanent skid trails reduces the extent of soil compaction and enables the soil between trails to recover from the compacted status applied during previous harvesting activities. On these trails, compaction can be further reduced using a brash mat of sufficient thickness.

The use of reduced impact logging techniques, such as permanent skid trails, lowered soil contact pressure of machines or brash mats, is strongly recommended. However, mechanized forest harvesting will always impose a certain impact on the forest soil that cannot be prevented (such as sealing of soil pores). Forest soil compaction can not be mechanically eliminated at large scale using agricultural loosening techniques (e.g., subsoiler). These methods may induce severe direct damage to the soil ecosystem and should thus only be applied in exceptional cases. In general, soil compaction needs to recover under the impact of natural processes, such as the freezing of soil water or swelling of clay particles. The impact of biological activity on recovery is also important, especially when soils lack the ameliorating influence of freezing water and swelling clay particles. A smooth progress of this ecological restoration requires favourable soil conditions and the presence of anecic earthworms. Admixtures with tree species that provide good quality litter, perhaps combined with liming may imply a stimulation of biological activity and a decrease of the compaction degree (Chapter 7). The large-scaled introduction of earthworms is not feasible. Although it poses a sound alternative to mechanical loosening in case soil conditions are favourable, it should be remarked that restoration of compacted soils based on biological activity is time-consuming. Forest management should therefore in first place aim for a reduction of the soil area that is influenced by machine traffic and a decrease of the compaction degrees.

8.5 Suggestions for further research

Results of Chapter 2 emphasized that quantifying the soil impact based on solely BD or PR may lead to a serious underestimation of the real soil impact, especially in soils with high precompression stress that leads to small to negligible increases of BD or PR. A change of pore continuity (and thus the impact on soil aeration, saturated hydraulic conductivity,…) is not necessarily correlated with the induced compaction degree and may, for example, be serious although no impact was stated using BD or PR. Moreover, earthworms may have beneficial effects on soil structure restoration that cannot be stated using only BD or PR. We therefore argue to quantify impacts on soil structure not only based on BD or PR, but taking into account results on variables that are more sensitive to soil structural change, such as CO_2 concentration. More research is needed to evaluate the usefulness and feasibility of CO_2 measurements in detecting and quantifying soil compaction. Results in Chapter 2 showed that CO_2 concentration is a better, more sensitive indicator of soil damage. The overall use of soil CO_2 concentration would probably have resulted in a much higher amount of significant differences between treatments in Chapters 2, 3, 6 and 7. Moreover, soil CO_2 concentration can be directly related to potential ecological consequences of machine traffic. However, we do not possess a device that is adapted to measure soil CO_2 concentration accurately and efficiently. For the sandy forest soil in Kapellen 2 (Chapter 2), we were able to use the portable gas chromatograph of the Forstliche Versuchs- und Forschungsanstalt (FVA) in Baden-Württemberg. So, although we are fully aware of the importance of CO_2 concentration for the assessment of soil damage, we unfortunately could not further make use of this indicator. Moreover, we remark that the chapter order does not reflect the chronology in which the field trials were executed. Measurements for Chapters 3 and 6 were already performed before the suitability of the soil CO_2 concentration for quantification of the machine impact became clear at measurements in Kapellen 2. Comparing numbers of roots in skid trails and untrafficked soil (e.g., Schaffer et al. 2009) would also provide a better image of the direct ecological impact of machine traffic.

Several studies examined compaction degrees in function of traffic intensity, and several indicated a logarithmic relation (e.g., Brais & Camiré 1998). However, it would be interesting to sort out if a similar logarithmic relation also exists between machine mass (or better soil contact pressure) and compaction degree, with a stabilization of the impact at higher masses or soil contact pressure.

Literature review concerning the impact of soil compaction on tree growth and survival showed that predominantly shade intolerant species were examined. This is not surprising as most studies were performed on clear cut areas, with high light availability, where, in general, light demanding species occur more frequently. However, this implies that no conclusions could be drawn concerning the tolerance to soil compaction of shade tolerant species. It is not certain that the sensitivity to soil compaction is similar for both groups of tree species. For example, compaction is often accompanied by a reduction of the plant available water amount (and thus likely increases drought stress; Ballard 2000) while Niinemets & Valladares (2006) showed that shade tolerant tree species had a lower tolerance to drought and water logging. Small & McCarthy (2002) showed severe growth and biomass reductions for *Osmorhiza claytonii*, a shade-tolerant perennial, after soil compaction. Further research is needed to draw general conclusions concerning the effect of soil compaction on performance of shade tolerant tree species. Moreover, it is possible that the long-term impact differs from the impact on tree saplings in the first years after soil was compacted, as was examined in Chapter 5. This should be examined through long-term monitoring.

Recovery of compacted forest soils formed the object of several studies. However, by our knowledge, none of these studies was performed in an integrated way, comparing different textures under different forest types, starting from a well-documented compaction degree. Texture determines the recovery resulting from the freezing process of soil water and the swelling process of clay particles. Site and stand characteristics also have a strong influence on biological activity, such as the burrowing of anecic earthworms (Chapter 7), that may contribute to the restoration of compaction forest soils and induce significant differences in recovery rate between forest sites. The actual relative contributions of these processes to the recovery of compacted forest soils have not been quantified so far. Moreover, it is assumed that higher precompression stresses induce a longer recovery process, but it is not clear whether this is only due to a higher absolute difference in, for example, BD between the tracks and the non-disturbed area, needing more time to recover, or whether the higher initial compaction degrees really slowed down the recovery processes, for example by a negative influence on biological activity. Short-term monitoring of the effect of litter quality, soil acidity and burrowing of anecic earthworms on the recovery of compacted forest soils could not indicate clear beneficial effects on the compaction degree, probably due to the short study period. However, based on the obtained results we speculated that recovery of compacted forest soils by biological activity is possible, provided that soil conditions are improved. The potential of ecological restoration of compacted forest soils should be examined by means of long-term monitoring, for example after eight years as this is a common period between two harvesting activities.

Finally, it must be remarked that a lot of the studies examining the abiotic or biotic effects of soil compaction lacked necessary basic information such as number of replications and information about the precision of the measurements. This information is necessary to perform a good and balanced meta-analysis. The higher the number of studies with complete information that can be used, the more reliable are the results, the clearer are the relationships and the more universally applicable are the conclusions. It is thus crucial for future publications that attention should be given to the detailed reporting of basic statistics so that the results can be used in meta-analyses. Moreover, information on soil precompression stress, water content, acidity and the real soil contact pressure of the machine is also necessary in order to make more reliable conclusions. Results of Chapter 2 clearly indicated the importance of soil water content and precompression stress to the obtained soil compaction degree. Machines with the same total mass may have a totally different impact due to other tyre dimensions, number of tyres, tyre pressure, or other characteristics that change the contact area between soil and machine and thus the soil contact pressure. However, information about these characteristics was absent or not available in great detail in most studies and could thus not be controlled for in the analysis, resulting in extra sources of unexplained variation.

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Curriculum vitae

Education

2000-2005	MSc in Bioscience engineering, Land & Forest Management Ghent University, Faculty of Bioscience Engineering
1994-2000	Secondary School (Mathematics-Sciences), Sint-Jozefscollege, Izegem

Professional experience

January 2007- present	PhD research at Ghent University, Faculty of Bioscience Engineering, Department of Forest and Water Management, Laboratory of Forestry
July 2006-December 2006	Scientific worker at Ghent University, Faculty of Bioscience Engineering, Department of Forest and Water Management on the project 'Validatie en optimalisatie bosvriendelijke houtexploitatie in Vlaanderen'
April 2006-June 2006	Scientific worker at Ghent University, Faculty of Bioscience Engineering, Department of Forest and Water Management on the project 'Opstellen van een referentie- en afwegingskader voor natuurontwikkeling en –herstel op vermeste en verzuurde terreinen'
January 2006-March 2006	Worker at Ghent University, Faculty of Bioscience Engineering, Department of Forest and Water Management

Scientific publications

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Ampoorter E, Verheyen K, Hermy M (2009) Impact van gemechaniseerde houtoogst op Vlaamse bosbodems. Abstract of oral presentation in: Abstracts symposium Starters in het Bosonderzoek 2009, Brussels, Belgium.

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Conference ‚Sustainable Forest Operations: the future is now!’, 2007, Mont-Tremblant, Canada, CD-ROM.

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Scientific reports

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Verheyen K, De Schrijver A, Staelens J, Baeten L, De Frenne P, Adriaenssens S, Verstraeten G, **Ampoorter E**, Van Nevel L, Demey A, Wuyts K, Gruwez G (2010) Pilootstudie naar kwantificering van de relaties tussen de achteruitgang van biodiversiteit en chronische overschrijding van kritische lasten. Studie in opdracht van het Instituut voor Natuur- en Bosonderzoek (Natuurrapportering), Ghent University, Ghent, Belgium.

MSc thesis

Ampoorter E (2005) Compactie van zandbodems na gemechaniseerde houtoogst met vaste uitsleeppistes. MSc thesis, Ghent University, Ghent, Belgium.

Scientific activities

Participation in congresses, symposia or workshops

Participation with oral presentation

15-18 June 2009. Soil damage after skidding: results of a meta-analysis. 32nd Annual Meeting of the Council on Forest Engineering: Environmentally sound forest operations, Kings Beach, California.

19 March 2009. Impact van gemechaniseerde houtoogst op Vlaamse bosbodems. Starters in het Bosonderzoek, Brussels, Belgium.

6-7 March 2008. Soil damage after skidding: results of a Flemish field experiment. Kolloquium Walderschlieβung & Bodenschutz: Bodenverformung-Erosion-Hochwasserschutz, Freiburg, Germany.

Participation with poster presentation

30 May 2008. Effect of soil characteristics, machine weight and traffic intensity on soil compaction by forest harvesting. Aardse Zaken, Leuven, Belgium.

17 October 2007. Effect of soil characteristics, machine weight and traffic intensity on soil compaction by forest harvesting. 13th PhD symposium on Applied Biological Sciences, Leuven, Belgium.

1-4 October 2007. Effects of soil characteristics, machine weight and traffic intensity on forest soil compaction. IUFRO 3rd Forest E Engineering Conference ‚Sustainable Forest Operations: the future is now!’. Mont-Tremblant, Canada.

22 March 2007. Validatie en optimalisatie bosvriendelijke houtexploitatie in Vlaanderen. Starters in het Bosonderzoek. Brussels, Belgium.

22 March 2005. Compactie van zandbodems na gemechaniseerde houtoogst met vaste uitsleeppistes. Starters in het Bosonderzoek. Brussels, Belgium.

Participation without presentation

6 May 2010. Bodemverdichting: de spanning tussen machine en bodemstructuur. Geel, Belgium.

27 November 2008. Interactie tussen bosbouw en houtverwerking. Ghent, Belgium.

30 September 2008. Bos en Klimaat. Brussels, Belgium.

Review tasks for international journals

2009: Canadian Journal of Forest Research (1)

2008: Canadian Journal of Forest Research (1)

2007: Forest Ecology and Management (1)