EFFORTE –

'Efficient forestry by precision planning and management for sustainable environment and cost-competitive bio-based industry'

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Task 1.3 – Ground pressure metrics and stress distribution at the tyre/track-soil interface Task 1.4 – Soil deformation due to mechanized forest operations Task 1.5 – Resilience of soil to compaction: long term effects of forest traffic on soil functioning			
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Author(s), organisation(s)		Philippe RUCH (FCBA), Matti Siren, Jari Ala-Ilomäki, Harri Lindeman, Jori Uusitalo (LUKE), Tomas Keller (Agroscope), Maria Sandin (SLU), Eva Ring, Isabelle Berqkvist (Skogforsk) Noemie Pousse (ONF)	
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1 Introduction

1.1 EFFORTE project objectives

EFFORTE is a research and innovation project providing the European forestry sector with new knowledge and knowhow that will significantly improve the possibilities of forest enterprises to assemble and adopt novel technologies and procedures.
The project aims at enhancing the efficiency of silviculture and harvesting operations; increasing wood mobilization and annual forest growth; increasing forest operations' output while minimizing environmental impacts; and reducing fuel consumption in the forest harvesting process by at least 15%.

The project is based on three key elements of technology and knowhow:

- Basic understanding of fundamentals of soil mechanics and terrain trafficability is a crucial starting point to avoid soil disturbances, accelerate machine mobility and assess persistence of soil compaction and rutting. The key findings and recommendations of trafficability related to EFFORTE can immediately be adapted in all European countries.
- Due to decreasing Cost-competitiveness of manual work and maturity of technology it is now perfect time to realize the potential of mechanization in silvicultural operations. EFFORTE pursues for higher productivity and efficiency in silvicultural operations such as tree planting and young stand cleaning operations.
- 'Big Data' (geospatial as well as data from forestry processes and common information e.g. weather data) provides a huge opportunity to increase the efficiency of forest operations. In addition it adds new possibilities to connect knowledge of basic conditions (e.g. trafficabillity), efficient silviculture and harvesting actions with demand and expectations from forest industries and the society. Accurate spatial information makes it possible for forestry to move from classic stand-wise management to precision forestry, i.e. micro stand level, grid cell level or tree-by-tree management. EFFORTE aims at achieving substantial influence to the implementation and improved use of Big Data within Forestry and through this increase Cost-efficiency and boost new business opportunities to small and medium size enterprises (SME) in the bioeconomy.

EFFORTE researchers will develop and pilot precision forestry applications that, according to the industrial project partners, show the greatest potential for getting implemented immediately after the project.

1.2 WP1 "Methodologies to predict trafficability of forest soils" objectives

Forest work is heavily disturbed by high seasonal variation. Machine utilization is especially low during periods of snow melting and when wet conditions almost completely make logging and road transport impossible. Superimposed are impacts of climate change that most likely will add to the complexity and increase the seasonal variation and increase the risks of damages to soil and water. In this context EFFORTE's WP1 aims to establish a basis and to develop methodologies to predict trafficability of given forest stands or permanent extraction trails prior to forest operations in the most common sensitive situations. In this purpose, the soil compaction risk of forest operations is evaluated by considering soil type and conditions, machinery properties, forest stand and climate.

WP1 includes following objectives:

- O1.1 Develop models that predicts bearing capacity of forest soils prior to forest operation
- O1.2 Develop models to predict soil deformation in operational forest contexts
- O1.3 Provide forest practitioners with sustainable recommendations on terrain trafficability and propose knowledge-based preventive measures for efficient risk mitigation while planning forest operations

In order to compare results of the existing and new trials, as well as data collected in the different countries, a common protocol was developed by all scientists involved in WP1. The objective was to harmonize experimental design and measurements. The common protocol was presented at the scientific workshop “Forest soil trafficability”, organized by FCBA within EFFORTE’s project (Champs-sur-Marne, France, March 28th, 2017). 18 participants attended the meeting: 11 EFFORTE’s partners and 7 scientists from other European research institutes (see extracts in the EFFORTE Deliverable 1.1 Appendix A and C).

1.3 Deliverable D1.2: Database and models for soil type specific trafficability

In EFFORTE we have mostly focused on modelling rutting but some attempts have also been made to analyze and model soil compaction. We have studied two different approaches to predict soil rutting. First, we have constructed simple machine-dependent empirical models for comparing rutting caused by most typical 8-wheeled forest machines (Chapter 2). It means that the models are valid only for machines having similar characteristics (tyre sizes, tyre pressures and loads carried out by tyres). However, modelling of the behavior of the single machine includes elements that can be generalized in other machine types and soil conditions also.

Second, we have also developed and tested methodology to build two stages, machine-independent models where rut prediction is based on two empirical model structures; on moisture content – soil strength (PR) relationship and on empirical formulas describing interaction between soil and wheel (Chapter 4). We have employed so called WES methodology for wheel-soil interaction. The methodology is based on empirically created, non-dimensional Wheel numerics which relate the measured PR to the load carried out by tyre and various principal tyre dimensions.

Forest trafficking do not always lead to visible rutting but soil compaction may permanently or at almost permanently (for decades) interfere soil biological activity. Therefore more focus in the future should be directed at cause and effect of forest soil compaction. In EFFORTE, we have made empirical measurements of soil compaction (Chapters 2 and chapter 3) and effect of machine mass and tyre pressure on soil stresses (Chapter 3). We will also report our findings about the duration of soil deformations caused by forest trafficking (Chapter 4).

2 Empirical machine-dependent models to predict soil deformations

Jori Uusitalo, Matti Sirén, Jari Ala-Ilomäki and Harri Lindeman

The Natural Resources Institute Finland (Luke)

2.1 Introduction

Soil bearing capacity and risk for soil deformation is connected to weather conditions. The impact of soil moisture on bearing capacity is known to be strongest in cohesive, fine-grained soils (i.e. clays and loams) and weakest in sandy soils (Vega-Nieva et al. 2009; Campbell et al. 2013; Jones and Arp 2017). In Finland the accepted levels of rutting and soil damage are set by the forest legislation (Forest Act 1996) and forestry recommendations. In planning and implementation of harvesting operations we should know the critical limits for soil water content to keep the amount of deep ruts (> 10 cm) small.

Rut formation with many negative consequences on forest growth and health is a consequence of machine load that exceeds forest soil bearing capacity. As a visible damage, it has large impact on overall acceptability of forest operations. In addition to visible ruts machine trafficking tends to cause soil compaction. Soil compaction will inevitably lead to reduced porosity, which implies limitations in the oxygen and water supply to soil microorganisms and plants, with negative consequences for soil ecology and forest productivity (Cambi et al. 2015).

In this chapter we present results of the work that aimed at creating empirical models valid for 8-wheeled forest machines (harvester and forwarder, CTL-method) having typical tyre sizes, tyre pressures, equipping and loads. We conducted series of wheeling experiments that were carried out on fine-grained and mid-grained upland soils.

2.2 Material and methods

A series of wheeling experiments was carried out at Vihti at 2015 on fine-grained soils (Toivio et al. 2017, Uusitalo et al. 2019) and at Kuru in 2017 on mid-grained soils (Sirén et al. 2019 b). The experimental design was about the same in both experiments. The whole data included 7 strip-roads; 3 at Vihti site 1, 2 at Vihti site 2 and 2 at Kuru. The strip roads were divided to 20 m long study plots each having four 5 meter long subplots with six measurement points.

Prior to test trials, diameter at breast height (dbh) of all trees within the sample plot was measured. The height of selected sample trees was measured and stand characteristics for each sample plot were calculated. Prior to the driving test, the penetration resistance (PR) of all six measurement points within each subplot was measured with an Eijelkamp Penetrologger 0615SA penetrometer consisting of a 11.28 mm diameter (1 cm^2), 60-degree cone. Before harvesting and after each machine pass two soil samples were taken from the centremost measurement points of each subplot with a core sampler at Vihti sites. The soil core extracted from the soil was divided into three sections, an organic layer and two mineral soil subsamples 10 cm in length, the first starting from the upper boundary of the mineral soil. The thickness of the organic layer was measured in the field while the bulk density (BD), volumetric water content (VWC), soil organic matter (SOM) and grain size distribution were later analysed in the laboratory, separately for the upper (0-10 cm) and lower (10-20 cm) part of the core sample.

At Kuru site two soil samples per subplot were taken only before harvesting. PR was measured in every measurement point before harvesting and after last machine pass, on one subplot per plot PR was measured after each machine pass. At Kuru change in PR values was used to describe soil compaction. The PR of a soil, when measured and interpreted correctly, is an easily obtained and useful measure of the degree of soil compaction (Bennie and Burger 1988). The relationships between the soil compaction levels and PR have been described in many studies (e.g. Grunwald et al. 2001).

The relative elevation of the measurement point was measured with construction laser level before harvesting and after each machine pass for rut depth observations. It was also checked whether there any stumps or superficial stones just at the measurement point. A very important feature in our wheeling tests was, that we wanted to eliminate the effect of logging residues on rut formation (McDonald and Seixas 1997; Han et al. 2006; Sirén et al. 2013a) to find the actual soil bearing capacity. At Vihti sites the harvester travelled strictly outside the actual study trails to keep the test site intact and trees were processed outside the study trails. At Kuru the harvester drived on study strip roads, but processed the trees outside the strip roads. Possible remaining residues were removed before forwarding wheeling test. At Kuru the harvester was a 8-wheeled Ponsse Scorpion King.

Forwarder test drives were carried with loaded 8-wheeled forwarders. At Vihti Ponsse ELK with load had a total mass of 29800 kg and at Kuru John Deere 1210 E had a total mass of 32 020 kg. Both machines had a typical equipment; chains in front and tracks in rear. Machines represent typical modern machinery and were driven by experienced operators.

On Vihti site 1 the wheeling tests were performed in three periods; in early September, November and December. On Vihti site 2 the test drives were only on September and November, as the bearing capacity collapsed in November. The number of machine passes was 10 except the site 2 in November, were the bearing capacity collapsed after three passes. Kuru test drives were carried in late May, with high moisture content after winter. Table 2.1 presents the soil conditions on our test areas. Soil type at Vihti site 1 was silty clay and at site 2 sandy loam/clay loam. At Kuru the soil type was mainly silty sand, in some subplots sandy silt.

In rut depth modelling the statistical significance of the variables was tested by using the Linear Mixed Models procedure of the IBM SPSS v.25 software. The REML estimation method was used. Models were compared by using fit statistics (Akaike Information Criterion, AIC) and residuals for the models. Modelling procedures are presented in Sirén et al. (2019b) and Uusitalo et al. (2019).

Table 2.1. Soil characteristics at the experimental sites. VWC = Volumetric water content 0-10 cm (%), BD = Soil bulk density 0-10 cm (g/cm^3), PR020 = Penetration resistance 0-20 cm (MPa), PR20 = Penetration resistance 20 cm, Clay= Clay content of soil sample 0-10 cm, Humus layer = Depth of humus layer (cm).

Time	Stand	VWC %	BD g/cm3	PR020 MPa	PR20 MPa	Clay %	Humus layer cm
September	Vihti Site 1	24.0	0.83	1.76	3.93	49.3	3.6
	Vihti Site 2	37.1	1.19	1.19	3.47	25.6	7.8
November	Vihti Site 1	36.2	0.89	1.01	1.78	49.3	2.9
	Vihti Site 2	48.2	1.22	0.96	1.30	25.6	10.2
December	Vihti Site 1	40.5	1.07	0.97	1.62	49.3	3.4
May	Kuru	33.5	1.17	0.77	1.48	5.0	10.2

2.3 Results

2.3.1 Rut formation

Rut formation of experimental sites is presented in Figure 2.1. Rut formation increased with machine passes, but average rut depths remained mainly under 10 cm at mid-grained site (Kuru) and at fine-grained site 1 (Vihti). On another fine-grained site (Vihti 2) the increasing water content, from 37 % in September to 48 % in November, collapsed the soil bearing capacity, and test was ended after third machine pass with average rut depth of 25 cm.

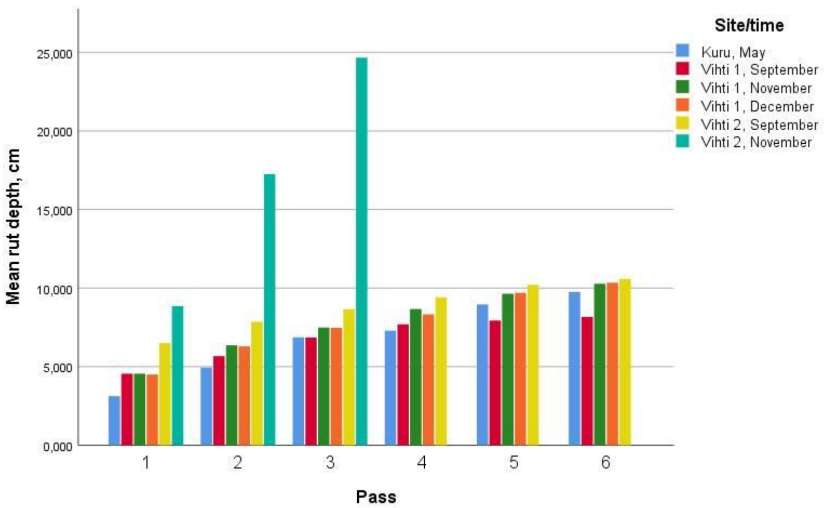

Figure 2.1. Mean rut depths at experimental sites after machine passes (1 pass = around 30 tonnes). Vihti 1 and 2 = fine-grained sites, Kuru = mid-grained site.

Moisture content and cumulative mass driven over measurement point are the most important explanatory variables in rut depth models. On fine-grained soils the depth of humus layer is also a good predictor for rutting,

Ruth depths for fine-grained soils (Uusitalo et al. 2019) can be expressed as:

$$RUT=-35.3+\ln(CM)+0.0000917*VWC^3-5.76*BD+1.11*Humuslayer \qquad (2.1)$$

and for mid-grained soils (Sirén et al. 2019b) as:

$$\ln(RUT)=0.028+0.0000084*CM+0.018*VWC \qquad (2.2)$$

Where
RUT= Rut depth (cm)
CM= Cumulative mass driven over measurement point (kg)
VWC=Volumetric water content (%)
BD= Bulk density, g cm^{-3}
Humuslayer= Thickness of humus layer, cm

The model is valid for 8-wheeled machines, having tyre width roughly 700 mm, typical tyre pressure, typical load distribution between front and rear frame. The influence of volumetric water content on rut formation is presented in Figure 2.

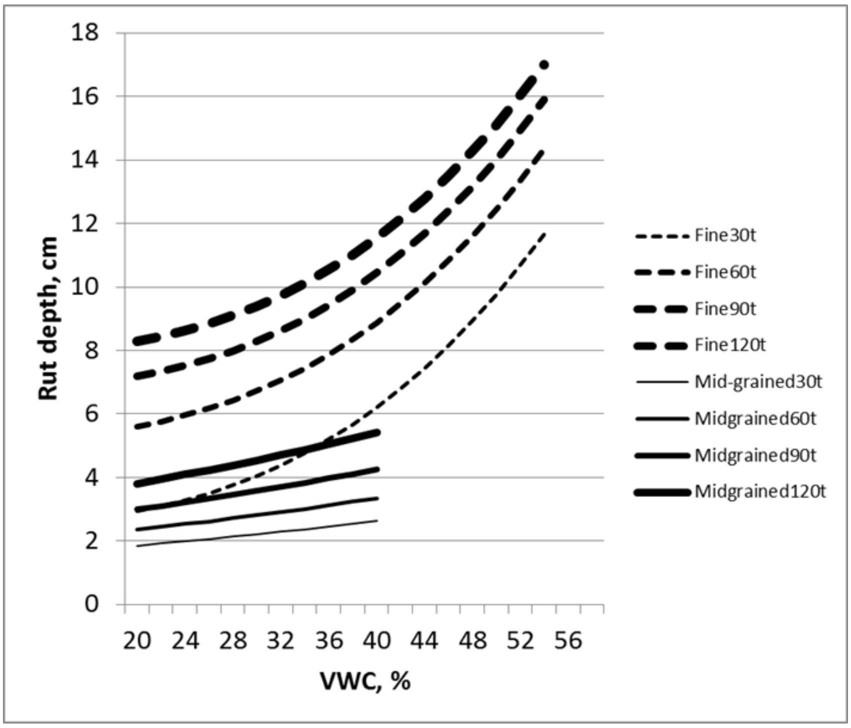

Figure 2.2. Influence of volumetric water content (%) on rut depth on fine-grained (Uusitalo et al. 2019) and mid-grained soils (Sirén et al. 2019b) as a function of different overpassed masses. Bulk density = 1.0 g cm^{-3}, Thickness of humus layer = 5 cm (humus layer depth not included in the mid-grained model).

In addition to models above we have other explanatory variables in models for different uses. Part of the explanatory variables need special measuring devices like penetrometer, some variables, e.g. thickness of humus layer, are easy to measure. Uusitalo et al. (2019) present four models for fine-grained soils and Sirén et al. (2019b) five models for mid-grained soils. In addition to water content, cumulative overdriven mass and humus layer depth penetration resistance and bulk density are explanatory factors in fine-grained models and penetration resistance and harvester rut depth in mid-grained models.

Rut depth after first machine pass (harvester) together with the total overdriven mass is a good predictor for rut depth. The same finding has been done by Sirén et al. 2013a on mineral soil, Sirén et al. 2013b on peatland and Sirén et al. 2019a on fine-grained mineral soil. With the presented models we can estimate, what is the allowed total overpassed mass to keep the rut depth under 10 cm. On mid-grained soil, the limit for the total overpassed mass with a 2 cm harvester rut is 250 000 kg, whereas on fine-grained soil it is 180 000 kg (Sirén et al. 2019b, Sirén et al. 2019a).

2.3.2 Soil compaction

At Vihti exprerimental soil bulk density increased and porosity decreased after the machinery passes. Soil moisture content increased on Vihti site 1 and mainly decreased on site 2. The first three passes caused the greatest compaction, the first pass having the strongest impact. The compaction and changes of soil physical properties appeared to be greater in dry conditions. In Vihti the PR measurements had higher values and greater compaction in dry September than in moister November and December. Penetration resistance and soil compaction were thus clearly lower in moist conditions. The greatest changes occurred in the top 60 cm soil depth. The first three passes had the greatest impact on the top soil of about 30 cm, whereas the further passes caused compaction at greater depths, especially in moist conditions (Toivio et al. 2017)..

At Kuru (Sirén et al. 2019b) on mid-grained soil compaction was estimated only as change in PR values. Changes in PR were highest at depths of 20–40 cm. Increase in BD and VWC decreased PR, which increased with total overdriven mass. After four to five machine passes PR values started to stabilize. PR-profiles before and after machine passes (10 passes at Vihti site 1, 6 at Kuru) are presented in Fig. 2.3 and Fig. 2.4.

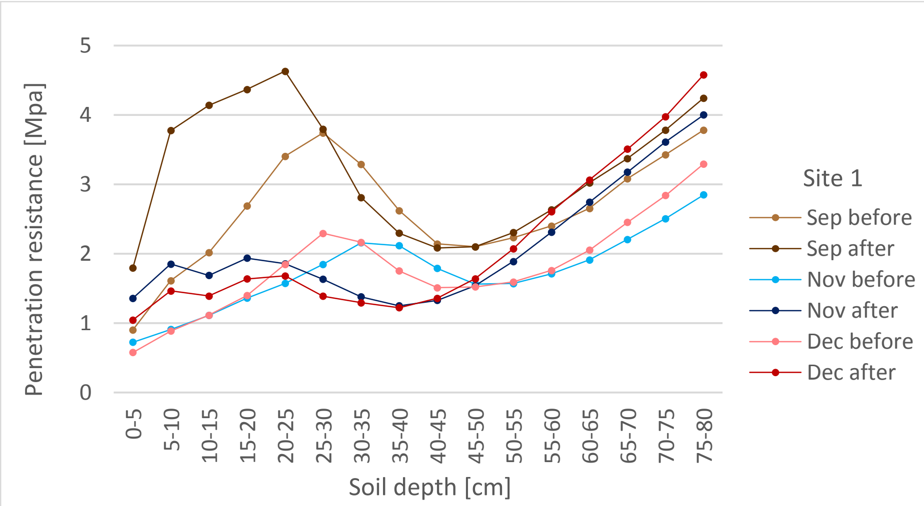

Figure. 2.3. Penetration resistance before and after harvesting on fine-grained soil (Toivio et al. 2017)

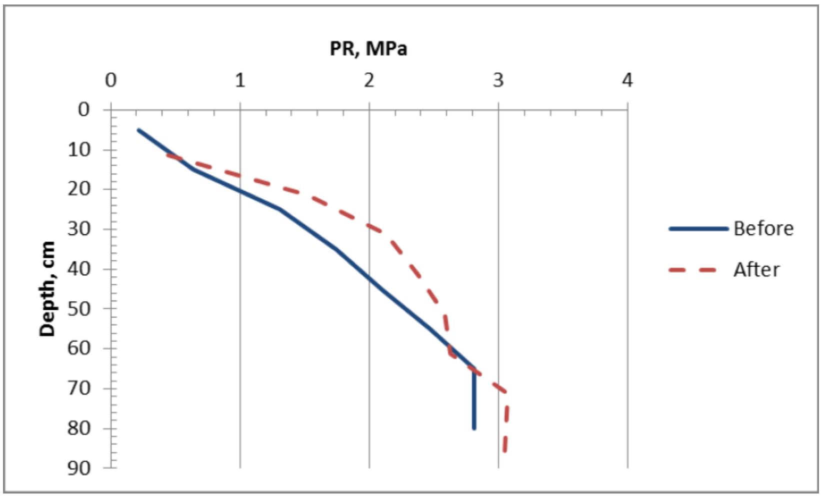

Figure 2.4. Penetration resistance before and after harvesting on mid-grained soil (Sirén et al. 2019b).

2.3.3 Conclusions

Our results supported the earlier findings of soil deformations after machine passes on fine- and mid-grained soils (Han et al. 2006; Vega-Nieva et al. 2009). In our data the radical changes in the bearing capacity on fine-grained soils occurred at VWC values of 40 % corresponding to saturation of soil roughly 80 %. According to our findings, complete saturation of the forest is soil at the depth of 0-10 cm is achieved at the VWC of 47-52%, depending on the bulk density and proportion of organic matter.

Rut formation can most efficiently be modelled with total overpassed mass, water content, depth of the organic layer, bulk density and penetration resistance. Rut depth after harvester a good predictor for forwarder rut formation. This opens good possibilities for forwarding operation tutoring and validation of pre-planning trafficability information, when promising results on harvester rut-depth measurements with LiDAR (Salmivaara et al. 2018) or from canbus-information (Ala-Ilomäki et al. 2019) are part of operational practice. There are promising results on harvesting planning tools like Bestway (Willen et al. 2017) basing on DTW-maps. Thus knowledge on soil type and water content can be linked to trafficability estimations.

In our experiments cover of logging residue mat was eliminated to find the actual soil bearing capacity. This must be remembered, when we look the results. Especially in Norway spruce thinnings we can often get a residue mat of 15 kg m^{-2} to cover the strip road. This kind of mat effectively protects the soil and roots (Sirén et al. 2013 a).

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3 Ground pressure metrics and stress distribution at the tyre- soil interface for forwarders

Philippe Ruch[1], Xavier Montagny[1], Maria Sandin[2], Matthias Stettler[4] and Thomas Keller[2,3]

[1]Institut Technologique Forêt Cellulose Bois-construction Ameublement (FCBA), Charrey-Sur-Saône, France
[2]Swedish University of Agricultural Sciences, Department of Soil & Environment, Uppsala, Sweden;
[3]Agroscope, Department of Agroecology & Environment, Zürich, Switzerland
[4] Bern University of Applied Sciences, School of Agricultural, Forest and Food Sciences HAFL, Länggasse 85, CH-3052 Zollikofen, Switzerland

3.1 Introduction and objectives

Vehicle traffic unavoidably exerts vertical and horizontal stresses as well as shear stresses to the soil (Keller et al., 2013). The main outcome is soil compaction. Soil compaction and its consequences on soil functioning has been studied by many authors. Soil compaction affects key soil functions including water flow and aeration, nutrient cycling, agricultural and forestry production, and habitats for soil organisms (Wilpert and Schäffer; 2006, Goutal et al., 2013; Keller et al., 2019). Although the general phenomenon of compaction is known to forest practitioners, the importance of compaction of deep soil horizons is much less understood. Indeed, subsoil compaction (depth > 25 cm) is of high importance as it has negative impacts on the root development, water infiltration and the water storage capacity of subsoil (Keller et al., 2019). In arable soil, subsoil compaction has been reported to be persistent (Håkansson and Reeder, 1994; Peng and Horn, 2008; Berisso et al., 2012) and can be observed up to 80 cm depth (Lüscher et al., 2019). The determining factor, for which stresses reach deep soil layers, is the wheel load, i.e. weight of the loaded machine divided per the number of wheels (Schønning et al., 2012).

In the field of agriculture, the weight and wheel loads of machinery has been steadily increasing. For example, wheel loads of combine harvesters have increased by approximately 65% between 1989 and 2009 (Schjønning et al., 2015). Consequently, the mechanical stresses exerted by today's machinery may exceed the strength of many arable soils (Horn and Fleige, 2003; Zink et al., 2010; Schjønning et al., 2015). A similar trend in increasing weight of machinery was noted in the forestry sector for forwarders in Sweden. The average total mass (curb weight + maximum load capacity) of forwarders has increased from about 20 tonnes before 1970 to ca. 32 tonnes in 2010 (Nordfjell et al., 2019). In the same time, the number of wheels has increased from four wheels to six and then eight wheels, helping to reduce wheel loads and nominal ground pressure thanks also to the increase in tire width. However, since eight wheeled machines are standard in European logging systems, the general trend in increasing weight has not stopped.

In France, since 2017, the 14-17 tonnes load capacity category, considered as "large" forwarders, is the best-selling category. It has replaced the 11-13 tonnes load capacity category, i.e. "medium", which was the most sold forwarder category for many years (Bonnemazou et al., 2019). In the sales catalogue of major manufacturers of professional machines, the smallest forwarders have load capacities from 9 to 10 tonnes, and these are named "small" forwarders. However, forest managers prefer small harvesters due to their supposedly lower impact on the soil.

In EFFORTE, our objective was to compare "small" to "large" forwarders regarding their potential impacts on the soil. This chapter will focus on (i) determining wheel loads of different categories of forwarders, (ii) measuring soil stress induced by the machines, and (iii) proposing recommendations for reducing the impact of forwarders on soil compaction. In chapter 4, the performances of these forwarders regarding rutting will be analyzed.

3.2 Material and methods

Wheeling experiments were carried out in France on permanent extraction trails (see chapter 4). At each location, we collected machine characteristics (load capacity, tire dimension, tire inflation pressure) and measured front and rear wheel loads (unloaded and loaded) by means of portable scales (figure 3.1).

Figure 3.1. Weighing the forwarder on the front axle with one portable scale per wheel.

On two locations ("Azerailles" and "Chaux"), we also measured (i) the footprint on hard soil using a caliper to estimate the ground contact area, which is often used to compare vehicles with each other, and (ii) soil stress using Bolling .

The Bolling probe is a cylindrical fluid inclusion type sensor. It has a rubber membrane tip and is filled with an incompressible fluid (in general de-aired water) that is hydraulically connected to a pressure gauge. The Bolling probe is deformable and cylindrical and therefore senses the mean radial stress experienced by the probe, which is related to the mean normal stress in the soil (Keller et al., 2016). Bolling probes were installed at 20 cm and 40 cm depth under the centre of the wheel track (figure 3.2). At least 7 runs over the probes were performed with loaded forwarders.

Figure 3.2. Experimental set up with four Bolling probes (two replicates per depth, 20 and 40 cm). The yellow line marks the centre of the wheel track below which the probes are located and serves as guidance for the driver.

3.3 Results and discussion

3.3.1 Wheel loads

Machine characteristics are depicted in table 3.1. On each location, a 9-10 tonnes forwarder was compared to a 14 tonnes forwarder. At the site "Chaux", the performance of a "very small" forwarder, the Novotny LVS520, which has a load capacity of 6.5 tonnes, was also evaluated.

All forwarders were eight wheeled machines with four bogie axles and two wheels per bogie.

Table 3.1. Forwarders main characteristics used during the tests.

Location	Azerailles		Chaux		
Model	John Deere 810D	Komatsu 860.4	Novotny LVS520	Ponsse Gazelle	Ponsse Buffalo
Load capacity (tonnes)	9	14	6.5	10	14
Tire dimension	600/50-22.5	710/45-26.5	600/40-22.5	710/40-22.5	710/45-26.5
Tire inflation pressure (bar)	4.0	4.1	1.65	5.0	5.0
Curb weight (tonnes)	13.9	19.3	8.5	16.1	18.4
Loaded weight during the tests (tonnes)	21.9	31.3	14.0	23.5	30.9

Mean wheel loads (figures 3.3 and 3.4) were the highest for the heaviest machines with 3.9 tonnes per wheel for the 14 tonnes forwarders (3.91 tonnes for Komatsu 860.4 and 3.86 tonnes for Ponsse Buffalo), while the wheel load was one tonne less for the 10 tonnes forwarders (2.74 tonnes for John Deere 810D and 2.94 tonnes for Ponsse Gazelle). Unsurprisingly, the Novotny LVS520 had the lowest wheel load, with 1.75 tonnes per wheel. However, the average values mask large differences between the rear and front wheels. Very high wheel loads of 5 tonnes were measured for the rear wheels of both 14 tonnes forwarders. This is nearly 1.5 tonne higher than the small forwarders. These high wheel loads induced high stresses in the soil (see chapter 3.3.2). Therefore, one should not only pay attention to the mean wheel load, but especially to the maximum wheel load, i.e. on the rear wheels for a fully loaded forwarder.

Although the mean ground pressure seems important to analyse, it can be misleading. For example, the mean ground pressures were nearly the same for the John Deere 810D (1.23 kg cm^{-2}) and the Komatsu 860.4 (1.20 kg cm^{-2}). However, considering each wheel separately reveals a different picture (figure 3.3): the Komatsu 860.4 had a much higher rear wheel load, resulting in higher subsoil stresses (Schjønning et al., 2012).

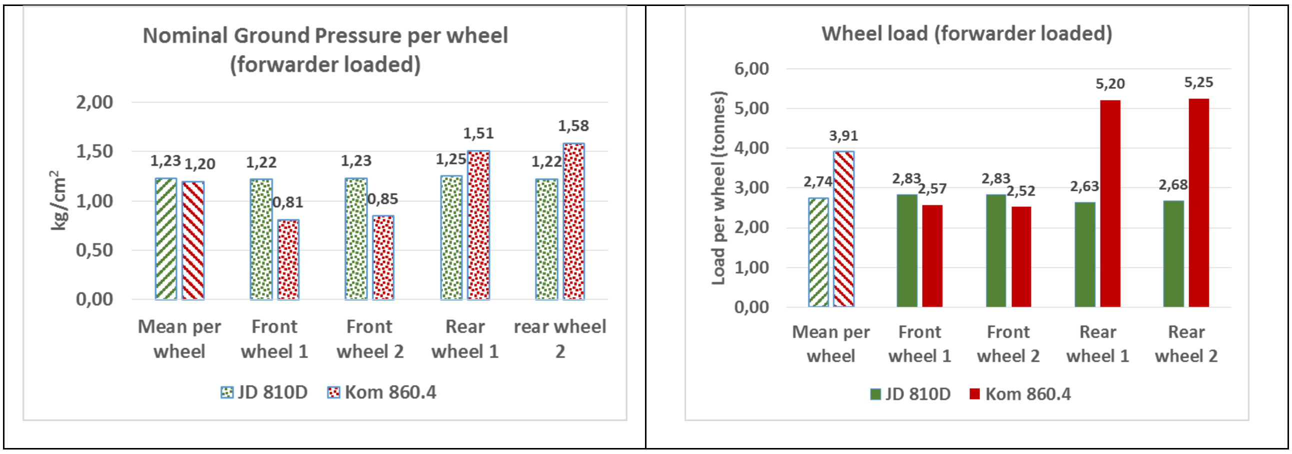

Figure 3.3. Nominal ground pressure (left) and wheel load (right) for 9 tonnes load capacity forwarder John Deere 810D (green) and 14 tonnes forwarder Komatsu 860.4 (red) at Azerailles site.

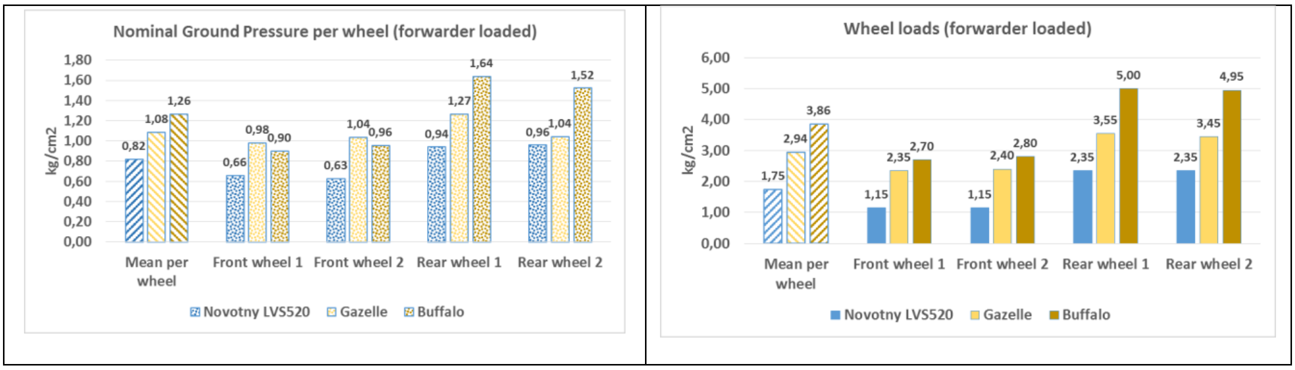

Figure 3.4. Nominal ground pressure (left) and wheel load (right) for 6,5T load capacity forwarder Novotny LVS520 (blue), 10T Gazelle (yellow) and 14T Buffalo (Brown) at Chaux site.

The distribution of the total weight between the front and rear wheels for the loaded forwarders can easily be derived from the weight measurements. The weight distribution was: Novotny LVS520 (front 36% / rear 64%), Gazelle (40% / 60%), Buffalo (36% / 64%), Komatsu (33% / 67%). This is in line with results by Nordfjell et al. (2019), who reported a mean weight distribution of 39% (front) to 61% (rear), based on an analysis of 57 forwarder types. We also conducted an analysis based on test reports of the German test institute KWF (Kuratorium für Waldarbeit und Forsttechnik). 16 test reports were available and the mean weight distribution was 33% / 67%.

However, the load distribution of the John Deere 810D was quite equal between the front and the rear wheels, i.e. 52% - 48% (see also figure 3.3, small difference between the front and rear wheel load). This is due to the fact that the crane is mounted on the front part of the machine (very close to the front axle), and moreover, during the tests the crane was positioned forward (figure 3.5).

Figure 3.5. John Deere 810D (left) with specific crane positioning that is however unusual. On the right, usual positioning of the crane for almost all forwarders.

We made other measurements with a 15 tonnes load capacity forwarder at the Donnement site using a John Deere 1510 (35.3 tonnes, fully loaded) to test the impact of the crane position on the wheel load (figure 3.6 and 3.7). By simply positioning the crane forward, the load distribution between the front and rear was changed from 39% / 61% to a more balanced 47% / 53%. Thus, the maximum wheel load decreased from 5.4 tonnes per wheel (mean for the rear wheels) to 4.6 tonnes. However, forwarders are typically not built to be driven with the crane positioned forward. Nevertheless, our results indicate an unused potential for manufacturers to improve the weight distribution of forwarders.

Figure 3.6. John Deere 1510 with two different crane positions.

Figure 3.7. Load per wheel for a loaded 15 tonnes forwarder with crane in position as usual (grey) and with crane in front (yellow)

3.3.2 Soil stress measurements using Bolling probes

The soil stress measurements show that soil stress generally increases with increasing wheel load. Soil stress was higher for the Komatsu 860.4 (maximum wheel load 5.2 tonnes) than for the John Deere 810D (maximum wheel load 2.8 tonnes) at the Azerailles site (figure 3.8, top). At the Chaux site (figure 3.8, bottom), soil stress was highest for the Ponsse Buffalo (maximum wheel load 5.0 tonnes) and lowest for the Novotny LVS520 (maximum wheel load 2.4 tonnes), while intermediate stress levels were measured for the Ponsse Gazelle (maximum wheel load 3.5 tonnes).

The data in figure 3.8 shows Bolling pressure, which is directly related to the soil mean normal stress and the soil's Poisson ratio (Berli et al., 2006). Here, the main aim was comparing different machinery rather than obtaining absolute values for mean normal stress, and therefore it was not needed to measure the soil's Poisson ratio (which is a soil property and therefore not different for different machineries compared at one site).

The large soil deformations and associated changes in soil properties (e.g. soil mechanical properties) and changes in the degree of saturation at the Chaux site are likely to have influenced the soil's Poisson ratio during wheeling, i.e. the soil's Poisson ratio might be a function of number of machine passes. Moreover, the differences in soil deformation between the different forwarders might have resulted in a different evolution of the soil's Poisson ratio for the different machinery. This may explain the slightly different evolution of Bolling pressure during multiple wheelings for the Ponsse Gazelle compared with the Novotny LVS520 (figure 3.8, bottom). Unfortunately, we have not measured the evolution of the soil's Poisson ratio as a function of number of vehicle passes, and we are not aware of any such data in the literature – it could be a subject of future research. The soil stress measurements at 40 cm depth reveal that the Bolling pressure is larger than 0.5 bar (50 kPa) for the forwarders with maximum wheel loads exceeding 3.5 tonnes (Komatsu 860.4 and Ponsse Buffalo), but smaller than 0.5 bar for the forwarders with maximum wheel loads smaller than 3.5 tonnes (John Deere 810D, Ponsse Gazelle, Novotny LVS520).

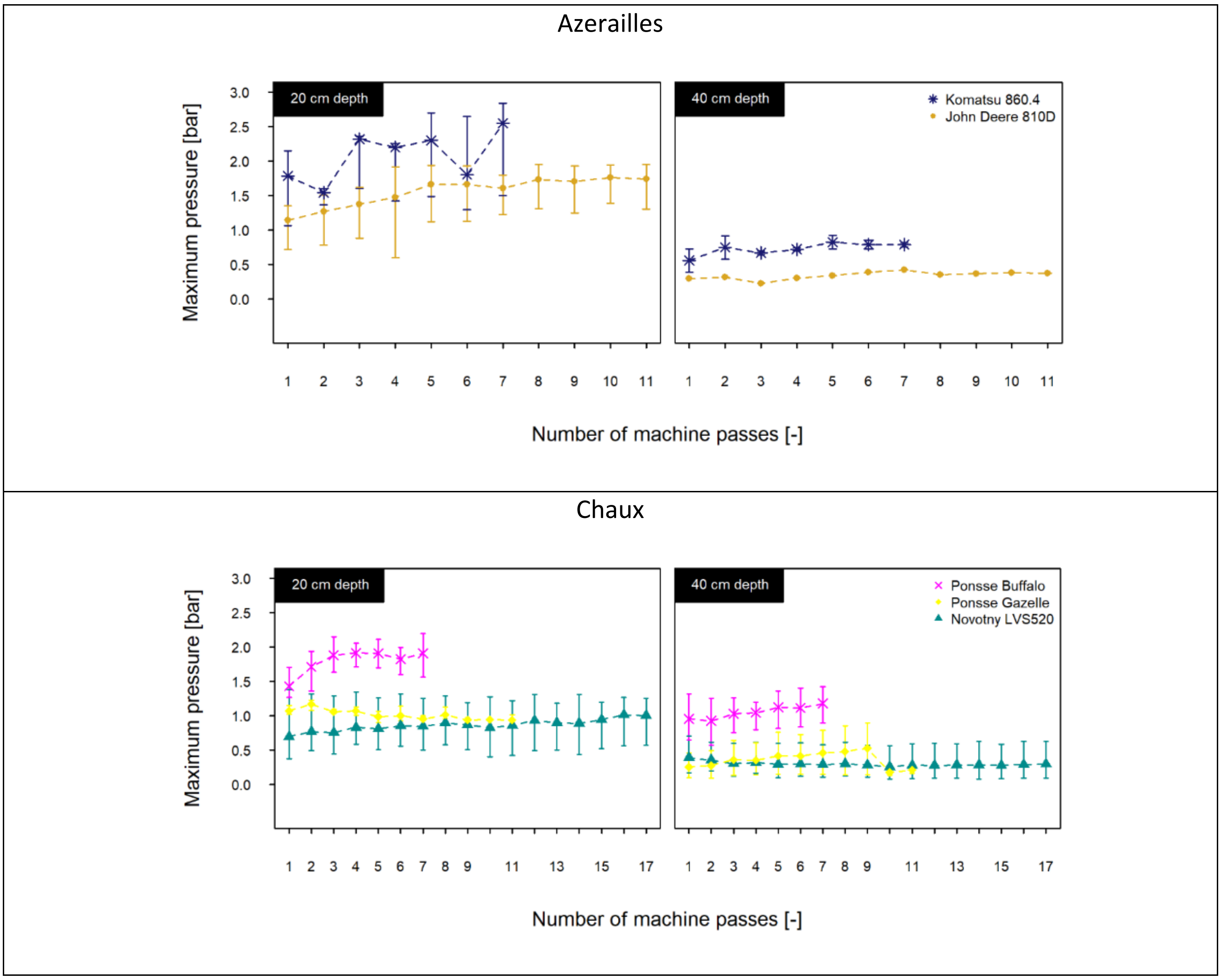

Figure 3.8. Maximum Bolling pressure at 20 cm (right) and 40 cm depth (left) beneath the different forwarders at Azerailles (top) and Chaux (bottom).

3.3.3 Recommendations regarding wheel loads

Schønning et al. (2012) suggested the "50-50 rule" for farmers: "At water contents around field capacity, traffic on agricultural soil should not exert vertical stresses in excess of 50 kPa at depths >50 cm." If we apply this rule to forest soils, wheel loads should not exceed ca. 3 to 3.5 tonnes (see table 3.2), which agrees well with our measurements as discussed above and presented in figure 3.8. It could be the subject of future research to establish a similar rule of thumb for vehicle traffic on forest soils. The many roots in forest soils may allow that the wheel load limit could be higher.

Table 3.2. Simulated vertical stress (kPa) under the centre of a tyre using SoilFlex (Keller et al., 2007) for the forwarders used during the wheeling experiments. For the simulations, a parabolic distribution of the vertical stress was assumed, with the maximum stress equal to 1.5 x tyre inflation pressure (Johnson and Burt, 1990).

Wheel load (Mg)	2,5				3				3,5				4				4,5				5				5,5			
Tyre width (cm)	71 cm		60 cm		71 cm		60 cm		71 cm		60 cm		71 cm		60 cm		71 cm		60 cm		71 cm		60 cm		71 cm		60 cm	
Tire inflation pressure (bar)	4	5	4	5	4	5	4	5	4	5	4	5	4	5	4	5	4	5	4	5	4	5	4	5	4	5	4	5
Depth (m)	**vertical stress (kPa)**																											
0,00	600	750	600	750	600	750	600	750	600	750	600	750	600	750	600	750	600	750	600	750	600	750	600	750	600	750	600	750
0,10	292	306	325	343	332	353	365	394	368	395	400	438	398	433	428	476	423	467	451	508	445	497	470	536	464	524	486	559
0,15	199	204	223	230	233	240	258	269	263	274	291	306	292	306	320	340	318	336	345	371	341	365	367	399	362	391	387	425
0,20	145	147	161	164	171	174	189	194	196	200	215	223	219	226	240	250	242	250	263	276	263	274	284	300	282	297	303	323
0,25	110	111	121	122	130	132	143	145	150	152	164	168	169	173	184	189	188	192	203	210	206	212	221	230	222	230	238	249
0,30	86	86,7	93,3	93,9	102	103	111	112	118	119	128	130	134	136	144	147	149	151	160	164	164	167	175	180	178	183	189	196
0,35	68,9	69,3	73,9	74,2	82,1	82,6	87,8	88,7	95,1	95,8	102	103	108	109	115	117	120	122	128	131	133	135	141	144	145	147	153	157
0,40	56,2	56,5	59,7	59,9	67,1	67,4	71,1	71,6	77,8	78,3	82,4	83,2	88,4	89,1	93,6	94,7	98,8	99,8	104	106	109	110	115	117	119	121	125	128
0,45	46,6	46,8	49,1	49,2	55,7	55,9	58,5	58,9	64,7	65	68	68,5	73,5	74	77,3	78	82,3	82,9	86,3	87,4	91	91,9	95,2	96,6	99,6	101	104	106
0,50	39	39	41	41	47	47	49	49	54	55	57	57	62	62	65	65	69	70	72	73	77	77	80	81	84	85	87	89

In Germany, KWF classifies forest machines according to the wheel load in kN (table 3.3).

Table 3.3. KWF grid for wheel load evaluation. 10 kN = ca 1 tonne

Wheel load in kN	<25	25 to 35	35 to 45	45 to 55	> 55
Score	++	+	0	-	--

According to table 3.3, and in agreement with the "50-50 rule", small forwarders (9-10 tonnes load capacity) induce a smaller risk of soil compaction than the large forwarders (14 tonnes load capacity). In light of these findings, one should recommend forwarders with low wheel loads to avoid subsoil compaction on permanent extraction tracks in order to preserve soil drainage capacities and so to ensure further trafficability. It also calls for action from the manufacturers, because today, the masses of the machines are constantly increasing (Nordfjell et al., 2019). As shown in figure 3.9, the rear wheel load of forwarders has steadily increased during the last about 30 years, resulting in an increase in subsoil stresses. We see an urgent need to reverse this trend.

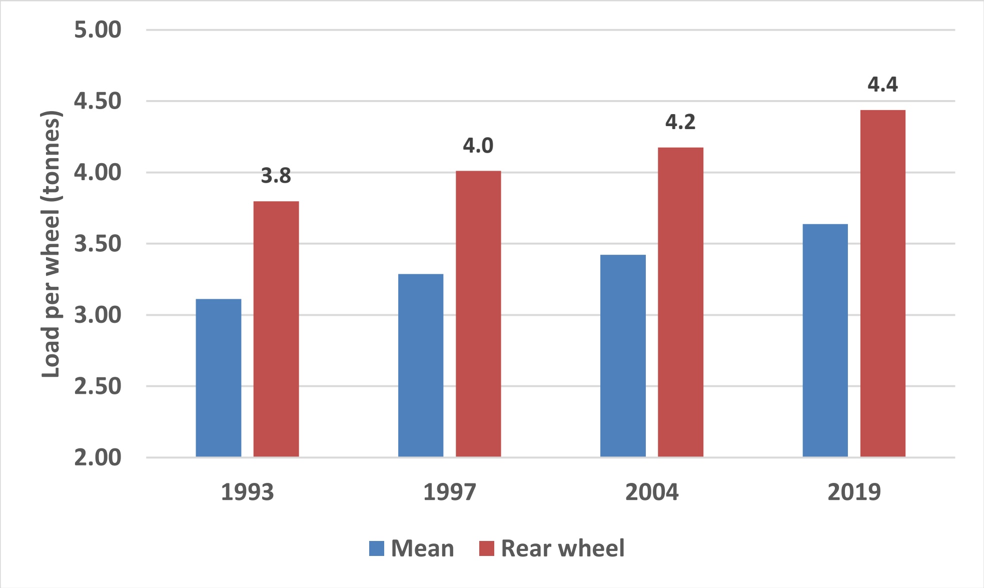

Figure 3.9. Evolution of wheel load of a 12 tonnes load capacity forwarder (medium category): mean wheel load (blue) and wheel load on the rear wheels (red), by assuming weight distribution according to Nordfjell et al. (2019) and considering curb weights given by the manufacturer (Brand Timberjack/John Deere). In 1993, the curb weight was 12.9 tonnes and in 2019, 17.1 tonnes.

The wheel load distribution is another topic to be investigated by the manufacturers. Changes will require a lot of redesign on ordinary forwarders.

The maximum allowable wheel load could also be increased by significantly lowering tire inflation pressures. For example, the “50-50 rule” allows a wheel load of almost 5 tonnes if the tire inflation pressure was 0.5 bars. However, while agricultural tires allow such low inflation pressures, this is not achievable in forestry with current tires. In fact, to protect the tires from damage by obstacles (such as stumps, stones) and for having the possibility to put on tracks, the tire inflation pressures used in forestry are very high: 4 to 5 bars (see table 3.1). This indicates a large potential to reduce soil stresses, and tire manufacturers are encouraged to try to find solutions to lower the inflation pressure. A first step has been taken in 2018 by the Alliance Tire Group. Their "F344 Forestar low pressure" tire has an inflation pressure at 2.5 bars. This is still rather high compared to inflation pressures used in agriculture at similar wheel loads, but half of the typical inflation pressure used today on forwarder tires.

Smaller machines with lower load capacity implies more traffic (more vehicle passes) in order to transport a given volume of wood. This has obviously a financial impact on the profitability of the logging operation and has, also to be taken into account by the forest sector. The intensity of machine traffic (number of passes) is a main controlling factor of rut depth, as demonstrated by several studies. However, most of these studies did not compare different forwarders based on an equal volume of transported wood. For example, it is not clear whether the rut depth differs between a 9-10 tonnes forwarder and a 14 tonnes forwarders: while more vehicle passes are needed with the 9-10 tonnes forwarder, the 14 tonnes forwarder is heavier. Results on this topic are presented in the next chapter.

3.4 References

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4 Modelling rut depth based on the mobility number

Maria Sandin[1], Philippe Ruch[2] and Thomas Keller[1,3]
[1]Swedish University of Agricultural Sciences, Department of Soil & Environment, Uppsala, Sweden;
[2]Institut Technologique Forêt Cellulose Bois-construction Ameublement (FCBA), Charrey-Sur-Saône, France ;
[3]Agroscope, Department of Agroecology & Environment, Zürich, Switzerland

4.1 Introduction and objectives

Rut depth affects vehicle performance (e.g. rolling resistance and therefore fuel consumption) and soil quality (e.g. soil structure degradation due to vehicle-induced soil deformation). When rut depth becomes larger than vehicle clearance, immobilization of vehicles occurs. This may cause significant economic costs to logging companies and large ecological damage to the soil. Moreover, in systems of permanent skid trails, deep ruts may jeopardize future use of the skid trails, e.g. by reducing the "window of trafficability" (i.e. occasions with optimum soil moisture conditions) of such trails. Therefore, predicting the rut depth caused by one or several vehicle passes is a key to successful planning of vehicle operations in forest management.

Several approaches exist for predicting rut depth due to vehicular traffic (see e.g. Défossez and Richard, 2002; Saarilahti, 2002; Zeleke *et al*., 2007; Vennik *et al*., 2017; He *et al*., 2018). The approaches differ in complexity and requirement for input parameters. More complex models have the potential for more accurate simulations, however, they typically require more input parameters, and these input parameters may not be readily available. Here, we used a model that makes use of a so-called "mobility number", which is a dimensionless number calculated from vehicle characteristics and soil cone penetration resistance (Freitag, 1966; Turnage, 1972). This type of model was initially developed by the US military at the Waterways Experimental Station (WES) in Vicksborg, MS, USA, and is therefore also known as "WES approach". This type of model is used and applied for prediction of rut depth of off-road vehicles, especially for military operations (e.g. Jones et al., 2005) and in forest management (e.g. Saarilahti, 2002).

The objectives of the wheeling tests carried out in France during the EFFORTE project were to (i) measure rut depth caused by single and multiple vehicle passage with different forwarders on different soils, (ii) to parameterize a mobility number model based on our measurements, and (iii) to use the model to estimate critical water contents for different scenarios of forwarder size, volume of transported wood and acceptable rut depth.

4.2 Materials and methods

4.2.1 Wheeling experiments with forwarders

We carried out wheeling experiments on permanent extraction trails at three sites in France ("Fuligny", "Azerailles" and "Chaux"). At each of these locations, we made measurements of rut depth with different forwarders (different load capacity hence different weight) and for different numbers of vehicle passes. The experiments were arranged in a way that made it possible to compare the different forwarders at equal mass of total transported wood.

The soil texture was a slit loam at both sites (Azerailles and Chaux). Cone penetration resistance was measured prior to wheeling with two different devices, a constant velocity cone penetration test (Eijkelkamp penetrologger; cone size: 1 cm^2; apex semi-angle: 30°), and a dynamic (repeated hammering) cone penetration test (Panda-2 probe, UCAP2 n°26-035-16; cone size: 2 cm^2; apex semi-angle: 45°). Rut depth was measured after one and multiple vehicle passes with a custom-made frame incorporating a water level bubble. Vehicle characteristics including wheel load, tyre inflation pressure and tyre width, diameter and section height were measured for each forwarder. Soil physical properties were measured on undisturbed soil core samples collected after one and multiple vehicles passes, however, these properties were not used for the modelling described here.

4.2.2 Model for estimation of rut depth

The basic model to predict rut depth, z_n (in m), as a function of as a function of a dimensionless mobility number, *N*, and the number of vehicle passes, *n*, applied here was (Turnage, 1972; Scholander, 1974; Abebe *et al*., 1989; Maclaurin, 1990):

$$\frac{z_n}{d} = (c_1 N^{c_2}) \left(n^{\frac{1}{a}} \right) \tag{4.1}$$

where *d* is the tyre diameter in m, c_1 and c_2 are dimensionless empirical model coefficients, and *a* is the dimensionless empirical multi-pass coefficient. The mobility number was calculated according to Turnage (1972):

$$N = \frac{Q\,d\,b}{W} \sqrt{\frac{\delta}{h}} \left(\frac{1}{1+\frac{b}{2d}} \right) \tag{4.2}$$

where *Q* is the average cone penetration resistance in kPa between 0 and 15 cm soil depth, *d*, *b* and *h* are tyre diameter, width and section height in m, respectively, *W* is wheel load in kN, and δ is the loaded tyre deflection in m, which we estimated from tyre inflation pressure *p* and wheel load as (see e.g. Wijekoon *et al*., 2012):

$$\delta = 0.008 + 0.001 \left(0.365 + \frac{170}{p} \right) W \tag{4.3}$$

where *p* is in kPa. The mobility numbers of the forwarders used in our experiments are presented in Table 4.1. A low mobility number implies a high impact on the soil, i.e. larger rut depth.

Table 4.1. Vehicle characteristics and mobility numbers of the forwarders and wheel loads used in the experiments. *N* = mobility number; *Q* = penetration resistance. The lowest and highest *N* for *Q* = 1 MPa are highlighted in red (lowest *N*) and green (highest *N*). Lower *N* indicates higher impact on the soil, i.e. larger rut depth.

	Komatsu 860-4		John Deere 810-D		Ponsse Buffalo		Ponsse Gazelle		Novotny LVS520	
Tyre diameter, *d* (m)	1.31	1.31	1.17	1.17	1.31	1.31	1.14	1.14	1.05	1.05
Tyre width, *b* (m)	0.71	0.71	0.60	0.60	0.71	0.71	0.71	0.71	0.60	0.60
Tyre section height, *h* (m)	0.32	0.32	0.30	0.30	0.32	0.32	0.28	0.28	0.24	0.24
Tyre inflation pressure, *p* (kPa)	410	410	400	400	500	500	500	500	165	165
Wheel load, *w* (kN)	26	52	26.5	28	27.5	50	24	35	11.5	23.5
Loaded tyre deflection, *δ* (m)	0.03	0.05	0.03	0.03	0.03	0.04	0.02	0.03	0.02	0.04
N/*Q* =	0.0084	0.0055	0.0066	0.0063	0.0078	0.0054	0.0076	0.0060	0.0135	0.0086
N for *Q* = 1 MPa	8.39	5.50	6.56	6.33	7.81	5.40	7.61	5.98	13.51	8.61

The model parameters c_1, c_2 and a (Eq. 1) were estimated as follows. First, c_1 and c_2 were found by fitting

$$\frac{z_{n=1}}{d} = c_1 N^{c_2} \tag{4.4}$$

to our data from single vehicle passes (i.e. n of Eq. (1) equal to 1). Second, the multi-pass coefficient, a, was found by fitting (Scholander, 1974; Abebe *et al.*, 1989):

$$z_n = z_1 n^{\frac{1}{a}} \tag{4.5}$$

to our data from single (i.e. n = 1) and multiple vehicle passes (i.e. n > 1).

4.2.3 Estimation of critical water content

The above equations can be used to estimate a critical (i.e. minimum) cone penetration resistance from vehicle characteristics and the number of vehicle passes for a given (i.e. maximum acceptable) rut depth (see e.g. Section 2 for acceptable rut depths in Finland). Combining Eqs. (1) and (2), and solving for Q, yields:

$$Q = \left\{exp\left[\frac{1}{c_2}\left(log\,\frac{z_n}{dc_1 n^{1/a}}\right)\right]\right\}\left[\frac{W}{db}\frac{1}{\sqrt{\frac{\delta}{h}}}\left(1+\frac{b}{2d}\right)\right] \tag{4.6}$$

Cone penetration resistance can be expressed as a function of soil bulk density, ρ_b, and water content, θ, as (Busscher and Sojka, 1987):

$$Q = \alpha \rho_b^{\beta} \theta^{\gamma} \quad (4.7)$$

where α, β and γ are empirical parameters. Eq. (7) can be rearranged to solve for water content:

$$\theta = exp\left(\frac{1}{\gamma}(logQ - log\alpha - \beta log\rho_b)\right) \quad (4.8)$$

Finally, Eqs. (6) and (8) can be combined to obtain a critical (i.e. maximum) soil water content for a given vehicle, number of vehicle passes and a maximum acceptable rut depth as:

$$\theta = exp\left(\frac{1}{\gamma}(log\left\{\left\{exp\left[\frac{1}{c_2}\left(log\frac{z_n}{dc_1 n^{1/a}}\right)\right]\right\}\left[\frac{W}{db}\frac{1}{\sqrt{\frac{\delta}{h}}}\left(1+\frac{b}{2d}\right)\right]\right\} - log\alpha - \beta log\rho_b)\right) \quad (4.9)$$

In EFFORTE, we estimated critical water contents for different scenarios, by combining different acceptable rut depths (z_n = 5, 10 or 20 cm), different forwarders (between 5 and 15 ton load capacity) and a range of different volumes of transported wood resulting in different number of required vehicle passes, *n*. The parameters α, β, and γ were found by fitting data from Goutal (unpublished) to Eq. (7). The values for the coefficients c_1 and c_2 and the multi-pass coefficient *a* were as described in Section 3.2.2.

4.3 Results and discussion

4.3.1 Rut depth model

We developed two models, one based on the penetrologger data including French and Finnish data, and one based on Panda-2 probe data that only included data from the measurements in France. It is not possible to combine the data sets from penetrologger and Panda-2 probe, because the obtained values for cone penetration resistance is different (e.g. NABO, 2018). For the French and Finnish data set measured with a penetrologger, we found the following model (Figure 4.1a):

$$\frac{z_n}{d} = (0.231N^{-1.221})\left(n^{\frac{1}{1.562}}\right), R^2 = 0.42 \quad (4.10a)$$

and for the French data set using data from the Panda-2 probe (Fig. 1b):

$$\frac{z_n}{d} = (0.551N^{-1.323})\left(n^{\frac{1}{1.917}}\right), R^2 = 0.66 \quad (4.10b)$$

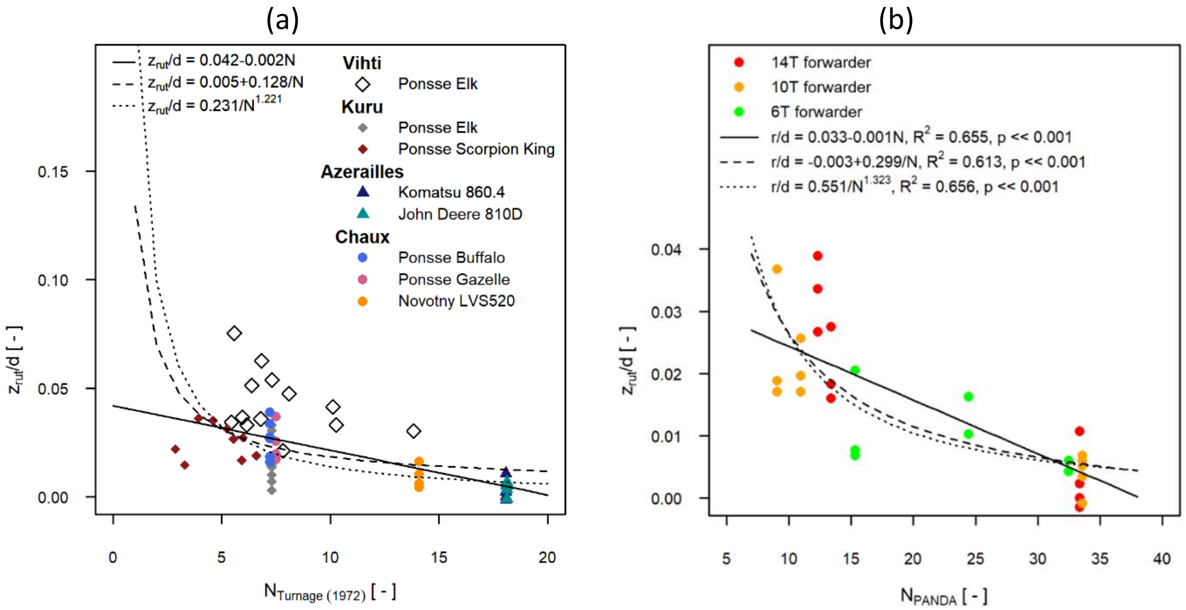

Figure 4.1. Relationship between normalized rut depth, z_n/d, where z_n is rut depth and d tyre diameter, and mobility number, N (Eq. 2), for data collected with a) a penetrologger and b) a Panda-2 probe.

The fit of Eq. (4.1) to the data is slightly better for the data set that only includes French data and uses cone penetration values obtained with the Panda-2 probe (Fig. 1b; Eq. (4.10b)) than the data including both Finnish and French data using penetrologger measurements (Fig. 1a; Eq. (4.10a)). This may be ascribed to the higher variability in soil texture and soil conditions in the latter. The values of the coefficients c_1 and c_2 found here for the model based on penetrometer data (Eq. 4.10a, with c_1 = 0.231 and c_2 = 1.221) are very similar to the coefficients of the Maclaurin (1990) model (c_1 = 0.224 and c_2 = 1.25). The values for the multi-pass coefficient, a (Eqs. (4.1) and (4.5)), found here (1.562 and 1.917, respectively; Eqs. (4.10a) and (4.10b)), are slightly lower than a = 2 that was suggested by Scholander (1974) and Abebe et al. (1989) for soft soil.

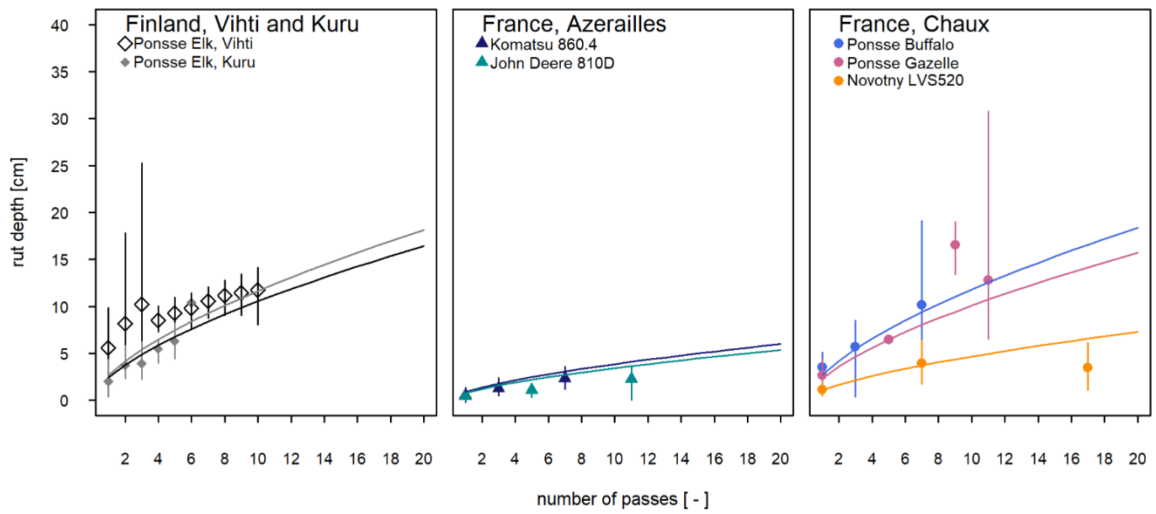

Figure 4.2. Measured (symbols) and predicted rut depth using Eq. (10a) (curves) for Finnish and French sites included in this study.

Predictions of rut depth with the model given in Eq. (4.10a) agreed well with measured rut depth (Figure 4.2). The average RMSE between simulated and measured rut depth was 0.033 m. Similar results were obtained when applying Eq. (10b) on the French data (RMSE = 0.032 m). Rut depth after one vehicle passes was well predicted except for "Vihti" where the model underestimated rut formation (Figure 4.2). The reason might be that the soil at Vihti is a clay soil (45% clay), while the other sites are silt loam (Azerailles, Chaux) and loamy sand (Kuru) soils. The development of rut depth with increasing number of vehicle passes was generally well captured by the model (Figure 4.2). The rut depths with small (John Deere 810D and Ponsse Gazelle) and large (Komatsu 860.4 and Ponsse Buffalo) machines were similar in Azerailles and Chaux after the same load (c.a. 80-90 tonnes) have been transported (11 runs for the small forwarders and 7 runs for the large forwarders). The Novotny LVS520 (very small forwarder) showed a different result. Although it performed 17 runs for 94 tonnes, the rut depth was considerably smaller than for the other two forwarders (Figure 4.2). This indicates that a really small machine could be an advantage under wet soil conditions. Most likely, the lower wheel load prevented the soil from a complete structural collapse and homogenisation. Further research is needed to better understand the interactions between load, number of wheel passes, soil initial conditions and rut formation.

We are aware that the measured rut depths shown in Fig. 4.2 were also used for parameterization of the model (Eq. 9a), which may explain the good fit of simulated with measured data. However, the data set was too small to be split into "training" and "validation" set. Therefore, the models (Eqs. (4.10a) and (4.10b)) need to be validated with independent data in the future.

4.3.2 Critical water content for forwarder traffic

The data from Goutal (unpubilshed) represent a large number of measurements, however, with a high variability (Figure 4.3a). Cone penetration resistance, Q, as a function of volumetric water content, θ, could be described as:

$$Q = 0.552\rho_b^{4.352}\theta^{-0.979},\ R^2 = 0.31 \qquad (11)$$

Here, Q is in MPa.

Due to the large variability in the measured data (Figure 4.3a), the prediction uncertainty is very high (Figure 4.3b). Moreover, the slope of the Q vs. θ function is very small at high water contents (Fig. 3a), which implies that a small difference in Q results in a large change in θ. Literature data show that the slope of the Q vs. θ function decreases with increasing θ (Vaz *et al*., 2011). Therefore, the prediction uncertainty will always be higher at higher θ. This is somewhat unfortunate, because accurate prediction of critical water contents would be most important under wet conditions. The RMSE given in Figure 4.3b is 3.8 MPa for Q(θ) and 0.46 $m^3\ m^{-3}$ for θ(Q), making any predictions practically unfeasible. Therefore, it is not feasible to present values for critical water contents.

Nevertheless, our simulations using Eq. (4.9) revealed that the critical water content decreases with increasing forwarder weight and with increasing number of vehicle passes. That is, drier soil conditions (i.e. a lower critical water content) are required in order not to exceed allowable rut depths when heavier vehicles are used, and when more wood is extracted. Moreover, the critical water content decreases with decreasing maximum allowable rut depth. For the three forwarders used in "Chaux" (Table 4.1), we simulated that similarly dry conditions were required for the two heaviest forwarders (e.g. Ponsse Buffalo and Ponsse Gazelle), while the traffic would be possible under slightly more moist conditions with the lightest forwarder (e.g. Novotny LSV520), despite the need for twice as many vehicle passes compared with the heaviest forwarder. This is in agreement with our rut depth measurements (Figure 4.2). However, the simulation results should be interpreted with care due to the large uncertainty as mentioned above. Moreover, subsoil stress was highest for the forwarder with the highest wheel load (e.g. Ponsse Buffalo), which implies a higher risk of subsoil compaction for the largest forwarder, as discussed in Section 3. Several studies show that subsoil compaction is long-lasting (several decades), see e.g. Cambi *et al*. (2015) and Schjønning *et al*. (2015).

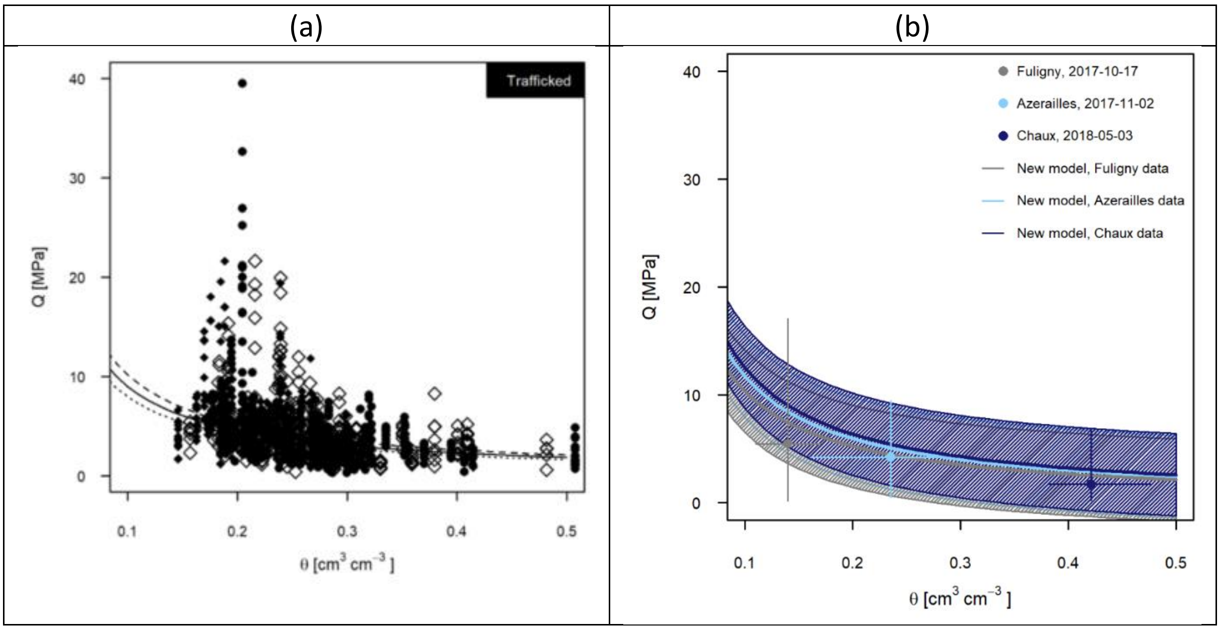

Figure 4.3. a) Measured (symbols) cone penetration resistance, *Q*, using a PANDA 2 probe as a function of soil volumetric water content, θ, at the Azerailles site (Goutal, unpublished) used for model parameterization (Eq. (11); grey curve). b) Measurements (symbols) and simulations using Eq. (10) (curves) for Azerailles, Chaux and Fuligny.

4.4 Conclusions and perspectives

We calibrated a model for estimation of rut depth based on the mobility number approach with data collected in EFFORTE. For the test conditions described in Sections 2 and 3, predicted and measured average rut depths agreed well, and the model could adequately reproduce the evolution of rut depth with number of vehicle passes. However, we could not test the model on independent data. Therefore, future work is required for validation of the model with independent data. We present a concept for deriving critical soil water contents for vehicle traffic not exceeding a maximum allowing rut depth, by combining the rut depth model with a function relating cone penetration resistance to water content. The mathematical framework (Eq. (9)) allows for calculation of critical water contents for different management scenarios (e.g. forwarder characteristics, forwarder load capacity, volume of extractable wood) and different values of maximum allowable rut depth. Because there was high variability in the cone penetration resistance data used to develop the relationship between cone penetration resistance and water content, the prediction uncertainty of Eq. (4.9) became very high, making practical recommendations with regard to critical water contents unfeasible. However, the model could be used to show that the critical water content decreases (i.e. drier soil conditions are required) when the forwarder weight increases or the volume of extractable wood increases. The smaller the maximum allowable rut depth, the drier the soil needs to be. For the three forwarder types that were used for measurements in "Chaux", we simulated a slightly higher critical water content (i.e. slight moisture conditions) for the light forwarder than the two heavier forwarders (in accordance with the rut depth measurements indicating no significant difference between the heavier machines, the small and the large forwarder, but smaller rut depth for the very small forwarder), despite the need of more vehicle passes for the light forwarder.

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5 Resilience of soil to compaction: long term effects of forest traffic on soil functioning

Noemie Pousse
Office National des Forets (ONF)

5.1 Introduction/Objectives

Understanding the natural evolution of compacted soils is essential to adapt traffic to the state of the soil and improve forest planning. The factors influencing soil natural restoration differ between European countries:

-soil biological activity: the colder the climate and/or the more acidic/coarser the soil the lower the biological activity,

-climate: the colder the climate the more intense the freezing-thawing cycles and the more variable the climate the more intense wetting and drying cycles,

-tree species composition: impact on soil protection strategies through brush mats (few brush mats built on skid trails in deciduous trees stands),

-timespan between two forest operations, being around 10-20 years in France against 20-40 years for northern countries.

The aim of task 1.5 of the EFFORTE project was to analyze the duration of the effect of heavy traffic on soil functions. The hypothesis tested was that, between two forest operations, soil functions remain impacted and do not come back to undisturbed levels.

5.2 Literature analysis

The natural processes affecting soil structure are physical (freezing/thawing, drying/ wetting; Pires et al., 2008) and/or biological especially thanks to soil fauna and roots activity (Capowiez et al., 2009; Lister et al., 2004). However, it is clearly ascertained that all these processes are affected by soil compaction. Wilpert and Schäffer (2006) reported a decrease in root density and Bottinelli et al. (2014a) reported a decrease in earthworms' populations due to heavy forest traffic. Besides, a diminution in root activity decreases soil water consumption, and hence drying intensity. A decline in water infiltration due to compaction will also decrease the drying intensity in surface soil layer and the wetting intensity in deep soil layers, both phenomena leading to less intense drying/wetting cycles (Horn, 2004).

According to the studies found in international literature, time needed for a compacted forest soil to regenerate towards undisturbed levels varies from several years to several decades. It depends on:

-soil type: fine textured soils are more prone to structural changes following wetting/drying cycles. Yet, even for these soils, regeneration may take at least 10 to 20 years (Ebeling et al., 2016). Rich soils are more prone to structural changes thanks to high biological activity, especially earthworms activity (Bottinelli et al., 2014a).

-initial impact: the more intense the impact of heavy traffic the longer the time required to regenerate soil structure (Page-Dumroese et al., 2006; Powers et al., 2005; Rab, 2004).

-climate: physical processes being linked to climate, a higher frequency of drying and wetting periods and/or a higher frequency of freezing will help soil structure regeneration.

-the soil properties studied, for example bulk density may evolve faster than macroporosity depending on the action of soil biodiversity and soil constituents (Bottinelli et al., 2014b; Ebeling et al., 2016; Goutal et al., 2013).

The small number of studies on forest soil regeneration following heavy traffic hinders analyzing the link between its duration and all the factors affecting it (soil, impact, and climate). Besides, rare studies address the long-term effect of compaction on trafficability.

Except for a few studies, soil damages after forest heavy traffic remain for period of more than 10 years, especially for soil functions related to tree growth and health (water and gas transfer, bulk density…). Therefore, in the case of uncontrolled traffic in the forest parcel (no dedicated permanent extraction tracks), soil should be mechanically soil loosened following to traffic in order to maintain forest productivity. In the case of controlled traffic (on dedicated permanent extraction tracks), medium term effect of compaction on soil trafficability should be assessed in order to analyze the need for mechanical improvement of extraction tracks between forest operations. In the following, we will focus on the duration of the effects of soil compaction on soil trafficability.

5.3 Material and Methods

During the EFFORTE project, two sites of long-term soil compaction monitoring were studied 10 years after compaction. The properties investigated were soil resistance to penetration and soil water content according to the common EFFORTE protocol.

The two sites studied were set up in northeastern France by INRA and ONF in 2007 (Azerailles site = AZ) and in 2008 (Clermont-en-Argonne site = CA) and monitored since then thanks to French public funding sources. They both display similar soils: a 50 cm thick silty loam layer laying on a clayey layer. The same forwarder (Valmet 840) about 25t fully-loaded drove on each site with an equivalent of two passes leading to mean rut depth of 5cm (soil water content close to field capacity). Heavy traffic increased soil bulk density (Goutal et al., 2012) and water logging (Bonnaud et al., 2019), disturbed porosity distribution and connectivity (Bottinelli et al., 2014b), reduced water and gas exchange between the soil and the atmosphere (Goutal et al., 2013) and soil fauna activity (Bottinelli et al., 2014a).

Several months after compaction, some structural changes could be observed (Bottinelli et al., 2014a; Goutal et al., 2013, 2012) in the first 10cm. Yet these changes were not sufficient to restore soil functioning towards undisturbed levels. Mostly they involved change from massive towards lamellar structure leading to diminution of bulk density in the trafficked plots, but porosity distribution, water and gas exchange were still impacted.

In order to investigate the effect of time following compaction on trafficability, soil resistance to penetration was measured in November 2008 (wet), June 2009 (dry), June 2010 (dry), June 2011 (dry), August 2018 (dry) and April 2019 (wet). For each measurement campaign, soil penetration resistance (PR) was measured down to 70cm using PANDA ® (15 to 30 measurements points * 3 blocks * 2 treatments (control and trafficked) * 2 sites) and soil gravimetric water content was measured down to 40cm next to panda measurements points (5 to 15 points * 3 blocks * 2 treatments (control and trafficked) * 2 sites).

5.4 Results

The impact of the forwarder traffic on penetration resistance of both sites was very variable through time. At CA, no significant effect of compaction could be detected when the soils were wet at the time of PR measurements (6 months and 10 years after compaction). When the soils were dry, the effect of compaction was significant and strong (figure 4.1). At AZ, the effect of compaction was significant when the soil was wet or dry but the difference between treatments was variable through time.

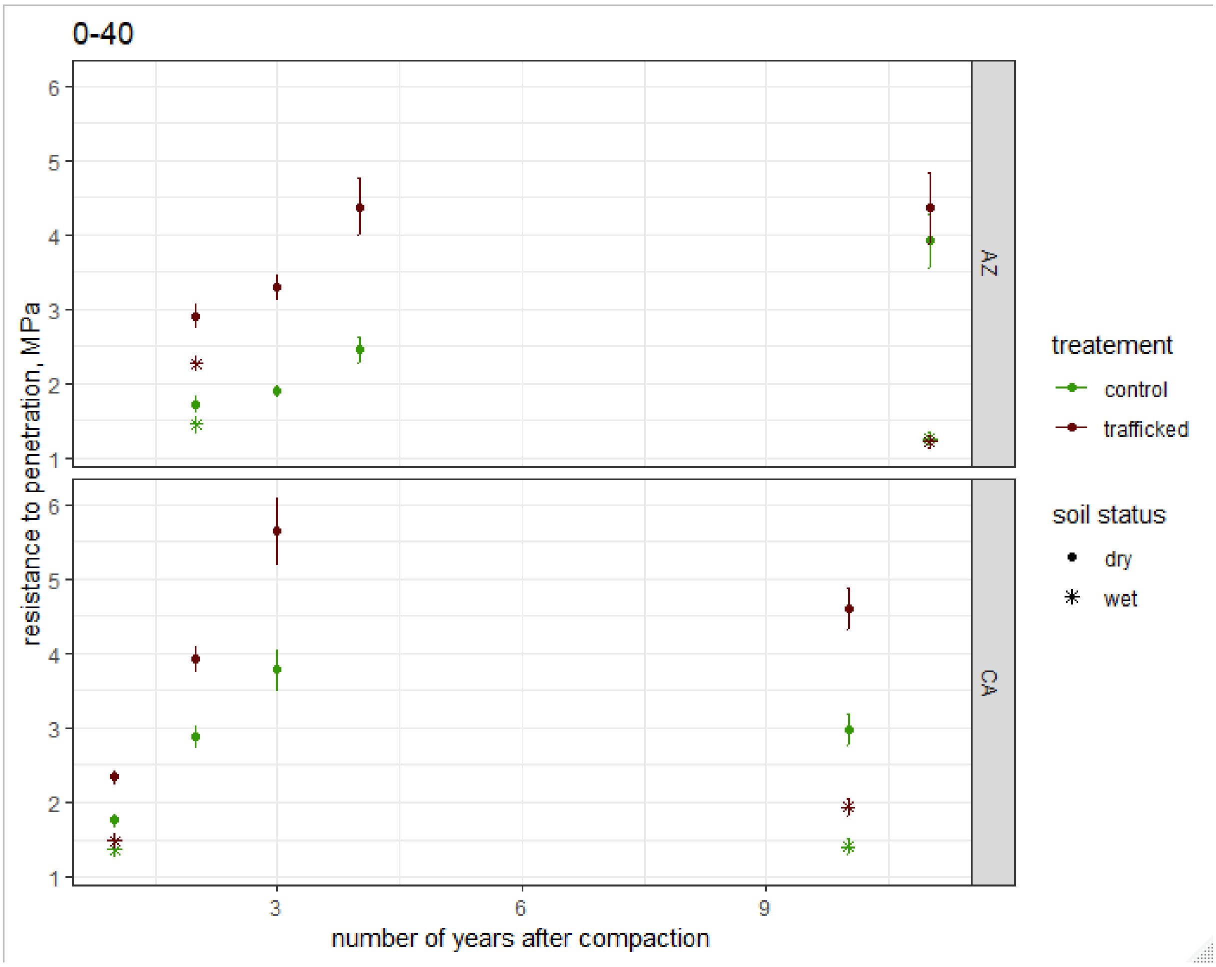

Figure 5.1. mean (dots) and standard error (vertical bar) of penetration resistance between 0 and 40cm at AZ (Azerailles) and CA (Clermont-en-Argonne) for different measurement campaign (soil status : time since compaction).

When considering only the measurements during dry periods (summers): the effect of heavy traffic on the sum of penetration resistance for the 0 to 40cm layer is significantly increasing over the years (same results for the mean and for the 40 to 70cm layer). At AZ, we can see that the difference of PR between treatments is slightly lower in summer 2018 (figure 5.1), yet the decrease is not significant.

In order to ascertain these results, the effect of soil water content on PR had to be taken into account. We tested all the relationships between penetration resistance, bulk density and gravimetric water content selected by Vaz et al. (2011), but changed the bulk density term into treatment (trafficked, control), depth and time since compaction (factors affecting bulk density). The relationship of Jakobsen and Dexter (1987, equation 5.1) gave the best fit, *i.e.* lowest AIC and BIC.

$$PR = e^{(a+b\times BD+c\times WC)} \quad (5.1)$$

With PR being the mean of penetration resistance per 10cm soil layers (MPa), a, b and c being parameters, BD being bulk density (g cm^{-3}) which was replaced by treatment, depth and time since compaction and WC being gravimetric water content (g g^{-1}).

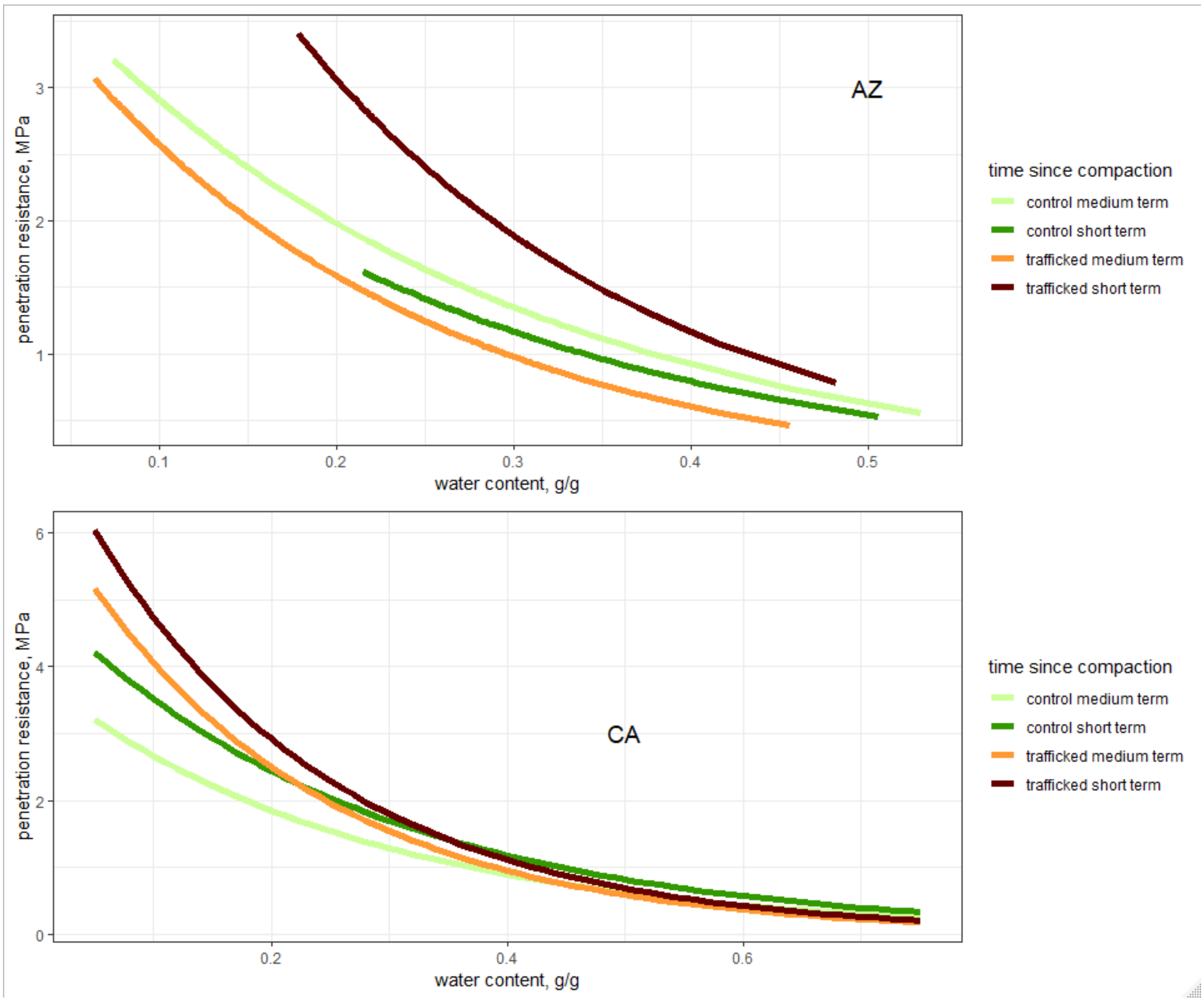

Figure 5.2. Penetration resistance as a function of soil water content (relationships fitted on mean values per 10cm layers between 0 and 40cm depth), treatment and time since compaction (short term: 1 to 3 years, medium term: 10/11 years after compaction) for the CA and AZ sites.

For both sites, compaction significantly changed the relationship between penetration resistance and water content (steeper in trafficked than in control plots, figure 4.2) and no significant effect of depth (between 0 and 40cm) could be detected. At AZ, a significant effect of time since compaction was observed with a significantly higher decrease of penetration resistance with time in the trafficked than in the control plots. At constant water content, mean PR of the 0-40cm layer is the same 11 years after compaction between trafficked and control plots. At CA, the significant effect of time led to a stronger penetration resistance decrease in the control than in the trafficked plots. At constant water content in the dry range, mean PR of the 0-40cm layer is still different 10 years after compaction between trafficked and control plots.

Without taking into account the effect of water content on penetration resistance, the assessment of recovery dynamic was inversed as soils were dryer from year to year and penetration resistance is more sensitive to difference in bulk density when soils are dry (Smith et al., 1997).

5.5 Conclusion

Penetration resistance and water content monitoring allows detection of changes between treatments and recovery dynamic. Yet it requires consequent number of measurements points and for forest soils. The large spatial variability in soil constituents may hinder easy assessment of recovery dynamic.

After two passes of a 25t forwarder, the impact on soils functioning was large (increase in bulk density, penetration resistance, water logging intensity; decrease in gas and water exchange capacity, in tree growth…). The impact on penetration resistance decreased after 10 years from 0 to 40cm depth on the less acidic site (AZ, pH of about 5). This should mean that the impact of compaction on soil bulk density disappeared in the 0 to 40cm layer in 10 years at AZ. The impact on penetration resistance remained 10 years after traffic on the more acidic site (CA, pH <4.5). Yet, we cannot rely only on PR measurements to **quantify** improvement of trafficability after compaction thanks to natural processes. Indeed, shortly after compaction PR was higher in the trafficked than in the undisturbed plots, hence trafficked plots had a probable higher bearing capacity. **Yet soil water content was most of the year higher in trafficked than in the undisturbed plots, hence trafficked plots had a lower bearing capacity most of the year**. Ten years after compaction, bulk density has decreased in the trafficked plots at AZ, hence PR and bearing capacity are lower at constant water content, but the decrease in bulk density may have improved, even if not completely restored, soil water transfer capacity. The intensity of regeneration of soil water transfer capacity is lacking to assess the dynamic of bearing capacity within each year and hence the dynamic of trafficability.

The initial impact was low as the forwarder drove only for two passes and led to 5cm ruts depth (low traffic intensity), this may explain the fast recovery dynamic of PR at AZ compared to other studies. Penetration resistance recovery dynamic following compaction may be faster than other soil properties monitored at the same sites. For example the impact of forwarder traffic on water dynamic was evolving but was still impacted on both sites 7 years after compaction, showing a probable remaining effect on infiltration properties (Bonnaud et al., 2019). We can assume that trafficability will evolve faster than soil functions related to tree growth and health, again favoring the use of permanent extraction tracks. We can also assume that trafficability can improve after compaction in 10 years for soils with pH in water above 4.5 and if the extraction tracks are only slightly impacted. Therefore, we recommend to care about initial impact when driving on permanent extraction tracks. Further studies are needed to quantify and check the reality of these assumptions.

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6 General conclusions

With typical 8-wheeled forest machines, having typical tyre pressures, risk of serious rutting significantly increases when VWC exceeds 40 %. These level moisture contents have literally only be found in fine-grained mineral soils. A methodology was introduced that calculates critical water level for each machine type individually. Unfortunately, our experiment includes too few findings and especially findings with high water content. Hence, no reliable levels for critical moisture content were able to be given.

Compaction can also occur at sandy and coarse grained soils. The heavier the mass of the machine, the more serious and permanent compaction it causes. Compaction seems to have rather permanent nature.