EFFORTE –

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

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Deliverable D1.1. – DATABASE AND MODELS REGARDING SOIL TYPE SPECIFIC BEARING CAPACITY AND HYDRAULIC TRANSFER PROPERTIES		
Work Package 1 – Methodologies to predict trafficability of forest soils		
Task 1.1 – Soil moisture behaviour and prediction Task 1.2 – Mechanical properties of forest soils		
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Nature of the Deliverable		
R	Report	R
P	Prototype	
D	Demonstrator	
O	Other	

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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 Appendix A and C).

1.3 Deliverable D1.1: Database and models for soil bearing capacity and hydraulic transfer properties

This report focuses on material and method descriptions for a number of individual studies that has, or will be done within WP1, while all the models developed within EFFORTE will be published later.

This report includes two sections:

1. Database set up in France on 12 plots to adapt an existing soil type specific hydrological model named PASTIS to forest conditions and the different calibration and validation steps of the model that will be delivered in June 2019.
2. Material, methods and models developed in Finland of “moisture content – soil strength relationship”. As a manuscript describing the experiments and models has been submitted to a scientific journal, all models will be published later.

D1.1 will be updated in July 2019.

2 Database and models regarding soil hydraulic transfer properties

2.1 Context/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.** The challenge now, is to maintain their long term trafficability. Indeed, several mechanized interventions are necessary during a silvicultural rotation (see table 1).

The specificity of soils on permanent extraction trails is their compaction, due to the intense traffic. Therefore soil moisture behaviour is different from undisturbed soils. Thus, the objective of Task 1.1 is to develop a water transfer model able to predict the moisture of compacted soil. The model will serve to establish a decision support tool to improve forest soil management and will supply the model of soil deformation developed in the second deliverable of WP1 (31/08/2019).

Table 1 : Example of operations program in French private high oak forest with hornbeam coppice for a 150-year rotation

Stand age	Operation	Storey	Product	Haulage machine	Harvested volume (m^3/ha)
25	Skid trail implementation		Wood energy	Forwarder	55
30	1st thinning		Wood energy	Forwarder	30
50	2nd thinning		Wood energy	Forwarder	30
60, 70, 80, 90, 100, 110, 120, 130	8 increment fellings	High forest	Logs	Skidder	25 / operation
			Wood energy	Forwarder	20 / operation
		Coppice	Wood energy	Forwarder	20 / operation
140	Regeneration felling	Coppice	Wood energy	Forwarder	10
		High forest	Logs	Skidder	120
			Wood energy	Forwarder	85
145	Regeneration felling	High forest	Logs	Skidder	120
			Wood energy	Forwarder	80
150	Final felling	High forest	Logs	Skidder	120
			Wood energy	Forwarder	80
14 operations in total					1 250

Water flow processes into these compacted soils must therefore be assessed. Thus, an observatory of permanent extraction trails was implemented within EFFORTE's project to monitor soil water behaviour in 7 different sites in France. This permanent extraction trail observatory provides thereby a database of hydraulic transfer properties according to several textures sensitive to compaction. The database allows to supply and test the hydraulic transfer model.

The objectives of chapter 2 are to (i) define and describe the database provided by the permanent extraction trail observatory and (ii) explain the theoretical bases of the first draft of the hydraulic transfer model. The model will be improved according to the futures results within the duration of EFFORTE's project.

2.2 Database construction: materials and methods

2.2.1 Permanent extraction trail observatory's specifications

The permanent extraction trail observatory comprises 12 different plots located in 7 sites across the Center and North-East of France (Figure 1). These plots are combined into 4 categories according to the monitoring level and the studying purposes:

- The **Instrumented sites (IS)** correspond to a group of 2 plots heavily instrumented by the National Institute for Agricultural Research (INRA) over more than ten years. Azerailles plot is related to long term monitoring of soil degradation and recovery after delibate and controlled compaction by a forwarder in 2007. Hesse plot is a long term monitoring site, since 1997, related to exchanges of carbon dioxide and vapor of water flux through the canopy. The climate and soil moisture data are used to calibrate the hydraulic transfer model.
- The **Moisture Sites 1 (MS1)** are an extension of IS, where soil moisture has been monitored on permanent extraction trails and undisturbed area since May 2017. The monitoring is automatic and continuous. Thus, it provides a strong dataset to (i) better understand soil water flow of circulated soils and (ii) supply inputs to calibrate the hydraulic transfer model. The 2 MS1 plots are close to IS plots in order to use the same climatic data and to compare soil moisture dynamic during periods of particular interest.
- The **Moisture Sites 2 (MS2)** correspond to a group of 2 sites (named Pochon and Pourlans), each composed of 2 plots distinguished by a different level of soil disturbance on the permanent extraction trails. The moisture monitoring is manual and is focused on periods after rain episodes to assess wetting and drying dynamics. The collected data will be used to validate the hydraulic transfer model
- The **Moisture Sites 3 (MS3)** consists of 4 plots: Verneuil, Verrières du Grosbois (2) and Sauvigney with more silty or sandy texture than the previous sites. These plots are deliberately less described and monitored, as the aim is to test the hydraulic transfer model in different situations with minimal characterization of the sites.

MS1, MS2 and MS3 were installed for the purpose of EFFORTE project. Their selection and the implementation of the plots took into account the state of degradation of the permanent extraction trail due to previous traffic.

Table 2: Plots composing the permanent extraction trail observatory

Category	Nb plot	Name	Soil moisture monitoring	Objectives
IS	1 1	Azerailles Hesse	Heavily instrumented	Calibrate the model
MS1	1 1	Azerailles Hesse	Automatic & continuous	Calibrate the model + study of water dynamic of compacted soil
MS2	2 2	Pochon Pourlans	Manual and punctual	Validate the model
MS3	1 2 1	Verneuil, Verrières du Grosbois Sauvigney	Manual and punctual	Test the model with less inputs
Total	12			

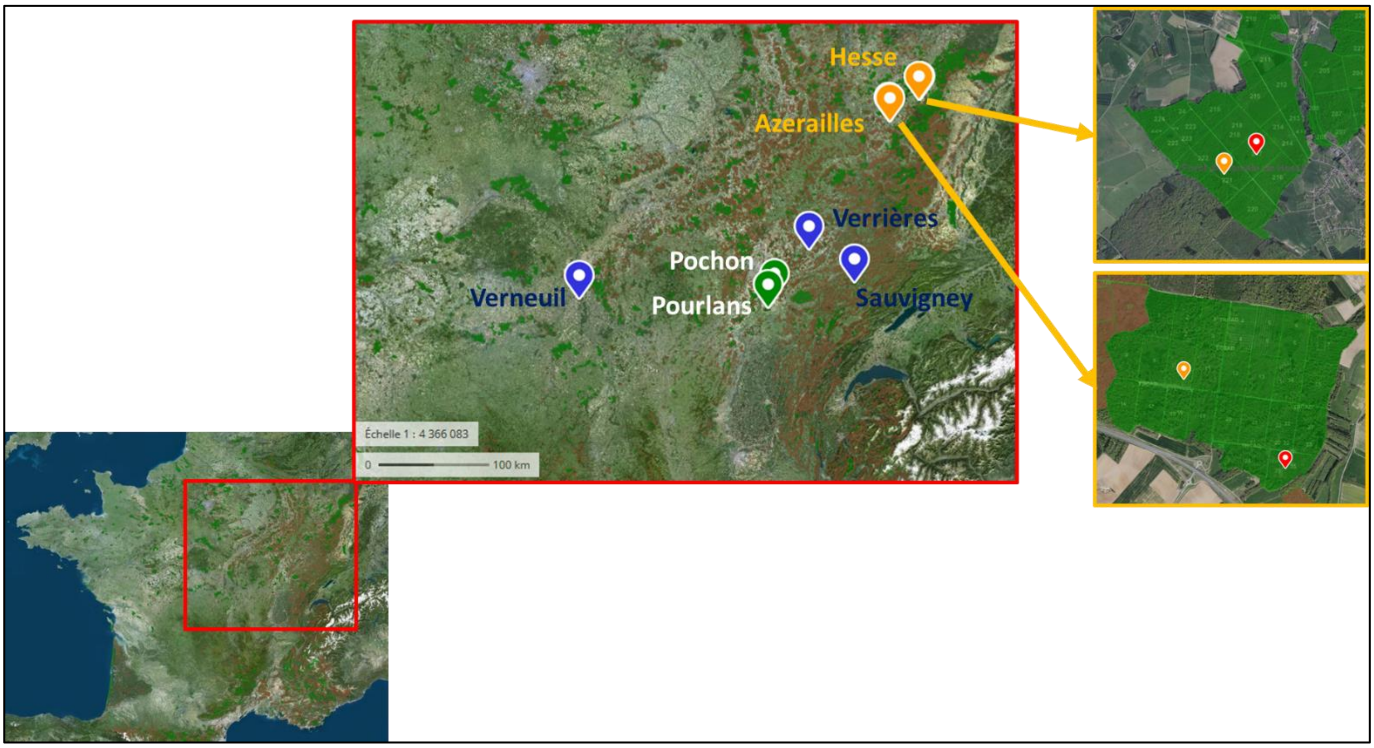

Figure 1: Location of the plots composing the permanent extraction trail observatory

2.2.2 Data collection

Several measures are performed in order to characterize the sites of the observatory and to supply the model with parameters and data. The following parameters are collected:

- Soil data: soil description, size particle distribution, organic carbon content, bulk density and hydraulic properties,
- Stand data: stand description (density, ages and species), maximum leaf area index (LAI).

Soil characterizations were performed on existing permanent extraction trails (i) (and hence compacted) named **T** for trafficked and in the stand (ii) (and hence on undisturbed area) named **C** for control, in order to compare the two treatments and assess the soil degradation due to compaction. The soil was described in pits on control and trafficked areas. Samples were taken at different depths (see table 3) to measure bulk density. The assessment of the hydraulic parameters was realized with BEST (Beerkan Estimation of Soil Transfer parameters) method developed by Lassabatère et al. (2006). This method provides respectively, shape and scale parameters from particle-size distribution analysis and single ring infiltration experiments at null pressure head, to model water retention $\theta(h)$ and hydraulic conductivity curves $K(\theta)$. To take into account forest soil heterogeneity, a minimum of four tests were done per treatment (control and trafficked) at 3 depths (0-10 cm, 15-25 cm, 30-40 cm) for MS1 and 2 depths (0-10 cm, 15-25 cm) for MS2 & MS3. The values used as model inputs correspond to the averages of the repetitions.

Detailed protocols are presented in Appendix A.

2.2.3 Permanent extraction trail observatory description

Each plot of the permanent extraction trail observatory implemented at the beginning of the project are characterized according to its category of monitoring. Appendix B presents the description of the plots in the form of a description template with the following information:

- location (forest name, coordinate, stand),
- forest historic (stand and permanent extraction trail ages),
- soil profile (detailed description and picture of the pit),
- size particle distribution per layer,
- chemical parameters (pH, organic carbon),
- soil water transfer properties.

It should be noted that missing values in the description will be collected/completed in autumn 2018.

2.3 Database overview

A summary of the collected data on the 12 plots of the observatory are presented in table 3. This database will be supplied with measurements, particularly for moisture monitoring until 31/12/2018.

Table 3: Overview of the data collected on the permanent extraction trail observatory

Variables	Devices	Replicates	Measurement repetitions in time	Sites type	Time range of the monitoring
Moisture monitoring					
Soil moisture	HS10 probes	1 to 3 per depth and treatment	1 per 30 min	MS1	15/05/2017 to 31/12/2018
	TDR probes at 0-20cm	28 per treatment	Several per drying period	MS2	01/01/2018 to 31/12/2018
	TDR probes at 0-10 and 15-25cm	5 per depth and treatment	~6 at different period	MS3	01/01/2018 to 31/12/2018
Soil temperature	T107 probes	1 probe per depth	1 per 30 min	MS1	15/05/2017 to 31/12/2018
Pressure head	MPS6 probes	1 probe on the top and the bottom	1 per 30 min	MS1	15/05/2017 to 31/12/2018
Sites characterization					
Bulk density	Soil sample	3 to 5 per depth (topsoil : 0-10, 15-25 and 30-40 cm)	1	MS1, MS2, MS3	2017
		1 to 3 per depth (bottom : 50-60, 60-70cm)	1	MS1, MS2	
Size particle distribution	Soil sample	5 fractions at 0-10, 15-25 and 30-40 cm	1	MS1, MS2, MS3	2017
pH	Soil sample	0-10, 15-25 and 30-40 cm	1	MS1, MS2	2017
Organic Carbon	Soil sample	0-10, 15-25 and 30-40 cm	1	MS1, MS2	2017
LAI max	Photography	9 pictures	1	MS1, MS2, MS3	Summer 2018
Roots profile	Inventory counts	1 grid per treatment	1	MS2	2017
Stand description	Inventory counts	1 description per plot	1	MS1, MS2, MS3	Autumn 2018
Other measurements for the task 1.2					
Penetration resistance	PANDA	5 per treatment	~3 at different periods	MS2	01/01/2018 to 31/12/2018
		5 per treatment	~6 at different periods	MS3	01/01/2018 to 31/12/2018

2.4 Hydraulic transfer model

The water transfer model will be built upon the dataset. This chapter describes the first version of the model, its futures adaptations within EFFORTE's project and the methodology that will be adopted to calibrate and validate the final version of the model. The different steps of the model construction are presented in figure 2.

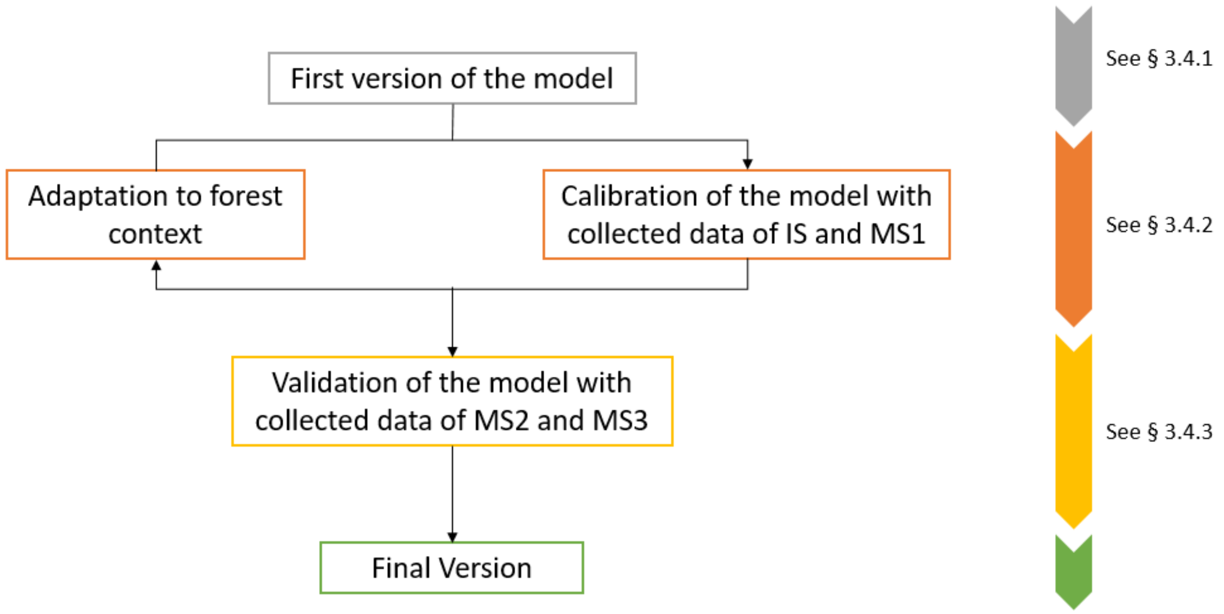

Figure 2: Steps of model building

2.4.1 Model description

Modelling is applied on the Virtual Soil platform developed by the EMMAH unit of the National Institute of Agricultural Research. The platform offers models of soil and plant interactions coupling physical, chemical and biological processes.

The model named PASTIS (Prediction of Agricultural Solute Transfer In Soils) was developed by Lafolie (1991) and improved by Findeling et al. (2007). It is a one-dimensional mechanistic model of soil-plant-atmosphere system able to simulate the water and heat transfer of soil. It is usually used in agriculture. It is robust and reliable to simulate soil water transfer, especially for soil with low hydraulic conductivity as compacted soils. The water flow modelling is built according to the combination of Darcy's law and Richard's equation. The simulated water balance is simplified in figure 3, showing the physical interactions between atmosphere, canopy, litter and soil. Main parameters and variables of the model are listed in table 4. This model is now the core of the Virtual Soil modelling platform.

PASTIS model is usually used for soil crop dynamics involving some adaptations regarding water interception and evapotranspiration partition by the canopy. The advantages to use this model in forestry is that all processes are well simulated and need small adjustments on computer programming. An effort, though, needs to be done on the calibration phase (see §2.4.2). Furthermore, in contrast with other forest models defining soil as a reservoir, PASTIS uses a more robust and accurate method thanks to Richards's equation to simulate soil water flow. Retention and hydraulic conductivity curves are necessary as inputs for the model and are measured by infiltration experiments with Beerkan method (Lassabatere et al., 2006).

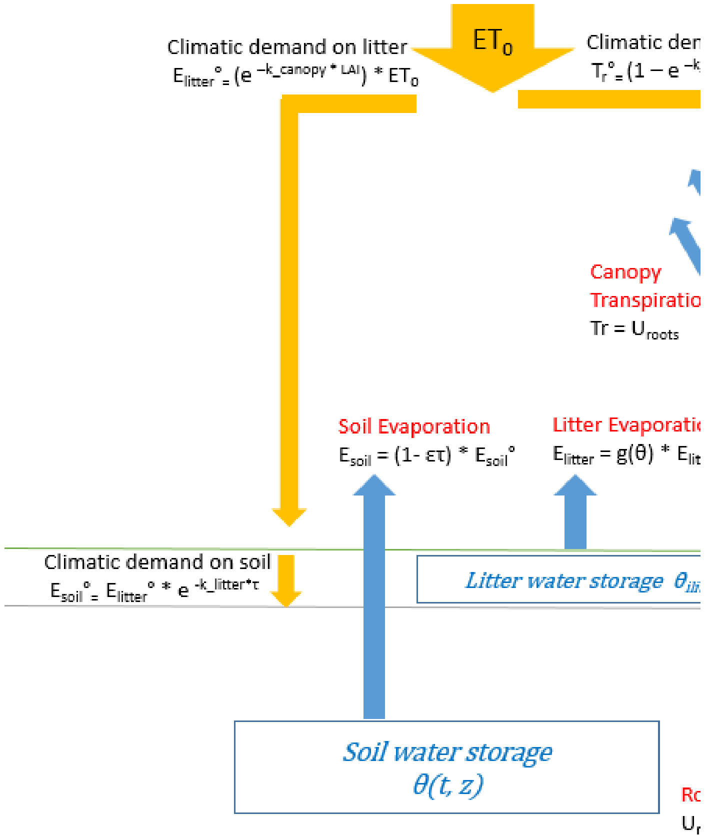

Figure 3: Simplified scheme of the water balance modelling by PASTIS model. Blue arrows correspond to water flux exchanges and orange arrows correspond to climatic demand. Processes are simulated according to the associated relations. Legend parameters is done on the table 3 and otherwise refer to Lafolie (1991) and Fideling et al. (2007)

Table 4: List of the main parameters and variables used by PASTIS model

Process	Parameters/ variables	Definition
Climatic demand		
	K_c	Multiplying factor to modify demand according to canopy type
	ET_0	Potential Evapotranspiration of Penman
	E°, Tr°	Potential Evaporation and Potential Transpiration $ET_0 = E° + Tr°$
	LAI	Leaf Area Index
	k_{canopy}	Beer's law coefficient for radiation attenuation through the canopy
Interception by the canopy		
	I_{max}	Maximum interception capacity of precipitation by the canopy
	α_{canopy}	Empirical coefficient of interception
	R_{canopy}	Part of the rainfall intercepted by the canopy
Interception by the litter		
	R_{litter}	Part of the rainfall arrived across the litter
	f(θ)	Function that decrease the absorption of the litter with the water content increasing. When the litter is saturated, the function is nul. $f(\theta) = \exp(-\alpha * (\theta_{litter\_max} - \theta_{litter\_min})/(\theta_{litter\_max} - \theta_{litter}))$
	α_{litter}	Empirical coefficient of interception
Evapotranspiration of the canopy		
	E, Tr	Real evaporation and transpiration
	a	Aerodynamic resistance of the canopy
Root water uptake		
	L(t)	Maximum length of the roots system
	α(Ψ)	Moderate function of the roots water uptake according to the hydric stress and soil water content available
	U_{max}	Maximum of roots uptake rate $U_{max} = Tr° / L(t)$
Soil and litter evaporation		
	E_{soil}, E_{litter}	Real evaporation of the soil and the litter
	$g(\theta_{litter})$	Moderate function of litter water evaporation according to the variation of the litter water content $g(\theta) = ((\theta_{litter} - \theta_{litter\_min})/(\theta_{litter\_max} - \theta_{litter}))^{\varepsilon}$
	τ	Litter covering rate
	ε	Controlled parameter on the lost water rate during evaporation
	k_{litter}	Beer's law coefficient for radiation attenuation through the litter
	ɣ	distance soil - litter
	ρ	Multiplying factor to calculate the soil water flux from the soil to the litter during evaporation period. The water flux is calculated with Darcy's law and matrix potential of the soil and the litter. This process occur for litter decomposition. The litter has no effect on real evaporation of the soil
Soil water flow		
	K_{sat}	Hydraulic conductivity at saturation
	θ_{sat}	Soil water content at saturation
	h(θ), K(θ)	Scale and shape parameters of the retention and conductivity hydraulic curves

2.4.2 Adaptation and calibration of the PASTIS model: materials and method

First step of modelling consists in improving the effects of the litter and the canopy on the water balance to adapt the model formalisms from the agricultural context to the forest context. Experimentations will allow to determine forest parameters used by processes presented in table 4:

- Regarding the litter: in the initial version of the model, the litter corresponds to a mulch composed of two layers (the first one on the top in contact with the atmosphere and the second one at the bottom in contact with the soil). PASTIS is able to model the mulch decomposition with microbiological processes. In our case, we are only interested in the capacity of the litter (i) to intercept the precipitations and (ii) to have an effect on soil evaporation. The litter will then be simplified to one layer defined with a maximum water content and a multiplying factor that reduces soil evaporation. These parameters for deciduous and coniferous litters will be measured in laboratory.
- Regarding the canopy: a device was installed on MS1 plots to assess Beer's law coefficient for radiation attenuation by the canopy. The experimental device consisted of 4 pyranometers measuring radiation under the canopy. Data were collected in the stand and permanent extraction trails for the two sites Azerailles and Hesse. The other canopy parameters (related to rainfall interception and storage) are obtained from the bibliography.
- Regarding stand phenology: evolution over time of the leaf area index (LAI) is based on BILJOU model (Granier et al., 1999). For broadleaved trees, LAI increases linearly until its maximum value 30 days after the budbreak. The same pattern is used during the leaf senescence, LAI decreases linearly from the beginning of the senescence to 30 days after. The maximum of LAI and phenology are the only parameters needed to characterize stand.
- Regarding soil water dynamics and evapotranspiration water flux: simulated flux will be compared to experimental data collected on IS and MS1 plots (evapotranspiration water flux is monitored only on Hesse IS).

In the second step, simulated soil water transfer will be compared between control and trafficked soil to better understand the impact of the compaction of the soil on water dynamics (soil wetting and soil drying from evaporation and trees transpiration). The hydric properties are obtained from in situ (Beerkan test) and laboratory measurements (Wind method).

An overview of the mean steps of the model adaptation are presented in figure 4, below.

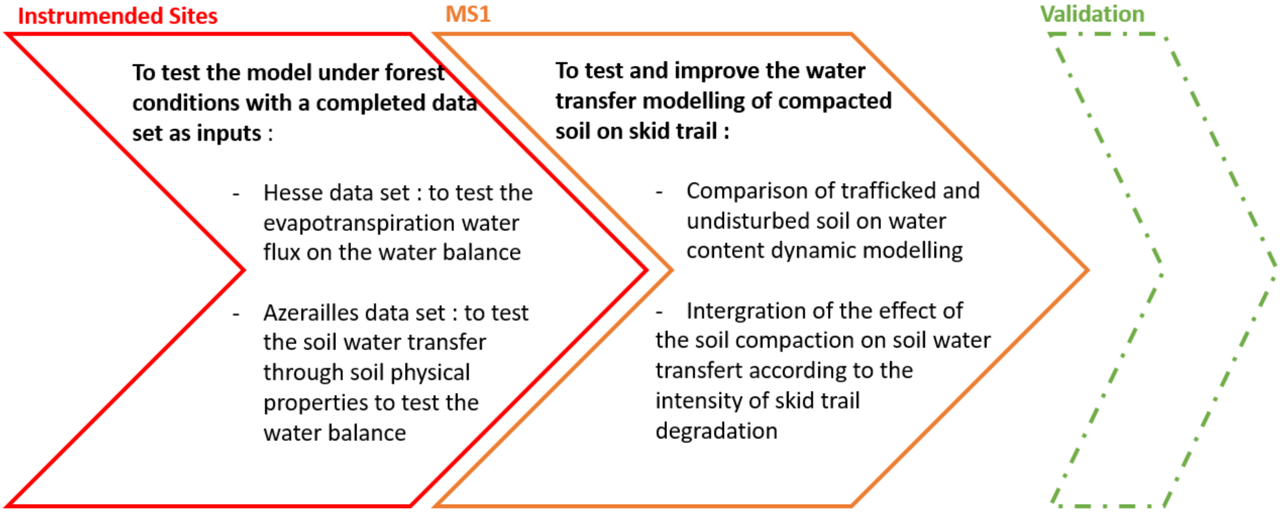

Figure 4: Description of the model adaptation and calibration steps

All the parameters (Table 4) will be adjusted in order to obtain a precise simulation compared to the experimental data. An example of the comparison of experimental data and simulated soil water dynamic is presented in figure 5. Simulated curve shows same dynamic but overestimates the soil water content and smooths some rainfall period in August and October. The gap between the two curves could be explained by a too important soil incident rainfall. It should be noted that this example is a preliminary draft of the calibration steps. More parametrization adjustments will be done in autumn 2018 to improve modelling accuracy.

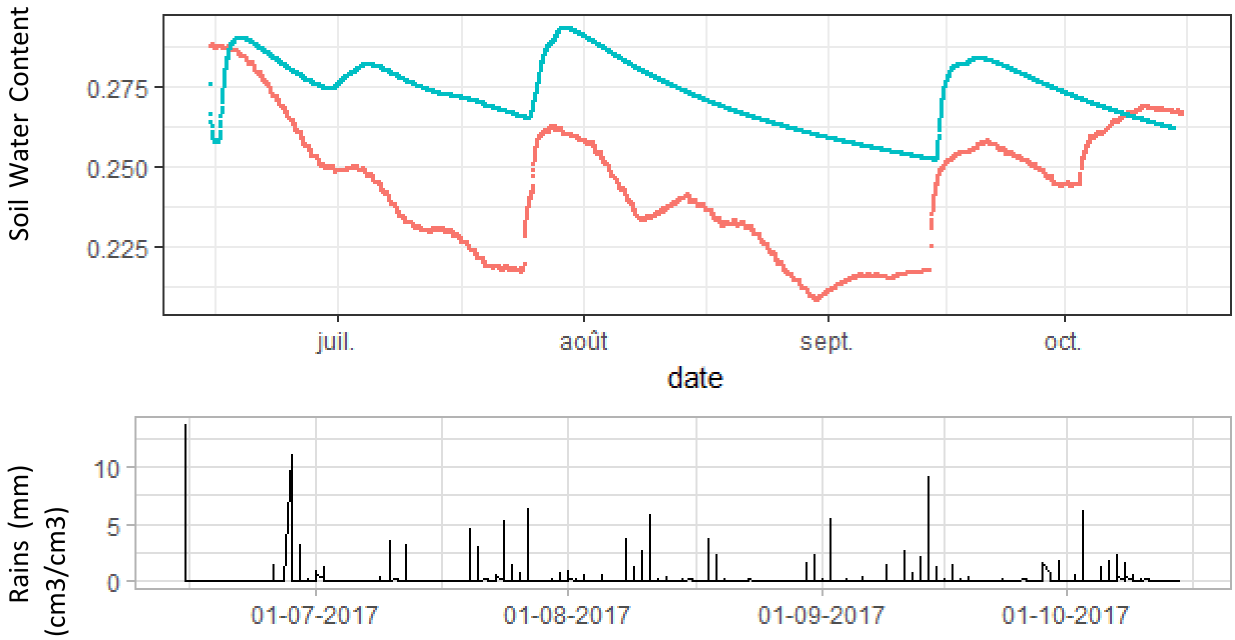

Figure 5: comparison of simulated soil water content dynamic (blue curve) with experimental data (red curve) for Azerailles MS1 at 30 cm depth of control area.

2.4.3 Model validation: materials and method

Punctual measurements performed with TDR probes on MS2 and MS3 plots will be used to validate the model. The predictive soil moisture will be compared with soil moisture measurements at different periods of soil drying, thus allowing to test the model in different pedoclimatic conditions (different geographic area, soil texture and stand).

The final version of the model will be able to predict soil moisture of permanent extraction trail to supply soil mechanical and deformation models.

An overview of the mean steps of the model validation are presented on **the figure 6** below.

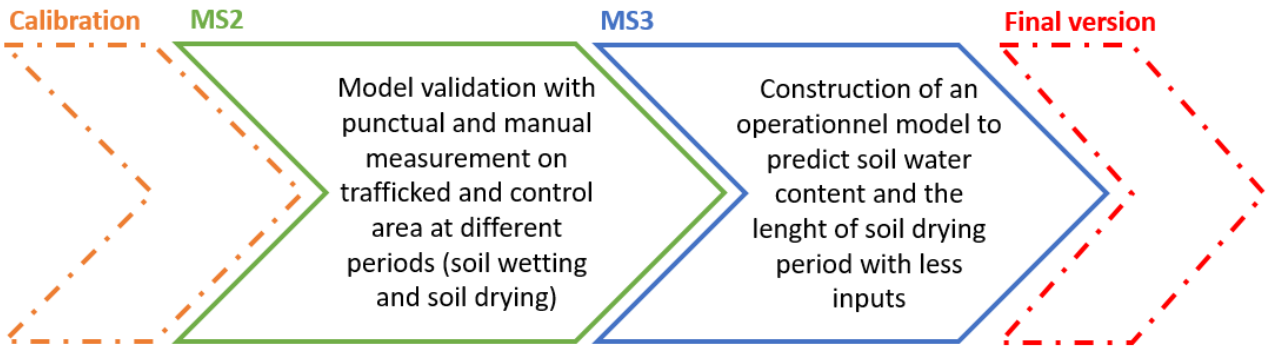

Figure 6: Description of the model validation steps

2.5 Next steps

Initial characterization of the permanent extraction trail observatory has been carried out. Data have been collected on IS and MS1 plots to test and calibrate the initial version of PASTIS model in autumn 2018. The adaptation to the forest context of the model is conducted simultaneously.

Once the calibration and adaptation steps are conclusive, then the model validation will be performed. The final version will be delivered at the beginning of 2019 and published mid-2019. D1.1 will then be up-dated at the end of EFFORTE project.

The results of the forest version of PASTIS will allow to have a better understanding of the soil drying dynamics on permanent extraction trails. Combined with deformation modelling, the results will be used as a basis for recommendations for forest practitioners.

3 Database and models regarding soil type specific bearing capacity

3.1 Introduction/Objectives

The strength of inorganic soil is most conveniently measured with a cone penetrometer. Cone penetrometer measured penetration resistance (PR) values are mainly utilized for two different purposes. First, the PR of the topsoil (generally first 10-20 cm) is generally utilized in predicting the rutting of vehicles passing over the soil. In forestry, rutting models are very useful in avoiding visual soil damage. Second, the PR can be used in measuring degree of soil compaction which is very harmful for the future growth of crops and trees. The term PR is also widely known as cone index (CI) or Cone penetration resistance (CPR).

In inorganic soils, PR is known to be controlled by the three main factors, which are moisture content, bulk density and clay content. Obviously, the proportion of organic substrate affects PR as well, but its role is thought to be more important as the clay content decreases. Most of the investigations dealing with PR – moisture content relationship has been in agricultural soils and will still lack information how the previous findings fit in forest soils. The aim of EFFORTE task 1.2 was to develop models for estimation of mechanical properties of forest soils from soil texture, soil moisture status, and forest stand, which are applicable both in boreal and temperate regions. Modelling of "moisture content – soil strength relationship" is based partly on data collected prior to EFFORTE project and partly on data collected during the EFFORTE project.

This task has greatly benefitted from the common protocol coordinated by FCBA.

3.2 Materials and Methods

Field studies were conducted on two separate forest sites in Southern Finland. The data consisted of parallel measurements of dry soil bulk density (BD), volumetric water content (VWC) and penetration resistance (PR). In Jokioinen site (blocks 1-3), the PR and the VWC measurements were carried out on 8 separate occasions during a 15 month period. In Vihti (blocks 4-5), the measurements were carried out in conjunction with the wheeling test on three separate occasions in early September, in November and in December. The whole master data set comprised 696 measurements from 84 sample plots that were grouped hierarchically into 11 columns and 5 blocks.

From each study plot a soil sample was extracted and the soil core was divided into three sections: the organic layer and two mineral soil subsamples 10 cm in length. The first mineral soil sample started from the top of the mineral soil (0-10 cm) and the second 10 cm below that (10-20cm). The thickness of the organic layer was also measured. The mineral soil samples were sealed in a plastic bag and then delivered to the laboratory for further analysis.

The volumetric water content (VWC) was measured with the FieldScout TDR 100 –soil moisture meter with two 7.5 cm long rods. The VWC readings were taken from the top layer of the mineral soil by first removing the organic layer. The mineral soil samples were analysed in the laboratory with standard laboratory procedures for bulk density, water content and grain size distribution. Prior to the particle size analysis, the content of the organic matter was determined using standard burning procedures. The TDR measurements were calibrated with soil samples extracted from the upper part of the mineral soil (0-10 cm).

Since the data had a nested structure, modelling the relationship between the moisture content and strength of soil was executed with the mixed modelling technique. The relationship was most efficiently modelled by converting the dependent variable PR to its inverse. Clay content within the soil samples were classified with two different ways. First, the soils were classified into three classes: class 1(clay content <10%), class 2 (clay content 10-30%) and class 3 (clay content >30%). Later when it was found that the behaviour of classes 2 and 3 only displayed a rather small difference, a two-class classification was constructed: class 1 (clay content <10%) and class 2 (clay content >10%). Roughly speaking the first classification divided the soils into sands, silts and clays while the second one divided the soils into sands and silty-clays.

3.3 Soil strength models

Several mixed regression models predicting PR of the first 15 cm of the soil have been created. A manuscript describing the experiments and models has been submitted to a scientific journal. As expected, the PR was controlled by the VWC, BD and clay content. The VWC is clearly the best predictor of PR and this relationship is not linear. Clay content, expressed in our models with clay classes has also significant effect on the strength behavior of the soil. The BD was also found to be an important predictor of PR but not as significant as the VWC. One of the models created to predict PR is depicted in figure 7. The model can mathematically be described as:

$$InvPR15 = 0.441 + 0.0291\ VWC - 0.364\ BD + 0.618\ Clay\ class\ 1(<10\%) + 0.183\ Clay\ class\ 2\ (10\text{-}30\%) \qquad (Model\ 4.1)$$

Where

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

While bulk density is too laborious to measure in practice prior to forest operations, as is the exact clay content, model with two soil classes (sand, silty/clayey) including VWC as the main predictor can be regarded as very appropriate for practical solutions.

$$InvPR15 = 0.120 + 0.0284\ VWC + 0.349\ Clay\ class\ 1(<10\%) \qquad (Model\ 4.2)$$

Where

InvPR015	Inverse of penetration resistance (first 0-15 cm from the surface)
VWC	Volumetric water content
Clay class	1=Clay content less than 10%
	2= Clay content more than 10%

The whole list of models created will be presented in separate database which will an appendix of the final updated deliverable.

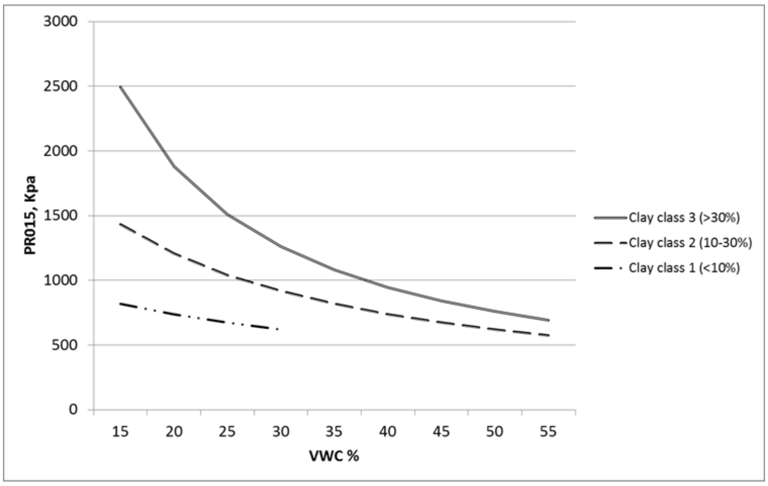

Figure 7: The penetration resistance (PR) of the soil for the first 15 cm below the ground level as a function of by volumetric water content (VWC) and clay content. (Bulk density constant 1.2 gcm-3) (Model 4.1).

3.4 Discussion and conclusions

The performances of the models created were very logical, and the results were in harmony with earlier findings. Results confirmed that PR is controlled by moisture content, clay content and bulk density. Organic content was not found to be significant in our analyses. The main reason was that the organic content had rather a small variation.

The models developed can be linked to mobility models predicting either risks of rutting or compaction, rolling resistance and thrust. While spatial hydrological modelling is taking significant steps forwards, in the future the risk of soil damage in forest operations will be possible to manage by utilizing modular moisture content - PR – soil deformation model structures. For this purpose we need specific formulas describing interaction between soil and wheel. In EFFORTE, we will employ 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.

4 Conclusions

Next steps for T1.1 will be to deliver the final model(s) regarding soil moisture behaviour on permanent extraction trail developed in France. Next step for T1.2 will be to test models developed in Finland in French forest conditions. Penetration resistance has also been collected on MS3 plots at different seasons. D1.1 will then be updated in July 2019.

Once the models of tasks 1.1 to 1.4 are calibrated and validated for European forest soils conditions, T1.5 “Resilience of soil to compaction” will assess how a small change in soil hydraulic conductivity (as can be expected during 5 to 10 years following heavy traffic) will affect soil water content prediction and hence soil mechanical properties and deformation during the following forest operations.

This will serve as a scientific basis for the development of the recommendations for knowledge-based planning of forest operations. These will be the ultimate output and deliverables to forest industry.

5 References

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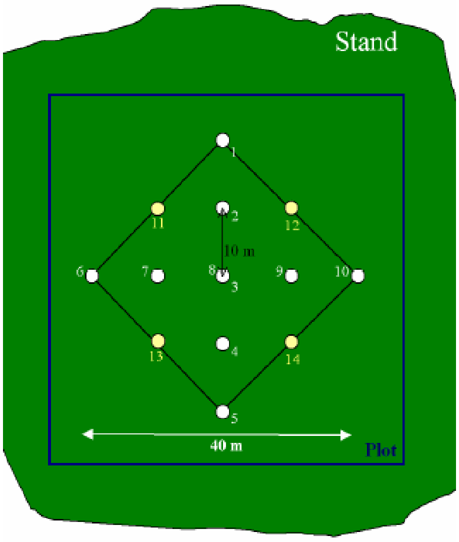
APPENDIX A: Detailed protocols for task 1.1 Soil moisture behaviour and prediction

(Extract of the common protocol)

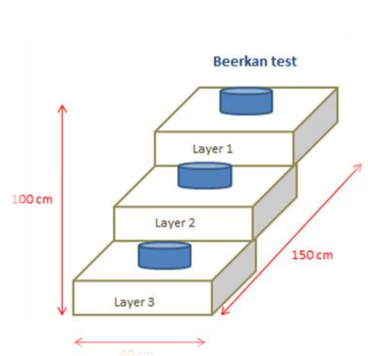
Protocol 1: Stand characterization

Objectives	Stand characterization (species, tree density, height, circumferences, budburst and senescence dates)
Method	Based on NFI inventory (IGN)
Methodological protocol	Dendrometric measurements on circular plots (radius 25m) located between 2 permanent extraction trails. Parameters collected on trees (diameter over 7.5 cm): tree species, diameter breast height (1.30 m), 10 heights per dominant class of diameter. Budburst and senescence dates are recorded.
Sites	All sites
Frequency	Once in autumn 2018 (for all data and budburst in spring 2018)

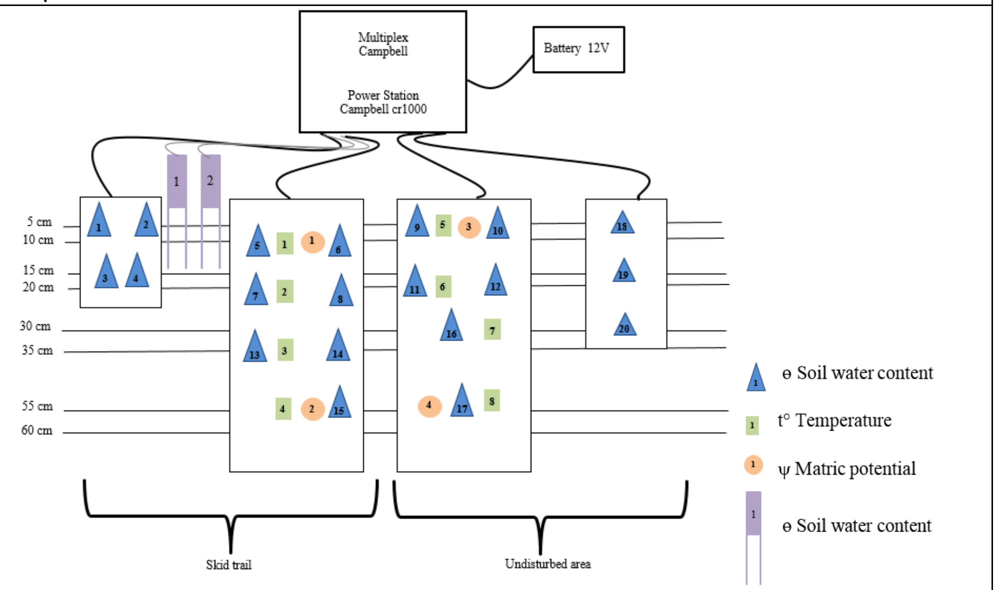
Protocol 2: LAI measurements

Objectives	To measure the maximum value of the LAI
Method	Digital Hemispherical Photography (DHP) (Bréda et al., 2002)
Methodological protocol	9 pictures per plots fixed all 10 meter in a plot (see following picture from DHP manual). The points 1 to 5 are located on the middle of the permanent extraction trail. LAI determination will be calculated with CAN EYE or DHP software. 
Sites	All sites
Frequency	1 campaign in June/July 2018

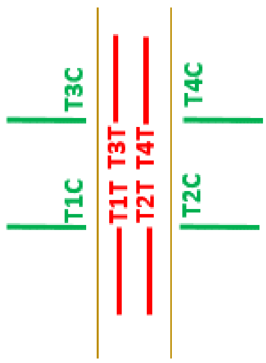
Protocol 3: Soil characterization

Objectives	Soil description
Method	2 pit descriptions per site: control + trafficked soil (permanent extraction trail).
Methodological protocol	Excavation of the pits Soil description Retention and hydraulic conductivity curves determination at 3 depths with BEST method (Lassabatère et al., 2006)  Roots profile For each layer 1 soil sampling will be done with cylinder method to determine: - Particle size distribution, initial water content, bulk density for BEST method - pH, organic carbon content Probes installation
Sites	MS1 and MS2 For MS3, the soil characterization is lighter: soil description with auger and infiltration tests at 2 depths
Frequency	1 campaign: May 2017 – July 2018

Protocol 4: Moisture monitoring for MS1

Objectives	θ(t, z) moisture monitoring at several depth + comparison of water transfer on control and trafficked soils
Method	Moisture, temperature and pressure probes installed in the 2 pits dug for soil description
Methodological protocol	
Sites	MS1
Frequency	Automatic measurements: 1 measurement/30min since 05/2017 (end 12/2018)

Protocol 5: Moisture monitoring for MS2

Objectives	θ(t, x, y) topsoil (20 cm) moisture monitoring + comparison of water transfer between control and trafficked soils	
Method	Itinerant survey with TDR probes + TRASE central	
Methodological protocol	4 transects of 7 points (spacing of 1m) per modality: control (in green, see figure) and trafficked (in red)	
Sites	MS2	
Frequency	t+1 and t+n days after a rainy episode until soil drying is complete ~20 data collection per plot (Spring 2018 – Autumn 2018)	

Protocol 6: Moisture monitoring for MS3

Objectives	Punctual moisture measurement on various soil
Method	Measurement with TRIME probe
Methodological protocol	5 repetitions per modality (control and trafficked), 2 depths (5-15 and 25-35cm)
Sites	MS2
Frequency	~6 field campaign per plot at different seasons

APPENDIX B: Database description of the 10 plots

AZERAILLES (MS1)

Location		Forestry historic	
Forest	Forêt Domaniale des Hauts-Bois	**Age of the stand**	~ 90 years
Municipality	Azerailles (54122)	**Age of the permanent extraction trail**	Opened in 2013-2014
GPS coordinates	48.506426, 6.691669	**Last harvesting**	2015-2016
Altitude	326	**Other information**	
Stand	Beech		

Soil profile	
Name of the soil on control	Stagnic Dystric Cambisol (Geoabruptic)
Method of description	Pit
Date of the description	12/05/2017
Oligomull **A horizon**: 0 to 3-5cm loamy texture, strong granular structure (<5 mm), 8 to 16 roots/dm^2 (main root diameter <5 mm), strong evidence of biological activity, >40% of porosity (main pore diameter 2 to 5 mm) **S_{al} horizon**: 3-5 to 35-40cm loamy texture, granular structure (5 mm), strong evidence of biological activity, < 8 roots/dm^2, 15 to 40% of porosity (main pore diameter 0.5 to 2 mm) **g horizon**: 35-40cm silty loam texture, strong blocky and moderate subangular polyhedral (3 cm) structures, no roots, no pores, 40 to 80% of oxidation task (task diameter > 2 mm) and 15 to 40% of discoloration task (task diameter > 2 mm), 5 to 15% of ferromanganese nodules (main nodule diameter 6 to 20 mm)	

Particle size distribution (g/kg)	Control			Trafficked		
	Layer 0-10cm	Layer 15-25 cm	Layer 30-40cm	Layer 0-10cm	Layer 15-25 cm	Layer 30-40cm
0-2	144	149	166	145	157	182
2-20	411	403	397	398	392	384
20-50	259	263	259	261	261	248
50-200	71	69	70	73	72	69
200-2000	115	116	108	123	117	116

Chemical parameters	Carbon organic (g/kg)		pH	
	Control	**Trafficked**	**Control**	**Trafficked**
0-10 cm	29.98	54.03	4.18	4.18
15-25 cm	6.70	11.04	4.18	4.19
30-40 cm	4.22	2.83	4.14	4.25

	Dry bulk density (g/cm^3)		Water parameters		
	Control	**Trafficked**		**Control**	**Trafficked**
0-10 cm	1.07 (0.16)	1.38 (0.10)	**Hydraulic conductivity at saturation**	Results autumn 2018	
15-25 cm	1.13 (0.03)	1.45 (0.003)	**Water content at saturation**		
30-40 cm	1.16 (0.05)	1.39 (0.02)	**n**		
			m		

HESSE (MS1)

Location		Forestry historic	
Forest	Forêt Domaniale de Hesse	**Age of the stand**	~ 60 years
Municipality	Hesse (57400) / France	**Age of the permanent extraction trail**	Opened in 2011
GPS coordinates	48.672862, 7.062028	**Last harvesting**	2013
Altitude	306	**Other information**	
Stand	Beech and hornbeam		

Soil profile	
Name of the soil on control	Stagnosols (control pit) at Reductic Stagnosols (trafficked pit)
Method of description	Pit
Date of the description	11/05/2017
Eumull **A horizon**: 0 to 20cm loamy texture, loose, strong granular (5mm) structure, strong evidence of biological activities, > 32 roots/dm² (main root diameter >20mm), 2 to 5% of porosity (main pore diameter 0.5 to 2 mm), strong evidence of biological activity (or many biological features), 1% of sandstone gravel alongated and subangular **g1 horizon** (stagnic horizon): 20 to 40-45cm loamy texture, strong granular (5mm) and moderate blocky subangular (20mm) structures (admixture), strong evidence of biological activities, 16 to 32 roots/dm² (main root diameter 5 to >20mm), 2 to 5% of porosity (main pore diameter 0.5 to 2 mm), 3% of sandstone gravel alongated and subangular, 5 to 15% of oxidation task (task diameter 2 to 6mm), 2 to 5% of ferromanganese nodules (main nodule diameter 20 to 60mm) **g2 horizon** (stagnic horizon): 40-45cm loamy texture, moderate blocky subangular (15mm) and strong granular (1mm) structures, 8 to 16 roots/dm² necrotic (main root diameter 0.5 to >2mm), 2 to 5% of porosity (main pore diameter <0.5mm), 40 to 80% of oxidation task (task diameter 6 to 20mm) and 15 to 40% of discoloration task (task diameter 20 to 60mm), 5 to 15% of ferromanganese nodules (main nodule diameter 6 to 20mm)	

Particle size distribution (g/kg)	Control			Trafficked		
	Layer 0-10cm	Layer 15-25 cm	Layer 30-40cm	Layer 0-10cm	Layer 15-25 cm	Layer 30-40cm
0-2	223	236	243	235	247	
2-20	381	382	333	367	388	
20-50	259	245	240	242	222	
50-200	110	108	140	114	111	
200-2000	28	30	45	42	33	

Chemical parameters	Carbon organic (g/kg)		pH	
	Control	**Trafficked**	**Control**	**Trafficked**
0-10 cm	53.65	66.89	5.09	7.01
15-25 cm	20.62	14.64	6.56	7.19
30-40 cm	7.22		6.74	

	Dry bulk density (g/cm^3)		Water parameters		
	Control	**Trafficked**		**Control**	**Trafficked**
0-10 cm	1.07 (0.13)	0.86 (0.16)	**Hydraulic conductivity at saturation**	Up-coming Results autumn 2018	
15-25 cm	1.18 (0.11)	1.35 (0.08)	**Water content at saturation**		
30-40 cm	1.32 (0.12)	1.45 (0.12)	**n**		
			m		

POCHON 1 (MS2)

Location		Forestry historic	
Forest	Forêt Domaniale de Pochon	**Age of the stand**	~ 60-70 years
Municipality	Losne (21170) / France	**Age of the permanent extraction trail**	unknown
GPS coordinates	47.076865. 5.322116	**Last harvesting and type of machine if known**	2015-2016
Altitude	186 m	**Other information**	
Stand	Oak		

Soil profile	
Name of the soil on control	Stagnosol (Ruptic)
Method of description	Pit
Date of the description	26/07/2017

Mesomull

A1 horizon: 0 to 5-10cm

Loam texture, strong granular (50mm) structure, >32 roots/dm² (main root diameter 0.5 to 2mm), >200 pores/dm² (main pore diameter <0.5mm)

A2 horizon: 5-10 to 20-25cm

Loam texture, strong grenue (5mm) structure, >32 roots/dm² (main root diameter 0.5 to 2mm), >200 pores/dm² (main pore diameter <0.5mm)

g horizon (stagnic horizon): 20-25 to 50cm

Loam texture, strong polyhedral subangular (100mm) and moderate grenue (5mm) structures, 16 to 32 roots/dm² (main root diameter 5 to 2mm), 50 to 200 pores/dm² (main pore diameter <0.5mm), <2% of oxidation task (task diameter <1mm)

IIg horizon: 50 to 60-75cm

Clay texture, strong blocky and moderate polyhedral subangular (100mm) structures, 8 to 16 roots/dm² (main root diameter 0.5 to 2mm), 1 to 50 pores/dm² (main pore diameter 0.5 to 2mm), 15 to 40% of discoloration task (task diameter 6 to 20mm) and 5 to 15% of oxidation task (task diameter 2 to 6mm), 5 to 15% of ferromanganese nodules (main nodule diameter 2 to 6mm)

IIC horizon: 60-75cm

Clay texture, strong blocky and moderate polyhedral subangular (500mm) structures, <8 roots/dm² (main root diameter 0.5 to 2mm), 1 to 50 pores/dm² (main pore diameter 0.5 to 2mm), 40 to 80% of oxidation task (task diameter >60mm) and 15 to 40% of discoloration task (task diameter 20 to 60mm), 40 to 60% of ferromanganese nodules (main nodule diameter 20 to 60mm)

Particle size distribution (g/kg)	Control			Trafficked		
Layer	0-10cm	15-25 cm	30-40cm	0-10cm	15-25 cm	30-40cm
0-2	143	145	142	141	146	188
2-20	400	395	410	403	404	385
20-50	367	374	361	368	364	347
50-200	69	68	70	69	67	64
200-2000	21	17	16	18	20	16

Chemical parameters	Carbon organic (g/kg)		pH	
	Control	**Trafficked**	**Control**	**Trafficked**
0-10 cm	52.59	26.08	4.25	4.46
15-25 cm	15.24	16.24	4.53	4.35
30-40 cm	9.47	9.77	4.47	4.6

	Dry bulk density (g/cm^3)		Water parameters		
	Control	**Trafficked**		**Control**	**Trafficked**
0-10 cm	0.82 (0.09)	0.94 (0.09)	**Hydraulic conductivity at saturation**	Up-coming Results autumn 2018	
15-25 cm	0.99 (0.13)	1.23 (0.01)	**Water content at saturation**		
30-40 cm	1.24 (-)	1.34 (-)	**n**		

			m	

POCHON 2 (MS2)

Location		Forestry historic	
Forest	Forêt Domaniale de Pochon	**Age of the stand**	~ 60-70 years
Municipality	Losne (21170) / France	**Age of the permanent extraction trail**	unknown
GPS coordinates	47.076865. 5.322116	**Last harvesting and type of machine if known**	2015-2016
Altitude	186 m	**Other information**	
Stand	Oak		

Soil profile	
Name of the soil on control	Stagnosol (Ruptic)
Method of description	Pit
Date of the description	27/07/2017

Eumull

A1 horizon: 0 to 3-5cm

Loam texture, strong granular (50mm) structure, strong evidence of biological activities, >32 roots/dm² (main root diameter 0.5 to 2mm), >200 pores/dm² (main pore diameter <0.5mm)

A2 horizon: 3-5 to 5-10cm

Loam texture, strong granular (3mm) and polyhedral subangular (10mm) structures, moderate evidence of biological activities, 16 to 32 roots/dm² (main root diameter 0.5 to 2mm), 50 to 200 pores/dm² (main pore diameter <0.5mm)

g horizon (stagnic horizon): 5-10 to 30cm

Loam texture, strong blocky and moderate polyhedral subangular (100mm) structures, moderate evidence of biological activities, 8 to 16 roots/dm² (main root diameter 5 to 2mm), 1 to 50 pores/dm² (main pore diameter 0.5 to 2mm), 2 to 5% of oxidation task (task diameter <1mm)

gII horizon: 30 to 40-45cm

Clay texture, strong blocky and moderate polyhedral (100mm) structures, <8 roots/dm² (main root diameter 0.5 to 2mm), 1 to 50 pores/dm² (main pore diameter 0.5 to 2mm), 40 to 80% of discoloration task (task diameter >60mm) and 2 to 5% of oxidation task (task diameter 1 to 2mm), 2 to 5% of ferromanganese nodules (main nodule diameter 1 to 2mm)

CII horizon: 40-45 to 100cm

Clay texture, strong blocky and moderate polyhedral (50mm) structures, <8 roots/dm² (main root diameter 0.5 to 2mm), 1 to 50 pores/dm² (main pore diameter 0.5 to 2mm), 40 to 80% of oxidation task (task diameter >60mm) and 15 to 40% of discoloration task (task diameter 20 to 60mm), 15 to 40% of ferromanganese nodules (main nodule diameter >60mm)

Particle size distribution (g/kg)	Control			Trafficked		
Layer	0-10cm	15-25 cm	30-40cm	0-10cm	15-25 cm	30-40cm
0-2	127	129	145	123	127	183
2-20	363	360	358	360	365	348
20-50	304	317	306	313	313	284
50-200	85	85	83	87	83	78
200-2000	120	109	109	117	112	108

Chemical parameters	Carbon organic (g/kg)		pH	
	Control	**Trafficked**	**Control**	**Trafficked**
0-10 cm	24.96	20.22	4.53	4.36
15-25 cm	9.44	12.27	4.49	4.46
30-40 cm	4.93	3.98	4.67	4.68

	Dry bulk density (g/cm^3)		Water parameters		
	Control	**Trafficked**		**Control**	**Trafficked**
0-10 cm	1.05 (0.09)	1.17 (0.06)	**Hydraulic conductivity at saturation**	Up-coming autumn 2018	Results
15-25 cm	1.11 (0.14)	1.29 (0.04)	**Water content at saturation**		
30-40 cm	1.39 (-)	1.41 (-)	**n**		

			m	

POURLANS 2 (MS2)

Location		Forestry historic	
Forest	Forêt Domaniale de Pourlans	**Age of the stand**	~ 80-100 years
Municipality	Pourlans (71270) / France	**Age of the permanent extraction trail**	unknown
GPS coordinates	46.978997. 5.241265	**Last harvesting and type of machine if known**	2015-2016
Altitude	194	**Other information**	
Stand	Oak and beech		

Soil profile	
Name of the soil on control	Stagnosol (Ruptic)
Method of description	Pit
Date of the description	25/07/2017

Mesomull

A horizon: 0 to 10-15cm
loam texture, strong fluffy (2) and moderate granular (20mm) structures, strong evidence of biological activities, >32 roots/dm² (main root diameter 2 to 5mm), <50 pores/dm²

g1 horizon (stagnic horizon): 10-15 to 35-40cm
loam texture, strong blocky and moderate polyhedral subangular (20mm) structures, 16 to 32 roots/dm², <50 pores/dm², 40 to 80% of reduction task (task diameter 2 to 6mm) and 5 to 15% of oxidation task (task diameter 2 to 6mm)

g2 horizon: 35-40 to 60-70cm
loam texture, strong blocky and moderate polyhedral (30mm) structures, 8 to 16 roots/dm² (main root diameter 2 to 5mm), <50 pores/dm², 15 to 40% of oxidation task (task diameter 6 to 20mm) and 15 to 40% of reduction task (task diameter 6 to 20mm), 2 to 5% of ferromanganese nodules (main nodule diameter 1 to 2mm)

IIC$_g$ horizon: 60-70cm
clay texture, strong blocky and moderate polyhedral (40mm) structures, <8 roots/dm², no pores, 15 to 40% of oxidation task (task diameter 6 to 20mm) and 15 to 40% of reduction task (task diameter 6 to 20mm), 1 to 2% of ferromanganese nodules (main nodule diameter 1 to 2mm)

Particle size distribution (g/kg)	Control			Trafficked		
Layer	0-10cm	15-25 cm	30-40cm	0-10cm	15-25 cm	30-40cm
0-2	175	148		169	153	153
2-20	403	384		395	394	391
20-50	299	341		316	338	333
50-200	97	102		91	93	100
200-2000	26	26		29	23	22

Chemical parameters	Carbon organic (g/kg)		pH	
	Control	**Trafficked**	**Control**	**Trafficked**
0-10 cm	168.02	120.49	3.8	3.8
15-25 cm	22.06	26.52	4.04	4.16
30-40 cm		21.36		4.17

	Dry bulk density (g/cm^3)		Water parameters		
	Control	**Trafficked**		**Control**	**Trafficked**
0-10 cm	0.81 (0.12)	0.98 (0.17)	**Hydraulic conductivity at saturation**	Up-coming	Results
15-25 cm	0.94 (0.09)	1.16 (0.09)	**Water content at saturation**	autumn 2018	
30-40 cm	1.09 (-)	1.29 (-)	**n**		

			m	

POULANS 3 (MS2)

Location		**Forestry historic**	
Forest	Forêt Domaniale de Pourlans	**Age of the stand**	~ 80-100 years
Municipality	Pourlans (71270) / France	**Age of the permanent extraction trail**	unknown
GPS coordinates	46.978997. 5.241265	**Last harvesting and type of machine if known**	2015-2016
Altitude	194	**Other information**	
Stand	Oak and hornbeam		

Soil profile	
Name of the soil on control	Stagnosol (Ruptic)
Method of description	Pit
Date of the description	25/07/2017

Eumull

A horizon: 0 to 3-8cm
loam texture, strong granular (4mm) structure, strong evidence of biological activities, >32 roots/dm² (main root diameter 0.5 to 2mm), 5 to 15% of pores

g horizon (stagnic horizon): 3-8 to 30-35cm
loam texture, strong polyhedral subangular (20mm) structure, moderate evidence of biological activities, 16 to 32 roots/dm² (main root diameter 0.5 to 2mm), 5 to 15% of pores, 15 to 40% of oxidation task (task diameter 6 to 20mm) and 2 to 5% of reduction task (task diameter 1 to 2mm), <2% of ferromanganese nodules (main nodule diameter 1 to 2mm)

BT_g horizon: 30-35 to 50-60cm
loam texture, strong blocky and moderate polyhedral subangular (10mm) structures, 16 to 32 roots/dm² (main root diameter 0.5 to 2mm), 2 to 5% of pores, 5 to 15% of oxidation task (task diameter 2 to 6mm) and 5 to 15% of reduction task (task diameter 2 to 6mm), 5 to 15% of ferromanganese nodules (main nodule diameter 2 to 6mm)

IIC_g horizon: 50-60cm
clay texture, strong blocky and moderate prismatic (20mm) structures, <8 roots/dm² (main root diameter 2 to 5mm), <2% of pores, 15 to 40% of oxidation task (task diameter 6 to 20mm), 5 to 15% of ferromanganese nodules (main nodule diameter 6 to 20mm)

Particle size distribution (g/kg)	**Control**			**Trafficked**		
Layer	0-10cm	15-25 cm	30-40cm	0-10cm	15-25 cm	30-40cm
0-2	181	190	210	170	210	321
2-20	275	277	272	291	287	249
20-50	272	267	265	275	249	209
50-200	204	196	189	193	188	168
200-2000	68	70	63	71	65	53

Chemical parameters	**Carbon organic (g/kg)**		**pH**	
	Control	**Trafficked**	**Control**	**Trafficked**
0-10 cm	26.23	22.46	4.37	4.84
15-25 cm	16.02	10.3	4.34	4.74
30-40 cm	7.30	3.84	4.51	4.6

	Dry bulk density (g/cm^3)		**Water parameters**		
	Control	**Trafficked**		**Control**	**Trafficked**
0-10 cm	1.09 (0.09)	1.32 (0.10)	**Hydraulic conductivity at saturation**	Up-coming Results autumn 2018	
15-25 cm	1.29 (0.06)	1.43 (0.19)	**Water content at saturation**		

30-40 cm	1.46 (-)	1.54 (0.05)	**n**	
			m	

Sauvigney (MS3)

Location		**Forestry historic**	
Forest	Private forest	**Age of the stand**	~ 15 years
Municipality	Sauvigney les Gray	**Age of the permanent extraction trail**	3 years
GPS coordinates	47.471514 5.725793	**Last harvesting and type of machine if known**	2015
Altitude	244 m	**Other information**	
Stand	Oak and birch		
Soil data: data collected, results autumn 2018			

Verrière du Grosbois 6 (MS3)

Location		**Forestry historic**	
Forest	Forêt Domaniale de Verrière du Grosbois	**Age of the stand**	~ 50-60years
Municipality	Verrière du Grosbois	**Age of the permanent extraction trail**	
GPS coordinates	47.20306 6.283557	**Last harvesting and type of machine if known**	
Altitude	592 m	**Other information**	
Stand	Beech		
Soil data: data collected, results autumn 2018			

Verrière du Grosbois 11 (MS3)

Location		**Forestry historic**	
Forest	Forêt Domaniale de Verrière du Grosbois	**Age of the stand**	~ 50-60 years beech ~ 150 years oak
Municipality	Verrière du Grosbois	**Age of the permanent extraction trail**	
GPS coordinates	47.197851 6.289887	**Last harvesting and type of machine if known**	
Altitude	578 m	**Other information**	
Stand	Beech and oak		
Soil data: data collected, results autumn 2018			

Abbayes (MS3)

Location		**Forestry historic**	
Forest	Forêt Domaniale des Abbayes	**Age of the stand**	~ 75 years
Municipality	Verneuil	**Age of the permanent extraction trail**	Since 1977
GPS coordinates	46.4934 2.3424	**Last harvesting and type of machine if known**	2007
Altitude	170 m	**Other information**	
Stand	Oak and hornbeam		
Soil data: data collected, results autumn 2018			

APPENDIX C: Detailed protocols for task 1.2 Mechanical properties of forest soils

(extract of the common protocol)

1.2.1. Objectives of the task, models to develop and/or to test

Soil moisture content is known to have significant effect on soil strength, especially in fine-grained mineral soils. This being the case, trafficability of forest soils usually comprise large seasonal variation. Task 1.2 aims to develop models that estimate mechanical properties of forest soils based on soil texture, soil moisture status, and possible additional forest stand characteristics. The models to be developed should be applicable both in boreal and temperate regions.

The models will be developed based on data collected in this project. However, it is very important that the results obtained in our trials are in harmony with the preceding research findings. We focus primary on the following mechanical properties: 1) Penetration resistance (known also as Cone index) 2) Shear strength measured with shear vane.

1.2.2. Input data necessary for the model(s) and output data of the model(s)

Input: VWC, Soil type (Clay content or mean grain size), bulk density

Output: Penetration resistance (MPa), Shear strength (kPa)

1.2.3. Bibliography, previous and on-going work already done dealing with this task

Luke has conducted a series of field studies in Finland prior to EFFORTE and the results of the study are analyzed within the project. The study was conducted on a test site located in the municipality of Jokioinen in Southern Finland. Three separate blocks from three different corners of the stand were selected as study areas. Each study block comprised 8 study plots. Each study plot was repeatedly measured 8 times within a time period 1 and a half years. Within one measurement round, each study plot was measured for penetration resistance, shear vane and soil moisture content. In the second measurement round, soil samples were extracted enabling calibration of TDR and analyses for bulk density and grain size distribution. A manuscript of the scientific article presenting the results of this experiments will be submitted during the Spring 2017.

1.2.4. Strategy for the experimental field tests

Further measurements of penetration resistance will be carried out in conjunction of the driving test (task 1.4) to be carried out in Finland and France.

On each French site installed for the other tasks (T1.1 et T1.4), measurements of penetration resistance and shear strength will be carried out, in link with the soil description and the input data needed in T1.2. Thanks to these measures, the soil strength model developed for Finnish conditions will be tested and eventually modified in order to adapt it to French soil conditions.

1.2.5. Detailed protocols: description of all the measures and tests

- VWC with TDR moisture probe
- Soil samples for mineral soils
- Penetration resistance
- Shear strength

The minimum number of soil samples within one subsample is two. It is strongly recommended that the number can be doubled. It is recommended that at least two penetration measures is taken from each sampling point. The final result is the mean of these two measurements. It is recommended that at least two TDR measurements per each sample point is taken. The final result is the mean of these two measurements.

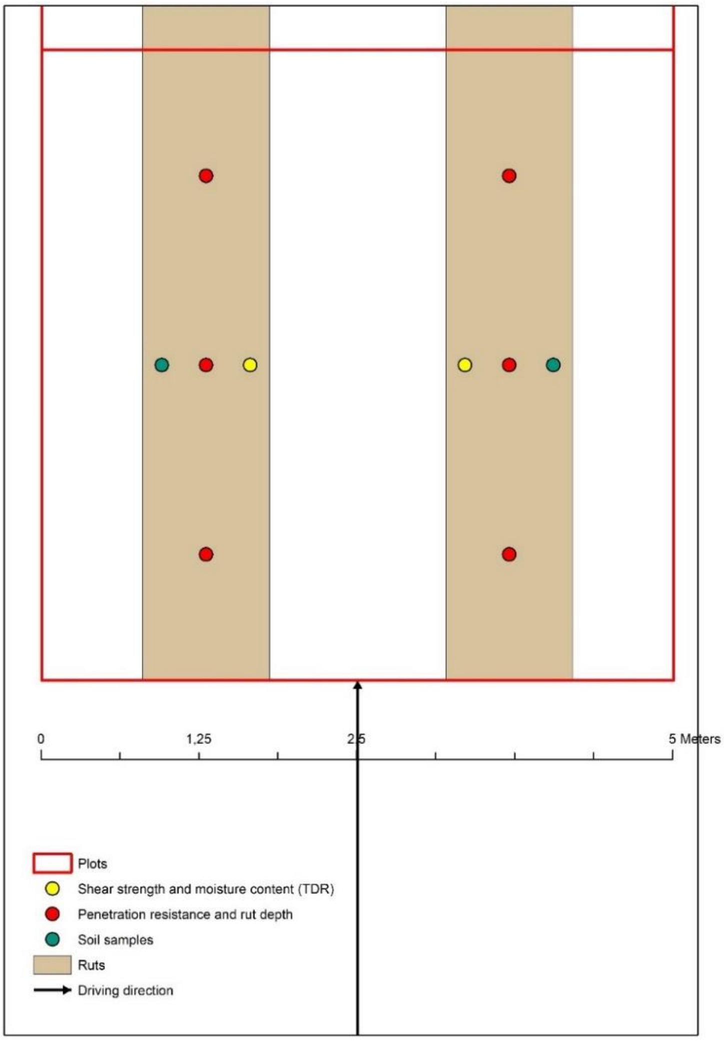


Figure 7: Layout for measures carried out in T1.2 in link with T1.4

1.2.6. Calendar of the planned work

Field test on how moisture-soil strength models already develop works in Finnish and French conditions will be arranged in conjunction of driving test (WP4) during spring and early Summer in 2017 in France and Finland.