Knowledge and Technologies for Effective Wood Procurement

Deliverable 3.5

TOP LEVEL FIGURES FOR MAIN TIMBER HARVESTING SYSTEMS

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Main contact: Giovanna Ottaviani Aalmo

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1 Publishable summary

The overall objective of this deliverable is to categorize the highest possible predictions of selected productivity functions (top level performance figures) for the main timber harvesting (felling, processing and extraction) systems in Europe and South Africa. The most common harvesting systems identified in this study were:

1) Harvester and forwarder in cut-to-length method
2) Winch-assisted harvester and forwarder in cut-to-length method
3) Chainsaw and skidder
4) Chainsaw and cable yarder in whole tree method

Outcomes from this deliverable will be helping in estimating harvesting costs and to evaluate if the harvesting system applied is the most efficient.

This deliverable has been compiled by collecting and systematizing information from existing research and by creating a dataset based on past records. The material consists of productivity functions and datasets.

Results indicate that among the studied functions the most relevant variables to predict the relative top level figures are:

For the harvester and forwarder in cut-to-length method: average stem size (in dm^3 or m^3), removal (m^3/ha), the number of assortments and diameter at breast height (cm). The highest productivity predicted for a thinning was 32.6 m^3/PSH_{15} and 164.4 m^3/PSH_0 for the clear cutting/final felling.

For the winch-assisted harvester and forwarder in cut-to-length method: tree volume (m^3). The highest productivity predicted was 46.0 m^3/PSH_{15}.

For chainsaw and skidder: machine gross power (kW), average tree volume (m^3) the payload size (m^3) in-field extraction distance (m), the time taken to load (min), the time taken to unload (min). The highest predicted productivity for skidding were 28.8 m^3/PSH with a farm tractor, while with was 89.0 m^3/PSH with a skidder.

Finally, for chainsaw and cable yarder in whole tree method the variables were: yarding distance (m), lateral yarding distance (m), number of logs per turn (#) and the average piece size (m^3). For this system the highest value was 29.0 m^3/PSH.

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2 Introduction

2.1 Background

During the last 30 years, in Europe we have been assisting at an inversion of trend in forestry, the forest area has increased, while wood harvesting has decreased. This has come as a result of energy policies at global level, but also of socio-economic challenges linked to the reduced marginal profit for forest owners and contractors. Despite this, still circa 500 000 million m^3 of timber are mobilized annually in Europe (EU27), using different harvesting systems. An additional 35 % could potentially be mobilized by increasing the efficiency of the forest harvesting operations and by addressing the socio-economic factors hindering the process (EEA, 2019)(Agency, 2019).

Forest operation efficiency is in fact closely related to the harvesting system, firstly by its choice and , secondly, by its performance. The choice of the harvesting system generally depends on the harvesting sites, in terms of vegetation and geographical characteristics i.e. accessibility, the possible level of mechanization and the socio-economic condition of the forest owner/contractors etc.

Forest management data have been recorded for centuries in Europe and many studies have been implemented in order to understand and predict the productivity of the different harvesting systems in use in different conditions/countries.

These predictions represent an important step in benchmarking and in finding solutions to achieve higher efficiency in timber harvesting operations.

Under the TECH4EFFECT project, a review/prediction study has been conducted to collect the different productivity models of the main harvesting systems and assess which one is predicting the highest output.

2.2 Objective of the deliverable

The overall objective of this deliverable is to categorize the highest possible predictions of selected productivity functions (top level performance figures) for the main harvesting systems in Europe and South Africa. These will be used to determine harvesting costs and to evaluate the harvesting system applied. While the array of the data herewith collected does not constitute a full inventory of productivity models available in the literature, the goal was to extract a representative sample. In this context, this document can be regarded as a limited benchmark to evaluate the efficiency of different harvesting operations.

3 Material and methods

This deliverable has been compiled by collecting and systematizing information from existing research and by creating a dataset based on past records. The material consists of productivity functions and datasets. Productivity functions are important for assessing the efficiency of forest operations and they are used in academia and in the field by the forest managers.

Among the numerous harvesting systems in use in Europe and around the world, four have emerged as the most common. This was deducted from the literature (Harrill, Visser, & Raymond, 2019; Mologni, Grigolato, & Cavalli, 2016; Moskalik et al., 2017; Munteanu & Borz, 2018; Spinelli, Magagnotti, &

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Facchinetti, 2013) and was corroborated by the TECH4EFFECT deliverable 5.1, "Mapping Forest Operations".

The most common harvesting identified in this study systems were:

1) **Harvester and forwarder in cut-to-length method**: This fully mechanized harvesting system originates from Scandinavia and represents the currently highest level of mechanization. Today, it is employed all across Europe mainly in coniferous forests and on flat or slightly sloping terrain.
2) **Winch-assisted harvester and forwarder in cut-to-length method**: Among the selected, this harvesting system is the most recent. It has been introduced in the early 2000s, primarily to reduce slip and associated soil disturbance by attaching a traction aid winch to fully mechanized harvesting and to increase safety during timber harvesting on slopes by mechanization. From early on, it has been employed on slopes not traversable with standard harvester and forwarders without excessive soil disturbance. The number of machines in operation has increased exponentially in recent years and is expected to increase even more
3) *Chainsaw and skidder*: This partially mechanized harvesting system has been widespread in Central, Eastern and Southern Europe in the past and continues to do so especially in Eastern and Southern Europe. Further, it is a very common harvesting system in management of forest owned by farmers, where a winch is attached to a tractor primarily used for agricultural purposes.
4) **Chainsaw and cable yarder in whole tree method**: This highly mechanized harvesting system is considered the most efficient system for timber harvesting on steep terrain not traversable by ground-based machinery. Furthermore, it is regarded superior to ground-based harvesting systems as regards soil disturbance.

The data and functions collection has been implemented in two steps. A survey was first administered to all the consortium members and then additional data/functions were retrieved by a literature review.

Ultimately, the different equations have been plotted using the dataset allowing the identification of the productivity function with the highest intercept (top level performance figure).

3.1 Data collection and dataset generation

During August/September 2018 a survey was administered to all consortium members. The survey's content was drafted in order to collect productivity functions for the four types of harvesting systems. More specifically, the survey was collecting for each partner:

- The year of the study
- Study location
- Machine model
- The productivity function in the form of $y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n + \varepsilon$
- The details on the variables (names, units, etc.)
- Any linked scientific publication

Not all partners could provide the required information and therefore additional meetings were conducted on one-one basis only with the responders. This allowed us to clarify doubts on the variables details and fill existing gaps in terms of missing information on the data.

The collected equations were describing productivity functions of harvesting operations of broadleaf and coniferous silvicultural systems in various settings. A summary of the amount information gathered is given in table 1. The harvesting systems considered were those described within the TECH4EFFECT

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project document and selected by the consortium experts. As mentioned above, together with the productivity functions, the related datasets were made available in order to use them as a basis to create the simulated data-cloud used to plot all the available functions.

The studies used in this deliverables have been collected by partners from Norway, Italy, Austria, Germany, Finland and South Africa. Other partner countries were not able to provide functions or data. The list of functions and studies used for the analysis and the variables details are provided in Annex1.

A data cloud was then generated using R in order to be able to plot all the functions, the variables were generated on the basis of existing datasets or by using a normal distribution with minimum, maximum and SD described in the related scientific articles. For categorical variables the sample function was used, and probabilities were applied on the basis of the literature, in order to simulate as close as possible the reality. The cloud was clustered with regards to the variables included in the functions and to the type of operation (i.e. clear felling/thinning) and with regards to the forest types (i.e. coniferous, coppice).

Table 1: Overview of the information contribution per partner

Partner	Number of productivity functions/dataset provided				Studies timeframe	Number of machine models considered
	H+F/CTLM	***WAH+F/CTLM***	***CS+SK/TLM***	***CS+CY/WTM***		
BOKU	7	3	3	4	2002-2017	14
NIBIO	0	0	0	1	2014	1
CNR	5	0	3	4	2000-2017	15
LUKE	27	0	0	0	1994-2013	13
STU	17	0	2	0	2011-2017	14
TOTAL	**56**	**3**	**8**	**9**		

4 Results

4.1 Harvester and forwarder in cut-to-length method

Data from Finland, Norway, Austria, Italy and South Africa were used. Depending on the source function type, output is presented as m^3 per productive system hour including (m^3/PSH_{15}), not including (m^3/PSH_0) delays of up to 15 minutes or otherwise the PSH will include all type of delays. Further, the results for this harvesting system have been clustered with regard to the silvicultural treatment (thinning or final/clear felling).

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4.1.1.1 Thinning (Boreal Forest)

Fitted functions predicting m^3/PSH_0 and m^3/PSH_0 were plotted separately. The boxplots (Figures 1 and 2), give an indication of the functions predicting the highest values in each case.

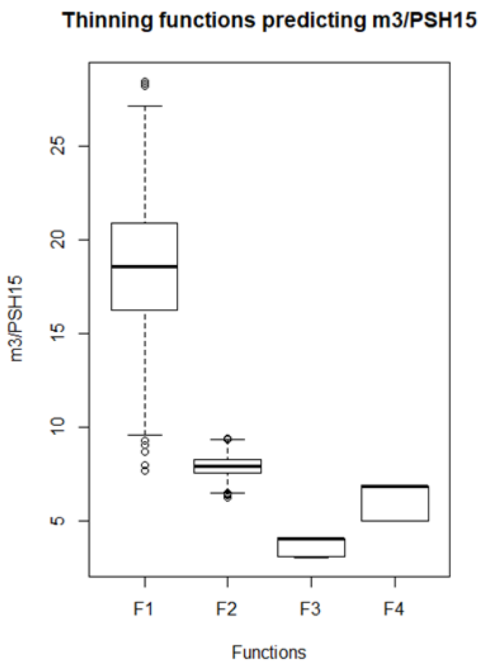

Figure 1: Prediction of functions for thinning with harvester and forwarder in cut-to-length method including delays up to 15 min.

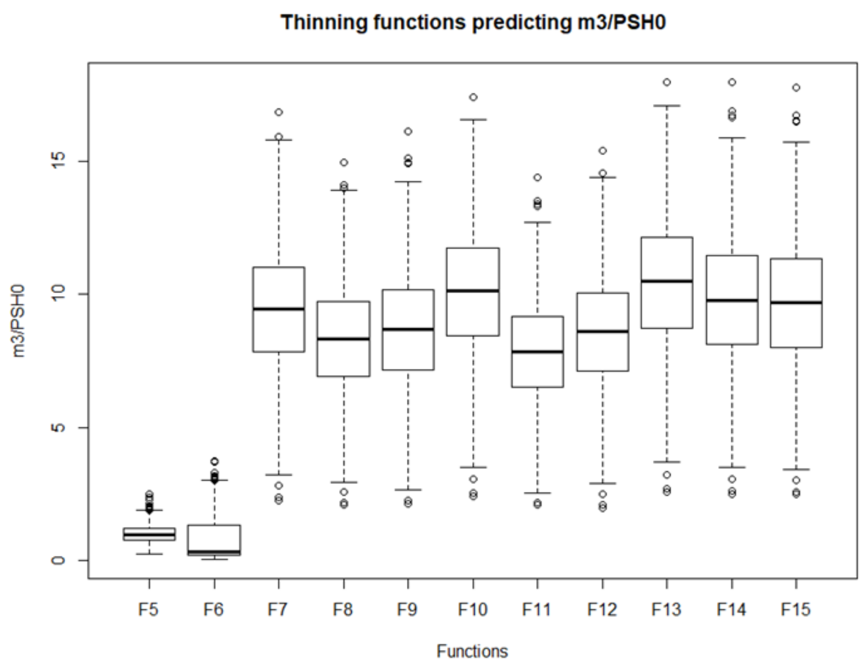

Figure 2: Prediction of functions for thinning with harvester and forwarder in cut-to-length method not including delays up to 15 min

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The delay free predictions show a general higher value (Figure 2). The functions 5 and 6 were designed to predict the productivities of first thinning and therefore it is logical to expect a lower outcome.

Among the functions inclusive of delays, the one predicting the highest values is the one described by Sirén and Aaltio (2003):

$$y = \beta_0 + \beta_1 x_1 + \beta_2\, x_2 + \beta_3 x_3$$

where x_1 is the average stem size (dm^3), x_2 is the removal (m^3/ha) and x_3 is the number of assortments (#). The values predicted by these functions are between 9.2 and 32.6 m^3/PSH_{15} (Figure 3), the productivity is increasing with increasing average stem size (Figure 4) and increasing removal (Figure 5), while it is decreasing with an increasing number of assortments (Figure 7).

The highest predicting function for the delay- free is part of a study by Kärhä, Rönkkö, and Gumse (2004) and the function is as follows:

$$y = \beta_0 + \beta_1 x + \beta_2\, x^2$$

where x is stem size (dm^3). The values predicted by this function are between 8.9 and 17.6 m^3/PSH_0 and they are proportionally increasing with the stem size (Figure 6).

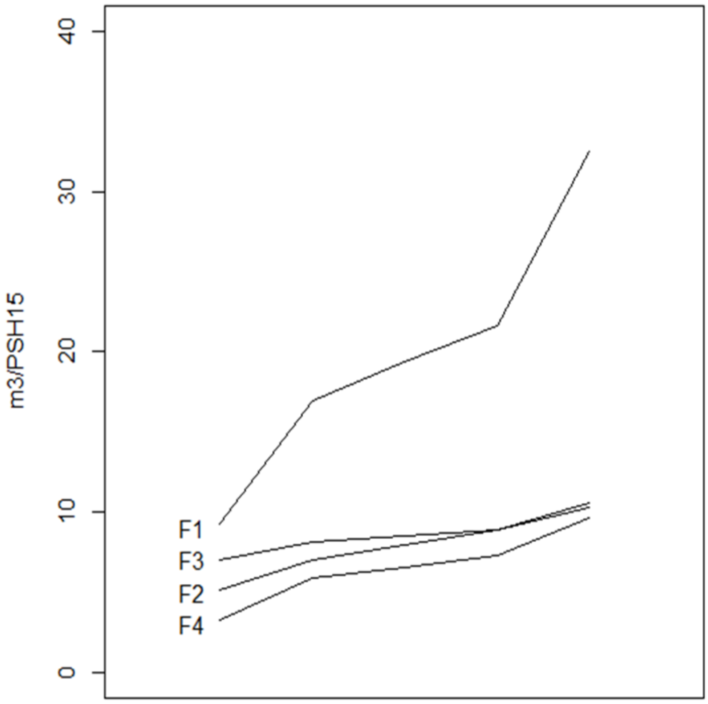

Figure 3: Visualization of the productivity functions F1-F4 using the minimum, 1st quartile, mean, 3rd quartile and maximum values.

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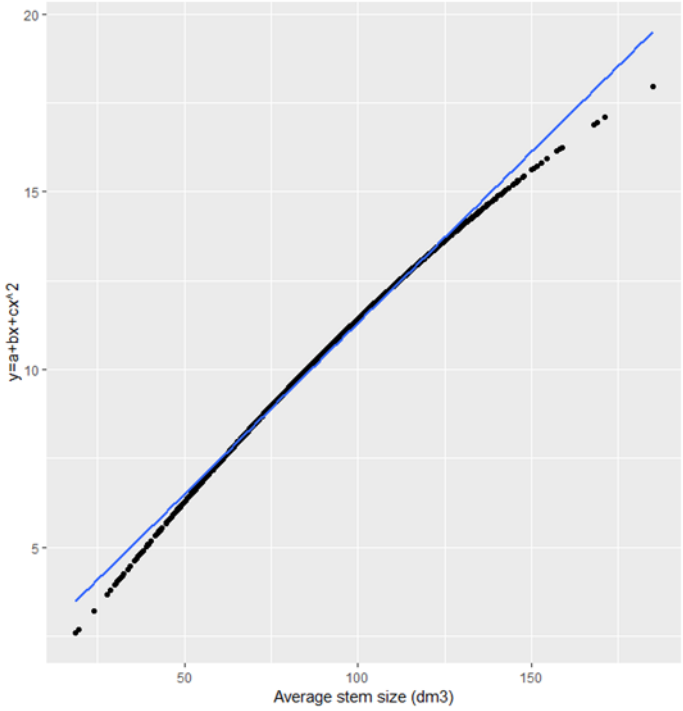

Figure 4: Effect of average stem size on thinning with harvester and forwarder in cut-to-length method including delays up to 15 min

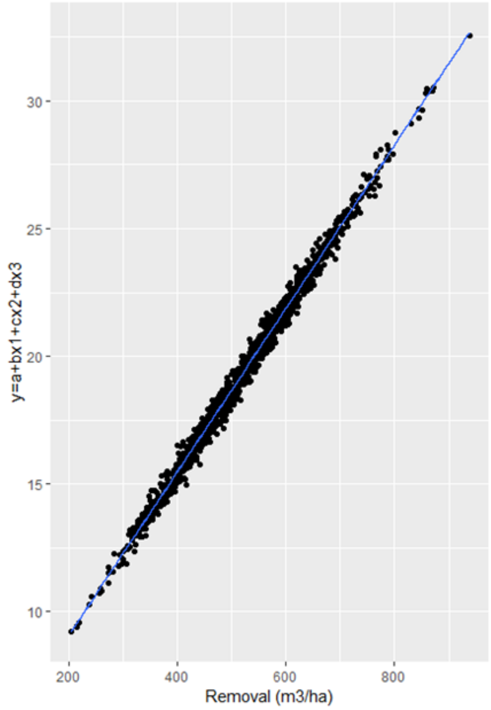

Figure 5: Effect of removal on thinning with harvester and forwarder in cut-to-length method including delays up to 15 min

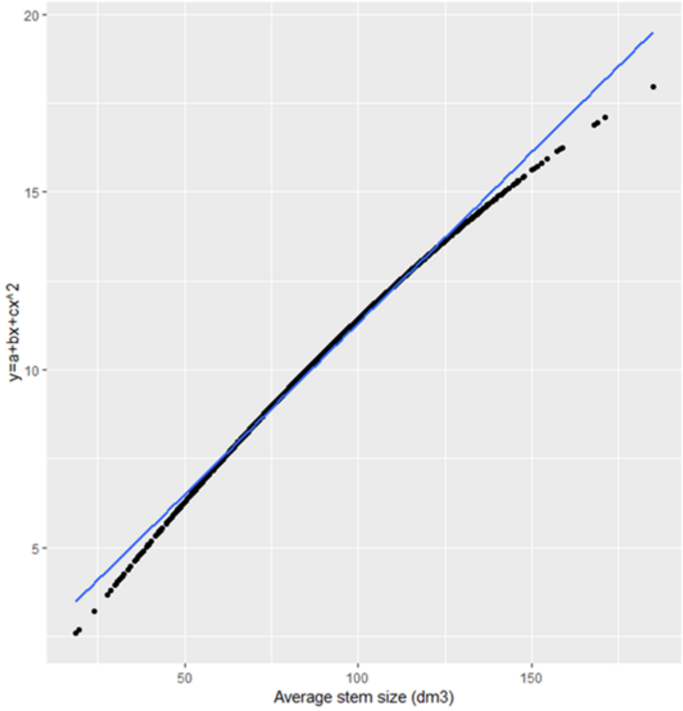

Figure 6: Effect of average stem size on thinning with harvester and forwarder in cut-to-length method not including delays up to 15 min

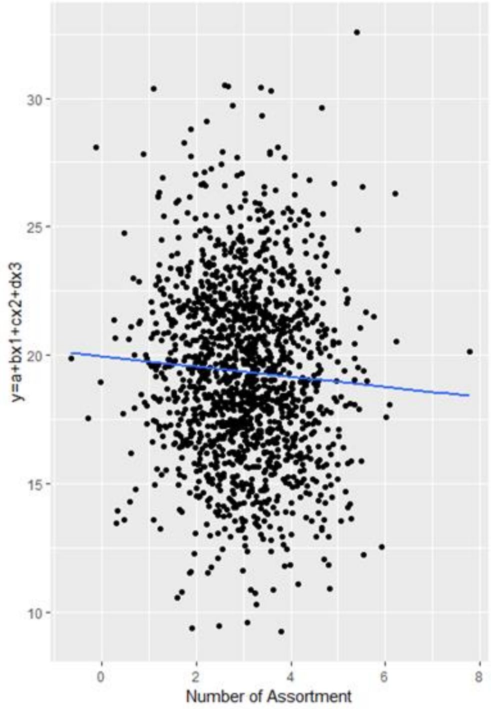

Figure 7: Effect of the number of assortments on thinning with harvester and forwarder in cut-to-length method including delays up to 15 min

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4.1.1.2 Clear cutting (Boreal and temperate forest)

A total of 20 productivity functions were provided by the partners, 7 for the boreal environment and 13 for the temperate. Two of the functions for the **boreal forest** were discarded because of the unit disagreement and therefore only five have been plotted, all using the unit m^3/PSH_0 (Figure 8).

The function predicting the highest values is F15 described in the master thesis of Wolfgang Plessl for temperate forest:

$$y = \beta_0 + \beta_1 x_1 + x_2$$

where β_0 is -6.204, β_1 is 2.034, x_1 is the average diameter at breast height (cm) and x_2 is a dummy for the silvicultural system and its value is 0 for a final felling. Plessl's study was conducted during late thinning and final fellings with a John Deere 1270 E in spruce-dominated stands in Styria and Lower Austria. The study was conducted on single tree level. A productivity model was developed from time consumption and volume data and time consumption was then intersected with fuel consumption data to develop a fuel consumption model. However, only slope had a significant impact on fuel consumption. The values predicted are between 61.87 and 101.37, with an average of 81.36 m^3/PSH_0, which are higher values than for the other functions (Figure 9).

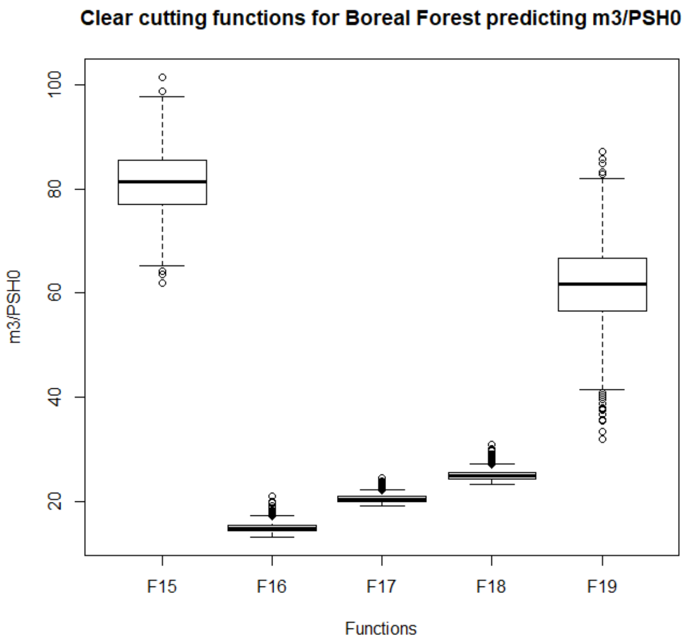

Figure 8: Prediction of functions for clear cutting in boreal forests with harvester and forwarder in cut-to-length method not including delays up to 15 min

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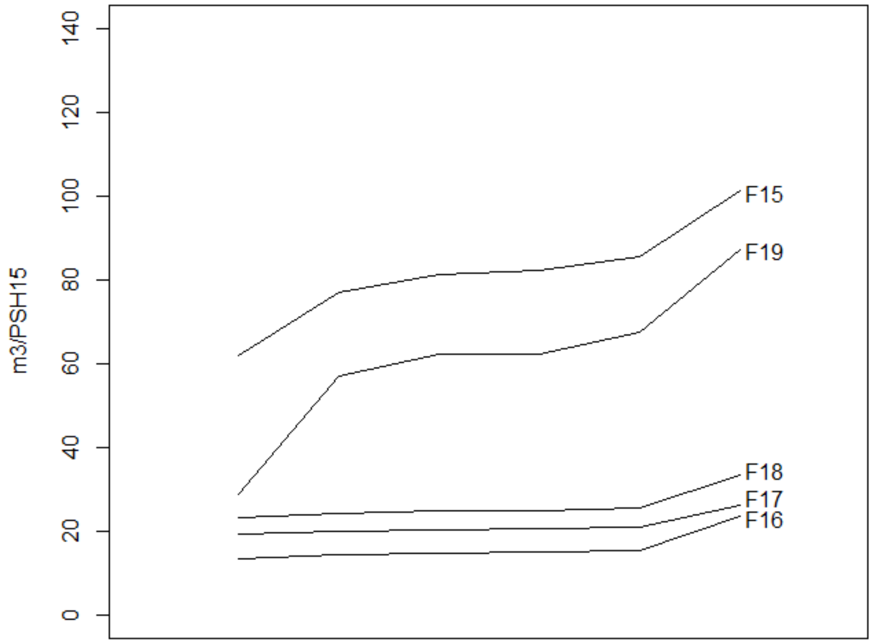

Figure 9: Visualization of the productivity functions F15-F19 using the minimum, 1st quartile, mean, 3rd quartile and maximum values.

For the **temperate forest,** 17 functions were collected but because of lack of data only 14 were studied and they are plotted in figure 10. In this case, delay times were recorded regardless of duration. Productivity was expressed in m^3 per productive system hours (PSh_0).The function predicting the highest value is the function described in the study Norihiro, Ackerman, Spong, and Längin (2018):

$$y = \beta_0 + \beta_1 x_1$$

Where β_0 is 5.8, β_1 is 102.74, x_1 is the tree volume in m^3. The values predicted range between 42.9 and 173.5 m^3/PSH_0 (Figure11)

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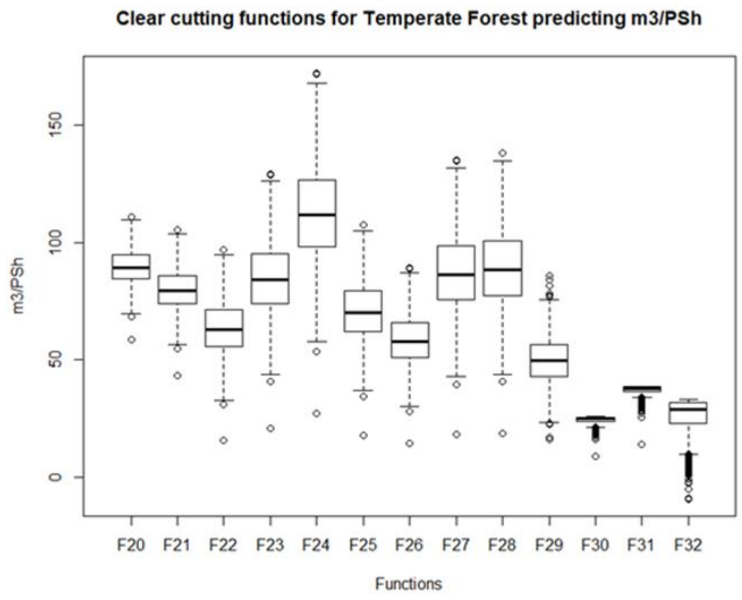

Figure 10: Prediction of functions for clear cutting in temperate forests with harvester and forwarder in cut-to-length method not including delays up to 15 min

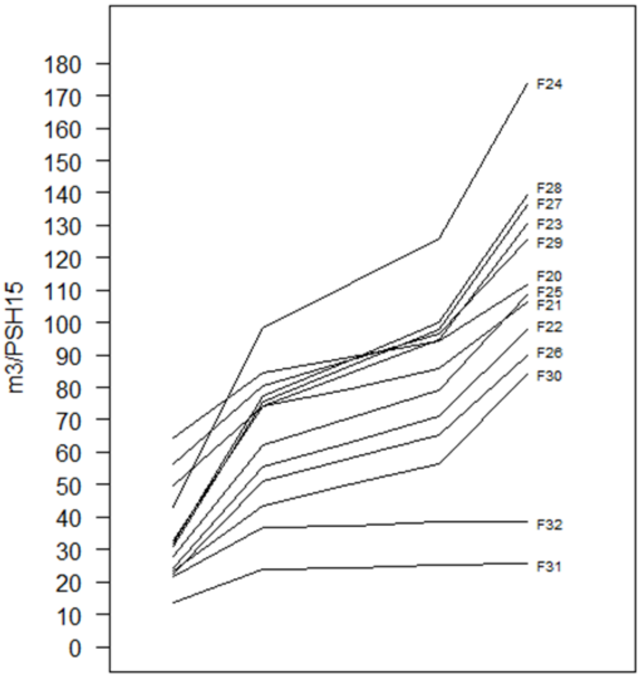

Figure 11: Visualization of the productivity functions F20-F32 using the minimum, 1st quartile, mean, 3rd quartile and maximum values.

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4.2 Winch-assisted harvester and forwarder in cut-to-length method

The functions for identifying, among existing productivity functions, the one predicting highest values for this harvesting system, were provided by only one consortium partner, BOKU. Three productivity functions were assessed, all using the units m^3/PSH_{15} (Figure 12). Among the three, the one predicting higher values is F33, which was described in the master thesis of Norbert Brandtner.

$$y = c/(a + \beta_1 {x_1}^b)$$

Where x1 is the tree volume (m^3); c is a constant equal to 60; β_1 is a constant equal to 1.8711 and b is a constant equal to -0.688.

Data for Brandtner's productivity model was collected during thinning and final felling operations in Spruce-dominated stands. For felling and processing a John Deere 1170E equipped with a Haas traction winch was employed on slopes of up to 58 %. A total of 521 m^3 was harvested and the average felling diameter and volume were 19.1±8.0 cm and 0.30±0.40 m^3. The function described below predicts values between 14.0 and 46.0 m^3/PSH_{15} (Figure 13).

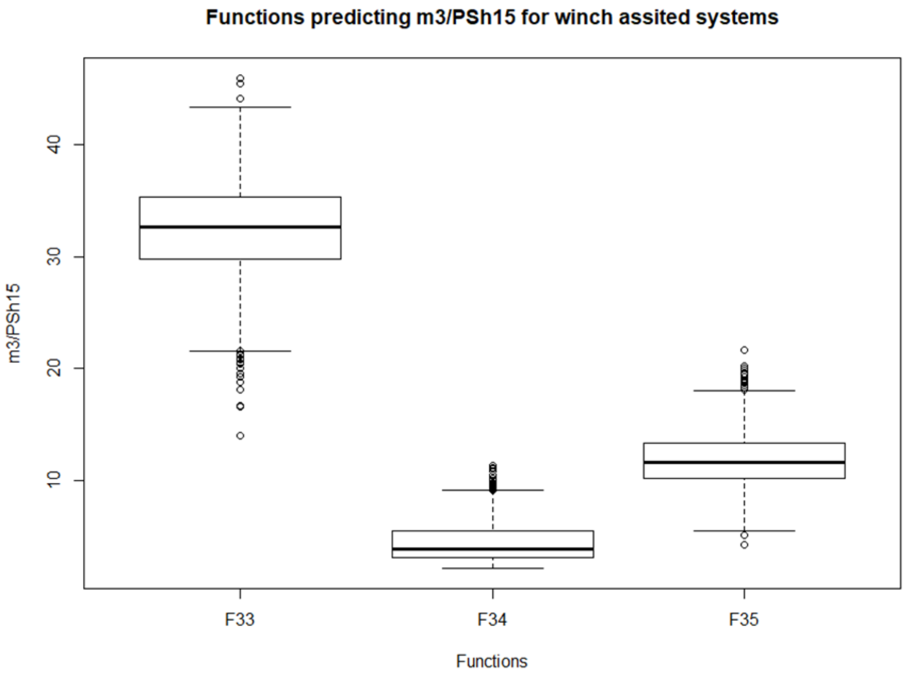

Figure 12: Prediction of functions for winch-assisted, fully-mechanized harvesting systems in cut-to-length method including delays up to 15 min

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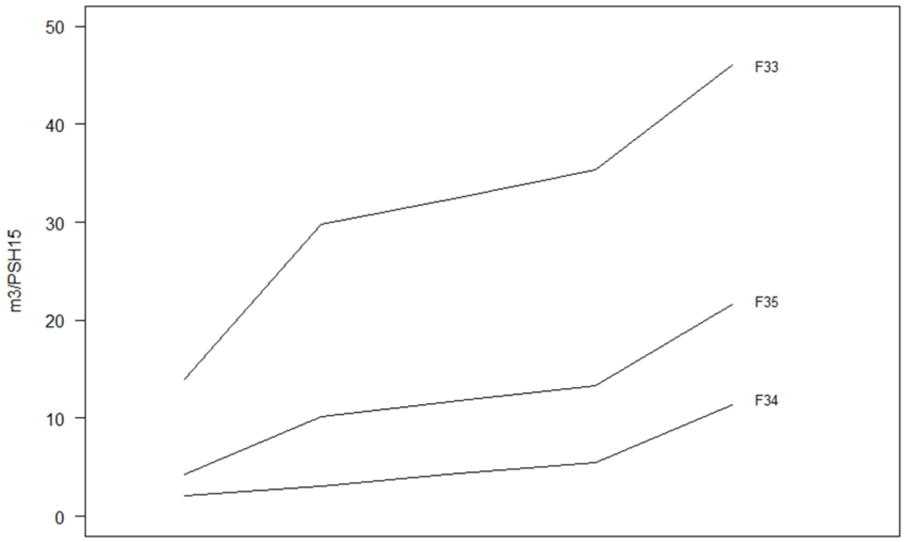

Figure 13: Visualization of the productivity functions F33-F35 using the minimum, 1st quartile, mean, 3rd quartile and maximum values.

4.3 Chainsaw and skidder in tree-length method

The functions considered in this section are 3 for skidders and 4 for farm tractors. They were provided by partners in Austria, Italy and South Africa where this system is more common and therefore research has been more active into improving the efficiency of such operations. The analysis was performed separately for skidders and for farm tractors.

4.3.1 Skidders

The functions for identifying, among existing productivity function, the one predicting higher values for this harvesting system, were provided by only several consortium partners. Three productivity functions were assessed, all using the units m^3/PSH (Figure 14). Among the three, the one predicting highest values is F36, which was described in Ackerman, Pulkki, and Gleasure (2014). Machine make and model as well as gross power rating were studied and productivity was estimated around 43.9 m^3/PMH for cable skidders and 123.9 m^3/PMH for grapple skidders.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 - c$$

Where y is the productivity in m^3 /PMH; x_1 is the machine gross power (kW), β_1 is a constant equal to 0.652; x_2 is the average tree volume (m^3) and β_2 is a constant equal to 10.455; x_3 is the payload size (m^3) and β_3 is a constant equal to 6.031; x_4 is the in-field extraction distance (m), β_4 is a constant equal to –0.031; x_5 is the time taken to load (min) and β_5 is a constant equal to -0.622; x_6 is the time taken to unload (min) and β_5 is a constant equal to -0.622; c is a constant equal to -66.912. The function described above predicts values between 2.0 and 89.0 m^3/PSH (Figure 15).

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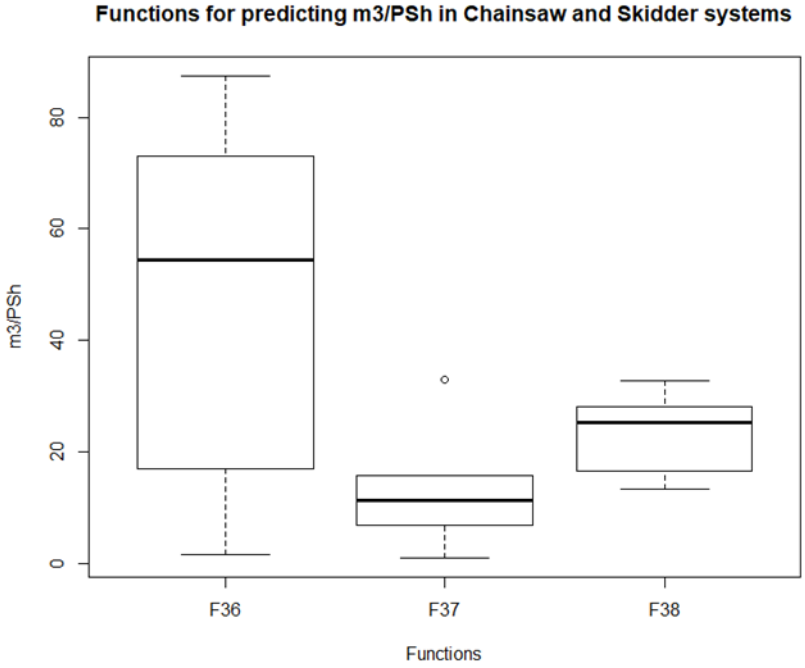

Figure 14: Prediction of functions for dedicated skidders in tree-length method

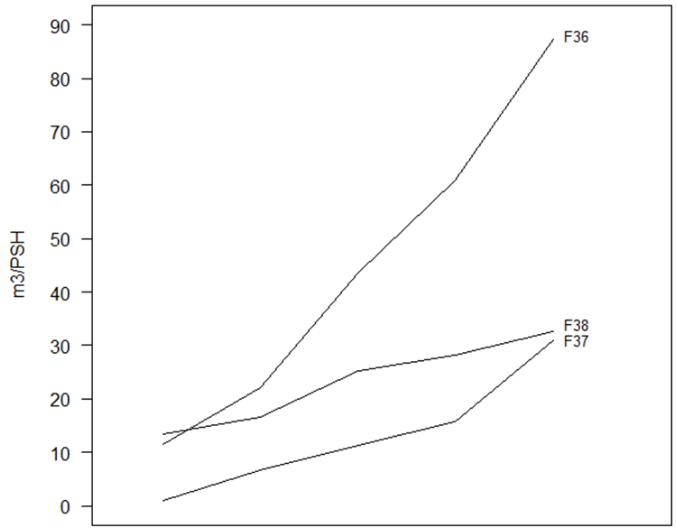

Figure 15: Visualization of the productivity functions F36-F38 using the minimum, 1st quartile, mean, 3rd quartile and maximum values.

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4.3.2 Farm tractors

The functions for identifying, among existing productivity function, the one predicting higher values for this harvesting systems, were provided by BOKU and CNR. Four productivity functions were assessed, all using the units m^3/PSH (Figure 16). Among the four, the one predicting higher values is F41, which was described in Spinelli et al. (2016).

$$y = \beta_1 x_1^a * z_1^b + \beta_2 x_2$$

Where β_1 is 51.305, a is 102.74, c is −0.574, β_2 is 0.009. x_1 is Load per turn (m3), z_1 is the Distance (m) and x_2 is the Total removal (m3/ha). The function described below predicts values between 5.6 and 28.8 m^3/PSH (Figure 17).

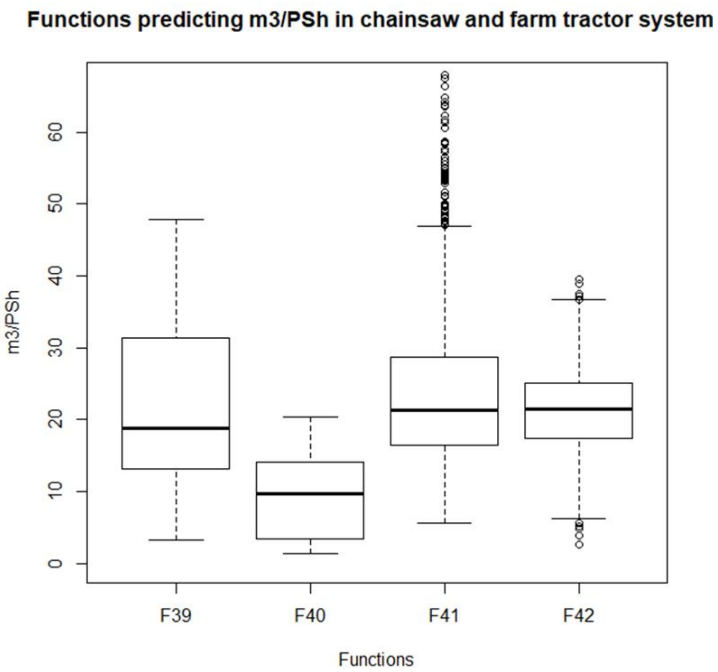

Figure 16: Prediction of functions for farm tractors in tree-length method not including delays up to 15 min

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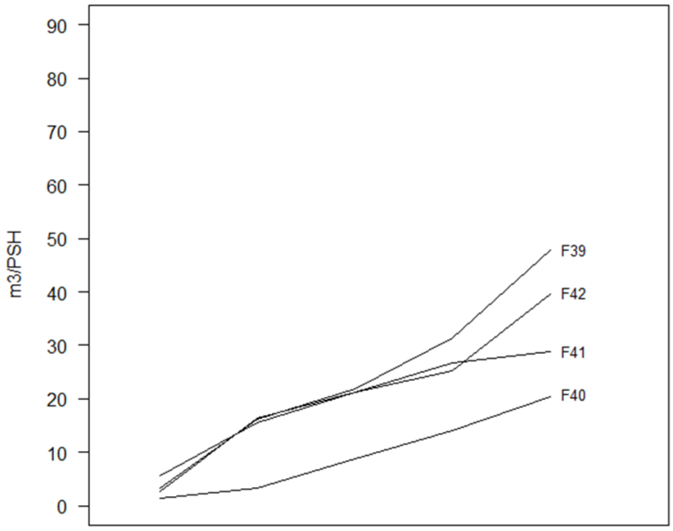

Figure 17: Visualization of the productivity functions F39-F42 using the minimum, 1st quartile, mean, 3rd quartile and maximum values.

4.4 Chainsaw and cable yarder in whole-tree method

Most of the productivity functions for this harvesting system are modelling the time consumption min/m^3 to bring the loads to the yarding site. Only a few are instead modelling the productivity of the whole system, i.e. including the felling with m^3/PSH as an output. The TECH4EFFECT consortium members provided 9 functions for this harvesting system modelling but for one the dependent variable was time and was therefore discarded. Only functions predicting m^3/PSH were considered in our study. Eight productivity functions were assessed, all using the units m^3/PSH (Figure 16). Among them, the one predicting higher values is F48, which was described in Spinelli, Maganotti, and Visser (2015) .

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4$$

Where β_0 is a constant equal to -13.9; β_1 is a constant equal to -0.048 and x_1 is the yarding distance (m); β_2 is a constant equal to -0.143 x_2 is the lateral yarding distance (m); β_3 is a constant equal to 1.11 x_3 is the number of logs per turn (#); β_4 is a constant equal to 15.28. and x_4 is the average piece size (m^3). The results of the models' predictions are presented in figure 18. The function described above predicts in our study values between 17.3 and 29.0 m^3/PSH (Figure 19).

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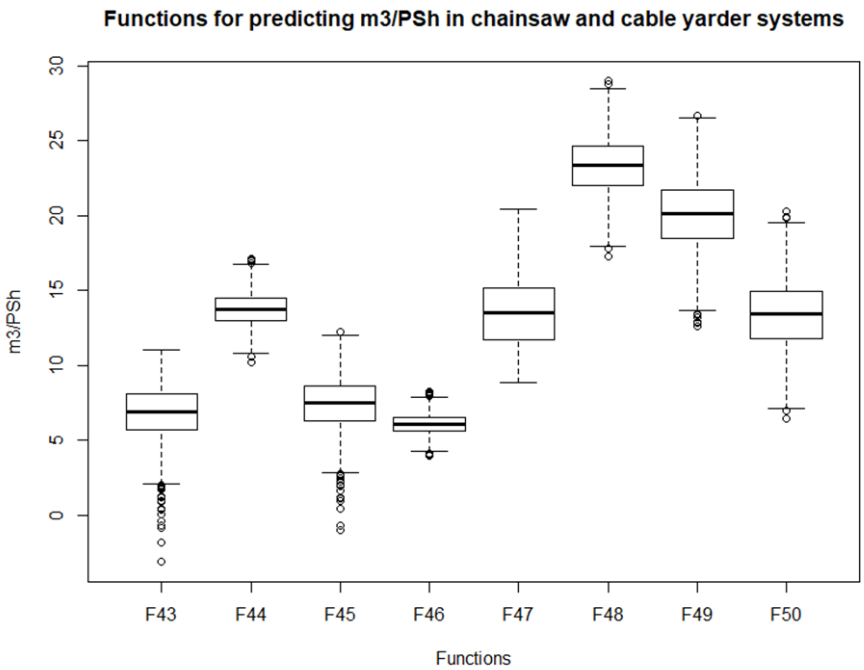

Figure 18: Prediction of functions for chainsaw and cable yarding in whole-tree method

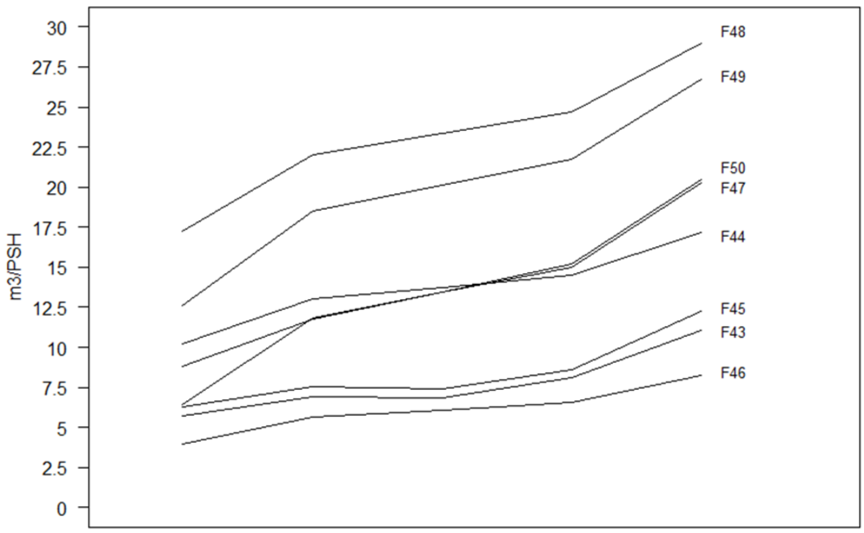

Figure 19: Visualization of the productivity functions F43-F50 using the minimum, 1st quartile, mean, 3rd quartile and maximum values.

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5 Conclusions

A total of fifty functions for the four different harvesting systems were categorized, fitted and plotted. Subsystems were considered as well in order to capture the different productivities. For each harvesting system, regardless of how well the function fitted the original dataset (R^2), the one predicting the highest values was identified. From the results of these study indications on the most relevant parameters predicting the top performance figures among all those included in the fifty studies (Annex1) are as follow:

For the harvester and forwarder in cut-to-length method: average stem size (in dm^3 or m^3), removal (m^3/ha), the number of assortments and diameter at breast height (cm). The highest productivity predicted for a thinning was 32.6 m^3/PSH_{15} and 101.37 m^3/PSH_0 for the clear cutting/final felling.

For the winch-assisted harvester and forwarder in cut-to-length method: tree volume (m^3). The highest productivity predicted was 46.0 $m^3/PSH_{15.}$

For chainsaw and skidder: machine gross power (kW), average tree volume (m^3) the payload size (m^3) in-field extraction distance (m), the time taken to load (min), the time taken to unload (min). The highest predicted productivity for skidding were 28.8 m^3/PSH with a farm tractor, while with was 89.0 m^3/PSH with a skidder.

Finally, for chainsaw and cable yarder in whole tree method the variables were: yarding distance (m), lateral yarding distance (m), number of logs per turn (#) and the average piece size (m^3). For this system the highest value was 29.0 m^3/PSH.

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6 Annex 1

* Harvesting systems: 1- Harvester+Forwarder CTL
2- Winch assisted Harvester and Forwarder CTL
3-Chainsaw and skidder TLM
4- Chainsaw and Cable Yarder WTM

Variable description	Units	Type	Harvesting system n.*
Diameter at breast height	cm	Numerical continuous	1
Average forwarding distance	m	Numerical continuous	1
Average load volume	m^3	Numerical continuous	1
Average piece volume	m^3	Numerical continuous	1, 2, 3
Average tree volume	m^3	Numerical continuous	1,2, 3
Age of the trees	years	Numerical continuous	1
Stem size	m^3 (dm^3 in Finnish studies)	Numerical continuous	1
Forwarding distance	m	Numerical continuous	2
Moving time	min/stem	Numerical continuous	1
Loading distance	m	Numerical continuous	2
Removal	m^3/ha	Numerical continuous	1
Number of timber assortments	pieces	Numerical continuous	1
Stem processing time ratio	n	Numerical continuous	1
Volume of merchantable tree volume	m^3	Numerical continuous	1
Number of processing passes	n	Numerical continuous	1
Average slope	%	Numerical continuous	1,2
average distance moved per felling cycle	m	Numerical continuous	1
Average load volume	m^3	Numerical continuous	1, 2
Average distance travelled when loaded	m	Numerical continuous	1
Time used to cut	min	Numerical continuous	1
Time used to haul	min	Numerical continuous	1
Type of silvicultural system	n	Factor	1
Handling time	min	Numerical continuous	1

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Winching time	m	Numerical continuous	1
Winching distance	m	Numerical continuous	1
Machine Gross Power	kW	Numerical continuous	3
Load size- number	number	Numerical continuous	1
Load size	m^3	Numerical continuous	1, 2, 3
Loading time	min	Numerical continuous	1, 3
Unloading time	min	Numerical continuous	1, 3
Dummy variable to model the presence of the Choker-setter	0,1	Factor	3,4
Dummy variable to model the type of machine: crawler/skidder	0,1	Factor	3
in-field extraction distance	m	Numerical continuous	3
Average forwarding distance	m	Numerical continuous	1
Average winching distance	m	Numerical continuous	3
Team identification number	n	Numerical continuous	4
Lateral yarding distance	m	Numerical continuous	4
Yarding distance	m	Numerical continuous	4
volume per running meter of skyline	m^3/m	Factor	4
Harvesting season	n	Factor	4
Yarding type	n	Factor	4
Felling direction	n	Factor	4
Span length	m	Numerical continuous	4
Harvesting intensity	%	Numerical continuous	4
Lateral extraction distance	m	Numerical continuous	4

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