Assessing the effects of initial soil characteristics, machine mass and traffic intensity on forest soil compaction

E. Ampoorter[a1], L. Van Nevel[a], B. De Vos[b], M. Hermy[c], K. Verheyen[a]

[a] *Laboratory of Forestry, Department Forest and Water Management, Ghent University, Geraardsbergse Steenweg 267, B-9090 Gontrode, Belgium*

[b] *Research Institute for Nature and Forest, Gaverstraat 4, 9500 Geraardsbergen, Belgium*

[c] *Division Forest, Nature and Landscape Research, Department of Earth and Environmental Sciences, K.U.Leuven, Celestijnenlaan 200E – bus 2411, 3001 Heverlee, Belgium*

Abstract

An extensive field trial was set up in eight forest stands to examine the influence of soil texture (two stands on sand, four on loam to silt loam, two on clay), machine mass (light, heavy) and traffic intensity (1 and 5 skidding cycles) (i.e. pass back and forth on the skid trail) on soil compaction after mechanized harvesting. Dry bulk density (BD), penetration resistance (PR), micro-topography and soil carbon dioxide (CO_2) concentration were applied as response variables for soil compaction. Significant effects on BD were nearly absent (< 7% increase) and occurred occasionally for PR (60-70% increase, up to 150% on clay soils). Especially for loam to silt loam and clay soils, this was in contrast with the expectation. The negligible compaction degrees for loam to silt loam are attributed to high initial compaction levels that prevented further compaction, as was found by General Linear Modelling (GLM) for both BD as PR. For clay soils the small compaction degrees can be explained by the high water contents that result in plastic deformation instead of strong compaction degrees, as was confirmed by the micro-topographical measurements. GLM also revealed a significant impact of machine mass (BD) and soil water content (BD, PR) 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 depends on the position in relation to the wheel tracks and the machine that was used (PR).

In contrast with BD and PR, soil CO_2 concentration, measured in a forest stand on sand, showed significant increases within and between wheel tracks, even after one skidding cycle. Although soil compaction degrees were small to negligible, machine passes apparently had a strong negative impact on pore continuity. CO_2 concentration seems to be a more sensitive and thus better indicator for soil compaction.

Keywords: bulk density, penetration resistance, micro-topography, soil carbon dioxide

[1] Corresponding author: evy.ampoorter@ugent.be; Tel.: ++32(0)92649038; Fax: ++32(0)92649092

1. 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 typical processes that may appear as a result of inappropriate use of this heavy forest machinery. Rut formation may involve direct or indirect damage to the root system of trees (Stone and Elioff, 2000) and soil animals (Lindo and Visser, 2004), and altered soil and climatic conditions may increase plant diversity (Alban et al., 1994; Buckley et al., 2003). Soil compaction involves the compression of pores, which leads to a decreased porosity and pore continuity (Herbauts et al., 1996; Berli et al., 2003; Teepe et al., 2004). As a result, there is often an increase in dry bulk density (BD) (e.g. Alban et al., 1994; Miller et al., 1996), defined as the dry mass of the soil to its volume. In addition, smaller pore sizes reduce hydraulic conductivity (Benthaus and Matthies, 1993), leading to a slower water infiltration (Dickerson, 1976) and increased runoff. In general, gas exchange is also hampered (Gaërtig et al., 2002), possibly affecting growth and activity of roots and soil organisms (Schumacher and Smucker, 1981; Bathke et al., 1992), and leading to an alteration of chemical processes (Herbauts et al., 1996; Woodward, 1996; Arocena, 2000; Ballard, 2000). As pores become smaller, soil strength increases (Shetron et al., 1988). Aust et al. (1998) and Nugent et al. (2003) found a 30-50% increase of the penetration resistance (PR), a measure for soil strength. As root tips have to overcome soil strength to be able to elongate, root growth may be hampered (Greacen and Sands, 1980; Heilman, 1981), depending on soil type, water regime and tree species (Jones, 1983; Heninger et al., 2002; Dexter, 2004). The species composition of the herb layer may also experience changes (Buckley et al., 2003), due to species dependent sensitivity to soil compaction (Zwaenepoel, 1989; Godefroid et al., 2004). In the case of soil fauna hindrance of movements, physical damage or altered food or oxygen supply may occur (Smeltzer et al., 1982; Radford et al., 2001; Battigelli et al., 2004).

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). This research examines how in situ compaction intensity is influenced by (1) soil texture, (2) machine mass and (3) traffic intensity:

1) Soil texture: in general, it is assumed that soils with a clay or silt texture are more sensitive to soil compaction than sandy soils (Hillel, 1998; Fisher and Binkley, 2000). Gomez et al. (2002) stated that the highest BD and the lowest porosities after machine traffic were located on clay soils. Smith (2003) indicated that the clay content also has an important influence on the increase of PR after machine traffic. Brais and Camiré (1998) and Ampoorter et al. (2007) however, found that sandy soils may also be prone to compaction due to mechanized harvesting.
2) Machine mass: in this respect, the mean soil contact pressure is of importance. This value is defined as the ratio of the machine mass to the contact area of the machine with the soil (Febo et al., 2000) and 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): the first pass of a machine on a previously undisturbed forest soil may already induce a strong compression of the soil pores (Schäfer and Sohns, 1993; Williamson and Neilsen, 2000). Amongst others, Brais and Camiré (1998) and Seixas et al. (2003) found that the relationship between traffic intensity and BD increase is logarithmic. 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 and 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), 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, carbon dioxide concentration) are influenced by the treatments;
b) To determine which factors (soil texture, machine mass, traffic intensity) contribute to this extent.

2. Materials and methods

2.1 Experimental design

Eight forest stands, distributed over the Flemish region of Belgium, were selected for this field trial. Four are located in the Meerdael forest in Leuven on Luvisols (IUSS Working Group WRB, 2006) with textures ranging from *loam to silt loam*, two are situated on Gleysols in Walem with (sandy) *clay* loam textures, and the two Podzols in Kapellen have *sandy* textures (Table 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 (weather station Uccle) is 3.1°C in the coldest month (January) and 17.7°C for the warmest month (August) while mean annual precipitation is about 900mm. 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.

In each forest stand eight straight trails of approximately 40m long and 5m wide were marked. 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. Namely, the experiment was performed on half of the trails in summer conditions in September (*September*) on normally dry soils and on the other half in winter conditions in February (*February*) when soils are normally wet but not frozen (Table 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 1). Moreover, 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 considered semi-replicates. Treatments were applied, using two machines: a New Holland TCE 50 tractor, weighted with a winch (0.420 tons) to 1.88 tons to simulate typical Flemish small-scale fire wood harvest (*light*) (tyres front: 28cm wide, pressure 1.7 bar; tyres back: 36cm wide, tyre pressure 1.9 bar), and a John Deere grapple-skidder JD 640, loaded to 14.3 tons by using a concrete block (2.5 tons), hanging in the grapple, representative for Flemish machinery that is used to drag trees to forest roads (*heavy*) (tyres front and back: 77.47cm 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, 5 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.

2.2 Data collection

Several soil variables were measured to quantify the impact of each machine on the forest soil. Bulk density (BD) was sampled using Kopecky soil cores ($100cm^3$) from depth intervals 0-10, 10-20 and 20-30cm. Namely, several study results showed that the strongest soil impacts appear in these upper soil layers (Greacen & Sands, 1980; Ampoorter et al., 2007) and this was also confirmed by the PR results in this research (see further). Before treatments were applied, samples were taken on locations where future wheel tracks would approximately be situated (n = number of replicates = 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. As samples had to be oven dried (105°C) for 48h prior to weighing, no conditions were attached to the soil water content while taking the samples. Penetration resistance (PR) was determined using a penetrologger (Eijkelkamp Agrisearch Equipment, the Netherlands), that measures to a maximum depth of 80cm in depth intervals of 1cm. Cones have an apical angle of sixty degrees, a basal area surface of $1cm^2$ and a nominal diameter of 11.28mm. 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).

Table 1 Characteristics of forest stands in field trial. Laser diffraction was applied to determine amounts of sand, silt, clay in the upper 50cm (sand > 50µm, 50 > silt > 2µm, 2µm > clay; soils divided in soil types according to IUSS Working Group WRB (2006) and classified in texture groups according to the USDA soil classification system (Soil Survey Division Staff, 1993); SWC = gravimetric soil water content, averaged over all skid trails)

Forest stand	Leuven 1	Leuven 2	Leuven 3	Leuven 4	Kapellen 1	Kapellen 2	Walem 1	Walem 2
Dominant tree species	*Fagus sylvatica*	*Pinus sylvestris, Pinus nigra*	*Pinus sylvestris, Pinus nigra*	*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 (WRB)	Luvisol	Luvisol	Luvisol	Luvisol	Podzol	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 (USDA)	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 (10-20cm, %)	22.2	22.4	25.8	31.4	13.4	20.7	44.1	35.0

Table 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	/

To ensure comparability, PR was measured only in very wet circumstances after a long period of rain and current soil water content was determined as a routine check each time measurements were made. Therefore, soil was sampled at about ten locations spread over the measurement area with a soil drill on depths 0-10, 10-20, 20-30,…, 60-70cm. The samples were weighed, then dried (100°C) for 48h 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 neighborhood 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 (Table 3 and 4) were calculated by averaging the ratios of all measurement points for that specific treatment. In Figure 1 and 2 and Tables 3 and 4, treatment *mean reference* is an average of all values before applying treatments on all treatments for that specific stand.

Sand and clay are contrasting texture groups concerning vulnerability to soil compaction (Hillel, 1998; Fisher and Binkley, 2000). Therefore, analysis of micro-topography was examined in Kapellen 1 (sand) and Walem 1 (clay). To quantify rut depth, a horizontal slat (4m 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 10cm 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, carbon dioxide (CO_2) concentration was measured 10cm beneath the soil surface, using a portable gas chromatograph (Anderbrügge and Kaesler, 1992). 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. 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 sandy soil. Measurements were conducted after applying treatments on the skid trails where the heavy machine made 1 and 5 skidding cycles during the experiment in February. Across both trails, two blocks of 5 parallel transects (30cm interspace, width 5m) were placed (n = 5 per block). As with micro-topography, transects were centered over the skid trail, so that both wheel tracks and soil that was not driven were included in the measurement area. Along each transect, measurements of CO_2 concentrations were carried out at 25cm intervals.

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,…, 60-70cm 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 at these times (Table 1).

Table 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 penetration resistance after the September experiment (6 months).

2.3 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. 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 at least 8 years before the experiment. It indicates the initial compaction degree 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 20-30cm for BD and depths 5, 15 and 25cm 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 25cm 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 above, due to the contrasting vulnerability to soil compaction, the relationship between depth and BD or PR was examined more closely for Kapellen 1 (sand) and Walem 1 (clay) in Figures 1 and 2. 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. General Linear Modelling (GLM) was 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 reference values 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* (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 resistance results were processed graphically using Surfer 7.0. This was examined for Kapellen 1 (sand) and Walem 1 (clay) in Figure 3. Data were not analyzed 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 5 transects per block. Next, per block average values for the three zones were compared using One-Way ANOVA.

3. Results

a. Dry bulk density (BD)

Mean BD values and ratios between density before and after applying treatments are summarized in Table 3. 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. 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) in Figure 1. Reference BD values for the sandy soil (1481 ± 74kg/m³, 10-20cm) were significantly higher (p < 0.001) than for the clay soil (1008 ± 72kg/m³, 10-20cm) (Table 3). For Kapellen 1 (Fig. 1A), September treatments induced similar compaction degrees 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%, 0-10cm). In Walem 1 (Fig.1B), 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.

Results of ANOVA for depth interval 10-20cm (Table 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 Leuven 1 and Kapellen 1seemed 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 values after the treatments in comparison with the initial compaction degrees.

Table 3 Mean bulk density (kg/m³, upper value) and mean bulk density ratios (mean of ratios of density after applying treatments to density before treatments were applied, lower value) (± 95% confidence interval) of soil interval 10-20cm as influenced by treatments: position Po (between/within wheel tracks), Time Ti (February/September), machine weight Ma (light/heavy), traffic intensity Tr (one/five skidding cycles). For each forest stand, means are compared against each other after ANOVA using Tukey's test, p-values (significant when $p < 0.05$) are mentioned. Mean bulk density values within a column that differ significantly are marked with different letters (n = number of replications). Values for treatment *Mean reference* are obtained by averaging values before treatments were applied (reference values) on all treatments per forest stand. Ratios that differ significantly from 1 (thus indicating a significant effect) are marked in bold with *

Treatments				n	Leuven 1	Leuven 2	Leuven 3	Leuven 4	Kapellen 1	Kapellen 2	Walem 1	Walem 2
Po	**Ma**	**Tr**	**Ti**		**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

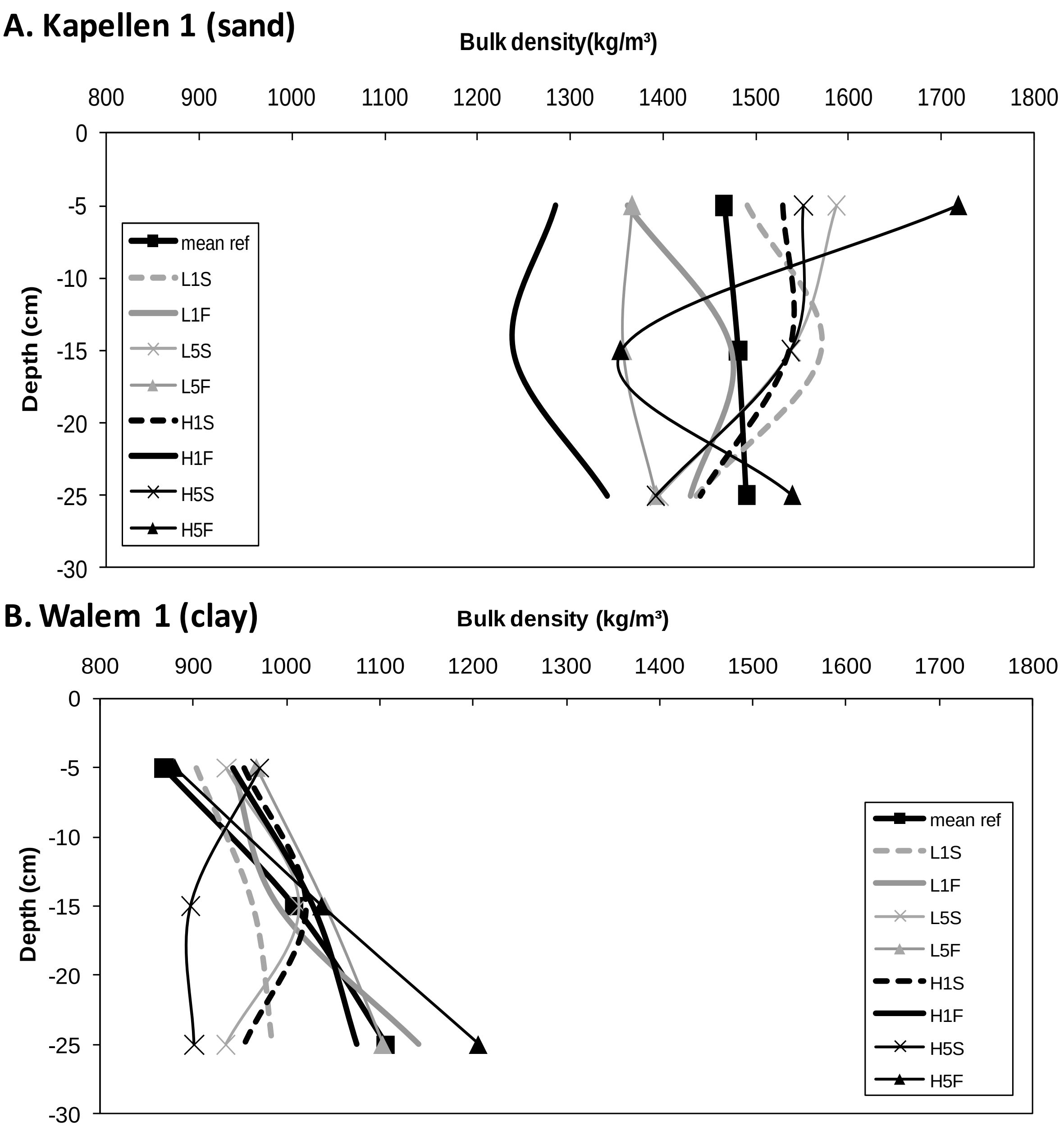

Figure 1 Treatment effect on bulk density within wheel tracks, as a function of depth in Kapellen 1 (A) on sand and Walem 1 (B) on clay (mean ref = reference values for all treatments averaged, L.. = light machine, H.. = heavy machine, .1. = one skidding cycle, .5. = five skidding cycles, ..S = September,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

Results of the GLM analysis are summarized in Table 5. According to these results, machine mass had a significant influence in the second ($p < 0.001$) and third ($p = 0.036$) depth interval. 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 20-30cm). 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 BDs 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 interval 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 interval 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 are 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.

b. Penetration resistance (PR)

Table 4 summarizes mean PR values and ratios between PR after and before applying treatments. 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). Based on the absolute PR values after applying treatments, it was not possible to distinguish among the different soil textures.

As with BD, Figure 2 illustrates the relationship between PR and depth for the treatments in Kapellen 1 and Walem 1. Only the first 50cm 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 were lower for clay than for sand, as was already concluded from the results in Table 4. At Kapellen 1 (Figure 2A), treatments executed in September (somewhat drier soils), especially L5S and H5S, led to an increase of 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) induced a steep increase in PR around 25cm depth. However, the impact of the other February treatments, especially L1F, was negligible. From Figure 2A, 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 compaction degrees after 5 skidding cycles than after one skidding cycle. At Walem 1 (Figure 2B), all treatments increased PR values to a certain extent. The September treatment H5S yielded a circa 90% increase of PR at 15cm depth and reached the highest values for the whole depth range. In the upper 20cm, the impacts of the other September treatments were similar (70-100% increase at 15cm) and exceeded the results of the February treatments to a small extent. Below 20cm, 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 5 skidding cycles of the heavy machine was most severe.

Table 4 **Mean penetration resistance values (MPa, first value) and mean resistance ratios (mean of ratios of resistance after applying treatments to resistance before treatments were applied, second value) (± 95% confidence interval) of soil depth 15cm as influenced by treatments: position Po (between/within wheel tracks), Time (February/September), machine weight Ma (light/heavy), traffic intensity Tr (one/five skidding cycles). For each forest stand, means are compared against each other after ANOVA using Tukey's test, p-values (significant when p < 0.05) are mentioned. Mean penetration resistance values within a column that differ significantly are marked with different letters (n = number of replications). Values for treatment *Mean reference* are obtained by averaging values before treatments were applied (reference values) on all treatments per forest stand. Ratios that differ significantly from 1 (thus indicating a significant effect) are marked in bold with ***

Treatments				n	Leuven 1	Leuven 2	Leuven 3	Leuven 4	Kapellen 1	Kapellen 2	Walem 1	Walem 2
Po	**Ma**	**Tr**	**Ti**		**p < 0.001**	**p = 0.002**	**p < 0.001**	**p < 0.001**	**p < 0.001**	**p < 0.001**	**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 ± 0.65 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 ± 029	**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 ± 026 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 abcde	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

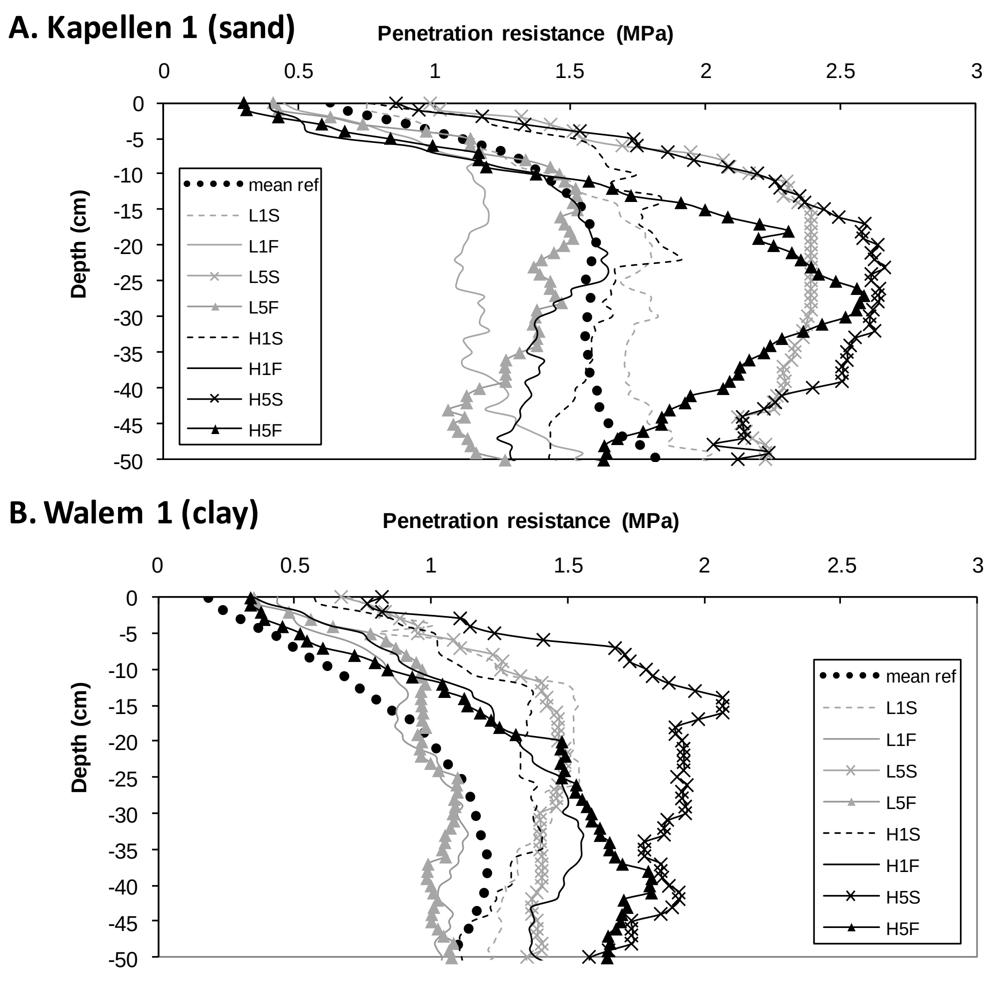

Figure 2 Treatment effect on penetration resistance within wheel tracks, as a function of depth in Kapellen 1 (A) and Walem 1 (B) (mean ref = reference values for all treatments and area between trails averaged, L.. = light machine, H.. = heavy machine, .1. = one skidding cycle, .5. = five skidding cycles, ..S = September, ..F = February). Number of replications (n) equal to 12, except for mean reference where n = 216.

Results of ANOVA for soil depth 15cm (Table 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, both within and between tracks after application of almost all September treatments, PR differed significantly from the mean reference values. 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 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 interval. 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 5cm depth, 0.094 ($p < 0.001$) at 15cm depth and -0.036 ($p = 0.180$) at 25cm 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 5cm, loam ($p = 0.021$) and clay ($p = 0.007$) at 15cm and for loam ($p = 0.001$) and sand ($p = 0.010$) at 25cm. Moreover, each of these significant relationships is negative, meaning that compaction degree decreases at increasing soil water content. At last, the reference values again determined the compaction degree to a large extent in a negative way. Namely, analysis of the correlation between PR ratios and reference values resulted in significant Pearson correlation coefficients of -0.576, -0.598 and –0.579 at 5, 15 and 25cm depth respectively (p-values < 0.001). The impact of traffic intensity seemed to depend on the machine mass for depths 15 and 25cm ($p = 0.005$ 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 25cm ($p < 0.001$) 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 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 (df) and p-value for analysis of variance (GLM). Significant values (p < 0.05) are depicted in bold

		Bulk density			Penetration resistance		
Source	**df**	**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		**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**

c. 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 0-10cm, 0.391 ($p = 0.001$) at soil depth 10-20cm and 0.226 ($p = 0.073$) at depth 20-30cm. As coefficients were significant for the first and second depth interval, we can conclude for these depths that PR reaches higher values as BD increases.

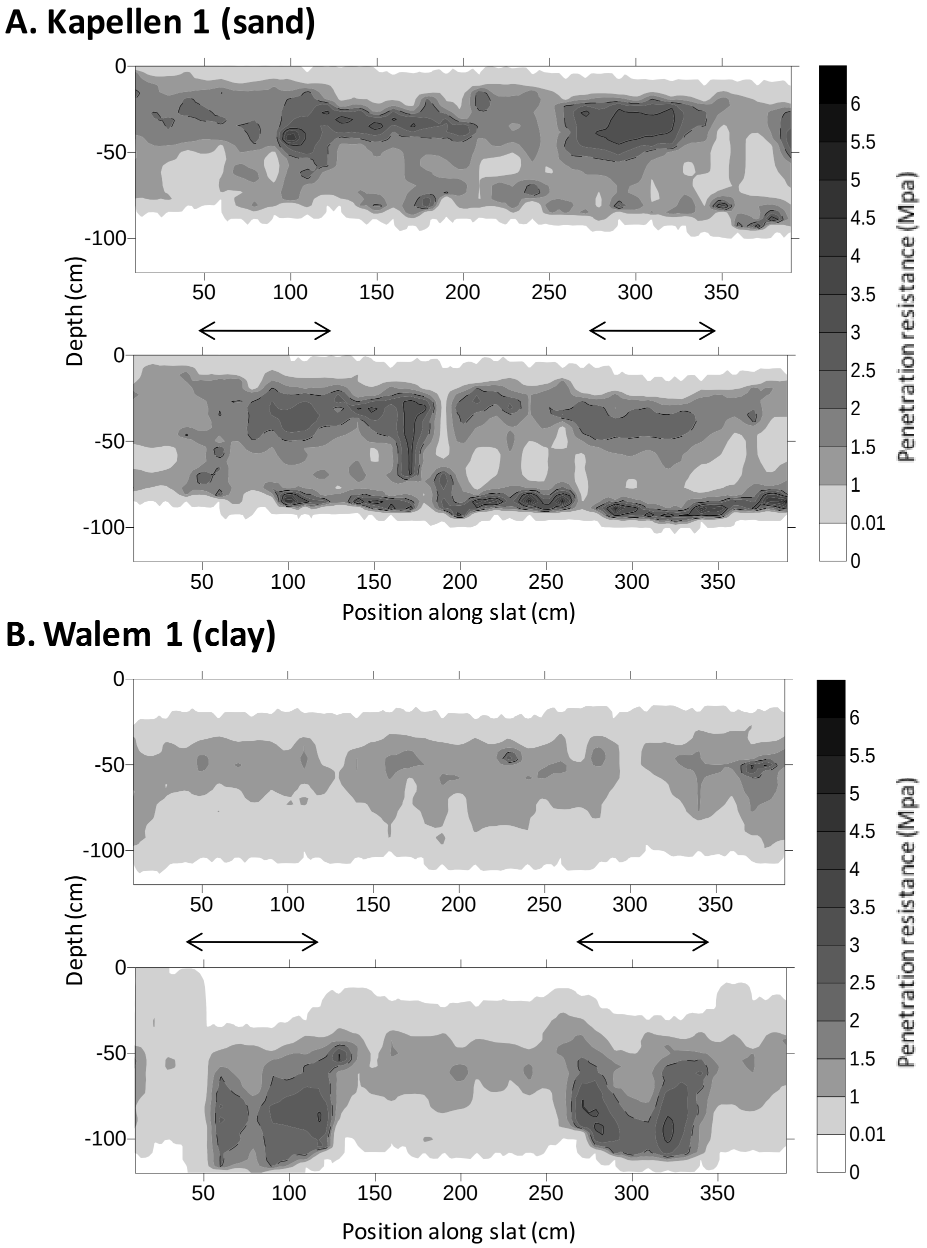

Figure 3 Microrelief (rut depth and penetration resistance) on a sand (A) (Kapellen 1) and clay (B) (Walem 1) texture, before (above) and after (below) five skidding cycles of the heavy machine in the experiment in February (n = 1). The legend indicates values of the penetration resistance, the dotted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

d. Micro-topography

The micro-topography before and after 5 skidding cycles of the heavy machine in February is shown in Figure 3 for Kapellen 1 (Fig 3A) and Walem 1 (Fig. 3B). It shows a vertical section of the soil, perpendicular to the direction of the skid trail. For Kapellen 1, in several parts of the soil PR before applying treatments already exceeded 2MPa, or even 3MPa. 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 very 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 2MPa, but they remained for the major part below 3MPa.

e. Carbon dioxide (CO_2) concentration

Soil CO_2 concentration was measured in one forest stand on sandy texture (Figure 4). Blocks A and B were located on skid trails where the heavy machine made one skidding cycle in February. 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, as values had clearly increased within tracks (30 to 100%). The area between wheel tracks also showed a slight increase of CO_2 concentration. After 5 skidding cycles of the heavy machine in February, the results were more pronounced. Both block 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.

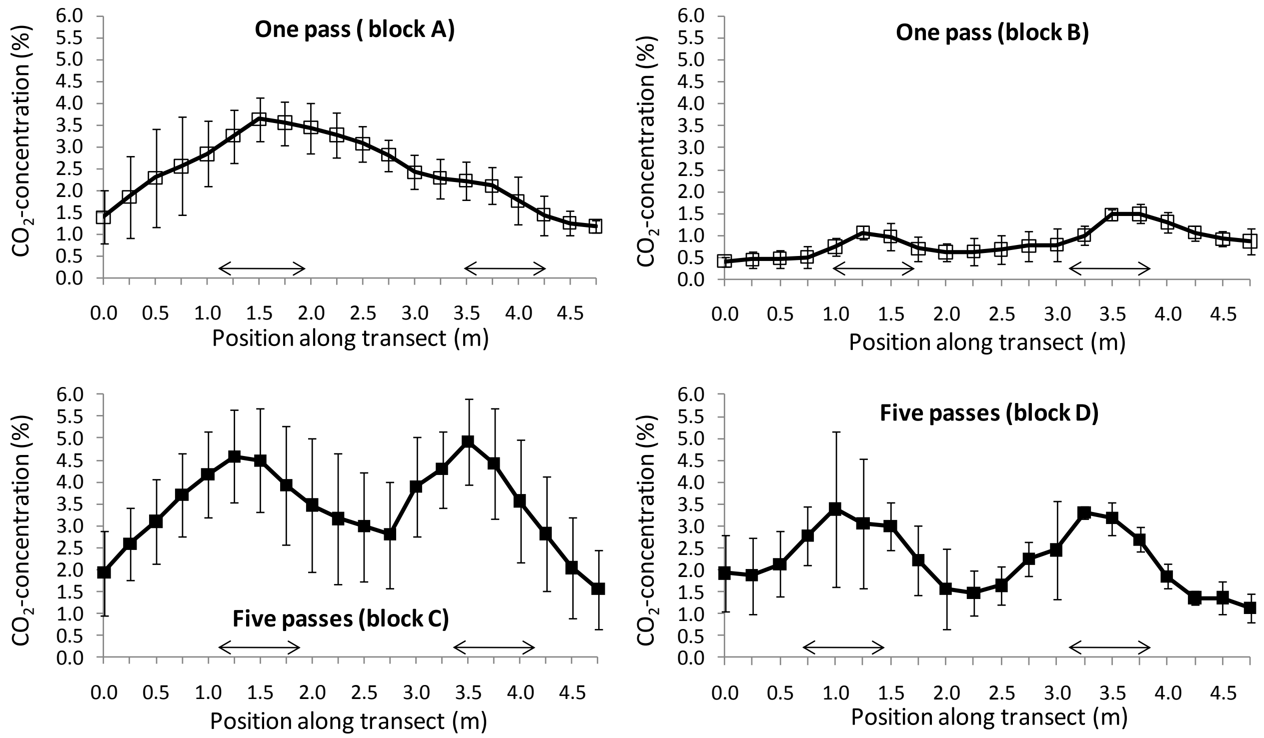

Figure 4 Mean CO_2-concentration in a sandy soil (Kapellen 2) after 1 (above) and 5 (below) skidding cycles of the heavy machine in the experiment in February (blocks A and B as replications for one skidding cycle, blocks C and D as replications for five skidding cycles) (within each block n = 5). The black horizontal arrows indicate the position of the wheel tracks after traffic. Error bars represent the 95% percent confidence interval.

Carbon dioxide 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 that has not been driven, 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 6). The area beside tracks always had the smallest CO_2-concentrations, mostly followed by the area between wheel tracks. The carbon dioxide 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 (< 2m). 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 carbon dioxide 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 next to the wheel tracks.

Table 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). Significant results ($p < 0.05$) are depicted in bold. 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

4. Discussion

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

Clay and silt to loam textures are considered to be more vulnerable to compaction than sand textures (Hillel, 1998; Fisher and Binkley, 2000). The small compaction degrees for **sand** are therefore not surprising, especially at these soil water contents (Hartmann and De Boodt, 1974). Initial BD values for sand are high but rather normal for this texture class. However, texture did not influence the compaction degree significantly and in contrast with the expectations, compaction degrees for loam to silt loam and clay soils were almost as low as for sand. A possible explanation for the rather low ratios of **loam to silt loam** soils follows from the initial BDs in Table 3. Ampoorter et al. (2008) compared the initial BDs of many forest stands in Flanders (110 forest stands measured on 10-20cm depth). They concluded that the initial BDs of the forest stands on loam to silt loam of this field experiment (especially Leuven 1 and 2) are higher than elsewhere in Flanders and thus too high for forest topsoil horizons in a natural state. It suggests an underlying compaction, due to uncontrolled machine traffic during past harvesting activities. Moreover, GLM and Pearson correlations showed a significant negative influence of the reference conditions 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. However, the resulting smaller pores exert a higher resistance to compaction (Shetron et al., 1988; Hillel, 1998; Berli et al., 2003). An extra machine pass on an already compacted soil thus results in a very limited additional impact (Incerti et al. 1987; Williamson and Neilsen, 2000; Page-Dumroese et al., 2006). If the initial soil status of the examined forest stands would have been less compacted, the soil impact due to the treatments would probably have been much higher and significant. The fact that the values after applying treatments were sometimes significantly lower than before applying treatments, especially for BD, does not mean that the soil was loosened up by traffic. A high spatial variation in the topsoil, amongst others of organic matter that has a strong influence on BD (Ruehlmann and Korschens, 2009), may have skewed the results. Taking a much higher number of replicates would be time consuming but could in part be a solution to solve these problems. The rather low compaction degrees on **clay soils** are not due to high initial compaction degrees but can be explained by means of the soil water content. Forces exerted by the machine are converted into a combination of soil compaction and plastic deformation, in the form of rutting (Abeels, 1989). The proportion between the two processes depends on the soil water content. McNabb and Boersma (1993) declared that fine-textured forest soils are less vulnerable to soil compaction in dry conditions, as a result of higher cohesion and aggregation of particles. Aust et al. (1998) mentioned that loading a moist-to-saturated fine-textured soil results in a combination of compaction and soil deformation. Hillel (1998) showed a graph for a medium to fine textured soil such as the soils in Walem, relating soil water content to the obtained BD when applying a certain force. Howard et al. (1981) and Williamson and 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. So in a saturated state, all pores are filled with water that cannot be compressed (Froehlich and McNabb, 1984). However, cohesion between particles is minimal (Al-Shayea, 2001) and the soil has only a very small ability to withstand machine forces. Therefore plastic deformation is the dominant process (Howard et al., 1981; Williamson and Neilsen, 2000). 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). In a very dry, fine to medium textured soil, the cohesion between the particles is maximal, limiting the compaction degree and more or less preventing plastic deformation (McNabb and Boersma, 1993). BD increases to an intermediate extent and small ruts are formed, without bulges at the edges (rut type 3). At intermediate soil water contents (around 16%, the optimum 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 entirely compensate for soil loss in the ruts (Howard et al., 1981; Williamson and Neilsen, 2000) (rut type 2). It should 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. Water contents in Walem were always above the optimum water content (Table 1) leading to plastic deformation (rut type 1) and small compaction degrees as was shown by Tables 2 and 3 and Figure 3.

Looking at all three texture groups together, Pearson correlations showed that compaction degrees seemed to increase with increasing <u>soil water content</u>. Compaction degrees were overall limited and GLM did not show a significant influence of texture. However these significant correlations may be due to the fact that the forest stands in Walem show somewhat higher compaction degrees compared to the other two soil texture groups, combined with much higher soil water contents. Looking at the correlations for each texture group separately, most of the relationships were negative. For loam and clay this can again be explained using the theory of Hillel (1998) for medium to fine textured soils. Soil water contents of Walem were much higher than the optimum soil water content. In Leuven, soil water contents in September were lower than the optimum soil water content and in February clearly higher than the optimum leading to higher compaction degrees in September (drier) than in February (wetter). Hillel's theory (1998) cannot be used for sandy soils as this soil texture behaves totally different in relation to soil water content (Hartmann and De Boodt, 1974). A coarse textured soil has minimal particle cohesion in dry conditions, leading to rut type 1 or in some cases rut type 2 with small compaction degrees. When soil water content increases (towards the critical soil water content of 12%), cohesion and aggregation reach a maximal value. Capillary forces interfere in such a way that the particles are interconnected and are so unable to fall into the closest packing when traffic is applied. As a result, compaction degrees are minimal and rut formation is restricted (rut type 1). At higher soil water contents (over 12%) (Table 1), the aggregation decreases again. The particles are no longer stable in the open packing and fall into a very close arrangement, leading to increasing compaction degrees and limited rut formation (Table 3) (rut type 2). Compaction is still possible at high water contents in contrast with fine textured soils. Namely, this soil texture contains 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 and Binkley, 2000). In Kapellen, soil water contents were generally situated around the critical soil water content, except for the February experiment in Kapellen 2, where soil water content was over 20%. As an insignificant or positive relationship is rather expected, the negative correlation between PR and soil water content for the sandy soils could not be explained.

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 pressure than the light machine and that soil compaction would thus be more severe (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 and Matthies, 1993), tyre pressure (Abu-Hamdeh et al., 2000), use of tracks (Murosky and 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 processed tree (Kairiukstis and Sakunas, 1989; Chancellor, 1994; Athanassiadis, 1997; Wehner, 2003).

The main effect of traffic intensity was generally insignificant but it showed a significant interaction with machine mass that is rather evident. GLM already showed that the impact of the heavy machine was higher than the impact of the light machine at every skidding cycle. The cumulative effect after five skidding cycles with the heavy machine was thus clearly higher than for the light machine where the difference with the effect after one skidding cycle was negligible. For the heavy machine, compaction degree is thus positively related to the traffic intensity. Normally, this relationship is logarithmic with smaller compaction degrees approaching zero at higher traffic intensities. At low traffic intensities pores are compressed and exert higher soil strength, protecting the soil from further compaction (Brais and Camiré, 1998; Seixas et al., 2003). 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 immediately under the tyres influenced, but also partially the soil around it (both between and next to the wheel tracks). Compaction between the tyres can be attributed to the lateral movement of soil from beneath the wheel tracks (Wronski, 1984) and the compaction degree between wheel tracks is normally lower than within wheel tracks, as this area is only influenced indirectly. According to GLM (Table 5) of BD and PR, no significant influence arises from the <u>position in relation to the wheel tracks</u>. This is not surprising as the compaction degree after most of the treatments was already negligible within wheel tracks (Tables 2 and 3). As a consequence, compaction degrees on the two locations were not very different from each other. However, GLM showed a significant interaction between <u>position and traffic intensity</u>. 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 <u>forest stands</u> (Table 5), likely due to differences in organic matter content (Sands et al., 1979), initial compaction status (Powers et al., 2005), soil water content (Hillel, 1998) or bioturbation. Moreover, the experiment was executed in the same stands and in the same way in February (wetter winter conditions) and September (drier summer conditions), resulting in different soil water contents. Due to the close relationship between compaction degree and soil water content, this may have lead to small differences in compaction ratios, explaining the significant impact of <u>time</u>.

Relationship between bulk density and penetration resistance

A positive relationship could be observed between the reference values of BD and PR. Namely, as BD increases, the pore space is reduced and becomes insufficient to accommodate the soil particles that are displaced by the intruding penetrologger cone. 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) also stated this positive relationship, and reported a logarithmic shape. Although BD remains more or less constant at higher values, PR may still increase. The shape of the relationship between BD and PR in this study was not clear because of high variation. Moreover, reference BDs at Leuven and Kapellen were probably already too high to be able to detect the logarithmic shape of the curve.

Impact of mechanized harvesting on soil carbon dioxide concentration

The natural carbon dioxide concentration in the atmosphere is about 0.03-0.04%. The mean concentration in the superficial layer of a loose soil that has not been driven is already more than tenfold higher due to decomposition of organic matter and respiration by fauna and flora (Ameryckx et al., 1995). Moreover, carbon dioxide concentration shows an increasing trend with depth due to slower and more difficult gas exchange (Hashimoto et al., 2004; Jassal et al., 2005). In contrast to BD and PR that showed small to negligible impacts, carbon dioxide 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 and Camiré (1998) and by Seixas et al. (2003) for other soil variables, due to increasing soil strength at higher compaction degrees. CO_2 concentrations within tracks were significantly higher than the soil beside the wheel tracks and reached concentration levels over 4%, whereas 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 at the soil surface. 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. Results of BD and PR showed that compaction degrees were small to negligible. The impact on CO_2 concentration was thus not a consequence of pore compression, but rather due to destruction of pore continuity and thus air conductivity leading to an alteration of CO_2 exchange between the free soil and the atmosphere (Gebhardt et al., 2009). The efflux of CO_2 from the soil was hampered and carbon dioxide, produced by soil organisms and chemical processes, accumulated in the sealed pores. Ponder (2005), studying the carbon dioxide efflux after soil compaction, concluded that the efflux was smaller after compaction in comparison with the undisturbed control. Conlin and van den Driessche (2000) showed that the altered gas exchange after soil compaction resulted in higher mean carbon dioxide concentrations and lower oxygen concentrations in the soil. This may cause problems at higher compaction degrees as root growth of seedlings is reduced when the oxygen concentration drops beneath the 6 to 10% range (Schumacher and Smucker, 1981; Grant, 1993; Fisher and Binkley, 2000).

5. Conclusions and recommendations for forest management

Although loam to silt loam and clay soils were expected to be sensitive to soil compaction, impact of machine traffic on BD and PR was small to negligible for all three soil textures. For sand, this was in accordance with the expectation that sandy soils are less sensitive to soil compaction. However, in the forest stands on silt loam to loam this was probably due to high initial soil compaction degrees that may have been caused by uncontrolled machine traffic during past harvesting activities. GLM indicated a very important influence of the initial compaction degrees. At the high initial PR and BD values present in the examined forest stands, the high soil strength prevented further compaction. Dominance of plastic deformation over compaction at high soil water contents may have restricted the compaction degrees in the forest stands on clay textures. GLM indicated that the soil water content at the moment that treatments were applied was of great importance to the resulting compaction degree and rut formation.

In contrast with the results of BD and PR, measurements of in situ CO_2 concentration showed a clear increase, even after one skidding cycle, due to the destruction of the pore continuity. So, although the compaction degree itself was negligible due to high initial compaction degrees and high soil water content, the soil was still clearly influenced by the machine traffic. Thus, in soils with initially elevated compaction levels, BD and PR are no reliable compaction indicators. CO_2 concentration seems to be a better, more sensitive indicator of soil damage. More research is needed to evaluate the usefulness and efficiency of this variable in detecting and quantifying soil compaction.

A good soil pore system is vital to soil biota, tree roots and ground vegetation. Recovery of a compacted soil is a long-term process that is largely based on freezing and melting of soil water (Alban et al. 1994; Startsev and McNabb, 2000), swelling and shrinking of clay particles (Cornelis et al., 2006) and biological activity of roots and soil animals that break up the soil (Jordan et al., 1999; Ponder et al., 2000). Literature shows that it can take at least 20 to 30 years before recovery is complete, depending on the soil type (Croke et al., 2001; Rab, 2004). Schäffer (2005) even showed that 30 to 40 years were not sufficient to allow complete recovery of gas diffusion and fine root densities under wheel tracks. High compaction degrees should thus be prevented.

Results showed that a smaller impact can be achieved by lowering the soil contact pressure, such as by using lighter machines. As Brais and Camiré (1998) and da Silva et al. (2008) state that the relationship between traffic intensity and compaction degree is logarithmic, with the highest impact in the first passages, this speaks in favour of permanent skid trails. In this way, only a small portion of the forest stand is damaged, while protecting the rest from soil compaction. By restricting machine traffic to designated skid trails in already compacted stands, the soil between the trails is left undisturbed and can recover from the compacted status. Proper soil moisture conditions are also a prerequisite for avoiding severe soil compaction during harvesting. Small-scale mechanical loosening (ploughing, milling) or stimulating bioturbation by liming compacted soils to enhance the recovery process could be considered.

6. Acknowledgements

This research was funded by the Flemish government through IWT (Institute for the Promotion of Innovation by Science and Technology in Flanders) and ANB (Agency for Nature and Forest). The authors would like to thank Jos Goethuys (plc Transgohout) for his cooperation in the execution of the experiment, Jürgen Schäffer and Sonja Amann (Forstliche Versuchs- und Forschungsanstalt, Freiburg) for performing the CO_2 measurements and Mathieu Pieters, Koen Vervaet and Koen Willems (Research Institute for Nature and Forest, Geraardsbergen) for their overall help in the field campaign.

7. References

Abeels, P.F.J., 1989. Forest machine design and soil damage reduction. In: Proceedings of the seminar on the Impact of mechanization of forest operations to the soil. Leuven, België, 195-210.

Abu-Hamdeh, N.H., Abu-Ashour, J.S., Al-Jalil, H.F., Khdair, A.I., Reeder, R.C., 2000. Soil physical properties and infiltration rate as affected by tire dynamic load and inflation pressure. Trans ASAE 43, 785-792.

Alakukku, L., Weisskopf, P., Chamen, W.C.T., Tijink, F.G.J., Van der Linden, J.P., Sires, S., Sommer, C., Soor, G., 2003. Prevention strategies for field traffic-induced subsoil compaction: a review. Part 1. Machine/soil interactions. Soil Till Res 73, 145-160.

Alban, H.D., Host, G.E., Elioff, J.D., Shadis, D.A., 1994. Soil and vegetation response to soil compaction and forest floor removal after aspen harvesting. Research paper NC-315, USDA Forest Service, St.Paul, Minnesota.

Al-Shayea, N.A., 2001. The combined effect of clay and moisture content on the behaviour of remolded unsaturated soils. Eng Geol 62, 319-342.

Ameryckx, J.B., Verheye, W., Vermeire, R., 1995. Bodemkunde. Gent.

Ampoorter, E., Goris, R., Cornelis, W.M., Verheyen, K., 2007. Impact of mechanized logging on compaction status of Sandy forest soils. Forest Ecol Manag 241, 162-174.

Ampoorter, E, Van Nevel, L., De Vos, B., Goris, R., Verheyen, K., 2008. Validatie en optimalisatie bosvriendelijke houtexploitatie in Vlaanderen. Agency for Nature and Forest, Brussels, Belgium.

Anderbrügge, T., Kaesler, H., 1992. Portable gas chromatograph for examination of mixtures of gases. Gas, Wärme International 41, 29-33.

Arocena, J.M., 2000. Cations in solution from forest soils subjected to forest floor removal and compaction treatments. Forest Ecol Manag 133, 71-80.

Athanassiadis, D., 1997. Residual stand damage following cut-to-length harvesting operations with a farm tractor in two conifer stands. Silva Fenn 31, 461-467.

Aust, W.M., Burger, J.A., Carter, E.A., Preston, D.P., Patterson, S.C., 1998. Visually determined soil disturbance classes used as indices of forest harvesting disturbance. South J Appl For 22, 245-250.

Ballard, T.M., 2000. Impacts of forest management on northern forest soils. For Ecol Manag 133, 37-42.

Bathke, G.R., Cassel, D.K., Hargrove, W.L., Porter, P.M., 1992. Modification of soil physical properties and root growth response. Soil Sci 154, 316-329.

Battigelli, J.P., Spence, J.R., Langor, D.W., Berch, S.M., 2004. Short-term impact of forest soil compaction and organic matter removal on soil mesofauna density and oribatid mite diversity. Can J For Res 34, 1136-1149.

Benthaus, M., Matthies, D., 1993. Regeneration befahrener Waldböden. Allgemeine Forstzeitschrift 48, 448-451.

Berli, M., Kulli, B., Attinger, W., Keller, M., Leuenberger, J., Flühler, H., Springman, S.M., Schulin, R., 2003. Compaction of Agricultural and forest soils by tracked heavy construction machinery. Soil Till Res 75, 37-52.

Brais, S., Camiré, C., 1998. Soil compaction induced by careful logging in the claybelt region of northwestern Quebec (Canada). Can J Soil Sci 78, 197-206.

Buckley, D.S., Crow, T.R., Nauertz, E.A., Schulz, K.E., 2003. Influence of skid trails and haul roads on understorey plant richness and composition in managed forest landscapes in Upper Michigan, USA. Forest Ecol Manag 175, 509-520.

Chancellor, W.J. (Ed.), 1994. Advances in Soil Dynamics. Volume 1. American Society of Agricultural Engineers, St. Joseph, Michigan.

Cornelis, W.M., Corluy, J., Medina, H., Hartmann, R., Van Meirvenne, M., Ruiz, M.E., 2006. A simplified parametric model to describe the magnitude and geometry of soil shrinkage. Eur J Soil Sci 57, 258-268.

Conlin, T.S.S., Van den Driessche, R., 2000. Response of soil CO_2 and O_2 concentrations to forest soil compaction at the long-term soil productivity sites in central British Columbia. Can J For Sci 80, 625-632.

Croke, J., Hairsine, P., Fogarty, P., 2001. Soil recovery from track construction and harvesting changes in surface infiltration, erosion and delivery rates with time. Forest Ecol Manag 143, 3-12.

Da Silva, S.R., de Barros, N.F., da Costa, L.M., Leite, F.P., 2008. Soil compaction and Eucalyptus growth in response to forwarder traffic intensity and load. R Bras Ci Solo 32, 921-932.

Dexter, A.R., 2004. Soil physical quality. Part I. Theory, effects of soil texture, density and organic matter, and effects on root growth. Geoderma 120, 201-214.

Dickerson, B.P., 1976. Soil compaction after tree-length skidding in Northern Mississippi. Soil Sci Soc Am J 40, 965-966.

Febo, P., Lucarelli, F., Pessina, D., 2000. Soil-tyre interaction parameters influencing soil compaction: a study of contact area prediction models. In: Horn, R., Van den Akker, J.J.H., Arvidsson, J. (Eds.). Advances in Geoecology 32, 191-201.

Fisher, R.F., Binkley, D., 2000. Ecology and management of forest soils. Wiley, New York.

Froehlich, H.A., McNabb, D.H., 1984. Minimizing soil compaction in Pacific Northwest sites. In: Stone, E.L. (Ed.). Proceedings of the sixth North American Conference on Forest Soils and Treatment Impacts. Department of Forestry, Wildlife and Fisheries, University of Knoxville, pp 159-192.

Gaertig, T., Schack-Kirchner, H., Hildebrand, E.E., von Wilpert, K., 2002. The impact of soil aeration on oak decline in southwestern Germany. Forest Ecol Manag 159, 15-25.

Gebhardt, S., Fleige, H., Horn, R., 2009. Effect of compaction on pore functions of soils in a Saalean moraine landscape in North Germany. J Plant Nutr Soil Sci 172, 688-695.

Godefroid, S., Koedam, N., 2004. Interspecific variation in soil compaction sensitivity among forest floor species. Biol Conserv 119, 207-219.

Gomez, A., Powers, R.F., Singer, M.J., Horwath, W.R., 2002. Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. Soil Sci Soc Am J 66, 1334-1343.

Grant, R.F., 1993. Simulation model of soil compaction and root growth. II. Model performance and validation. Plant Soil 150, 15-24.

Greacen, E.L., Sands, R., 1980. Compaction of forest soils. A review. Aust J Soil Res 18, 163-189.

Hartmann, R., De Boodt, M., 1974. The influence of the moisture content, texture and organic matter on the aggregation of sandy and loamy soils. Geoderma 11, 53-62.

Hashimoto, S., Tanaka, N., Suzuki, M., Inoue, A., Takizawa, H., Kosaka, I., Tanaka, K., Tantasirin, C., Tnagtham, N., 2004. Soil respiration and soil CO_2 concentration in a tropical forest, Thailand. J Forest Res 9, 75-79.

Heilman, P., 1981. Root penetration of Douglas-fir seedlings into compacted soil. Forest Sci 27, 660-666.

Henderson, C., Levett, A., Lisle, D., 1988. The effects of soil water content and bulk density on the compactibility and soil penetration resistance of some Western Australian sandy soils. Aust J Soil Res 26, 391-400.

Heninger, R., Scott, W., Dobkowski, A., Miller, R., Anderson, H., Duke, S., 2002. Soil disturbance and 10-year growth response of coast Douglas-fir on nontilled and tilled skid trails in the Oregon Cascades. Can J For Res 32, 233-246.

Herbauts, J., El Bayad, J., Gruber, W., 1996. Influence of logging traffic on the hydromorphic degradation of acid forest soils developed on loessic loam in middle Belgium. Forest Ecol Manag 87, 193-207.

Hillel, D., 1998. Environmental soil physics. Academic Press, San Diego.

Howard, R.F., Singer, M.J., Frantz, G.A., 1981. Effects of soil properties, water-content, and compactive effort on the compaction of selected California forest and range soils. Soil Sci Soc Am J 45, 231-236.

Incerti, M., Clinninck, P.F., Willatt, S.T., 1987. Changes in soil physical properties of a forest soil following logging. Aust Forest Res 17, 91-98.

IUSS Working Group WRB, 2006. World reference base for soil resources 2006. 2nd edition. World Soil Resources Reports No. 103. FAO, Rome.

Jassal, R., Black, A., Novak, M., Morgenstern, K., Nesic, Z., Gaumont-Guay, D., 2005. Relationship between soil CO_2 concentrations and forest floor CO_2 effluxes. Agr Forest Meteorol 130, 176-192.

Jones, C.A, 1983. Effect of soil texture on critical bulk densities for root growth. Soil Sci Soc Am J 47, 1208-1211.

Jordan, D., Li, F., Ponder, F.J., Berry, E.C., Hubbard, V.C., Kim, K.Y., 1999. The effects of forest practices on earthworm populations and soil microbial biomass in a hardwood forest in Missouri. Appl Soil Ecol 13, 31-38.

Kairiukstis, L., Sakunas, Z., 1989. Impact on soil of machinery used for cutting and reforestation. In: Proceedings of the seminar on the Impact of mechanization of forest operations to the soil. Leuven, België, 133-145.

Lindo, Z., Visser, S., 2004. Forest Floor microarthropod abundance and oribatid mite (Acari: Oribatida) composition following partial and clear-cut harvesting in the mixedwood boreal forest. Can J For Res 34, 998-1006.

McDonald, T., Way, T., Löfgren, B., Seixas, F., 1996. Load and inflation pressure effects on soil compaction of forwarder tires. Can Pulp Paper Ass, 67-70.

McNabb, D.H., Boersma, L., 1993.Evaluation of the relationship between compressibility and shear strength of Andisols. Soil Sci Soc Am J 57, 923-929.

Miller, R.E., Scott, W., Hazard, J.W., 1996. Soil compaction and conifer growth after tractor yarding at three coastal Washington locations. Can J Forest Res 26, 225-236.

Murosky, D.L., Hassan, A.E., 1991. Impact of tracked and rubber-tired skidders traffic on a wetland site in Mississippi. Trans ASAE 34, 322-327.

Nugent, C., Kanali, C., Owende, P.M.O., Nieuwenhuis, M., Ward, S., 2003. Characteristic site disturbance due to harvesting and extraction machinery traffic on sensitive forest sites with peat soils. Forest Ecol Manag 180, 85-98.

Page-Dumroese, D.S., Jurgensen, M.F., Tiarks, A.E., Ponder, F., Sanchez, F.G., Fleming, R.L., Kranabetter, J.M., Powers, R.F., Stone, D.M., Elioff, J.D., Scott, D.A., 2006. Soil physical property changes at the North American long-term soil productivity study sites: 1 and 5 years after compaction. Can J For Res 36, 551-564.

Ponder, F.Jr., Li, F., Jordan, D., Berry, E.C., 2000. Assessing the impact of Diplocardia ornata on physical and chemical properties of compacted forest soil in microcosms. Biol Fert Soils 32, 166-172.

Ponder, F.Jr., 2005. Effect of soil compaction and biomass removal on soil CO_2 efflux in a Missouri forest. Commun Soil Sci Plan 36, 1301-1311.

Powers, R.F., Scott, D.A., Sanchez, F.G., Voldseth, R.A., Page-Dumroese, D., Elioff, J.D., Stone, D.M., 2005. The North American long-term soil productivity experiment: findings from the first decade of research. Forest Ecol Manag 220, 31-50.

Rab, M.A., 2004. Recovery of soil physical properties from compaction and soil profile disturbance caused by logging of native forest in Victorian Central Highlands, Australia. Forest Ecol Manag 191, 329-340.

Radford, B.J., Wilson-Rummenie, A.C., Simpson, G.B., Bell, K.L., Ferguson, M.A., 2001. Compacted soil affects soil macrofauna populations in a semi-arid environment in Central Queensland. Soil Biol Biochem 33, 1869-1872.

Ruehlmann, J., Korschens, M., 2009. Calculating the effect of soil organic matter concentration on soil bulk density. Soil Sci Soc Am J 73, 876-885.

Sands, R., Greacen, E.L., Gerard, C.J., 1979. Compaction of sandy soils in radiate pine forests. I. a penetrometer study. Aust J Soil Res 17, 101-113.

Schäfer, V.T., Sohns, D., 1993. Minderung der Bodenverdichtung durch eine Reisigauflage. Allgemeine Forstzeitschrift 9, 452-455.

Schäffer, J., 2005. Bodenverformung und Wurzelraum. In: von Teuffel et al. (Eds), Waldumbau für eine zukunftsorientierte Waldwirtschaft. Springer, Berlin, Germany, pp. 345-361.

Schumacher, T.E., Smucker, A.J.M., 1981. Mechanical impedance effects on oxygen uptake and porosity of drybean roots. Agron J 75, 51-55.

Seixas, F., Koury, C.G.G., Costa, L.G., 2003. Soil compaction and GPS determination of impacted area by skidder traffic. In: Proceedings 2nd Forest Engineering Conference. Techniques and Methods. Växjö, Zweden, 124-128.

Shetron, S.G., Sturos, J.A., Padley, E., Trettin, C., 1988. Forest soil compaction: effect of multiple passes and landings on wheel track surface soil bulk density. North J Appl For 5, 120-123.

Smeltzer, D.L.K., Bergdahl, D.R., Donnelly, J.R., 1982. Populations of selected forest soil organisms affected by soil compaction. Phytopathology 72, 257-257.

Smith, C.W., Johnston, M.A., Lorentz, S., 1997. The effect of soil compaction and soil physical properties on the mechanical resistance of South African forestry soils. Geoderma 78, 93-111.

Smith, C.W., 2003. Does soil compaction on harvesting extraction roads affect long-term productivity of Eucalyptus plantations in Zululand? South Afr Forest J 199, 41-54.

Soil Survey Division Staff, 1993. Handbook 18. Soil survey manual. Soil Conservation Service. U.S. Department of Agriculture.

Startsev, A.D., McNabb, D.H., 2000. Effects of skidding on forest soil infiltration in West-central Alberta. Can J Soil Sci 80, 617-624.

Stone, D.M., Elioff, J.D., 2000. Soil disturbance and aspen regeneration on clay soils: three case histories. Forest Chron 76, 747-752.

Teepe, R., Brumme, R., Beese, F., Ludig, B., 2004. Nitrous oxide emission and methane consumption following compaction of forest soils. Soil Sci Soc Am J 68, 605-611.

Vaz, C.M.P., Bassoi, L.H., Hopmans, J.W., 2001. Contribution of water content and bulk density to field soil penetration resistance as measured by a combined cone penetrometer-TDR probe. Soil Till Res 60, 35-42.

Wehner, T., 2003. Environmental impacts of modern harvesting systems on soil. New results of a technological assessment. In: Proceedings 2nd Forest Engineering Conference. Techniques and Methods. Växjö, Zweden, 96-102.

Whalley, W.R., Leeds-Harrison, P.B., Clark, L.J., Gowing, D.J.G., 2005. Use of effective stress to predict the penetrometer resistance of unsaturated agricultural soils. Soil Till Res 84, 18-27.

Williamson, J.R., Neilsen, W.A., 2000. The influence of forest site on rate and extent of soil compaction and profile disturbance of skid trails during ground-based harvesting. Can J For Res 30, 1196-1205.

Woodward, C.L., 1996. Soil compaction and topsoil removal effects on soil properties and seedling growth in Amazonian Ecuador. Forest Ecol Manag 82, 197-209.

Wronski, E.B., 1984. Impact of tractor thinning operations on soil and tree roots in a Karri forest, Western Australia. Aust Forest Res 14, 319-332.

Zwaenepoel, J., 1989. La vegetation herbacée, indicatrice du changement du milieu, après exploitation forestière. In: Proceedings of the seminar on the Impact of mechanization of forest operations to the soil. Leuven, België, 249-252.