EFFORTE –

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

This project has received funding from the Bio Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 720712
Project duration: 1.9.2016–30.8.2019.
Coordinator: Natural Resources Institute Finland (Luke).

Deliverable D4.1. – Validation of methods for predicting strength and bearing capacity of soil		
Work Package 4 – Methodologies to predict trafficability of forest soils		
Task 4.1 – Validation of methods for predicting strength and bearing capacity of soil		
Due date	31.08.2019	
Author(s), organisation(s)	Jori Uusitalo, Matti Siren and Jari Ala-Ilomäki (LUKE), Shaun Mochan (Woodilee) Ian Stewart (James Jones & Sons), Philippe Ruch and Xavier Montagny (FCBA)	
Date of publication	31.08.2019	
Dissemination level		
PU	Public	PU
PP	Restricted to other program participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	
Nature of the Deliverable		
R	Report	R
P	Prototype	
D	Demonstrator	
O	Other	

Table of Contents

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 Deliverable D4.1: Validation of methods predicting strength and bearing capacity of soil

In the EFFORTE project, we have developed numerous methodologies and models for predicting forest soil strength and bearing capacity. The models have been thoroughly described in Deliverables D1.1 and D1.2. This report summarizes actions that focus on testing validity of these models. Tests will reveal how accurately models created can predict soil strength and bearing capacity in various soil conditions.

2 Validity of the model predicting wetness –soil strength relationship

2.1 Introduction

Strength of inorganic forest soil is known to be dependent chiefly on four main characteristics, namely grain size distribution, bulk density, soil organic content and wetness. From these characteristics, wetness is the only characteristic that varies significantly by season the remainder being more or less permanent in nature. Understanding and modelling the relationship between wetness and strength of soil is very important when assessing trafficability of soil for forest operations at certain moment.

During the EFFORTE we have created a model that predicts the relationship between these characteristics. The model has been previously described in WP1.1. In this deliverable we report the goodness of the fit of the model in the independent test data that consisted of measurements in Vihti, Finland.

2.2 Materials and methods

The original model was based on studies conducted in Jokioinen, Finland. The test data utilised in analysing the fit of the model were based on field study conducted in Vihti, Finland. The formulation of the study layout differed to some extent between the two test sites. In the modelling data, prior to PR measurements, organic topsoil (2…20 cm) was removed and the measurement started from the upmost point of the mineral soil layer. In the test data top soil was not removed.

The model that was tested is as follows:

$$InvPR015 = 0.276 + 0.0263\ VWC - 0.483\ BD + 0.852\ Clay\ class\ 1 + 0.303\ Clay\ class\ 2 \qquad (1)$$

Where

InvPR015	Inverse of penetration resistance (first 0-15 cm from the surface), MPa
VWC	Volumetric water content, %
BD	Bulk density, g/cm^3
Clay class	1=Clay content less than 10%
	2= Clay content between 10-30%
	3= Clay class more than 30%

In order to compare the model estimates created with the Jokioinen data with the Vihti test data, estimates for Penetration resistance including both organic topsoil and mineral soil were created. For the topsoil a constant strength of 0.6 MPa and constant thickness of 5 cm was given. The new variables are as follows:

$$PR020\ (MPa) = 0.25 * 0.6\ (MPa) + 0.75 * PR015\ (MPa) \qquad (2)$$

where PR020 is the estimated value for the soil 0…20 cm from the surface (includes topsoil and the organic layer).

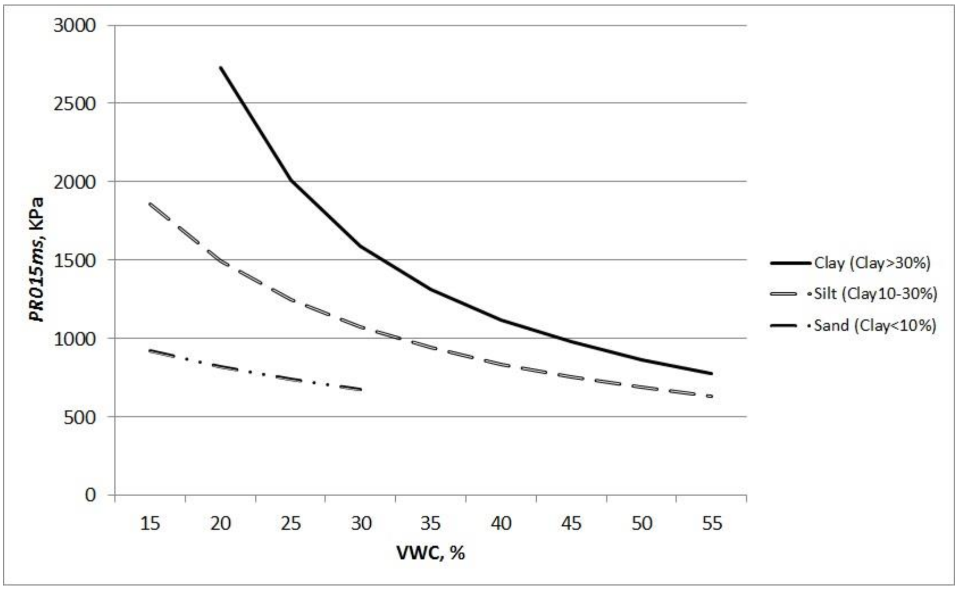


Figure 2.1. Illustration of the wetness- soil strength relationship in three different soil classes (model 1).

The main soil characteristics in the test data is summarized in table 2.1. Clay content varied 22.5-51.3%. This means that clay class 3 is applied in predictions.

Table 2.1. Mean (and standard deviation in parenthesis) of bulk density (BD), organic content (%), clay content (%) of the mineral soil samples and the thickness of humus layer (cm) in the test data set. N= Number of measurements.

BD	**Organic content**	**Clay**	**Humus layer**	**N**
g/cm^3	%	%	cm	
1.03	8.4	40.4	5.2	84
(0.2)	(2.4)	(15.3)	(3.5)	

2.3 Results

Prediction for the PR of the first 20 cm versus the measured ones are illustrated in Figure 2.2. No significant bias was found. Bias between predictions and measurements was 11 kPa (1.0%). Mean absolute error of predictions was 225 kPa (18.8%). This may be regarded as acceptable taken into account the character of the penetrometer tool.

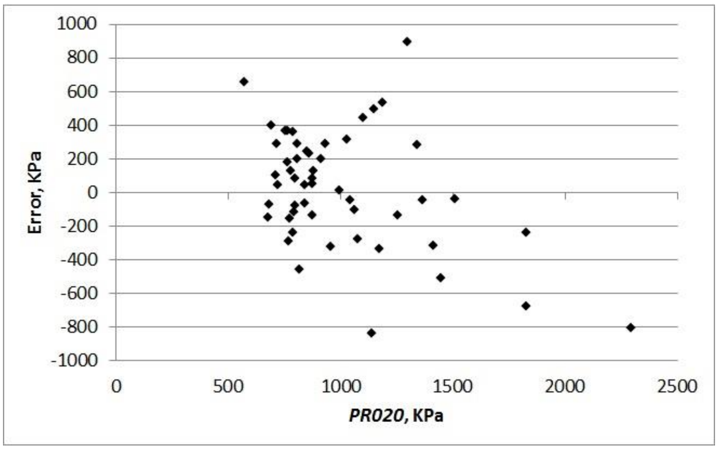


Figure 2.2. Illustration of the wetness- soil strength relationship in clayey soils (model 1).

References

Uusitalo J., Ala-Ilomäki J., Lindeman H., Toivio J., Siren M. (2019). Modelling soil moisture – soil strength relationship of fine-grained upland forest soils. Silva Fennica vol. 53 no. 1 article id 10050. https://doi.org/10.14214/sf.10050

3 Applicability of simple tools predicting soil strength and/or moisture

3.1 Introduction/Objectives

The establishment of a permanent corridor network in order to preserve soil from compaction and rutting is now common in French forest management. Forest machineries (harvesters, skidders and forwarders) must drive on these permanent extraction trails (in general implemented every 16 to 18 m, 4 m wide) in order to preserve the soil over 75 to 80% of the forest. The challenge for forest managers is to maintain the long term trafficability of the permanent extraction trails. Indeed, the time span between forest operations is more frequent than in boreal forests. Typically, forests are thinned every 6-12 years.

Two key indicators can help practitioners to evaluate the trafficability of the soil: soil moisture and/or soil strength. Collecting relevant data with expensive and complex instruments, such as the Penetrometer Panda (see table 3.2), is not realistic for practitioners. Thus, the aim of this study was to evaluate the relevance of easy to handle and quick methods of evaluation.

Within Efforte, 2 methods have been tested (description in table 3.2):

- **The screwdriver** penetration tests according to Agroscope's protocol: the operator evaluates the force (3 levels) necessary to push a screwdriver n°4, length 10 cm, entirely in the topsoil. (Diserens, 2004).
- **The tactile moisture estimation or Prosol moisture rating** of the upper soil according to the French Handbook for soil protection Prosol (Pischedda, 2009). The soil is classified into dry, fresh or humid soil.

Data were collected on 4 sites in France over a period of about 1 year. Sites and methodology are described in this report and results are presented and discussed.

3.2 Database construction: materials and methods

3.2.1 Site description

4 sites were selected with permanent logging trails and installed for the purpose of Efforte's project in broadleaved stands (see appendix Database description of the French 4 sites):

- Abbayes (ABB4) in public forest in the department of Cher, on a silty clay to clayey soil,
- Sauvigney 23 (SAU23) in a private forest in the department of Haute-Saône on a silty sandy soil,
- Verrière du Grosbois 6 (VDG6) in public forest in the department of Doubs, on a silty soil,
- Verrière du Grosbois 11 (VDG11) in public forest also in the department of Doubs, on a silty soil,

Table 3.1. Sites' main soil characteristics.

Site	Depth (cm)	Particle size mass distribution (%)					pH	Carbon organic (g/kg)
		Clay (< 2µm)	Fine silt (2-20µm)	Coarse silt (20-50µm)	Fine sand (50-200µm)	Coarse sand (200-2000µm)		
ABB4	5-15	**41**	31	10	9	8	5.35	101.36
ABB4	15-25	**52**	25	9	8	6	5.29	39.13
ABB4	25-35	**62**	21	7	6	4	5.39	17.22
SAU23	5-15	13	32	21	**28**	**7**	4.61	not measured
SAU23	15-25							
SAU23	25-35							
VDG6	5-15	27	**42**	23	5	3	4.55	86.52
VDG6	15-25	27	**43**	24	4	2	4.72	10.18
VDG6	25-35	27	**43**	24	4	2	4.72	10.18
VDG11	5-15	22	**44**	19	4	11	4.80	45.70
VDG11	15-25	26	**43**	19	3	9	4.52	29.05
VDG11	25-35	26	**43**	19	3	9	4.52	29.05

On each site, 10 plots were implemented: 5 on the permanent skid trails named T for Trafficked and 5 in the undisturbed stand named C for Control. Bulk density was measured at 3 different depths (5-15 cm, 15-25 cm, 25-35 cm). 120 soil samples were extracted: 1 per plot and depth and thus, 5 per depth and modality (T or C). Soil samples were collected by a rigid metallic cylinder (100 cm^3) and transported to the laboratory.

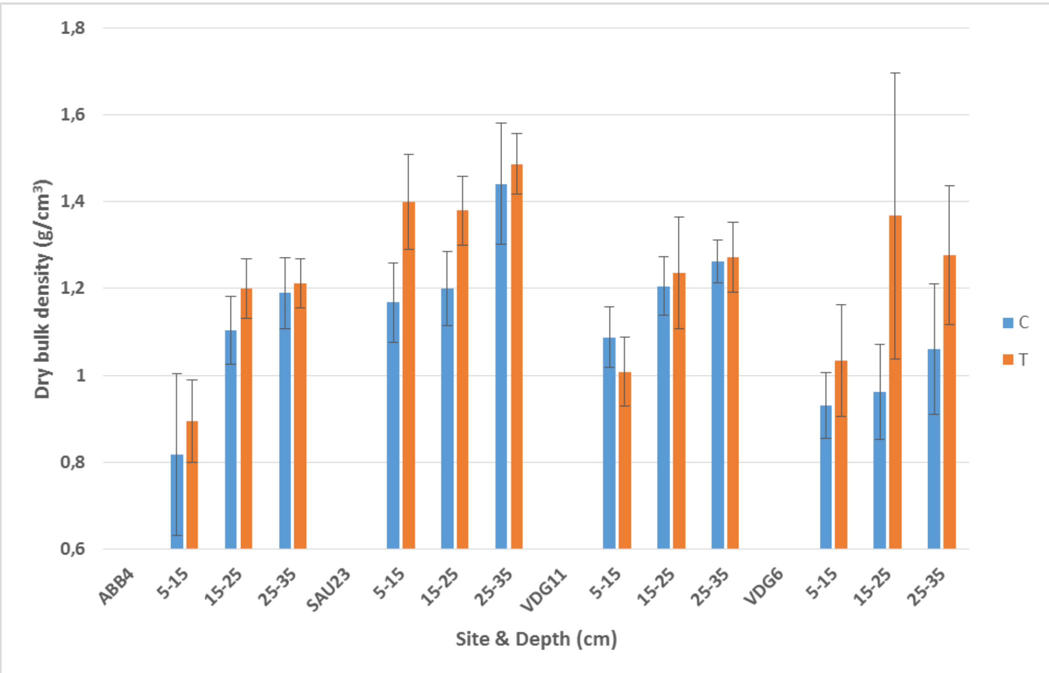


Figure 3.1. Dry bulk density (mean and confidence interval of 95%) for the 4 sites at 3 depths for permanent extraction trails (orange bars) and undisturbed soil (blue bars).

Dry bulk density values on the permanent extraction trails (T) are always higher than on undisturbed soil (C) due to previous traffic on these trails (figure 3.1). However, there is one exception for VDG11 (depth 5-15) and this is linked to the fact that these trails have scarcely been circulated in the past.

For VDG6, differences between T and C for the deep layers (15-25 and 35-35) are very high (respectively 0.405 g/cm^3 and 0.216 g/cm^3, corresponding to higher previous compaction due to heavy traffic. For SAU23 there are also high differences between T and C but located in the topsoil.

3.2.2 Periodic data collection

Data were collected at 6 different dates (from January 2018 until March 2019) corresponding to very varying soil moisture situations (figure 3.2) according to the protocol described in table 3.2. The driving force rating scores for the 10 cm long screwdriver and the tactile moisture evaluation are compared to PR 5-15, which is the sum of the penetration resistance (PR) measured for the depth 5 to 15 cm taken with the Panda device, considered as the reference.

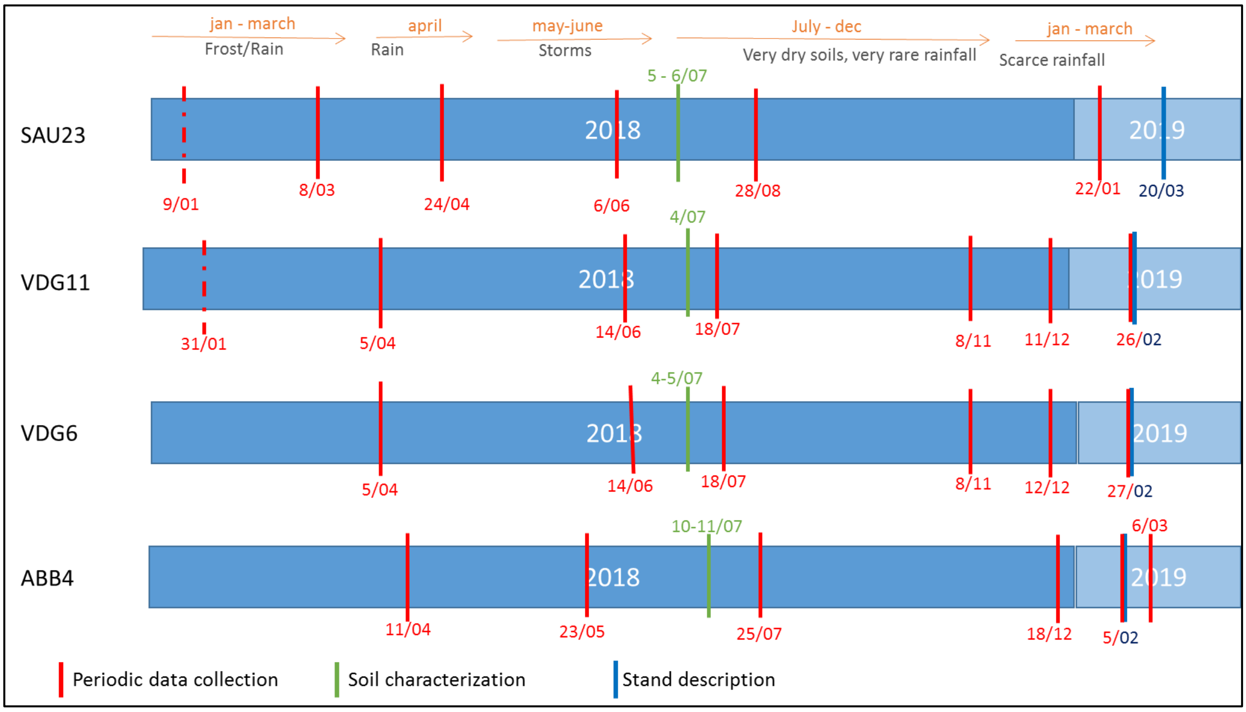


Figure 3.2. Data collection timetable

Table 3.2. Data collection protocol

Data	Device	Depth	Method
Cone Penetration Resistance (PR), MPa	Penetrometer Panda-2 probe, UCAP2 n°26-035-16; cone size: 2 cm^2; apex semi-angle: 45°, cone 2cm^2 *Note that PANDA's PR values are different from those taken with a penetrologger but curves and global results are similar.*	0-60 cm	Driving the rod in the soil with a hammer, cm per cm with automatic recording of resistance and driving depth. It's a dynamic (repeated hammering) cone penetration test. One measurement per plot.
Pushing force rating	Screwdriver n°4, length 10 cm	0-10 cm	Pushing the screwdriver in the topsoil over its entire length Three measurements per plot: Score 1 (soft soil) : Fits in by holding it with 2 fingers; thrust force < 5 kg Score 2 (intermediate soil) : Pushes in by holding it in full hand, positioned laterally; thrust force between 5 and 8 kg Score 3 (hard soil) : You must apply strong pressure by holding the screwdriver in your hand to push it in; thrust force > 8 kg The operator's calibration on a weighing scale is required.
Prosol moisture rating	By touch	0-20 cm	Taking a soil sample with a spade at depth 0-20 cm, tactile moisture estimation. Prosol defines the limit between dry, fresh and wet soil through the log of pressure (pF) One measurement per plot: Score 1.5: Dry soil, (pF) pF > 3.5 Score 3.5: Fresh soil, 2.5 < pF ≤ 3.5 Score 5.5: Humid soil, pF ≤ 2.5 Soil behavior for different humidity and soil textures are described in Prosol. The operator's calibration is required with soil samples.

3.3 Results

3.3.1 Relationship screwdriver penetration test and PR (Panda)

When comparing the averages of sum of PR 5-15, there are significant differences between screwdriver scores 1, 2 and 3 for almost all the sites (figure 3.3 and table 3.3). Yet PR 5-15 per screwdriver score is highly variable. Thus, for a given Panda measurement, an operator can have any screwdriver measurement value if the measurement is only done once.

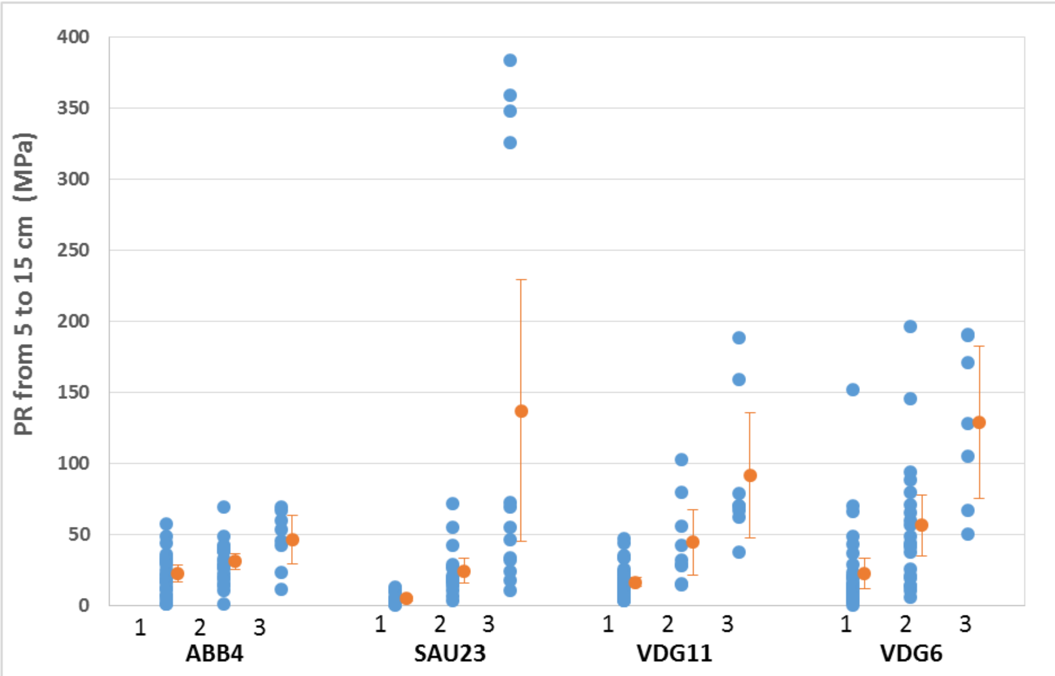


Figure 3.3. Penetration resistance for depth 5-15 cm gathered by score for the screwdriver penetration test (1, 2 or 3): individual measurements (blue dots), mean and confidence interval of 95% (orange dots and bars). The 3 scores for the screwdriver penetration test for each site correspond to the different measurement periods with various soil water content (presented in figure 3.2).

Table 3.3. Anova analysis to compare within each site the average values of PR5-15 for the different scores. Different letters (a,b,c) added to PR5-15 show statistically significant differences within each site ($p < 0.05$).

Site	Score	PR5-15 (MPa)
ABB4	3	46.5 a
	2	31.1 b
	1	22.6 c
SAU23	3	136.8 a
	2	24.4 b
	1	4.7 b
VDG11	3	91.6 a
	2	44.4 b
	1	16.4 c
VDG6	3	128.7 a
	2	56.3 b
	1	22.6 c

The screwdriver penetration test can be a good predictor of PR of the topsoil in many sites (significant differences for all sites except for SAU23 scores 1 and 2), but as there is a high variability in individual measurement. Thus, the recommendation for forest practitioners is to multiply the test per relevant zone on the logging site. This is realistic as this test is quite easy and rapid to implement. However, the screwdriver penetration test performed on his own does not allow to evaluate soil moisture, an important factor of soil strength.

3.3.2 Relationship tactile moisture estimation according to Prosol and PR (Panda)

It is well documented that PR has a strong relationship with moisture content. For wet soils (score 5.5 of Prosol rating, see table 3.2), i.e. beyond field capacity, PR 5-15 are always very low (< 50 MPa, mean 18.5 MPa). But in dry conditions (score 1.5) it varies at lot (figure 3.3). In fact, PR is also closely linked to bulk density and grain size distribution. Thus, a dry loose soil has a low PR 5-15 MPa even in dry conditions (e.g. VDG6 for undisturbed soil C, mean = 27 MPa).

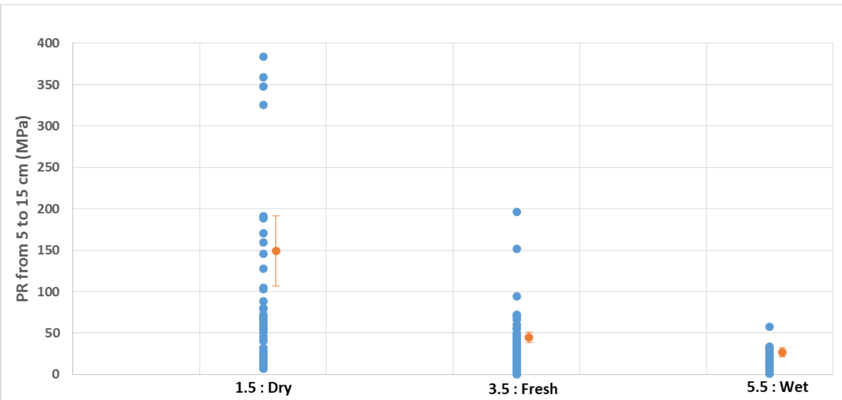


Figure 3.1. Penetration resistance for depth 5-15 cm gathered by score for the soil moisture: individual measurements (blue spots), mean and confidence interval of 95% (orange spots and bars) for all sites

The tactile moisture estimation is a very good soil strength predictor for all 4 sites when soils are being diagnosed as wet (score 5.5). However, the intermediate note (score 3.5), which corresponds to a fresh soil, has a mean PR 5-15 value of 39 MPa and a relatively large amplitude, linked to the soil characteristics described beforehand. Determining whether a soil sample is fresh is not always easy, because the range of water content for a sample to be considered fresh is very narrow (see table 3.4).

Table 3.4. Volumetric Water Content (VWC) thresholds between dry, fresh and humid soils. These VWC were determined using pedotransfer function from Bruand & Al (2004) according to the sites' soils characteristics and Prosol's pF (see table 3.2)

	VWC		
	Dry	Fresh	Humid
ABB4	< 30%	From 30% to < 37%	≥ 37%
SAU23	< 13%	From 13% to < 27%	≥ 27%
VDG11	< 20%	From 20% to < 29%	≥ 29%
VDG6	< 20%	From 20% to < 29%	≥ 29%

To improve diagnosis in intermediate conditions, it is essential to calibrate oneself regularly (with identified soil samples) so the operator has a higher accuracy of assessment.

3.3.3 Conclusion/discussion: combination screwdriver penetration test and soil moisture estimation according to Prosol for improved trafficability diagnosis

To contribute to a more relevant decision support tool, it is proposed to combine Agroscope's recommendations (screwdriver resistance) and Prosol's recommendations (moisture) (see colours in table 3.5). This should lead to better diagnosis, particularly for the intermediate category "fresh".

In table 3.5, you will find all the readings (screwdriver score and Prosol's tactile score for each plot) taken over a period of more than one year at the 4 sites. It should be noted that for compacted soils, i.e. important difference between T and C regarding bulk density (figure 3.1) the screwdriver penetration test has a higher score, as soil is more dense. For example, for VDG6 and SAU23 in fresh conditions (moisture score 3.5), 24 data have been assessed with score 2 and 7 with score 1, while for control, all 37 data were evaluated with score 1.

Table 3.5. Combination of screwdriver penetration score (column) and soil moisture score (rows) for all 4 sites (230 data) and trafficability on fine grained soils for conventional wheeled logging machines: green trafficable, orange trafficable under certain conditions, red not trafficable

(230 data)		Screwdriver penetration score of the topsoil (0-10 cm)		
		Score 1: soft soil	Score 2: intermediate	Score 3: hard soil
Moisture score of the topsoil (0-20 cm)	1.5: dry	6	18	28
	3.5: fresh	82	47	8
	5.5: wet	33	8	0 (should not be possible)

Accuracy of the diagnosis could be improved in multiplying the screwdriver test and in improving operator's capacity to determine soil moisture accurately. In both cases, operator's calibration (and training) is mandatory.

Combining the screwdriver penetration test with the soil moisture estimation, both easy to implement for a practitioner, should allow the relevancy of the diagnosis of the load-bearing capacity of the soil, and thus the trafficability in fine grained soils. For sites, where there is high probability for a water table to be present below 50 cm, additional investigation has to be made, as described in Prosol (drilling a hole with an auger to check the water table depth, no traffic for water table depth at < 50 cm).

Furthermore, when soil water content increases, PR decreases only slightly (see chapter 4 of D1.2). Therefore PR is maybe less sensitive to water content variation in the fresh to humid water content ranges than screwdriver's or Prosol's tactile test. The chosen reference for soil trafficability should be further studied, the easily accessible field tests being perhaps more relevant for wet soil conditions.

This diagnosis method can now be implemented on several logging sites to be validated content-wise and regarding its practical implementation.

3.4 References

Diserens, E., Spiess, E., 2004, Interactions entre train de roulement et sol en grandes cultures (in french), Agroscope Rapports FAT, 14p.

Pischedda et al, 2009, Pour une exploitation respectueuse des sols et de la forêt "Prosol" (in French), ONF-FCBA, 110p.

4 Validity of the models predicting rutting

4.1 Predicting bearing capacity of forest soil in Scotland with the models created in Finland

4.1.1 Introduction

Scotland is ideal for tree growth, thanks to its mild winters, plentiful rainfall, fertile soil and hill-sheltered topography. The forest area is dominated by planted non-native conifers such as Sitka spruce, Lodgpole pine, Norway spruce and Douglass fir. Spruce forests typically situate on fertile hillsides. Planted forests have typically been ploughed which means that the proportion of organic content in the mineral soil layer is relatively high and bulk density is relatively low.

Winters are rather mild. Snow cover may stay from couple of weeks to two months in mountainous regions but due to relatively mild temperatures, forest soil does not freeze properly. It means that forest soils are literately saturated during winter time.

During the springtime of 2018, a field trial was arranged in the Knockespoke forest in Aberdeenshire. The field trial aimed at investigating how well the models developed in Finland can predict bearing capacity in Scottish conditions.

4.1.2 Materials and Methods

The study was carried out on a test track that was 40 m long. The test track was divided in eight 5 long blocks. Within each block six measurement points were marked on the ground. The measurement points were placed along the planned trails of the machine; 0.5, 2.5 and 4.5 meters from the starting point of the plot (Figure 4.1).

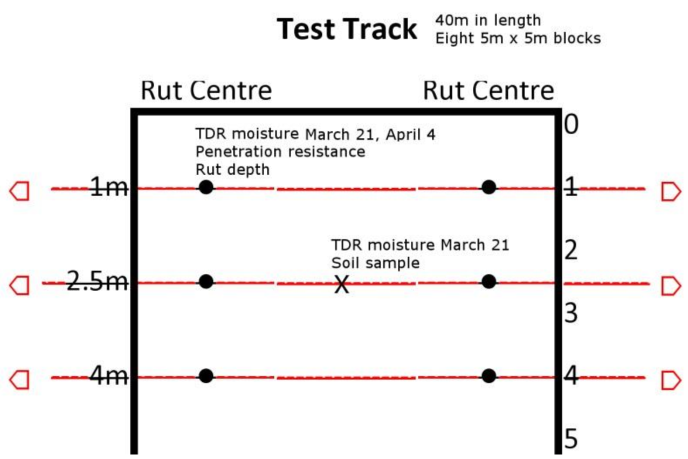


Figure 4.1. Layout of the study design in Knockespoke forest.

Prior to driving test, Penetration resistance (PR) of all six measurement points within each block was measured with the Eijelkamp Penetrologger 0615SA penetrometer consisting of a 11.28 mm diameter (1 cm^2), 60-degree cone. At the same time, volumetric water content in the soil was measured with the The volumetric water content (VWC) was measured with the FieldScout TDR 100 –soil moisture meter with two 7.5 cm long rods.). Prior to these measurement of VWC organic topsoil (2…20 cm) was removed and the measurement started from the upmost point of the mineral soil layer. Thickness of 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.

Test drives were conducted during two periods in the spring of 2018. Harvesting of the test track was carried out with 8-wheeled JD 1270E in March 21. Due to extensive snowing, forwarding with the 8-wheeled JD1110G was postponed to April, 4. Both the harvester and the forwarder were not equipped with the tracks nor chains. Both machines had Nokia Forest King TRS2 710/45-26.5 tyres with inflation pressure of 552 kPa. The mass of the harvester was 24 tons and the mass of the loaded forwarded varied between 28 tons to 31 tons. Forwarder drove along the test tracks loaded 5 times. Depths of the ruts (cm) were measured after the harvester pass and after each forwarder pass, separately.

The following model was tested (Uusitalo et al. 2019):

Rut depth= -35.3 + 3.86*ln(Cumulative mass) + 0.0000917*VWC^3 - 5.76*Bulk Density +1.11*Humus layer

Where
RUT= Rut depth, cm
CM= cumulative mass driven over measurement point; both harvester and forwardwer (kg)
VWC=Volumetric water content (%)
BD= Bulk density (the first 10 cm below the surface of the mineral layer), g cm-3
Humuslayer= Thickness of humus layer, cm

Characteristics of the soil data is summarized in table 4.1. Soil organic matter is roughly 10 %. The soil may be regarded as fine-textured soil since the proportion of clay exceeds 10%.

Table 4.1. Characteristics of the soil data Knockespoke forest.

	BD, g cm-3	**VWC, %**	**Thickness of humus layer, cm**
Mean	0.79	37.2	8.6
Minimum	0.45	30.2	5.0
Maximum	1.09	48.9	15.0

4.1.3 Results

Our test in Aberdeenshire show high correlation between bulk density of soil (the first 10 cm down from the top of the mineral soil) and thickness of the humus layer. It means that sample with low bulk density (= and high organic content) are taken from a spot where plough has touched the ground and vice versa; samples with high bulk density can be found from those spots where plough has not touched the ground (Figure 4.2).

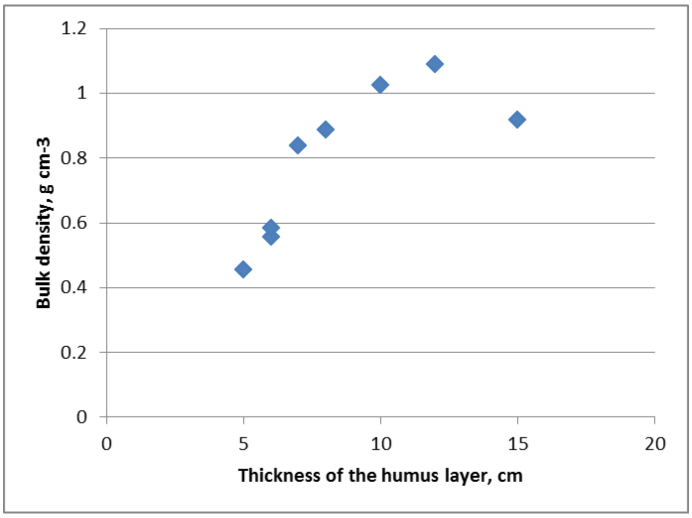


Figure 4.2. Correlation between Bulk density (the first 10 cm below the surface of the mineral layer, g cm-3) and thickness of the humus layer in study plot in Aberdeenshire.

Rut depths and prediction errors with model developed in Finland are illustrated in figure 4.3. The mean error (MAE) is relatively high (5.8 cm) but the model shows very small bias (0.22 cm).

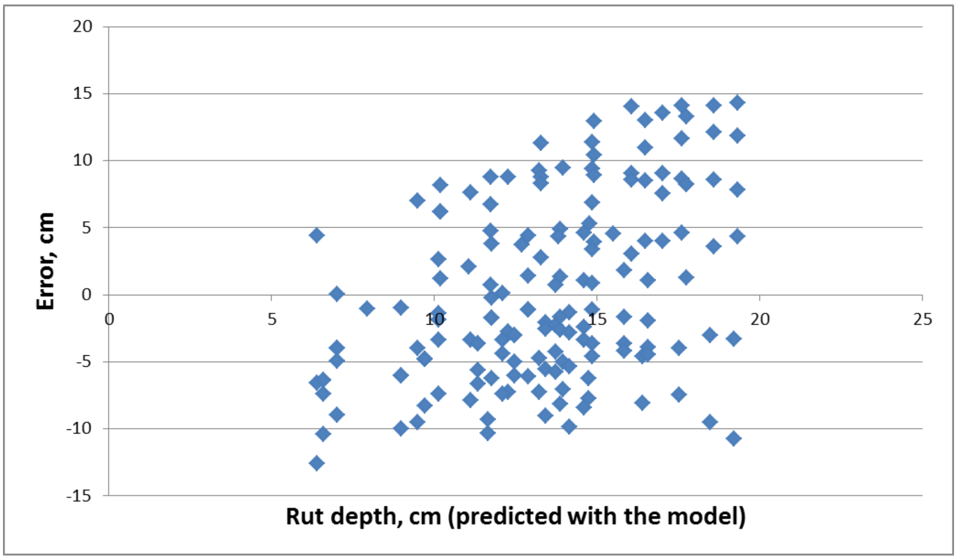


Figure 4.3. Accuracy of the model predicting rut depths in Knockespoke forest.

4.2 Predicting bearing capacity of forest soil in France with the models created in Finland

4.2.1. Introduction

Conditions in French forests differ significantly to the forest conditions in North Europe. French forests are predominantly composed of deciduous trees (two thirds of forest) although coniferous trees can also be found in mountainous areas and poor soils. The resource of oak and beech of high quality is located in the plains of the north-east and in the center of France. Those forests grow, mostly on silty soil and as the climate is wet and mild (oceanic climate in the western part and continental in the eastern), soil disturbances have to be limited to preserve soil fertility.

Compared to boreal forests, temperate broadleaves forest has almost no organic topsoil cover. Moreover, almost all forests seem to have rather high clay or silt contents. It means that soils strength is very low when soil water content is high. In the wettest conditions, forest trafficking should be avoided and during moderately wet conditions forest operations should be carried out with extra care.

Despite significant differences between the countries, the validity of the models created in Finland was tested with the French data.

4.2.2 Materials and Methods

French wheeling tests data included 9 data sets from 6 different regions. Following criteria were applied when choosing data sets for validation tests:

- 8-wheeled forwarders with 700 mm wide tyres without floating tracks
- Tyre pressure normal 4-5 bars
- Runs exceeding 7 times were excluded

General description of data set and soil characteristics are summarized in tables 4.2 and 4.3.

Table 4.2. Characteristics of the data sets chosen for the validation tests.

Site	Machine	No of pass	Rut depth mean, cm	N
Azerailles	JD810D	5	1.1	6
Azerailles	KOM 860.4	3	1.3	6
Azerailles	KOM 860.4	7	2.3	6
CHAUX-852	Buffalo	3	5.7	6
CHAUX-852	Buffalo	7	10.2	6
CHAUX-852	Gazelle	5	6.5	6
Donnement	JD 1510 E	3	5.3	6
Fuligny	JD 1510 E	4	2.6	4
Fuligny	JD 810 D	6	3.2	4

Table 4.3. Means of the main soil properties. The abbreviations are as follows: Clay%_5_10: Clay content of the soil sample taken 5-10 cm below the soil surface; Silt%_5_10: Silt content of the soil sample taken 5-10 cm below the soil surface; BD_5_10: BD of the soil sample taken 5-10 cm below the soil surface; VWC%_5_10: VWC of the soil sample taken 5-10 cm below the soil surface; SOM%_15_20: Soil organic matter of the soil sample taken 15-20 cm below the soil surface.

site	Clay %_5_10	Silt %_5_10	BD g/cm3_5_10	VWC %_5_10	SOM (%)_15_20
Azerailles	0.15	0.66	1.33	0.26	0.02
CHAUX-852	0.15	0.83	1.20	0.43	0.04
Donnement	0.29	0.62	0.84	0.45	0.09
Fuligny	0.13	0.50	1.01	0.14	0.02
Total	0.16	0.69	1.17	0.32	0.04

The following model was tested (Uusitalo et al. 2019):

Rut depth= -35.3 + 3.86*ln (Cumulative mass) + 0.0000917*VWC3 - 5.76*Bulk Density +1.11*Humus layer

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

Since temperate broadleaves forest has almost no organic topsoil cover, humus layer was set as a constant of 1cm.

4.2.3. Results

Rut depths and prediction errors with model developed in Finland are illustrated in figure 4.4. The mean error (MAE) is 2.1 cm but the model shows very small bias (0.24 cm).

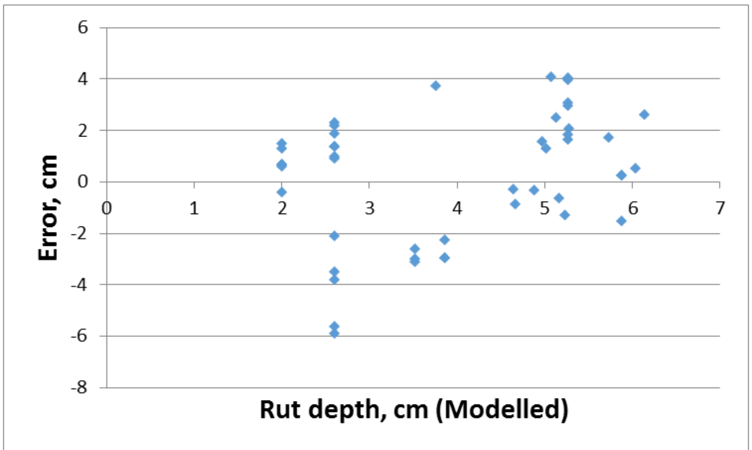


Figure 4.4. Accuracy of the model predicting rut depths in French test sites.

References

Sirén M., Ala-Ilomäki J., Lindeman H., Uusitalo J., Kiilo K.E.K., Salmivaara A., Ryynänen A. (2019). Soil disturbance by cut-to-length machinery on mid-grained soils. Silva Fennica vol. 53 no. 2 article id 10134. https://doi.org/10.14214/sf.10134

Uusitalo J., Ala-Ilomäki J., Lindeman H., Toivio J.; Siren M. 2019. Predicting rut depths induced by forest machines in fine-grained boreal forest soils. Submitted article. 10 p. + 5 tables + 6 pages.

5 Conclusions

Our investigations and validations confirm that there exists very logical relationship between soil moisture content and soil strength. Assuming that conditions are well documented or measured, this relationship seems to be rather constant, although some variation exits, naturally. Grain size distribution, especially clay content seems to be the most important characteristic that controls wetness and strength; and their relationship. Our many field studies show, that clay content 10% seems to be the most important breakeven-point in dividing soils to cohesive and non-cohesive soils. Clay content also seems to be strongly correlated with mean grain size.

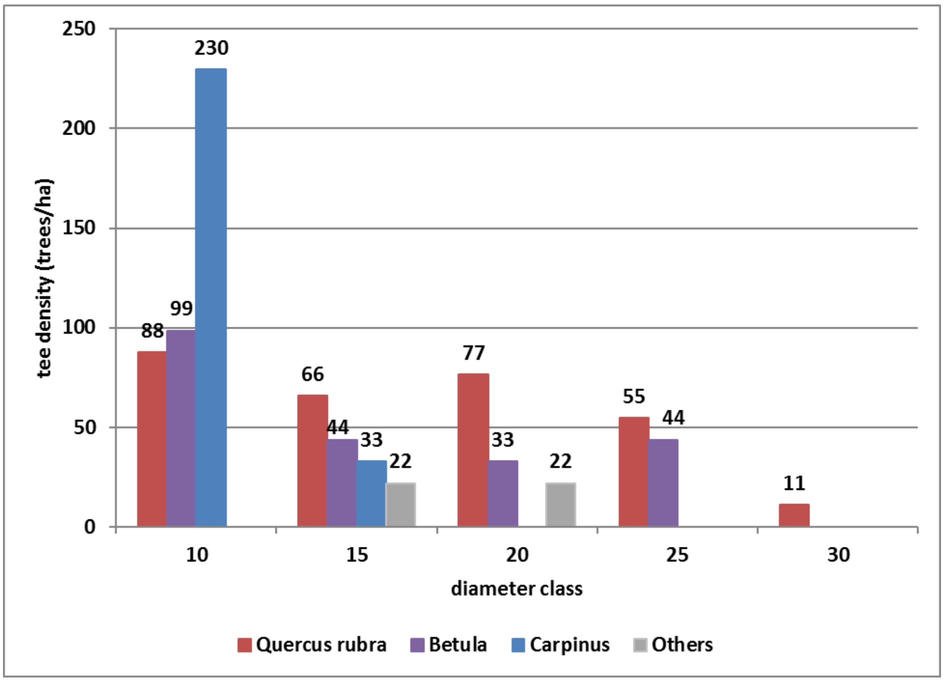
Thickness of the organic top layer of the soil varies significantly between soil types and between geography. Broadleaved forests in temperate regions seem to have much thinner organic layer than boreal forests dominated by conifer trees. Thickness of the organic top layer also correlates with organic content found in the uppermost layers of the inorganic soil and with the main grain size. All these factors have significant role when assessing strength of bearing capacity of forest soil.

APPENDIX: Database description of the French 4 sites

Sauvigney 23 (MS3)

Location		**Forestry historic**	
Forest	Private forest	**Stand**	Oak and birch
Municipality	Sauvigney les Gray	**Age of the stand**	~ 25 years
GPS coordinates	47.471514 5.725793	**Last harvesting and type of machine if known**	2015
Altitude	244 m	**Others informations**	

Stand characterization					**Date of the description:** 20/03/2019
Permanent extraction trail Set up in 2015 Distance between 2 trails**: 15,5 m** % area trafficked: **31 %** Mean width of extraction trail**: 4,9 m**					
Tree characteristics	Main crop		Subsidiary crop		
	Quercus rubra	Betula verruc.	Carpinus betulus	Others	
Species Distribution	36 %	27 %	32 %	5 %	
Dominant Height (m)	17,4	18,7	12,9	NS	
DBH (cm)	15,9	14,6	9,5	16	
Density (n/ha)	296	219	263	44	
Basal area (m^2/ha)	12,8	8,3	3,7	1,7	

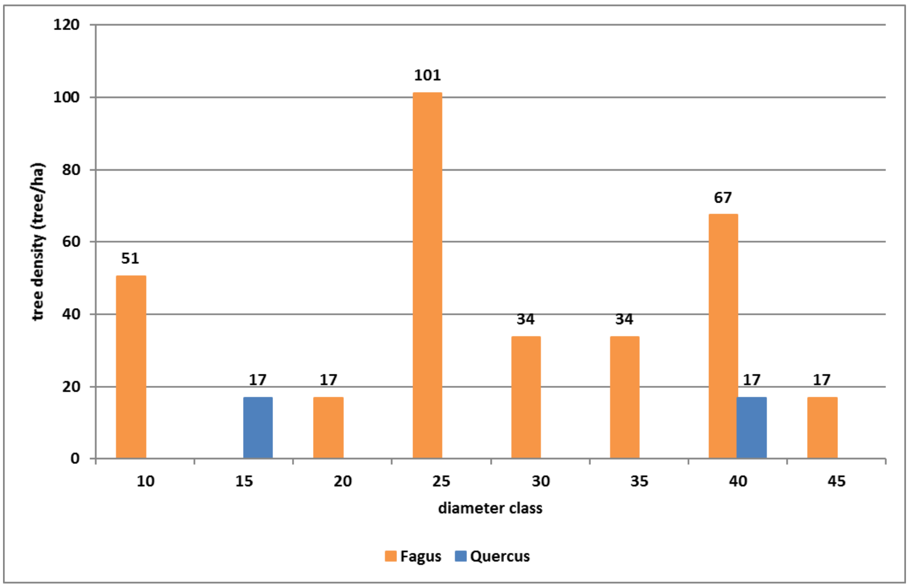


Verrière du Grosbois 6 (MS3)

Location		**Forestry historic**	
Forest	Forêt Domaniale de Verrière du Grosbois	**Stand**	Beech
Municipality	Verrière du Grosbois	**Age of the stand**	~ 50-60 years
GPS coordinates	47.20306 6.283557	**Last harvesting and type of machine if known**	2013
Altitude	592 m	**Others informations**	

Stand characterization			**Date of the description:** 27/02/2019
Permanent extraction trail Set up in 1988 Distance between 2 trails**: 18 m** % area trafficked: **19 %** Mean width of extraction trail**: 3,5 m**			
Tree characteristics	Main crop		
	Fagus sylvatica	Quercus sp.	
Species Distribution	90 %	10 %	
Dominant Height (m)	25,1	Ns	
DBH (cm)	27,7	Ns	
Density (n/ha)	320	34	

Basal area (m²/ha)	22,2	2,2	

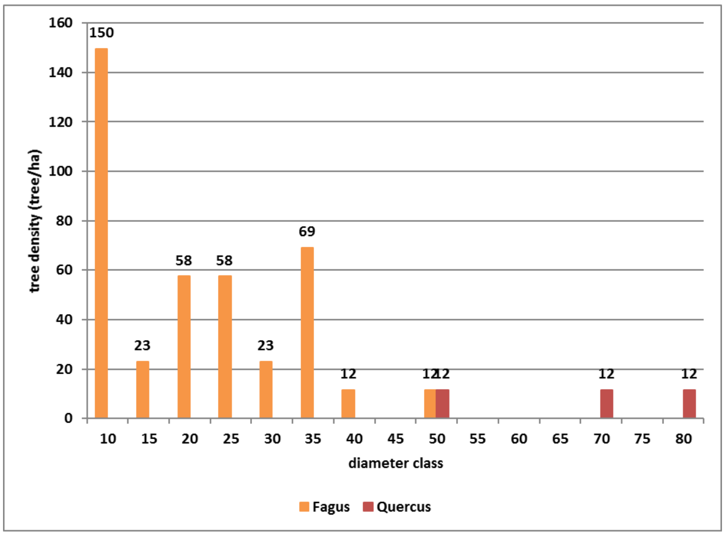


Verrière du Grosbois 11 (MS3)

Location		**Forestry historic**	
Forest	Forêt Domaniale de Verrière du Grosbois	**Stand**	Beech and oak
Municipality	Verrière du Grosbois	**Age of the stand**	~ 50-60 years beech ~ 150 years oak
GPS coordinates	47.197851 6.289887	**Last harvesting and type of machine if known**	2014
Altitude	578 m	**Others informations**	

Stand characterization			**Date of the description:** 26/02/2019
Permanent extraction trail Set up in 1989 Distance between 2 trails**: 19,7 m** % area trafficked: **16 %** Mean width of extraction trail**: 3,2 m**			
Tree characteristics	Main crop		
	Fagus sylvatica	Quercus sp.	
Species Distribution	92 %	8 %	
Dominant Height (m)	25,1	Ns	

DBH (cm)	27,7	Ns	
Density (n/ha)	320	34	
Basal area (m²/ha)	22,2	2,2	



Abbayes 4 (MS3)

Location		**Forestry historic**	
Forest	Forêt Domaniale des Abbayes	**Stand**	Oak and hornbeam
Municipality	Verneuil	**Age of the stand**	~ 65years
GPS coordinates	46.4934 2.3424	**Last harvesting and type of machine if known**	2011
Altitude	170 m	**Others informations**	

Stand characterization	**Date of the description:** 5/02/2019

Permanent extraction trail

Set up in 1977 and 1983
Distance between 2 trails: 25,7 m
% area trafficked: 11 %
Mean width of extraction trail: 2,8 m

Tree characteristics	Main crop	Subsidiary crop	
	Quercus sp.	Carpinus betulus	Acer campestris
Species Distribution	38 %	61 %	1 %
Dominant Height (m)	24,4	16	-
DBH (cm)	28	11,9	Ns

Density (n/ha)	330	533	11	
Basal area (m^2/ha)	20,9	6,6	Ns	