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

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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:
1) 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.
2) 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.
3) '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.

2 Introduction to precision forestry in regeneration

In current forest management practice forest stands are delineated and formed either on operational or biological basis. Typically, the size of forest stand varies between 1 to 10 hectares. However, stands comprise rather broad small-scale variation regarding tree species mix, soil properties, fertility, etc. The term **'Precision forestry'** is an emerging forest management concept based on observing, measuring and responding to the intrinsic variability within forest stands.

Based on modern techniques (e.g. airborne laser scanning and harvester data) it is possible to produce trustworthy and in spatial scale precise predictions on site quality indices, diameter-height distributions and micro-topography for a given point, grid cell or on micro stand level. Interlinking information of tree attributes and site index with topographical, cartographical and hydrological information provides a way forward to upgrade forestry efficiency. Further, precision forestry gives forest practitioners tools to adjust the unique features of the site by managing the forest more according to biological prerequisites.

Precision forestry philosophy – division of stand to smaller units and managing the stand at micro stand, grid cell or tree-by-tree level – provides a huge possibility to increase the forest growth. In regeneration phase by adjusting species selection, soil preparation, intensity of regeneration measures (planting density and material) and young stand treatment procedures according to precise information on soil properties (fertility, wetness, soil type) and micro-topography will inevitably lead to an increasing growth of a single tree and the whole stand. However, optimal solutions to execution have to be assessed via proper feasibility analyses including trustworthy information on growth and costs.

This report describes an approach about how to utilize harvester data to delineate micro stands inside a large forest stand and to decide the best silvicultural regime for each micro stand. The report is based on a case study carried out on Finsilva forest property in Central Finland.

3 Case study

3.1 Description of study stands

The study material comprised six mature mixed Scots pine – Norway spruce forest stands. All these stands were final felled in summer and autumn 2017. Delineation of cutting areas was done by Metsä Groups' forest management experts based on forest data and field inspection. Area of chosen study stands varied from 1.3 to 23 ha; all together 68 ha. Site types according to Finnish site type classification varied in these study stands from quite unfertile Vaccinium type to Myrtillus type (Cajander 1926). The main tree species was Norway spruce in 2 study stand and Scots pine in 4 study stands. All of these stands had some birch admixture (varying from 2 to 13 % of stand volume). Average cutting volumes varied from 199 to 303 m3/ha (table 1).

Table 1. Stand volumes by tree species in the study stands before cutting.

	Stand characteristics						
Study stand no.	Area, ha	Main site type	Mean age, a	Pine m3/ha	Spruce m3/ha	Birch m3/ha	Total m3/ha
2	1,3	MT*	91	142	112	18	272
118	1,7	MT	67	93	121	31	245
140	5,1	VT**	60	121	53	25	199
49	9,8	MT	78	65	106	12	183
84	12,8	MT	65	112	111	18	241
127	23,3	MT	65	182	113	8	303

* Myrtillus site type, ** Vaccimium sitr type

All study stands situated on a limited area within 15 kilometers radius in western Finland near Tampere. When simulating development of next stand generation with Motti simulator all study stands were assumed to situate in the area.

4 Process for tree species selection for regeneration

4.1 Estimation of growth potential

4.2.1 HPR-data conversion

All stands were harvested with Komatsu harvester equipped with the harvester measurement system and GPS-receiver. While harvesting, information on cut trees were registered. The most important tree characteristics included: geographic location of tree (=location of machine at the moment the tree had been felled), butt end and top end diameters of each log, length of each log and assortment of each log. After harvesting tree information was converted in the hpr-format (Skogforsk 2018). Next, this hpr-file was interpreted and analysed with the HprAnalys software developed by Skogforsk. With this tool tree information was converted into the ESRI Shapefile-format. In the ArcGIS-tool, a new vector grid layout of 16 x 16 m was created and each tree was categorized to the one specific grid cell according to its location (Figure 1).

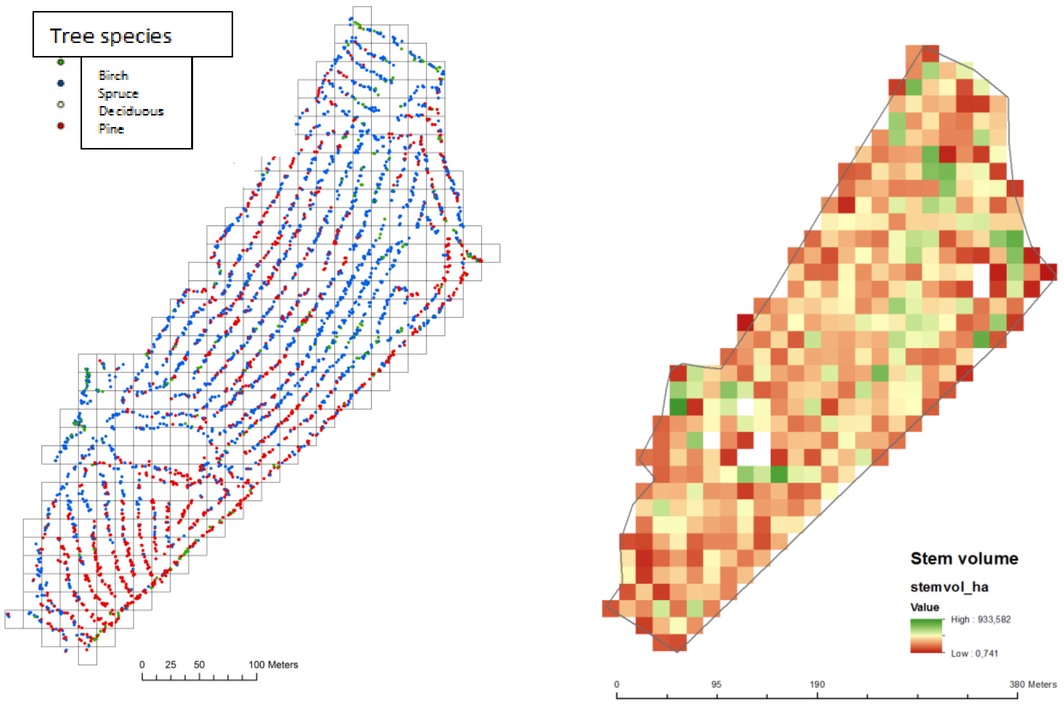

Figure 1. Illustration of the location of the machine at the moment the tree has been processed in study stand 49 (on the left). Stem volumes in each 16 x 16 m grid were also based on the locations of the machine at the moment the tree was processed (on the right). On the right picture the stem volume varied from 1 m3/ha (dark red) up to 900 m3/ha (dark green) between grid cells.

4.2.2 Estimation of site index

Site index for each grid was calculated with equations for artificially regenerated stands by Vuokila and Väliaho (1980) and for naturally regenerated stands by Gustavsen (1980). Tree height was based on harvester data and modelled top height. At first, height of each felled tree was estimated by aid of dbh, height of the last cut and diameter of the stem at the height of the last cut. Top height was estimated by model of Varjo (1995). Secondly, from each grid cell, three tallest trees were selected as the dominant trees. Thirdly, stand age was based on stump age measurements. Age of trees in the forest was estimated by a separate systematic sampling and reading of year rings from 20 sample stumps. However, later it was noticed that the measured ages was well in harmony with the forest stand data.

Next, site index (i.e. H_{100}=height of dominant trees at the age of 100 years) for each grid cell was estimated with the following equations given by Gustavsen (1980):

Pine

$$H_{100} = 128.229exp\left[\frac{ln(H_{dom}) - ln128.229}{\exp\left(\frac{4.70248}{T^{0.47692}} - \frac{4.70248}{100^{0.47692}}\right)}\right]$$

Spruce

$$H_{100} = 147.481exp\left[\frac{ln(H_{dom}) - ln147.481}{\exp\left(\frac{4.64631}{T^{0.29981}} - \frac{4.64631}{100^{0.29981}}\right)}\right]$$

Where

H_{dom}= Height of dominant trees at the moment of harvest

T= Biological age of dominant trees at the moment of harvest

Finally, mean annual volume growth for the period of 100 years (i_v) (m3/ha/year) was estimated with the equations presented by Vuokila and Väliaho (1980):

Spruce: $i_v = 0.11 + 0.0095\ H^2_{100}$

Pine: $i_v = -0.44 + 0.0098\ H^2_{100}$

Greater value of these growths (pine or spruce) was selected to represent growth potential of each grid cell (Figure 2).

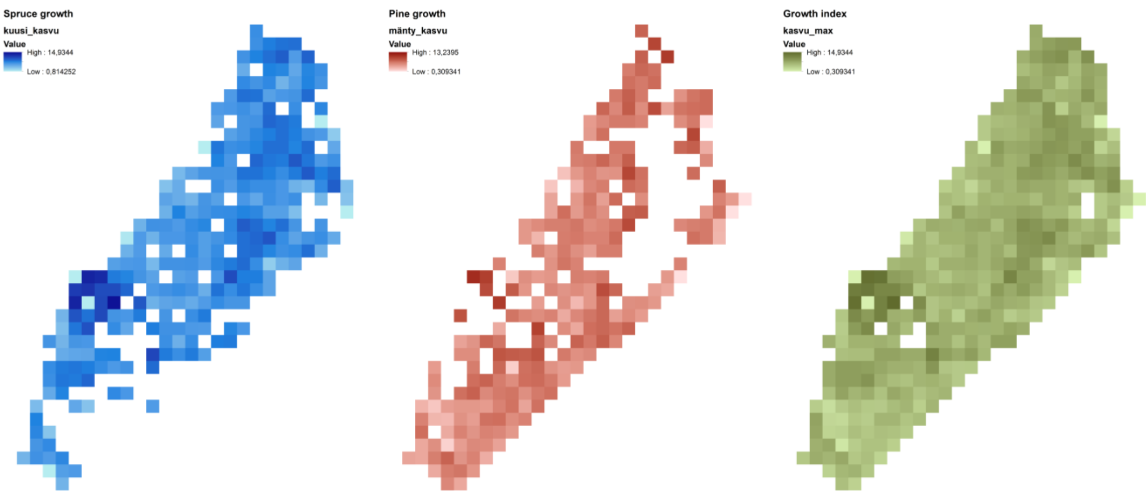

Figure 2. Maps of mean annual volume growth potential (m3/ha/a) in study stand 49 estimated by the past growth of spruce (left), pine (middle) and combined with maximum value of spruce or pine (right). In this stand growth varied from 0.3 m3/ha/a up to 14 m3/ha/a.

4.1 Creation of micro stands

Delineation of micro stands were based on the growth potential (mean growth within 100 years, m3/ha/a) of each grid cell. In order to scale out variation in growth potential between adjacent grid cells the average value of nine grid cells (the center cell plus eight adjacent cells) was used as the growth potential value for the center cell.

Alternative threshold values were crated in order to categorize with which tree species each micro stand should be planted. The threshold values were based on stand simulations carried out with the Motti stand simulator developed at Luke (details of Motti simulations, see chapter 4.3) (Figure 3). Annual volume increment of pine and spruce seemed to be quite equal on Myrtillus site type varying from six to eight m3/ha/a. So on Myrtillus site type both spruce and pine could be good option for planted tree species.

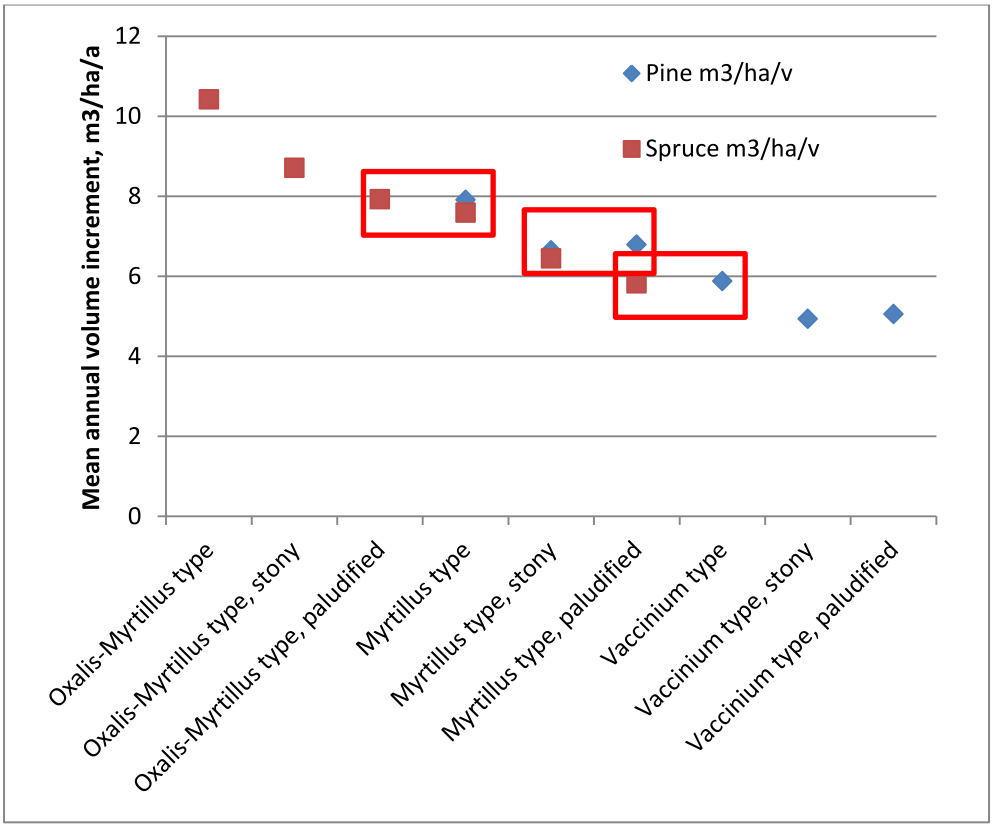

Figure 3. Mean annual volume increment (m3/ha/v) of spruce and pine on different sites based on Motti simulation results.

Two different methods were used to apply precision forestry philosophy. In the first method, one single threshold value was created for the mean annual volume increment. In this method, either spruce or pine was selected, solely based on that threshold value. The used threshold values were 6, 7 and 8 m3/ha/a. If the growth exceeded the threshold value spruce was selected otherwise pine was used as planting material. The second method contained two threshold values of 6 and 8 m3/ha/a simultaneously. If the growth was under 6, pine waschosen. If the growth exceeded 8, spruce was chosen. In the case, where growth was between 6 and 8, either pine or spruce was chosen. The precision forestry alternatives were then compared to the conventional practices where the whole stand was planted with one tree species.

To summarize, simulations included seven options (see Figure 4):

1. Planting with spruce (pure spruce stand)
2. Planting with pine (pure pine stand)
3. Pine up to threshold value of 6 m3/ha/a and spruce above it (mixed stand)
4. Pine up to threshold value of 7 m3/ha/a and spruce above it (mixed stand)
5. Pine up to threshold value of 8 m3/ha/a and spruce above it (mixed stand)
6. Pine up to threshold value of 6 m3/ha/a and spruce above threshold value of 8 m3/ha/a. The middle category is planted with pine (mixed stand)
7. Pine up to threshold value of 6 m3/ha/a and spruce above threshold value of 8 m3/ha/a. The middle category is planted with spruce (mixed stand)

Micro stands were generated from cells with same tree species taking to account that the area of minimum micro stand was at least 0,23 ha (nine grid cells). The software to generate micro stand maps was coded in Python programming language. In this software user defines threshold value for categorization and gives them as an input to the software. An iterative process is run to segment the growth potential data to areas larger than the threshold value (nine grid cells). First, the program segments given growth potential data and recognises the continuous areas of different categories. Cells in areas smaller than threshold value (nine grid cells) are identified and their growth potential values are converted to the closest value in a neighboring segment. The segmentation, area identification and cell value transformation are repeated until all the continuous areas are larger than the minimum micro stand value.

Alternative micro stand solutions looked quite different in the same study stand (Figure 4). For instance in study stand 49 the one threshold solutions (alternatives A-C in figure 5) differ totally from each other and the double threshold solution seems to combine the features of one threshold solutions with solutions 6 and 8 m3/ha/a. All micro stand solutions are presented in appendix 1.

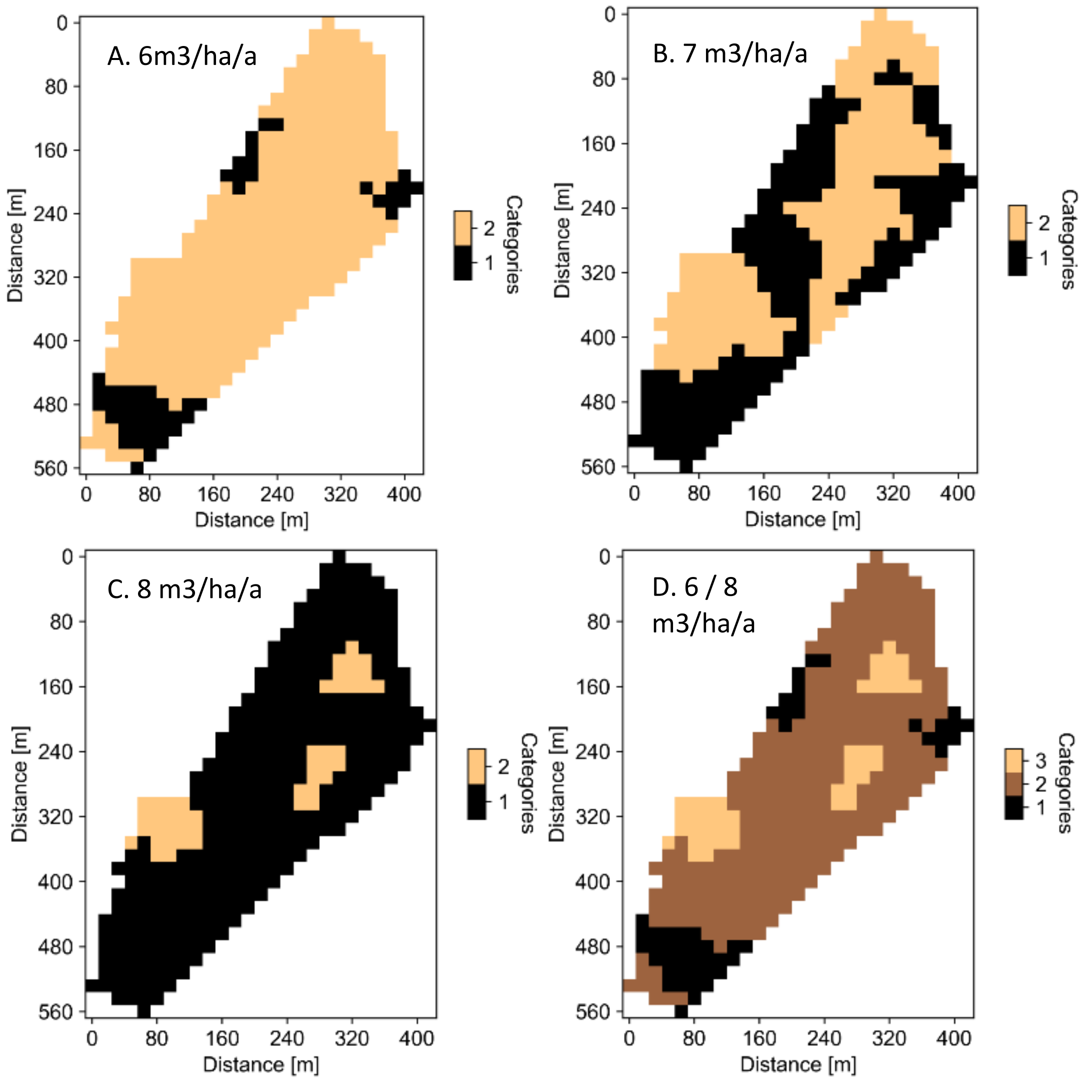

Figure 4. Visualization of micro compartments in study stand 49 categorized with single threshold values of 6 (A), 7 (B) and 8 m3/ha/a (C); and double threshold values of 6 and 8 m3/ha/a (D). A-C: Category 1= pine, 2= spruce, D: 1= pine, 2= pine or spruce and 3= spruce.

According to micro stand delineation the number of micro stands varied from 1 to 13 in different solutions in study stands (table 2). In the smallest study stands (stands 2 and 118) delineation to micro stands did create only two micro compartments. This was obvious because the total area of these stands was less than two hectares. In larger study stands the number of micro compartments was clearly higher. In these larger study stands the average number of micro compartments in one threshold value solutions was six and in double threshold value solutions nine.

The average area of micro stands was 1.68 ha (excluding one micro stand solution in study stand 127). In larger study stands (stands 2 and 118 not included) the average micro stand area was more than two hectare. The minimum area of micro stand averaged 0.46 ha (excluding one micro stand solution in study stand 127) and in larger stands 0.27 ha correspondingly.

Table 2. Number and mean, minimum and maximum area of micro stands (ha) in different threshold values in study stands. Study stands are arranged in ascending order in area.

Study stand no.	Threshold value, m3/ha/a	Number of micro stands	Average micro stand area, ha	Minimum micro stand area, ha	Maximum micro stand area, ha
2	6	2	0.64	0.36	0.92
	7	2	0.64	0.44	0.84
	8	1	1.28	1.28	1.28
	6 and 8	2	0.64	0.36	0.92
118	6	1	1.66	1.66	1.66
	7	1	1.66	1.66	1.66
	8	2	0.83	0.36	1.31
	6 and 8	2	0.83	0.36	1.31
140	6	2	2.68	0.23	5.12
	7	3	1.78	0.26	4.10
	8	4	1.34	0.28	2.28
	6 and 8	5	1.07	0.23	2.28
49	6	5	2.02	0.23	8.55
	7	6	1.68	0.23	3.61
	8	4	2.52	0.31	8.93
	6 and 8	8	1.26	0.23	7.40
84	6	8	1.88	0.54	7.78
	7	12	1.25	0.23	5.07
	8	6	2.50	0.26	11.98
	6 and 8	13	1.16	0.23	5.15
127	6	1	24.42	24.42	24.42
	7	5	4.88	0.28	23.09
	8	13	1.88	0.26	17.33
	6 and 8	11	2.22	0.26	17.33

According to micro stand delineation the proportion of spruce/pine varied from 0 to 100 % (table 3). In two study stands (118 and 127) the result was spruce dominated stock in every micro stand solution. Also options threshold value 6 m3/ha/a and double threshold value 6/8 m3/ha/a with spruce in middle category gave always a spruce dominated stand as result. Most often pine dominated stands were found when threshold value was 8 m3/ha/a, which was a quite obvious outcome.

Table 3. Proportion spruce (%) in different micro stand delineation alternatives. Spruce dominated stand options are marked with bolded numbers. Study stands are arranged in ascending order in area.

	Delineation alternative				
Study stand no.	Pine/ spruce threshold 6 m3/ha/a	Pine/ spruce threshold 7 m3/ha/a	Pine/ spruce threshold 8 m3/ha/a	Double threshold 06/08 m3/ha/a, middle category pine	Double threshold 06/08 m3/ha/a, middle category spruce
2	**53**	34	0	0	**72**
118	**100**	**100**	**78**	**52**	**100**
140	**96**	**81**	43	43	**96**
49	**87**	**51**	11	11	**87**
84	**72**	30	9	10	**71**
127	**100**	**95**	**74**	**76**	**100**

4.3 Stand simulations with different micro stand solutions

Stand simulations were done by Motti software which is developed at Natural Resources Institute Finland (Luke). Motti is a stand-level forest management and decision support tool that consists of stand-level models and distance-independent individual-tree models for predicting stand dynamics (regeneration, growth and mortality) and stand structure (Salminen et al. 2005, Siipilehto et al. 2014, Hynynen et al. 2015). The growth and yield models of the Motti system are based on extensive empirical data covering all commercial wood tree species (Hynynen et al. 2014, Hynynen et al. 2002). The predicted responses to different forest management practices are based on empirical data which covers all common forest management practices applied in practical forestry in Finland over recent decades.

In total 36 simulations were calculated for the study sites. All stands located quite nearly (same temperature sum), so simulation results for single stand were utilized for all study stands. At first it was assumed that main tree species were either Scots pine or Norway spruce. And for those were simulated the forest management chain based on silvicultural guidelines (Rantala et al. 2011) at Myrtillus site type. After that, same timing for management practices was assessed in simulations when site type and main tree species were varied. In order to simulate sets with varying tree species and site type for pine dominated stand and similarly for spruce dominated stands. Timing of silvicultural operations for spruce and pine dominated stands are in table 4. According to Motti simulations on Myrtillus site type following silvicultural guidelines rotation period for spruce dominated stand was 64 years and for pine dominated stand 61 years.

In all simulations the site preparation was mounding. Regeneration was planting for Norway spruce 1800 seedlings per hectare and for pine 2200 seedlings per hectare. Survival was assumed to 90% for both tree species. Both early cleaning (EC) and pre-commercial thinning (PCT) were assessed in all simulations. The density of sapling stand after EC was 3000–4000 seedlings per hectare, depending on the site type and tree species, but according to the models new saplings were immediately born to the site (Siipilehto et al. 2014). The total stem number after PCT was 2200 and 1800 for pine and spruce, respectively. In addition of main tree species in fertile site also birches were left to growing stock after PCT. In first thinning the strip roads were opened. Tree selection in thinnings was based on thinnings from below.

Table 4. Timing of silvicultural operations in simulations (stand age, a) by dominant tree species at Myrtillus site type. Same timings were used in all simulations (e.g. when varying site type and main tree species).

	Norway spruce	Scots pine
Early cleaning	5	5
Precommercial thinning	11	11
First commercial thinning	33	29
Commercial thinning	44	38
Final felling	64	61

For the economical calculations the amount of saw logs and pulp wood was calculated also in Motti. The merchantable stem volume was calculated using assortment rules widely applied in Finland. For pulpwood, the minimum length was 3.0m and the minimum top diameter over bark 6.0 cm for pine and broadleaved trees and 7.0 cm for spruce. The minimum saw log length was 3.7 m for pine and spruce and 3.0 m for birch. The minimum top diameter over bark was 15 cm for pine and 16 cm for spruce increasing progressively with increasing saw log length. From the length of 4.3 m the minimum diameter was 20 cm. For birch logs the minimum top diameter over bark was constantly 20 cm.

The costs of silvicultural treatments were defined using time consumption models of Motti and unit costs (long-term mean values) from statistics (Table 5). Cost for early cleaning (EC) and pre-commercial thinning (PCT) were based on time consumption models. Time consumption of EC and PCT were based on the number and size (diameter at stump and height) of removed trees. Planting was done manually. For harvesting revenues, we used stumpage prices by cuttings (first commercial thinning, intermediate thinning, final felling) based on statistics (Table 5). Prices and costs were based on annual statistics from years 2002 to 2016. The original nominal time series of prices and costs were deflated by the cost-of-living index to the year 2016 (Official Statistics of Finland (OSF) 2017) in order to attain unit prices and costs in real terms, i.e. net of inflation. The used time period is the longest available from 2000s, and it includes both peak and bottom of the prices and costs.

Table 5. Real (i.e., deflated) stumpage prices and silvicultural costs € m^{-3}, € $plant^{-1}$, € $hour^{-1}$ or € ha^{-1}.

	Stumpage prices[1]. € m^{-3}								
	First commercial thinning			Intermediate thinning			Final felling		
	Pine[2]	Spruce[2]	Birch[2]	Pine	Spruce	Birch	Pine	Spruce	Birch
Saw logs	41.81	41.93	37.12	50.24	49.73	41.66	59.33	58.96	48.95
Pulpwood	12.6	14.92	12.07	15.63	19.52	14.28	18.36	23.77	17.88

Silvicultural costs	Pine	Spruce		
Labour costs of planting. € $plant^{-1}$	0.16	0.18	Mounding. € ha^{-1}	342.5
Material costs of planting. € $plant^{-1}$	0.19	0.21	Early cleaning (EC). € h^{-1}	35.0
			Precommercial thinning (PCT). € h^{-1}	35.0

[1]) The original time series of nominal stumpage prices and silvicultural costs (covering years 2002-2016) were deflated according to cost-of-living index (1951:10 = 100 and index value for year 2016=1913).

[2]) Pine = Scots pine. Spruce = Norway spruce. Birch = Silver birch and other broadleaved trees.

The Net Present Values (NPV) (€/ha) were calculated in Motti for each simulation according to the following formula:

$$NPV_x = \sum_{i>0}^{T} \frac{H_i}{(1+r)^i} - \frac{\sum_{k=1}^{K} sc_{kl}}{(1+r)^l} \qquad [1]$$

where NPV_x = net present value for a forest stand x, €, *H*= cutting income of thinning at year *i* or of final felling at year *T*, €, SC_{kl} = silvicultural cost at year *k*, *r*= discount rate (expressed as %).
Bare land value was not considered because the rotation was same in all simulations (61 years for spruce and 63 years for pine dominated stands).

Results from each simulation were the mean annual volume growth and NPV at 3% discount rate. Stand level simulation results were used in further analysis of micro stand solutions. In simulations the whole study stand was treated according to the management schedule of the main (dominant) tree species. It means that if pine was the main trees species (based on area) in the study stand all silvicultural operations, thinnings and final felling of the stand were done according to the silvicultural guidelines suited for pine stand (Rantala 2011).

The mean annual volume growth and NPVs were adjusted for each grid cell in each study stand with regression equations (Figure 5). The corresponding equations were calculated for log volume increment. When calculating the above mentioned values the tree species of micro stand and the main tree species of the whole stand was taken into account as selecting the correct equation for each grid cell. When comparing different micro stand solutions the stand level means of NPVs and log volume growth were used.

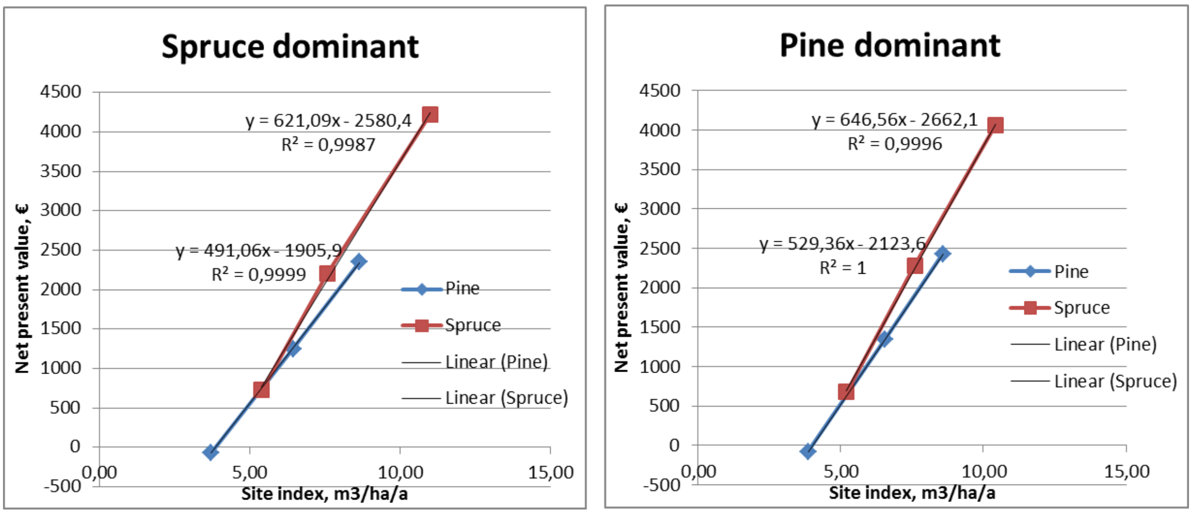

Figure 5. Linear regression equations used to calculate NPVs for each grid level site index.

In all study stands NPV of pure spruce stand was clearly higher than that of pure pine stand (Figure 6). In four out of six cases the NPV of mixed stand was a little bit higher than the one of pure spruce stand. All these mixed stands were spruce dominated and they were treated following silvicultural guidelines of spruce dominated stands. In one study stand (study stand 118) the NPV was significantly higher with the option where stand was planted with two tree species (delineation with threshold value 8 m3/ha/a) than with one tree species. On the other hand in all study stands there exists a mixed stand solution or solutions which gave about the same NPV outcome as the pure spruce stand.

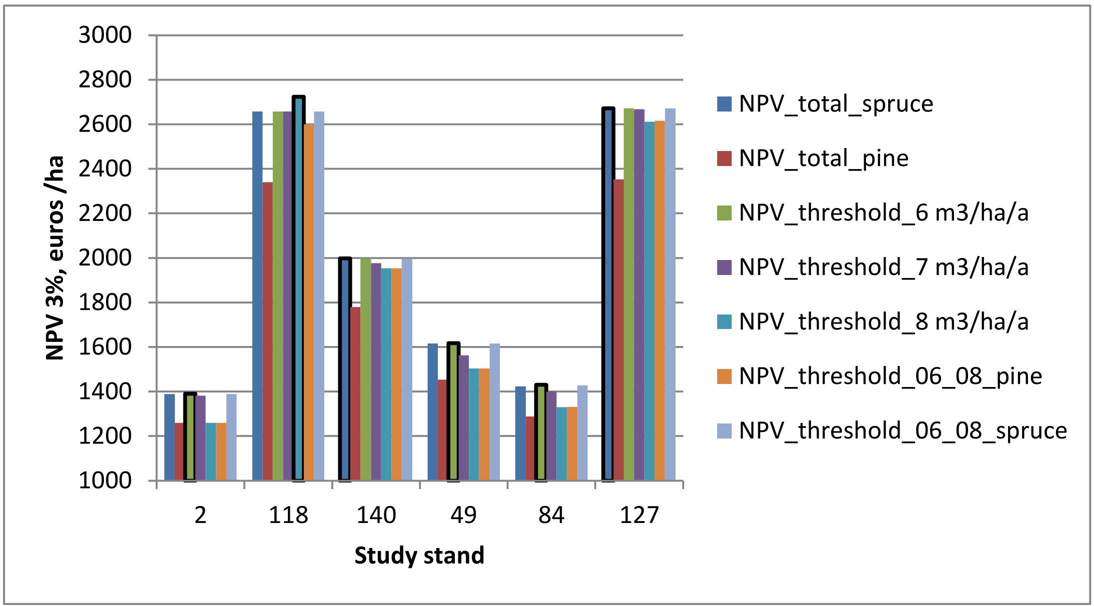

Figure 6. NPVs with seven different planting options by the study stands. The highest bar has bolded frames. Study stands are arranged in ascending order in area.

If we compare the micro stand solutions according to the log volume increment (m3/ha/a) the mixed stand solutions was better than pure spruce or pine stand except study stand 118 (Figure 7). In this small stand (1.66 ha in area) pure pine planting gave best result.

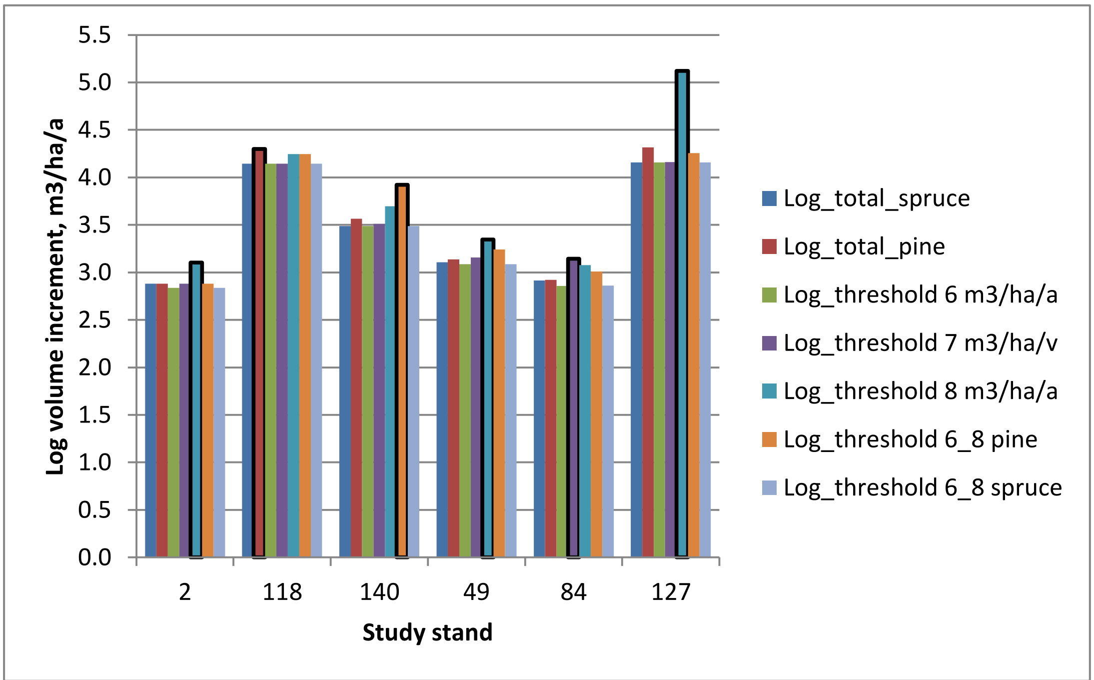

Figure 7. Log volume increments with seven alternative planting options by the study stands. The highest bar has bolded frames. Study stands are arranged in ascending order in area.

5 Discussion and conclusions

A method for creating micro compartments inside a large forest stand at regeneration phase was piloted in this study. Local site index was calculated for each grid cell using harvester data from final felling. Calculation was based on three biggest trees in harvester data for each grid cell. Study stands were thinned below in earlier cuttings so it could be assumed that the growth of dominant trees in final felling was a good estimate of local growth potential (site index). In our study we tried to measure the age of trees in field inventory. but it seemed that the age of stand in forest data was as good estimation as our field measurement. If the age of dominant trees could be detected automatically with some optical device during the felling operation it might give more precise estimate of local site index.

Site types in study stands were mostly classified as Myrtillus type in Finnish site type classification (Cajander 1926) which is quite suitable to regenerate both for spruce and pine. The estimate of local site index was used for delineation of micro compartments suitable for spruce or pine planting. The minimum micro compartment area was discussed with experts from practice and it seemed that the area of a micro compartment can be quite small without causing extra costs in site preparation or planting with varying tree species. In other silvicultural activities as well as cuttings the whole stand was treated with same operation and method. So the minimum compartment size was adjusted in this study to 0.23 ha. Practically this means for instance a 48 meters x 48 meters square. From biological point of view it is a good solution that the middle parts of micro compartment do not get border effects from neighbouring micro compartments. This is especially important if neighbouring micro compartments are planted with tree species with strongly differing growth rates. In our study most of the best micro compartment solutions according to NPVs had several micro compartments and the smallest ones were usually less than 0.5 ha in area.

Our simulations pointed out that the “precision forestry” option where the forest stand may be planted with two different species is a very promising alternative to the current forest practices. The mixed forest stand structure never produced a bad solution and in one case out of six stands provided distinctly better solution in terms of NPV than the single tree option.

The future stand development for Scots pine and Norway spruce dominated stands in different forest site types were predicted with Motti software. The predictions are based on statistical models which are based on empirical data and are designed to be applied across the country and different sites. In simulations, the stands were managed according to silvicultural guidelines. Based on the earlier research results (e.g. Mäkinen et al. 2005) Motti predicts reliable the development of managed commercial forests. However, growth models always predict the average development of the stand on a given area and site type. Predictions are depending on empirical data and its representativeness. Thus, in this study the most uncertainties related to the simulations are in predicting the development of the Norway spruce stand in infertile Vaccinium site type. This is due to the shortage of the empirical data for models covering the whole fertility variation of Vaccinium site type. This means that the Norway spruce stands are generally growing in the more fertile edge of Vaccinium site type whereas Scots pine stands are covering all variation of the Vaccinium type. Thus, the comparability of the predictions for Norway spruce and Scots pine on Vaccinium sites is not as good as on the other sites.

Researchers generally agree that wood production capacity in pure coniferous forest tend to exceed that of mixed broadleaves - coniferous forests but small mixture of broadleaves do not significantly hinder growth of conifers (Frivold and Frank 2002; Hynynen et al. 2011). However, mixed broadleaves- conifer forest structures can provide better outcomes in terms of biodiversity, recreational and aesthetic values. water quality and uncertainties caused by climate change(Paquette and Messier 2011; Gamfeldt et al. 2013; Felton et al. 2016; Mina et al. 2018).

The relationship between pines and spruces is far less studied than that of mixed broadleaves – conifer forests. According to (Felton et al. 2016). mixed pine-spruce forest are not that advantageous to mixed pine-birch and spruce-birch forest in terms of many ecosystem services since pines and spruces are genetically far closer than birches and conifers. However two species forest probably overcome pure stands in terms of wind throw risks, pest and pathogen outbreaks, bilberry production and hunting-related recreational values. Pure forests provide more cost-efficient solution for young stand management and logging operations but on the other hand increases risk of financial returns (Felton et al. 2016).

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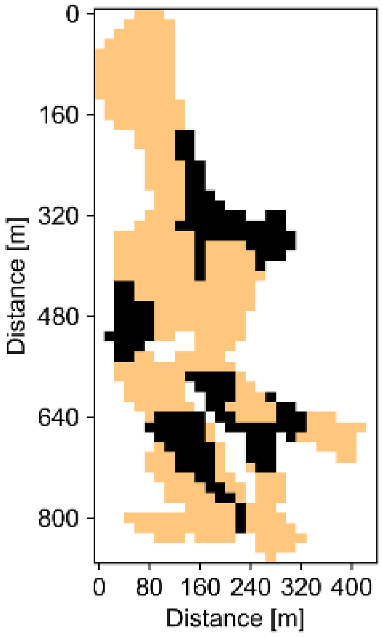
APPENDIX 1. Micro stand solutions with different threshold values and the original site index map in study stands.

STAND 84



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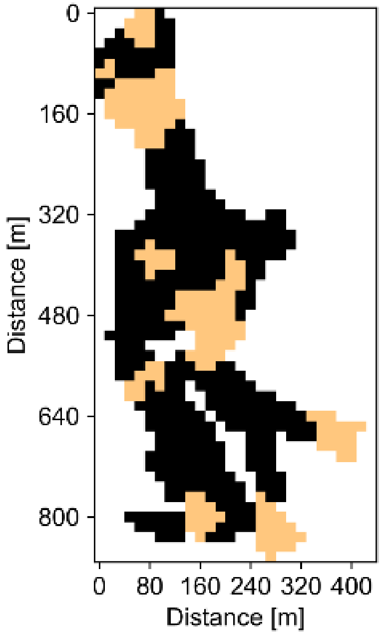

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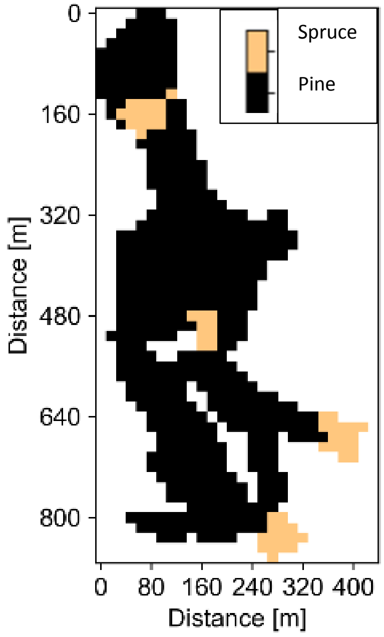
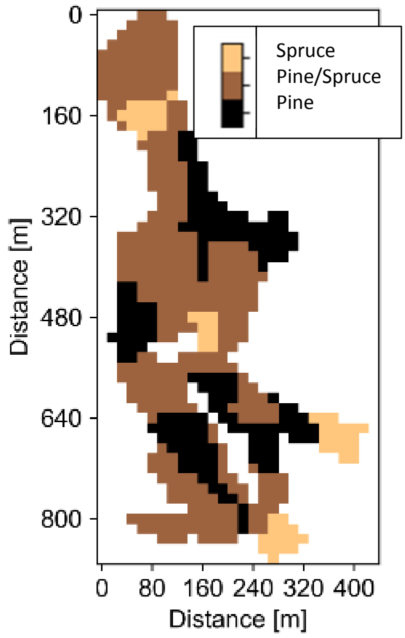


8 m3/ha/v



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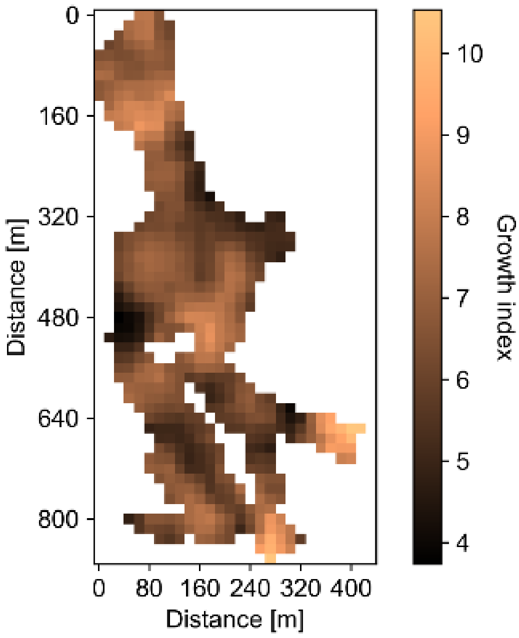
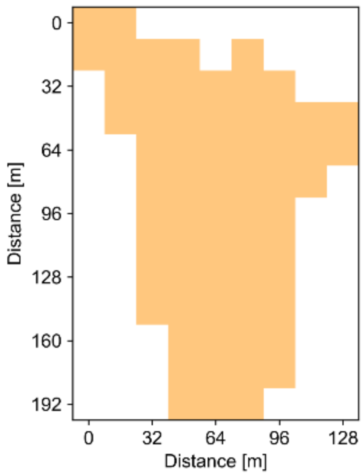


Original site index map

STAND 118



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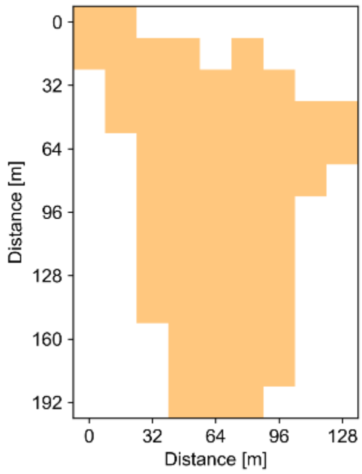

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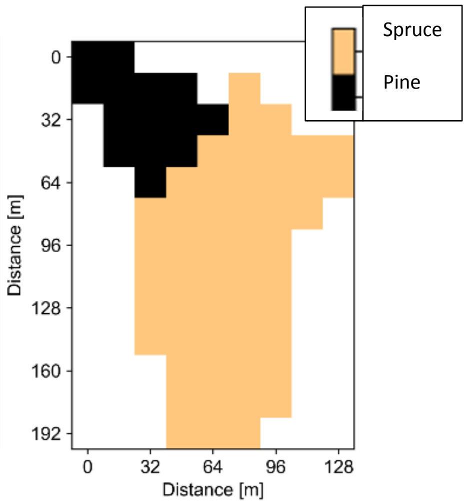
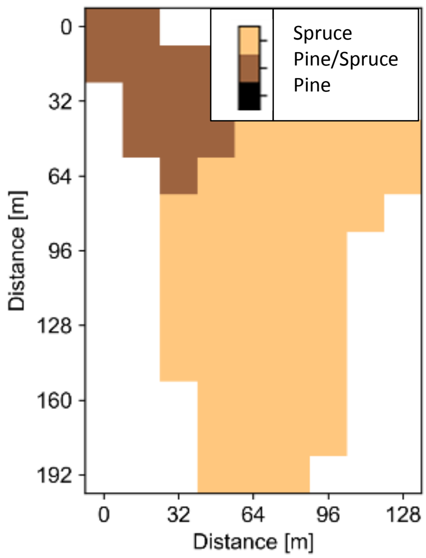


8 m3/ha/v



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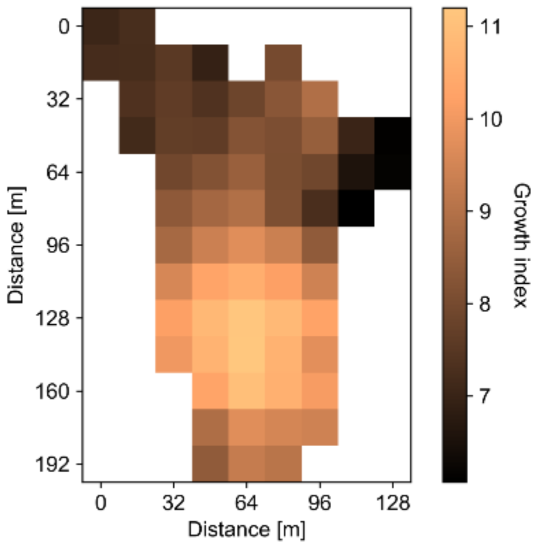
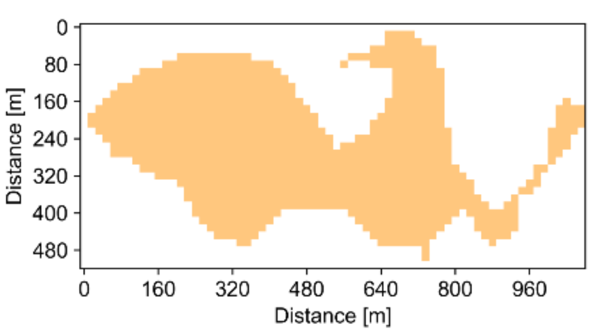


Original site index map

STAND 127



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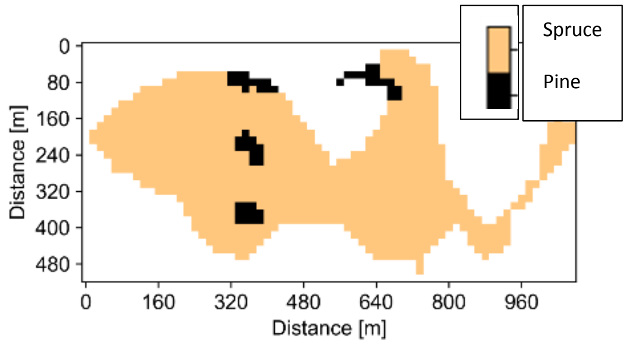

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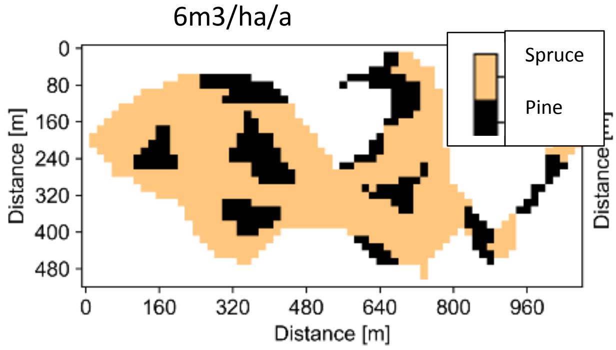

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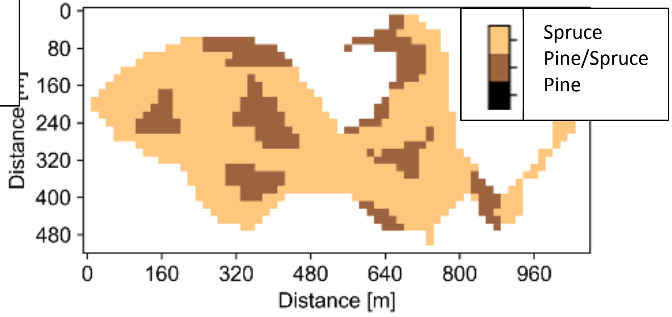
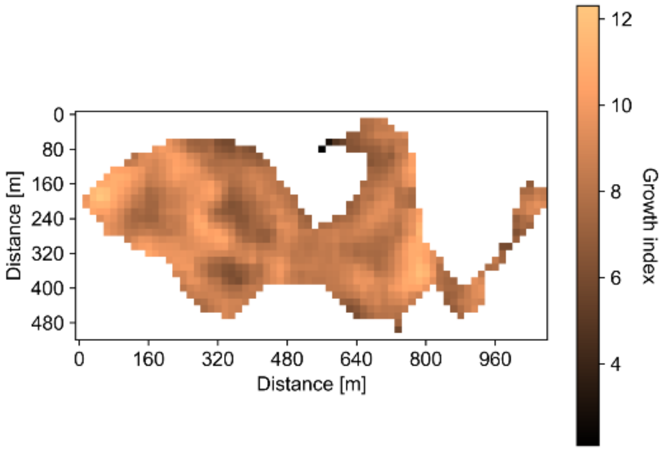
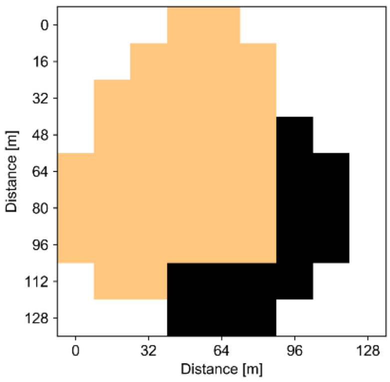


6/8 m3/ha/a

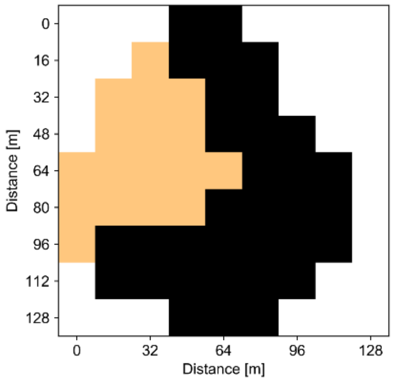


Original site index map

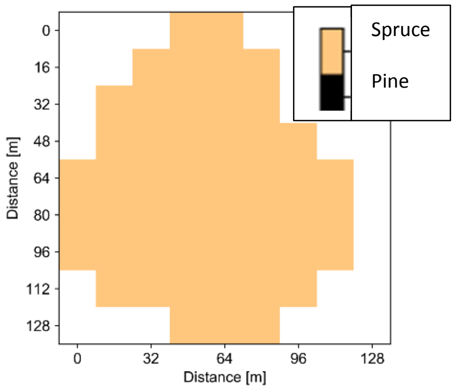
STAND 2



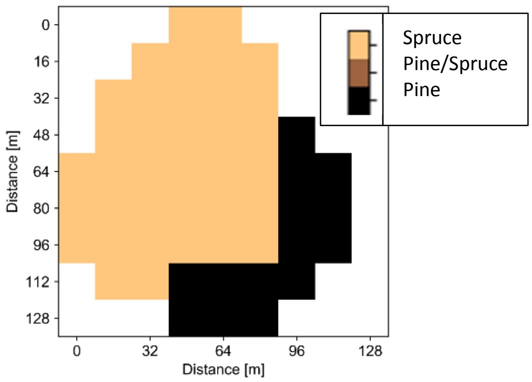
6m3/ha/a



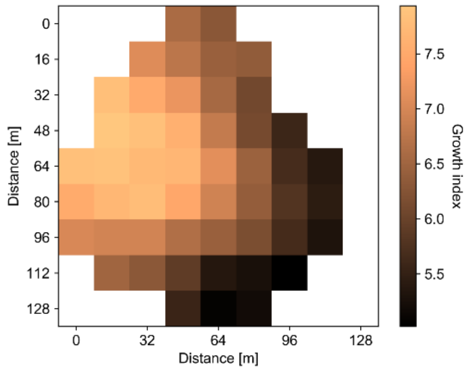
7 m3/ha/a



8 m3/ha/v

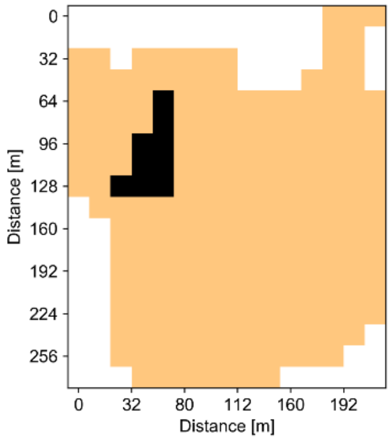


6/8 m3/ha/a

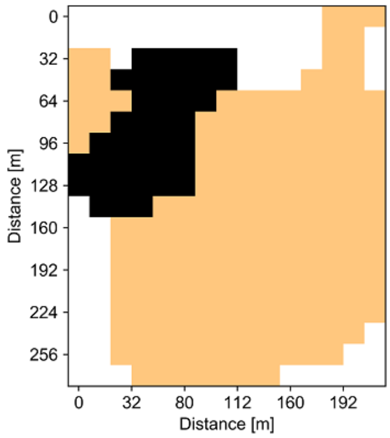


Original site index map

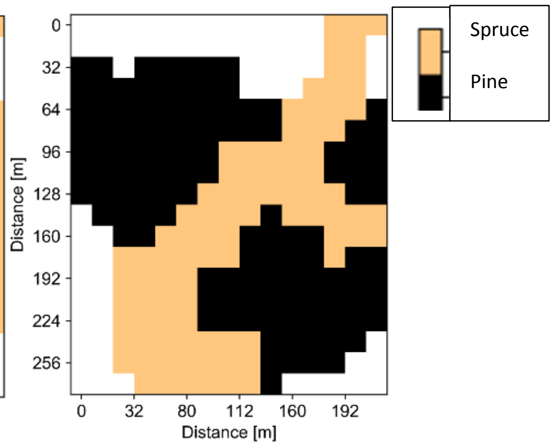
STAND 140



6m3/ha/a



7 m3/ha/a



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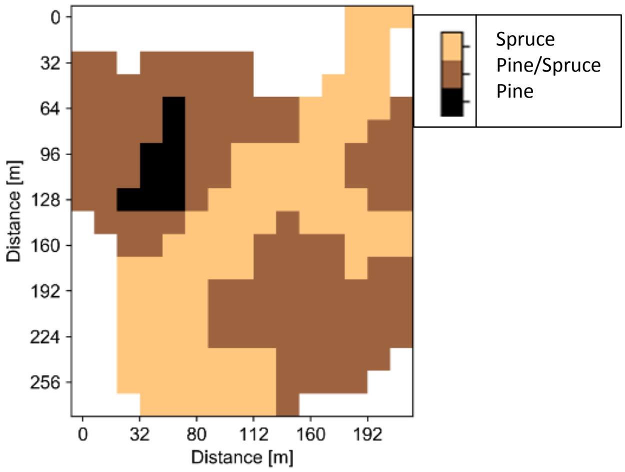

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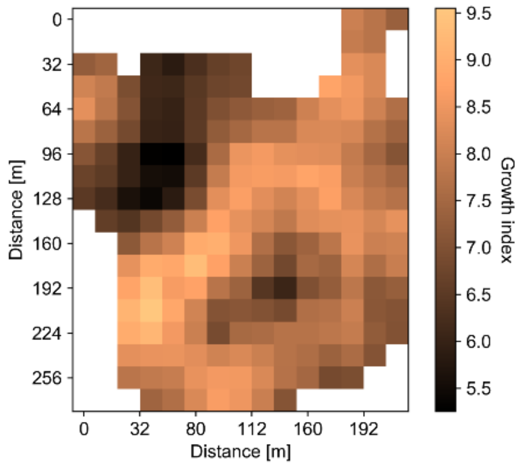
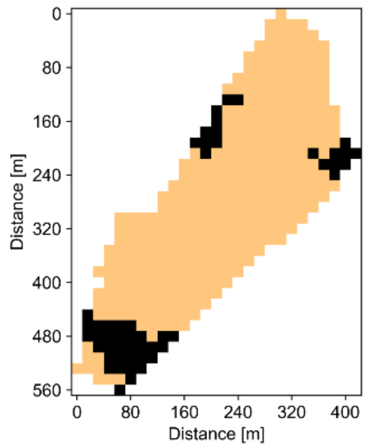


Original site index map

STAND 49



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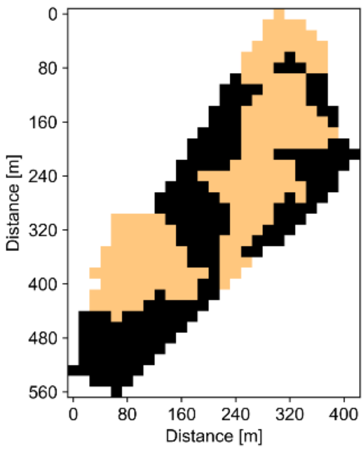

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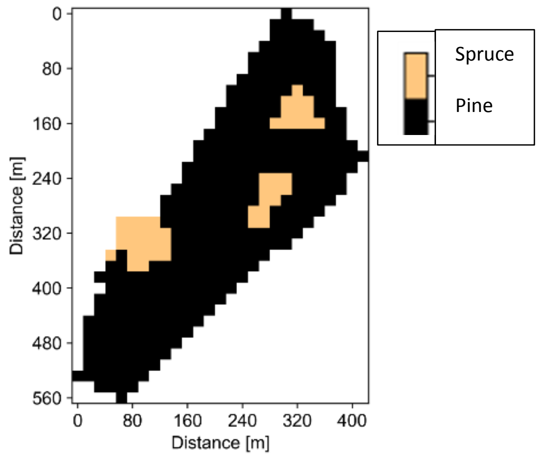

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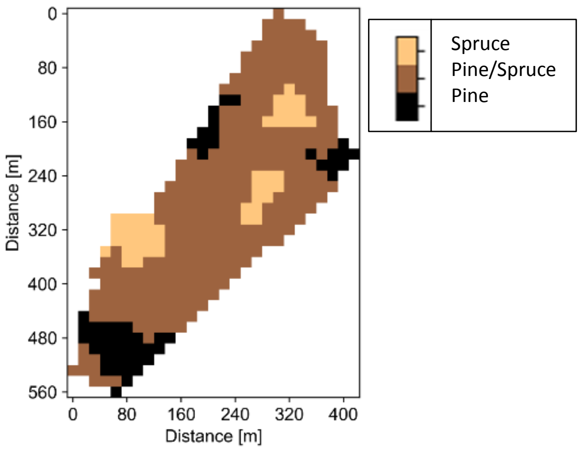

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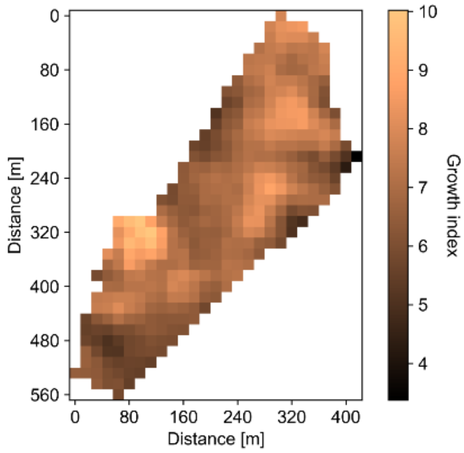

Original site index map