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 young stand management

Young stand management can traditionally be separated into two different treatments: early pre-commercial thinning (PCT), and ordinary PCT. Early PCT is to remove less valuable fast growing pioneering broadleaved tree species that hampering the growth of the desired tree species. Ordinary PCT is applied to adjust the density of the desired tree species for an optimal management (Uotila et al. 2012). Neglecting or postponing PCT operation leads to a significant decrease of forest growth. Country-specific forest management instructions and rules regulate the timing and extent of PCT operations needed to ensure sufficient production of forests in the coming years. Today nearly all PCT is done motor-manually with clearing saws.

In the traditional stand management, the dilemma of an early PCT (also called early cleaning; Uotila 2017) is that the cut stumps and roots of trees start to sprout. It means that a second PCT operation is needed a few years later. The efficiency of PCT can be improved at least in two different ways: 1) increase of systemization and mechanization of PCT operations (reducing the costs) and 2) prevention of sprouting and growth of unwanted tree species (minimizing a number of operations) after Early PCT. The typical mechanical PCT machine comprises of a small-size forest machine equipped with a suitable crane and felling head (Ligné et al. 2005).

To prevent hardwood sprouting after early PCT one promising mechanical solution is the Naarva uprooter (Pentin paja Oy) which uproots the hardwoods saplings from a conifer stand (Figure 1). The basic idea of uprooting is that the uprooted hardwoods do not offshoot new saplings. This uprooting device has been tested to be technically feasible and working method has been further developed (Hallongren & Rantala 2013, Hallongren et al. 2016). If the stand density is also reduced to target level (about 1800 stem ha^{-1} in a spruce stand) at this uprooting operation, there is no need for another PCT later on.

Figure 1. Uprooting device connected to harvester boom. Photo: Erkki Oksanen, Luke.

Another solution to prevent sprouting of stumps is biological treatment. *Chondrostereum purpureum* is decay fungus (Figure 2), which occur naturally in temperate and boreal vegetation zones of the northern and southern hemispheres. It penetrates freshly wounded stump of broad-leaved trees and decays the wood. Promising *C. purpureum* strains and formulates for biological control products have been developed in Finland and Canada (Hantula et al. 2012). It is obvious that spraying of *C. purpureum* inoculum on the surface of fresh stumps during PCT operation is technically feasible, but many practical experiments have to be carried out before the most cost-efficient method to prevent sprouting of stumps is found.

The aim of this study is to verify the silvicultural efficiency of these two above mentioned methods for early PCT and to evaluate the cost-efficiency of these young stand management operations.

Luukkonen made his master thesis of the uprooting data (Luukkonen 2018) and Salmi made his master thesis of the first-year biocontrol inventory data (Salmi 2017).

Figure 2. *C. purpureum* is a common decaying fungus. Photo Andreas Salmi.

3 Material and methods

3.1 Survey of uprooted plantations

Inventory of earlier uprooted (in year 2012, 2013, or 2014) Norway spruce plantations was done in autumn 2017.These plantations were sampled from the total uprooting area of 1864 ha. These plantations situated in Eastern and Central Finland in six different provinces (Figure 3). In each province, the target was to sample four plantations for each year. Because of the lack of uprooted areas in Central Finland province, the total number of sampled plantations was 68 and during the fieldwork two more cases were left unmeasured because of landowner changes. The total number of inventoried plantations was 66 and total of 190 ha in area. Most of these plantations were on UPM’s own forest land.

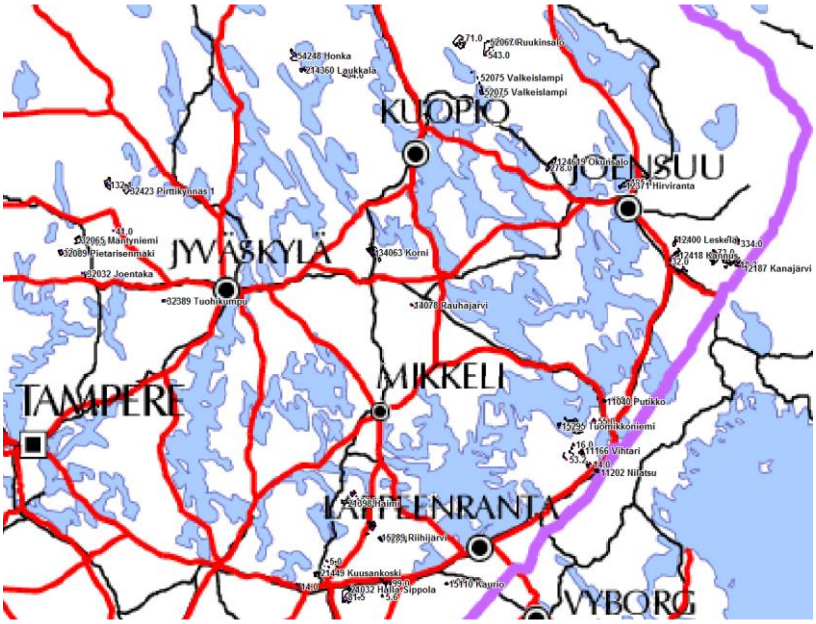


Figure 3. Location of inventoried plantations.

From UPM's registries the dates of logging, stump harvesting, soil preparation, and uprooting were collected for each plantation. In the field inventory, a systematic, regular-shaped sampling grid was used. Areas of 0.5–2.0 ha were measured with 15 sample plots, and larger areas were measured with 20 sample plots. For areas 10 ha and larger, an extra sample plot was measured for each area of half a hectare. The size of a temporary circular sample plot was 20 m^2 (r= 2.52 m). The variables recorded at the sample plot level were soil type (fine, medium, coarse and peat (>20cm peat layer)), site fertility (Rich - Oxalis-Myrtillus type, Medium - Myrtillus type, Sub-dry - Vaccinium type; Cajander 1926) and soil preparation method (patching, disc trenching, mounding, no preparation). In addition, the thickness of humus (average of five observations, cm) and the moisture of the ground was estimated based on the cover of sphagnum and haircap mosses into six classes (no cover, cover <1%, 1-10%, 11-25%, 26-50%, >50%; Tamminen and Mälkönen 1999). This classification was later collapsed into three categories (dry, fresh and moist).

On each sample plot crop trees were determined (maximum number six and distance from crop tree to crop tree at least one meter) and their heights were measured as well as the competition from other trees was estimated. This estimation was based on the height relations between the crop tree and other trees growing nearer than 1 meter (competing trees) from the crop tree as follows: 1. no competing trees or they shorter than 1/2 of crop tree, 2. height of competing trees are from 1/2 to 2/3 of crop tree, 3. height of competing trees are from 2/3 to 1/1 of crop tree and 4.the competing trees are taller than crop tree. Classes 1 and 2 were merged later and joint class was called freely growing crop trees. In addition, from the crop-tree spruce nearest to sample plot the present diameter at breast height and the yearly height growths from the uprooting year to inventory moment were measured. Also, the possible uprooting defects of the sample tree were determined (no defect, minor defect, serious defect). The number of competing stems (height > one meter) was calculated by tree species as well as their mean height and mean diameter at stump height were measured on each sample plot.

All together material consisted of 1150 sample plots (Table 1). About 30 sample plots were left out from analyze because the area of those sample plots has not been uprooted for some reason. This was recorded during the field work. At uprooting time age of plantations varied from two to seven years and at inventory time point their age varied from five to twelve years. The number of stump harvested areas were 29. In Northern Savo, Central Finland and Kymenlaakso provinces there was more stump harvested areas than non-stump harvested ones.

Table 1. Number of plantations and sample plots in different provinces and in different uprooting years.

	Province*						
	S K	S S	C F	KYM	N K	N S	All
Number of plantations	12	11	8	12	11	12	66
Number of sample plots	196	187	156	207	206	200	1152
Sample plots/uprooted 2012	52	63	45	66	81	59	366
Sample plots/uprooted 2013	75	77	72	68	75	71	438
Sample plots/uprooted 2014	69	47	39	73	50	70	348

*S K = South Karelia, S S = Southern Savonia, C F= Central Finland, KYM = Kymenlaakso, N K=North Karelia, N S Northern Savo

The basic statistical results were calculated with IBM SPSS Statistics version 22 software. The proportion of freely growing crop trees was modeled with GENLINMIXED command of same statistical software. The further height development of these young stands was simulated from the inventory moment to first thinning with Motti simulator (Hynynen et al. 2005).

3.2 Biocontrol experiments

Early PCT with biocontrol treatments of fungus *C. purpureum* of mixing ratios 1:100, 1:200 or 1:400 and control treatment (only early PCT) were carried out between June and September 2014. The work was done by Usewood Tehojätkä, a small-scale forest machine, equipped with a boom-mounted UW40-cleaning head (Figure 4). Tehojätkä was equipped with the tank (capacity of 200 l) for applying liquid suspension of *C. purpureum* mycelium. There were three different Tehojätkä machines in the study with two different applying methods. For control, the work was done by Tehojätkä machine without *C. purpureum* treatment. In some areas, control was done motor-manually by clearing saw (Table 2).

Fieldwork was done on eleven forest stands in central Finland located in eight geographically separate areas. On every stand there was one control treatment (n=11) and 1–3 different *C. purpureum* mixing ratio treatments 1:100 (n=8), 1:200 (n=5) or 1:400 (n=7), yielding together 31 treatments (Table 2). All treated areas were juvenile forests average age of 7 years (SD 2) needing early PCT. Stands were regenerated either to spruce (n=7) or pine (n = 4).

The inventories were done between September and November in the years 2015, 2016 and 2017 i.e. 1–3 years after treatments. Inventories were carried out by measuring a systematic regular-shaped grid of 15 circular sample plots (r=1.0 m) on every treatment and control (exception of control of stand 4 where 30 plots were measured). The distance between the plots was determined according to the area (0.3–0.7 ha) excluding buffer zone of 10 m between the treatments and from trees of neighboring stands to avoid their immediate effects on sprouting. Altogether the data consisted of 480 sample plots (mixing ratios 1:100 (n=120), 1:200 (n=75), 1:400 (n=105) and control (n=180)) of which 10 plots were missing on 2017 inventory (Table 2).

Figure 4. Tehojätkä in operation (photo: Veli-Matti Saarinen) and UW40-cleaning head (photo: www.usewood.fi).

Table 2. Description of the study design by stands (n=11): number of sample plots, regenerated tree species and year, mixing ratios of *C. purpureum* treatments, method used for control (CS = clearing saw, UW = Usewood Tehojätkä), Tehojätkä machine used (two different machines) and week number when work was done

Stand	Number of plots	Tree species	Regeneration year	Mixing ratio of *C. purpureum* treatment			Control	UW	Work-week
				1:100	1:200	1:400			
1.1	30	Pine	2005		x		UW	2	24
1.2	30	Pine	2005			x	CS	2	24
1.3	30	Pine	2005	x			CS	2	24
2.1	30	Spruce	2007			x	CS	2	28
2.2	30	Spruce	2003	x			CS	2	29
3.1	60	Spruce	2009	x	x	x	UW	1	24–26
4.1	60	Pine	2008	x	x		UW	1	27–28
5.1	60	Spruce	2008	x	x	x	UW	1	29–30
6.1	45	Spruce	2009	x		x	UW	1	30–32
7.1	60	Spruce	2008	x	x	x	CS	1	37–39
8.1	45	Spruce	2008	x		x	UW	1	40

From every sample plot moisture of the ground was evaluated on the six-level scale (very dry–wet) described in more detail by Tamminen and Mälkönen (1999). To evaluate the efficiency of *C. purpureum* inoculum, all stumps (>0.5 cm) and sprouts, as well as retained trees, were measured from the sample plots on 2015. From stumps following characteristics were measured: tree species, number and diameter (mm) of cutting surfaces, and the number of fruiting bodies of *C. purpureum* in stump. It was also recorded if the stump was a long stump i.e. having living branches underneath the cutting surface. From sprouts following characteristics were measured: number of stump sprouts, height (cm from the ground) and diameter (mm) of the highest living stump sprout. Also, the viability of the sprouts was evaluated on a three-level scale (good, weakened, dead/nearly dead). From retention trees following characteristics were measured: tree species, total height and annual height growth (dm), viability (good, weakened, dead/nearly dead) and the reason for possible damage (herbivores, overdriven, *C. purpureum* fungus, UW40-clearing head, other reason).

On 2016 inventory, the number of fruiting bodies of *C. purpureum* in stump, number of living stump sprouts, and the height (cm) of the highest living stump sprout were measured. On 2017 inventory following characteristics were measured from living stump sprouts: number in stump, average height (cm), maximum height (cm), and the average diameter (mm). The number of fruiting bodies of *C. purpureum* in stump was also measured. The height of all trees at the sample plot was measured. Selection of retained crop trees was done based on tree species, height, and distance from each other. Trees were evaluated as crop trees if they were >1 m apart from each other and the height was at least half of the average height of the regenerated species at the sample plot. Trees selected as crop trees were primary regenerated coniferous species and secondary other broadleaf species and rest were classified as non-crop trees. Characteristics of the research stands before and after early PCM are presented in Table 3.

A tree closest to the central mark was selected as a sample tree from which diameter at breast height (cm) and annual height growth (cm) were measured (n=211). Also, canopy competition, i.e. ratio of non-crop trees height to retained crop trees height within 1 m radius, on the four-level scale was evaluated from selected retained crop trees and sample trees. Trees were considered to be growing freely when non-crop trees did not exist or were less than half of the height of retained crop trees. Non-crop trees were considered to cause canopy competition if their height was 1/2, 2/3 of the height of the retained crop trees or if they were as height as or higher than retained crop trees. Due to an error in field measurement, canopy competition was evaluated only from sample trees trees.

Table 3. Main characteristics of research stands before and after early PCT.

Stand	Mean height of saplings 2014* (cm)		Mean density of stumps after (stumps ha^{-1})		Mean density of saplings after (saplings ha^{-1})		Mean density of saplings before (saplings ha^{-1})	
	Con.	Dec.	Con.	Dec.	Con.	Dec.	Con.	Dec.
1.1	154.7	117.8	1379	9125	5411	955	6790	10080
1.2	195.8	88.9	531	7851	6260	955	6790	8806
1.3	142.1	109.2	955	5305	6684	1273	7639	6578
2.1	213.8	109.5	106	14748	2759	2228	2865	16976
2.2	262.7	112.9	1061	14430	3926	1804	4987	16233
3.1	88.7	77.8	371	16658	2546	2281	2917	18939
4.1	92.1	74.6	690	4668	7851	1432	8541	6101
5.1	88.7	79.4	743	15862	3714	1645	4457	17507
6.1	78.7	79.7	354	15862	3183	2617	3537	18479
7.1	115.8	83.1	265	10663	2918	2759	3183	13422
8.1	142.5	102.9	2122	17613	3749	3395	5871	21008
Pooled	130.4	89.7	743	13468	4324	2029	5067	15497

* Of retained trees after early PCT in 2014 measured at 2015
Con. = coniferous, Dec. = Deciduous (i.e. broadleaved)

Results were analyzed based on the effects of different treatments (control vs. *C. purpureum* treatment) separately on the mortality of the stumps, sprouting (number and maximum height), and work quality (including canopy competition). The mortality means that stump had zero sprouts and thus was considered dead. Only stumps that were found both in 2015 and 2017 were included on mortality figures. On 2016, a total number of stumps was lower but results were still reported. Of all broadleaved stumps (n = 2143) 5.4 % were lost between 2015 and 2017.

As shown before, *C. purpureum* takes advantage of birch better than that of other broadleaved species (Hamberg et al. 2017). Thus results were presented separately for all broadleaved trees and birch. Silver birch (*Betula pendula*) and downy birch (*Betula pubescens*) were treated as one on the analysis.

Mean values (arithmetic means) and standard deviations (SD) of key variables of mortality, sprouting, and work quality were calculated. For statistical analyses, statistical program R was used. The mortality (0 = stump is alive, 1 = stumps is dead) of stumps the number of sprouts in living stump were investigated with generalized linear mixed models (GLMMs) using the function glmer in library lme4. For mortality, assumed a binomial error distribution and the logit link function, and for number of sprouts, a Poisson distribution with log link function was used. The maximum height of the sprout in different treatments was investigated with the linear mixed model (LMM) assuming normal error distribution, using lme function in the nlme library. Models were done separately to all broadleaved species and birch. All stumps were included in mortality models, but when investigating number and height of the stumps, only living stumps were included in the analysis.

All models included as explanatory variables: 1) treatment (a factor with four levels: control, and a fungal treatment of mixing ratios 1:100, 1:200, and 1:400), 2) work week (number of week when treatment was done), 3) the moisture of the plot (1–6), 4) density (number of trees at the plot before the early PCT), 5) basal area of stumps (mm^2). To separate effects of explanatory variables 2–5 from those of the treatment, they were included in the models as they may affect mortality. Site and sample plot were included as a random factor as conditions within the same stand and sample plot may be more similar than on randomly selected stand. Temperature and number of work week correlated (r=-0.47), thus only number of work week included in the analysis. Other correlations between the explanatory variables were <0.35.

Four-level canopy competition variable was recoded into binomial factor based on the height of competing trees being 0–2/3 of the height of the sample tree at <1m radius (0= freely growing, 1=canopy competition). Canopy competition was investigated with same methods as mortality with explaining variables of: 1) treatment (a factor with four levels: control, and a fungal treatment of mixing ratios 1:100, 1:200, and 1:400), 2) method of which early PCT was done (1=clearing saw 2=Tehojätkä 1, 3=Tehojätkä 2), 3) work week (number of week when treatment was done), 4) the moisture of the plot (1–6), 5) density (number of trees at the plot before the early PCT).

4 Results

4.2 Survey of uprooted plantations

4.2.1 Number of broadleaved trees after uprooting

The mean number of crop trees was 1950±255 stems ha^{-1} and 82 % of them were spruces (mean number of stems 1606±275 ha^{-1}). Defects caused by uprooting were observed less than in every other stand. In those stands, the mean proportion damaged spruce stems was two percent of crop-tree spruces number.

The mean number of competing broadleaved stems (height >1m) was 5320±5525 ha^{-1}, most of them were birches (3790±4810 ha^{-1}). Birch was considered to be the most harmful competitor to the crop-tree spruces and in the further analysis only birch was taken into account as competing tree whenever it was possible. In addition, there was also 1105±1613 auxiliary conifer stems ha^{-1} in an average plantation. Most of them were pine stems, especially on sub-dry sites.

The variation in number of birch trees was huge (Figure 5). In most of stands (57 out of 66) the number of birches was less than 6000 stems ha^{-1} and in every fifth stand the mean number birch was less than 2000 stems ha^{-1}. Highest numbers of birch were found in regeneration areas site prepared with ditch mounding. Also, some of these stands had some peat layered or otherwise quite wet spots. On stump harvested areas, the mean number of competing birches was 4690±3380 stems ha^{-1} and on non-stump harvested areas significantly less 3190±2300 stems ha^{-1} (*p=0.037*).

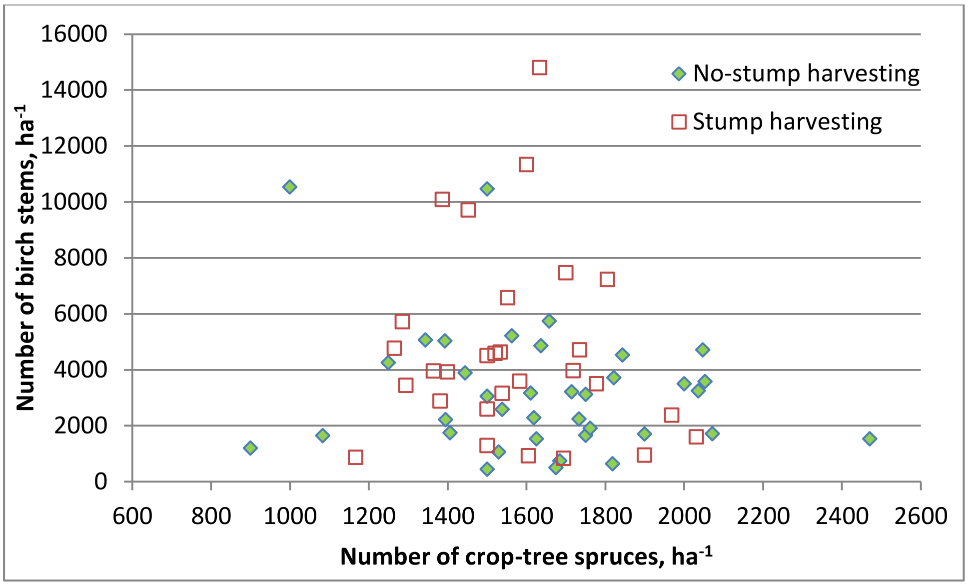


Figure 5. The number of competing birch stems according to the number of crop-tree spruces in the measured 66 plantations.

Neither the age of the stand nor the time since uprooting did have any major effect on the number of competing birches (Figure 6). Highest and lowest numbers of birch were found in eight, nine or ten years old stands regardless of the time passed since uprooting operation.

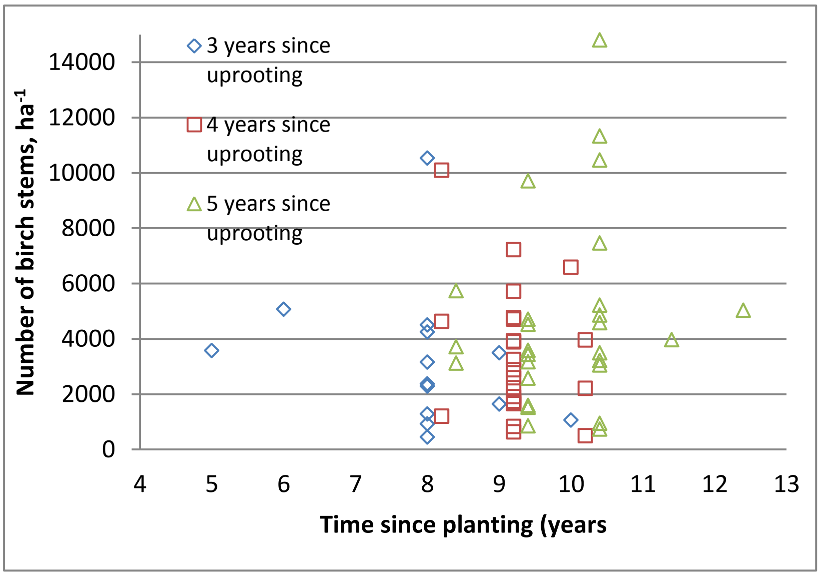


Figure 6. Number of competing birch stems in different aged stands. Stands have been grouped according to the time elapsed from uprooting operation to measurement.

4.2.2 Height relations between crop trees and competing trees

At the moment of inventory, crop trees were in most cases more than half a meter taller than competing trees (Figure 7). In two stands which were uprooted at age of two or three years after planting, competing trees were taller than crop trees. The mean height of crop trees was 275 cm and 185 cm for competing trees.

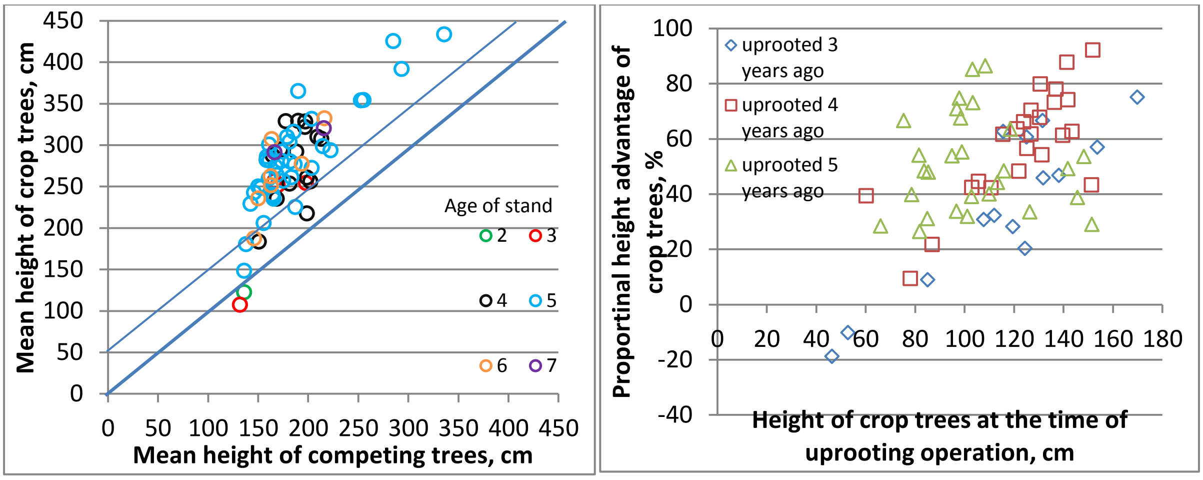
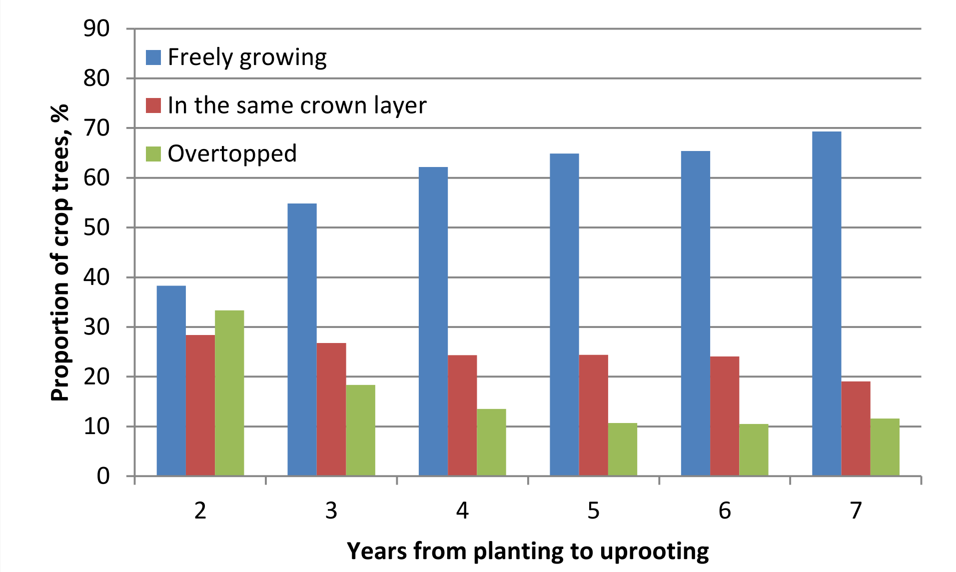


Figure 7. Height relationship of crop trees and competing trees in measured stands (left). The age of stand (from 2 to 7) at uprooting operation is marked with different colors. Height advantage of crop trees according to the height of crop trees at the uprooting time (right). The time elapsed since uprooting is marked with different markers.

In most cases (60 out of 66) crop trees was at least 25 % higher than competing trees. The mean height advantage of crop trees in stands uprooted three years ago was 36 % (57 cm), four years ago 58 % (100 cm) and five years ago 51 % (102 cm). The mean heights of crop trees at moment of uprooting operation were 115 cm, 122 cm, 104 cm in stands uprooted three, four and five years before inventory respectively. The height of crop trees at the moment of uprooting operation did not have a major effect on the height advantage at the time of inventory, except in those stands uprooted at quite early age. If the height of crop trees was more than one meter at the time of uprooting the height advantage was in most cases more than 30 %.

4.2.3 Growing space of crop trees

For each crop tree, the growing space was observed in the field. The proportion freely growing crop trees (no competing trees taller than 2/3 of crop tree's height) was over 60 % if the age plantation was at least four years at the time of uprooting operation (Figure 8). Additionally, in these older stands about 23 % of crop trees were growing in the same crown layer with competing trees (competing trees were more than 2/3 of crop tree's height but not taller than crop tree) and about 12 % of crop trees were already overtopped by competing trees (competing trees as tall as crop tree or taller).



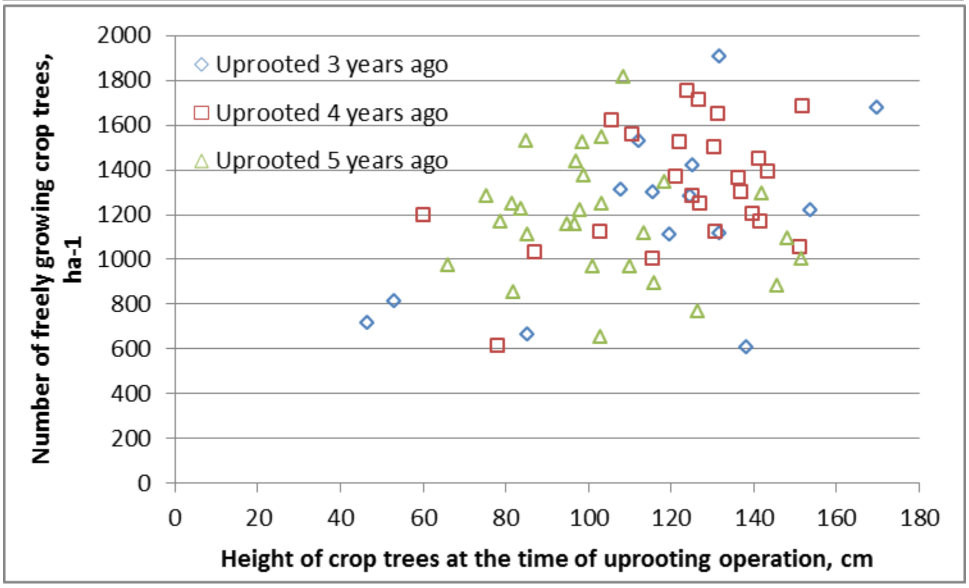


Figure 8. The proportion of crop trees in different growing conditions according to the time elapsed from planting to uprooting operation (upper picture). Number of freely growing crop trees in studied stands according to the height of crop trees at the time of uprooting operation (lower picture).

The mean number of freely growing crop trees was 1235 ha^{-1}, varying from 600 to 1900 stems ha^{-1}. In 4 out 5 stands there was at least 1000 freely growing stems ha-1. The uprooting moment did not have a clear effect on the growing conditions except in those stands uprooted before the crop trees had reached one-meter height. In these young stands every other had less than 1000 freely growing crop trees.

Stand development was further simulated with Motti simulator up to first thinning (mean dominant height of crop-tree spruces 14.4±1.3 meters). Simulation results showed that the stem number of spruce increased from 1640 to 1820 ha^{-1} because auxiliary spruce stems (not considered as crop trees in the inventory) and the number of birch trees decreased from 4260 to 830 stems ha^{-1} in the average case. At the first thinning the average total stem number was 3020 stems ha^{-1}.

According to simulations, the competing birch trees will reach the height of crop trees before first thinning in most cases (Figure 9). In most cases, birch will be less than 10% taller than spruces at the first thinning. This means an average height difference of 0.75 meters between crop-tree spruces and competing birch.

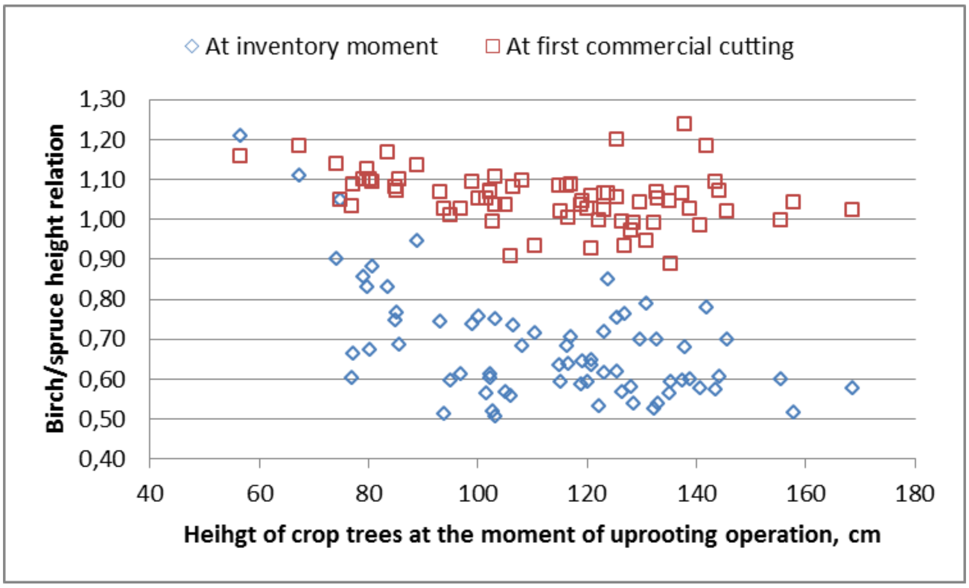


Figure 9. The height relationship between birch and spruce at the inventory moment and simulated to the time of first thinning with Motti simulator.

4.2.4 Model for the proportion of freely growing crop trees

The proportion of freely growing crop-tree spruces on the 20 m^2 sample plot was explained by the following variables: province, year of uprooting, the number of years between planting and uprooting, the number of years between uprooting and measurement, site fertility, soil type, thickness of humus, stump harvesting moisture of ground and height of crop trees at the moment of uprooting. The height of crop trees at the uprooting moment had the strongest effect on competition situation between crop spruce and competing trees (Table 4). The other significant ($p<0.1$) predictors of the model were moisture of the ground, time since uprooting to measurement, soil type, stump harvesting, and province.

According to the model, the proportion of freely growing crop trees was on fresh spots about 1.5 times and on dry spots about 1.8 times higher as compared to moist spots. Also, there were about 1.5 times more freely growing spruce crop trees in stands uprooted three or four years before measurement compared to stands uprooted five years earlier. Increasing the height of spruces at the time of uprooting from 70 cm to 120 cm increases the proportion of freely growing crop-tree spruces by 35 %. The effect of site fertility was logical but not statistically significant but the effect of stump harvesting was not so clear. According to the model, there were more freely growing crop-tree spruces on stump harvested areas as compared to non-stump harvested ones. This was most probably due to the unbalanced distribution of stump harvesting areas among the provinces. The fixed effect of province was statistically significant (F-value = 3.71, p-value = 0.002). This was also most probably due to the unbalanced distributions of stump harvesting areas, site fertility classes and ground moisture classes among the provinces.

Table 4. Generalized linear mixed model for the proportion of freely growing crop-tree spruces in the 20 m^2 sample plot. F-values are calculated to test the significance of the categorical variables in the model. The modeling data consist of 1131 sample plots.

Variable	Estimate	Std. err.	t-value	*p*-value
Intercept	-0.987	0.382	-2.59	**0.010**
Height of crop-tree spruces at uprooting moment, cm	0.006	0.001	5.07	**<0.001**
Soil type (ref. Peat)			F = 2.50	0.058
Fine	0.576	0.437	1.32	0.187
Medium	0.275	0.283	0.97	0.331
Coarse	0.599	0.310	1.93	0.053
Moisture of ground (ref. Moist)			F = 8.89	**<0.001**
Dry	0.553	0.131	4.22	**<0.001**
Fresh	0.390	0.127	3.07	**0.002**
Time from uprooting to measurement (ref. 5 years)			F = 4.45	**0.012**
3 years	0.364	0.195	1.87	0.062
4 years	0.459	0.160	2.87	**0.004**
Stump harvesting (ref. Yes)			F = 3.26	0.071
No stump harvesting	-0,269	0.149	-1.81	0.071
Site fertility (ref. sub-dry)			F = 2.24	0.107
Rich	-0.330	0.161	-2,05	**0.041**
Medium	-0.083	0.106	-0.779	0.436
Province (ref. N-S)			F = 3.71	**0.002**
SK	0.142	0.243	0.58	0.560
SS	0.568	0.251	2.26	**0.024**
CF	0.509	0.269	1.90	0.058
KYM	-0.184	0,253	-0.73	0.467
NK	0.718	0.257	2.79	**0.005**

4.3 Biocontrol experiments

4.3.1 Stump mortality

Stump mortality was higher on *C. purpureum* treated stumps than untreated stumps (Table 5). Mortality of untreated stumps was 14.5% for all broadleaved stumps and 15.1% for birch stumps. Mortality of all broadleaved stumps was 27.0%, 32.8% and 24.9% for mixing ratios 1:100, 1:200 and 1:400, respectively. Mortality of birch stumps was 33.5%, 38.8% and 28.3% for mixing ratios 1:100, 1:200 and 1:400, respectively. The difference between control and treatments was statistically significant (*p<0.001*) for all broadleaved stumps as well as birch stumps (Table 6). Of all stumps in the data, 95.5% was broadleaved stumps of which 74.3% were birch.

Table 5. Stump mortality for broadleaved stumps on years 2015–2017 and separately for birch stumps on the year 2017.

Treat-ment	Mortality of broadleaf 2017 (%)			Mortality of birch 2017 (%)			Mortality of broadleaf 2016 (%)		Mortality of broadleaf 2015 (%)	
	N	Mean	SD*	N	Mean	SD*	N	Mean	N	Mean
Control	733	14.5	8.5	529	15.1	5.8	672	9.5	733	6.3
1:100	422	27.0	17.8	316	33.5	24.4	413	21.8	422	16.1
1:200	253	32.8	16.1	188	38.8	25.3	249	28.1	253	19.0
1:400	527	24.9	18.7	403	28.3	23.5	525	19.4	527	13.9

* Standard deviation of stands where N = 31 (control = 11, 1:100 = 8, 1:200 = 5, 1:400 = 7)

Mortality varied greatly by the time of the treatment on 2014 (Figure 10). Mortality was greatest, 55%, July (week 29) on mixing ratio of 1:100 and poorest, 3%, at the end of the September (week 40) on mixing ratio of 1:400. Based on generalized linear mixed effect model, the work week was statistically significant factor to effect on mortality (*p<0.001*) (Table 6). As time of the early PCT increased, the mortality decreased (Table 6, Figure 10). Density (number of trees plot^{-1}) affected on mortality of all broadleaved stumps (*p=0.040*), but not on birch stumps (*p=0.109*). As density increases, the mortality of broadleaved stumps increases. Of all stumps, 43 were dead on 2015 i.e. had no living sprouts, but were alive on 2017, i.e. had one or more living sprouts.

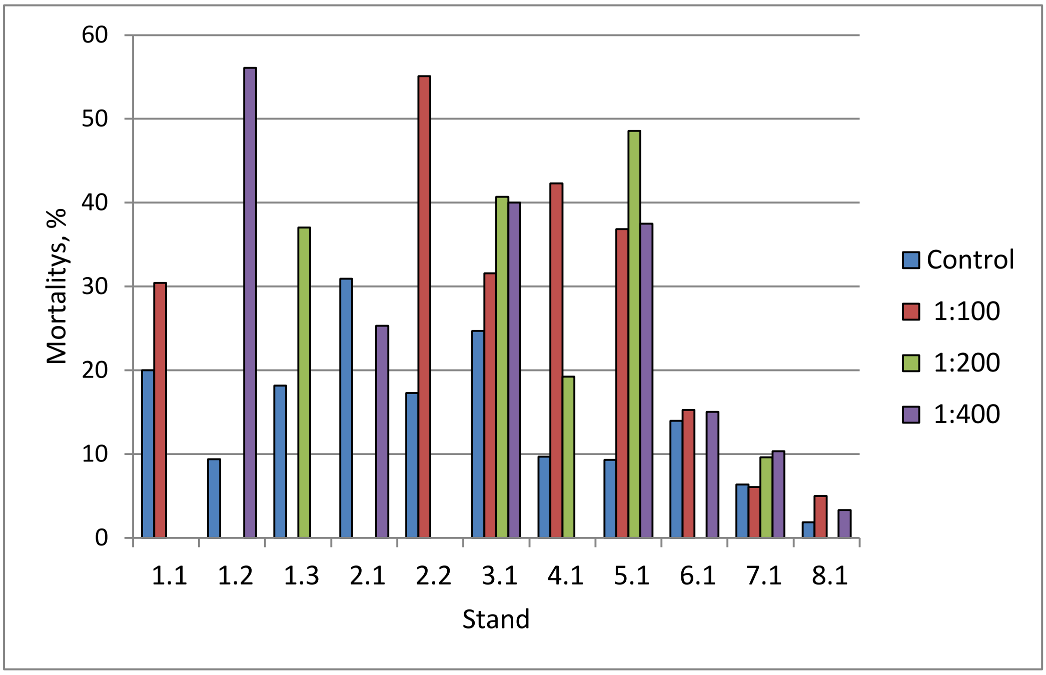


Figure 10. Mortality of broadleaved stumps on 2017 of stands and different mixing ratios of *C. purpureum* inoculum. Stands 1.1–1.3, 3.1, and 4.1 were done in June, stands 2.1, 2.2, and 5.1 were done in July, and stands 7.1, and 8.1 at September. Stand 6.1 was done at the turn of the July and August.

Table 6. The effects of the treatment (control as a reference vs. *C. purpureum* treatment with mixing ratios of 1:400, 1:200 or 1:100), work week, moisture of the plot, number of trees at the plot before early PCT, and the basal area of an investigated stump to mortality of broadleaved stumps and birch stumps (0=dead, 1=alive) (generalized linear mixed models).

	All broadleaved			Birch		
Variable	Estimate	Std. err.	*p*-value	Estimate	Std. err.	*p*-value
Intercept	2.152	0.84	**0.01**	3.161	0.84	**<0.001**
C. purpureum treat. 1:400	0.64	0.17	**<0.001**	0.886	0.19	**<0.001**
C. purpureum treat. 1:200	0.776	0.209	**<0.001**	0.97	0.227	**<0.001**
C. purpureum treat. 1:100	0.934	0.181	**<0.001**	1.314	0.201	**<0.001**
Work week	-0.145	0.024	**<0.001**	-0.165	0.024	**<0.001**
Moisture	-0.015	0.101	0.88	-0.096	0.102	0.346
Density (trees $plot^{-1}$)	0.021	0.01	**0.040**	0.017	0.01	0.109
Basal area (mm^2)	0.0002	0.0001	0.080	0.0002	0.0001	0.214

4.3.2 Sprouting

The number of sprouts in living stump for all broadleaved stumps was a bit higher (mixing ratios 1:100 and 1:200) or a bit lower (mixing ratio 1:400) compared to control without a treatment (3.1 sprouts in stump) (Table 7). In case of living birch stumps, all mixing ratios had fewer sprouts in stump compared to control (2.9 sprouts in stump). Based on generalized mixed effect model there were statistical difference only between control and *C. purpureum* treatment with mixing ratio 1:400 for all living broadleaved stumps (*p<0.001*) and birch stumps (*p=0.011*). Density (trees $plot^{-1}$) and basal area of the stump affected statistically significantly to number of sprouts. As trees $plot^{-1}$, i.e. density of the stand before the early PCT, increases the number of sprouts decreases and as basal area of the stumps increases, increases the number of sprouts (Table 7).

The maximum height of the sprout was only shorter than control (117.7 cm) on mixing ratio 1:400; other mixing ratios had higher sprouts (Table 7). The situation was the same in case of living birch stumps: the maximum height of the sprout was only shorter than control (127.1 cm) on mixing ratio 1:400. Over the years, sprouts got taller and their number in stump decreased. Based on generalized mixed effect model, there were statistically significant difference only between control and *C. purpureum* treatment with mixing ratios 1:200 (*p=0.025*) and 1:100 (*p=0.019*) (Table 7). However, stumps treated with mixing ratio 1:100 had higher sprout compared to control whereas mixing ratio 1:200 decreased maximum height of the sprout. In case of birch stumps, all mixing ratios differed statistically significantly from control. As in case of all broadleaved stumps, stumps treated with mixing ratio 1:100 had higher sprout compared to control, other mixing ratios decreased maximum height of the sprout. Basal area of stump increased the maximum height of the sprouts of all broadleaved (*p<0.001*) and birch (*p<0.001*) stumps, so that the larger basal area, the higher sprouts. In case of birch stumps, also work week increased the maximum height of the sprout (*p=0.05*)

Table 7. Number of sprouts in stump and the maximum height of sprout (cm) for broadleaved stumps on years 2015–2017 and separately for birch stumps on the year 2017 of different mixing ratios of *C. purpureum*.

	Treat-ment	Broadleaf 2017			Birch 2017			Broadleaf 2016		Broadleaf 2015	
		N	Mean	SD	N	Mean	SD	N	Mean	N	Mean
Number of sprouts in stump	Control	655	3.1	2.5	449	2.9	2.3	634	4.1	722	5.9
	1:100	314	3.2	2.4	115	2.8	2.0	332	4.2	367	6.2
	1:200	170	3.3	2.8	210	2.7	1.6	181	3.9	209	5.2
	1:400	405	2.8	2.0	289	2.5	1.5	432	3.6	485	5.1
Max. height of sprout, cm	Control	655	117.7	47.3	449	127.1	45.9	633	96.7	721	63.1
	1:100	314	131.9	54.6	210	151.7	51.7	332	104.0	367	69.6
	1:200	170	128.2	54.1	115	140.0	51.8	180	110.5	206	67.0
	1:400	405	112.8	41.4	289	120.9	40.4	432	93.4	483	62.0

Table 8. The effects of the treatment (control as a reference vs. *C. purpureum* treatment with mixing ratios of 1:400, 1:200 or 1:100), work week, moisture of the plot, number of trees at the plot before early PCT, and the basal area of an investigated stump to the number of sprouts in living broadleaved s and birch stumps as well as to maximum height of the broadleaved and birch stumps (generalized linear mixed models).

	All broadleaved			Birch		
Variable	Estimate	Std. err.	*p*-value	Estimate	Std. err.	*p*-value
Number of sprouts						
Intercept	1.140	0.292	**<0.001**	1.064	0.264	**<0.001**
C. purpureum treat. 1:400	-0.122	0.043	**0.001**	-0.134	0.052	**0.011**
C. purpureum treat. 1:200	-0.023	0.058	0.693	-0.069	0.072	0.34
C. purpureum treat. 1:100	-0.003	0.044	0.429	-0.089	0.056	0.110
Work week	0.007	0.009	0.455	0.008	0.007	0.248
Moisture	-0.020	0.03	0.493	-0.049	0.032	0.128
Density (trees plot^{-1})	-0.017	0.003	**<0.001**	-0.014	0.003	**<0.001**
Basal area (mm2)	0.0002	0.00002	**<0.001**	0.0002	0.0002	**<0.001**
Max. height of the sprout						
Intercept	59.911	32.724	0.067	76.849	37.148	**0.039**
C. purpureum treat. 1:400	-3.41	3.153	0.280	-8.394	3.532	**0.018**
C. purpureum treat. 1:200	-9.789	4.363	**0.025**	-11.713	4.874	**0.016**
C. purpureum treat. 1:100	7.554	3.207	**0.019**	9.425	3.625	**0.010**
Work week	1.61	1.057	0.128	2.350	1.202	**0.050**
Moisture	2.272	2.109	0.281	-3.517	2.193	0.109
Density (trees plot^{-1})	-0.215	0.217	0.322	-0.374	0.220	0.090
Basal area (mm2)	0.019	0.002	**<0.001**	0.016	0.002	**<0.001**

4.3.3 Quality

The density of broadleaved trees was significantly lower after early PCT (Table 3). On average 13% of broadleaved trees remained after early PCT varying from 9% to 23%. The density of coniferous trees after early PCT was 4324 saplings ha^{-1} varying from 2546 to 7851 saplings ha^{-1}. Of all trees retained after early PCT and found on 2017 inventory, 40% were selected as crop trees. Of selected crop trees 43% were pine, 51% spruce and 6% birch. Of selected crop trees, 58% were sample trees. The density of retained crop trees was 2452 trees ha^{-1} (Table 9).

The share of freely growing trees (disturbing trees <2/3 of the height of the selected crop tree) was 49% for control, 38% for *C.purpureum* treatment with mixing ratio of 1:100 and 1:200, and 44% for mixing ratio 1:400 (Table 9). This corresponds to 765 trees ha^{-1} for control and 521–562 trees ha^{-1} for treatments. The fact that a sample tree was freely growing (competing trees <2/3 of the height of the sample tree) was mostly explained by the method in which early PCT was done (Table 10). Compared to control done by clearing saw, both Tehojätkä 1 (*p<0.001*) and Tehojätkä 2 (*p=0.022*) statistically significantly increased canopy competition. Other explanatory variables in the model were not statistically significant.

Table 9. Density (trees ha^{-1}), mean height (cm), and canopy competition of retained crop trees for different treatments and control. Canopy competition is only for sample trees. It indicates the height of the non-crop trees in the ratio of sample tree height, for example, "0–1/2" means that non-crop trees were less than half of the height of the sample tree or they did not exist.

Treatment	N	Density (trees ha^{-1})	Mean height (cm)	Canopy competition, %				
				N	0–1/2	1/2–2/3	2/3–1	>1
Control	137	2436	290.6	88	35.2	13.6	35.2	15.9
1:100	80	2607	263.9	50	18.0	20.0	44.0	18.0
1:200	50	2180	221.8	32	21.9	15.6	53.1	9.4
1:400	95	2496	260.3	41	19.5	24.4	36.6	19.5

Of all trees retained after early PCT (N = 956), 17% had damage. Slightly more than half of the damage was caused by herbivores, moose most of the cases. Compression, as the Tehojätkä drove over the saplings, caused 22% of damage. Other reasons caused 22% of damage, mostly due to the undergrowth. Rest of the damages was caused by *C. purpureum* inoculum or UW40-cleaning head. Most of the damages were on stands which were operated by Tehojätkä (92%). Of all broadleaved stumps (N = 2019), 10% were high stumps, which had living brunches underneath the cutting surface. The average height of the high stumps was 48.4 cm as the average height of the rest were 34.0 cm. Most of the high stumps were done by the Tehojätkä (97%). The average height of the stumps done by clearing saw was 33.6 cm.

Table 10. The effects of the treatment (control as a reference vs. *C. purpureum* treatment with mixing ratios of 1:400, 1:200, or 1:100), method (control manually vs. Tehojätkä 1 or 2), work week, moisture of the plot, number of trees at the plot before early PCT to the freely growing sample tree (0= freely growing, 1=competing trees <1m radius) (generalized linear mixed models).

	Estimate	Std. err.	*p*-value
Intercept	-0.804	1.377	0.559
C. purpureum treatment 1:400	-0.452	0.497	0.363
C. purpureum treatment 1:200	-0.270	0.537	0.615
C. purpureum treatment 1:100	-0.248	0.438	0.571
Tehojätkä 1	1.973	0.531	**<0.001**
Tehojätkä 2	1.384	0.606	**0.022**
Work week	-0.007	0.036	0.84
Moisture	-0.115	0.233	0.622
Density (trees plot^{-1})	0.0460	0.037	0.213

5 Discussion and conclusions

5.1 Uprooting

Three to five years after uprooting there were quite a lot of competing broadleaved trees growing in these planted spruce stands. The mean number competing trees was altogether (broadleaved trees and auxiliary conifers) about 6250 stems ha^{-1} which is about half of the stem number after conventional motor manual PCT –operation (Uotila et al. 2013). The variation between stands was huge. Birch is the most powerful competitor in a spruce stand. The mean number of birch was about 3 800 stems ha^{-1} and in every fifth stand the mean number birch was less than 2000 stems ha^{-1}. These mean numbers include all stems higher than one meter so they all are not real competitors for the crop trees with mean height of 275 cm.

Generally, crop trees were at least half a meter taller than competing trees. The average height difference was 90 cm. Over 60 % of crop trees were classified as freely growing so they had at least a height advantage of one-third of their own height. The mean number of freely growing crop trees was 1235 ha^{-1}, ranging from 600 to 1900 stems ha^{-1} between stands. In 80 % of stands there was at least 1000 freely growing stems ha^{-1} which can be considered to be quite near the stem number to be left growing after first thinning in a spruce stand (900–1100 stems ha^{-1}; Äijälä et al. 2014).

The height of crop trees at the uprooting moment had the strongest effect on the competition situation of spruce and broadleaves. According to the model fitted to this material, an increase of 50 cm in crop trees height will increase the proportion of freely growing crop trees by 30 %. On the other hand on moist spots, the risk of crop trees overtopped by broadleaved trees was 1.5 times bigger. The effect of stump harvesting was not so clear because of unbalanced data among provinces. Also after stump harvesting the emergence of new birch seedlings happens much longer time than after "normal" site preparation (Saksa 2013) which might cause differences in height distribution of competing birches between stump harvested and non-stump harvested areas. Thus even these stump harvested areas had significantly more birch stems than non-stump harvested ones a major part these birches might have been lower height classes.

According to simulations with Motti simulator, the stem number of competing birch will decrease a lot before first thinning. If the number of crop-tree spruces is high enough to close the canopy (more than 1600 crop-tree spruces ha^{-1}) before the competing trees will catch the same height level the competing trees will not reach canopy layer and they will not survive because of lack of light.

According to simulations in most of stands birch will catch up crop-tree spruce in height development but they will be growing in the same crown layer and they will not overtop spruces. In most cases, birch will be less than 10% taller than spruces at the first thinning. So also the risk of stand with two storey after uprooting is low. The height growth of birch was somewhat overestimation because only the height development of silver birch was used for birches in these simulations. In reality, about half of the birches were downy birch which will grow significantly slower than silver birch.

As the final conclusion, this study shows that uprooting can serve as the only PCT-operation in a planted spruce stand. If uprooting is the only PCT-operation then it is cost-efficient as compared to total costs of two separate motor manual PCT-operations (early PCT and PCT). The timing of uprooting operation is crucial; optimal uprooting time is when crop spruces have reach about breast height but the competing trees have not yet harmed crop trees. If stand is uprooted too early the smallest trees will not be removed because they are not tall enough for the uprooting device. Also attention must be paid to selection of sites to uproot. On moist sites there is a risk to get new birch seedlings from seed after uprooting.

5.2 Biocontrol

Early PCT together with *C. purpureum* treatment increased mortality of stumps compared to early PCT with no treatment. However, mortality was lower compared to other studies. Hamberg et al. (2015) used the same *C. purpureum* strain R5 as in this study and they reported a mortality of 78% after three growing seasons. In this study, the average mortality of birch stumps with treatment was 32%, but there were differences between mixing ratios and timing. The best result for birch stump mortality was on stand 1.2 with mixing ratio of 1:400 where 72% of stumps were dead. The poorest result was 4% on stand 8.1 with a mixing ratio of 1:400.

One reason for low mortality was time when early PCT was done. In this study, number of work week, i.e. time when the treatment was done, was the only factor affecting mortality of stumps. Correspondingly, Vartiamäki et al. (2009) reported that *C. purpureum* treatment was less effective towards the end of the growing season. For reducing the number of sprouting stumps, the best time of the treatment was on May, June, or July and for reducing the number of living sprouts in stump the best time was on June or July. In this study, mortality of birch stumps was highest at June and July, 44% and 38% respectively, and reduced at the autumn being 22% at August (only one treatment) and 7.5% at September. Vartiamäki et al. (2009) also reported that *C. purpureum* effects on sprouting for a relatively long time since the effect of the treatment improved during the second year compared to the first year after treatment. This was shown in the results of this study too, as mortality of stumps increased annually from year 2015 to 2017. However, mortality increased for control as well but not as much.

C. purpureum treatment did not affect as clearly to number of sprouts or maximum height of the sprouts. Similarly, Vartiamäki et al. (2009) found that C. purpureum treatment had no statistically significant effect on the maximum height of the sprouts, even though the treatment did increase mortality of the stumps and decreased number of sprouts. Hamberg et al. (2015) used the same *C. purpureum* strain R5 as in this study and they reported that compared to liquid control, there was no statistically significant difference between number of sprouts and the maximum height of the sprouts two years after treatments. Basal area of the living stump increased both number and maximum height of the sprouts, similarly as in Hamberg et al. (2015) study.

Density (number of trees plot^{-1}) increased mortality of broadleaved stumps and decreased number of sprouts in stump. Same findings were in Hamberg et al. (2015) study as shading of neighboring trees causes shoot buds dying. On the other hand, mortality of stumps treated with *C. purpureum* inoculum might provide more space for stumps still living at the stand. This might cause an increment in number and the maximum height of the sprout and diminish the difference between the treatment and control.

Spreading of *C. purpureum* inoculum on the surface of fresh stumps during PCT operation is technically feasible with Tehojätkä but the accuracy of the spreading mechanism might not be satisfactory and there could have been malfunctioning. This might be a reason for low mortality and minor effect of the *C. purpureum* treatment on number and maximum height of the sprout obtained in this study. In the other researches, suspension of *C. purpureum* has been inoculated manually, for example via a plastic squirt bottle, to ensure high accuracy (Hamberg 2015, Vartiamäki et al. 2009, Vartiamäki et al. 2009). There is no exact information of the accuracy of Tehojätkä spreading mechanism into the surface of the cut stumps.

Despite differences between machines in treatments and methods in control, in the analysis, they were treated as one. It was tested that there were no statistical significance between control done by clearing saw and Tehojätkä ($p>0.05$). There were statistical significance between two different Tehojätkä machines ($p<0.05$), but the difference is mostly due to the fact, that other machine was only used in weeks 30–40 when results were poorer because of the other circumstances. There might be difference between operators as well but it was not taken into account.

There is a need for later PCT as the density of remaining crop trees was not controlled in the early PCT. If early PCT and later PCT are combined into one young stand management, there is a need to control both competition between wanted and unwanted tree species (=early PCT) and overall stem density (=PCT). Recommended densities after PCT are 1800–2000 trees ha^{-1} for spruce and 2000–2200 trees ha^{-1} for pine (Äijälä et al. 2014). In this study, densities of coniferous after treatments varied from 2546 trees ha^{-1} (stand 3.1) to 7851 trees ha^{-1} (stand 4.1). Furthermore, the share of freely growing trees was not satisfactory. 900–1100 freely growing trees ha^{-1} for spruce and 1100–1300 trees ha^{-1} for pine can be considered to be the density of trees left growing after first thinning (Äijälä et al. 2014). In this study, it is notable that the share of freely growing trees was greater for control than for treatment. This is mostly due to the fact that some of the control areas were done by clearing saw. The share of freely growing sample trees on control areas done by clearing saw or Tehojätkä was 90% and 48%, respectively.

There have been difficulties in the operational application by motor-manually and effectiveness of *C. purpureum* inoculum in practice. It takes 2.6 times longer to apply compared to traditional PCT done by clearing saw, mainly due to the additional operations needed and weight of the equipment (Roy et al. 2010). If work could be done mechanically, advantages of biocontrol could be achieved. The machine could easily carry the load of *C. purpureum* inoculum. Applying *C. purpureum* at freshly cut stumps and additional operations require longer time compared PCT without biocontrol treatment, but the fact that later PCT is not required make savings when looking the whole chain of young stand management.

In conclusion, it remains possible to decrease stump sprouting with *C. purpureum* treatment but implementation into practice need more testing. In this study, there were so many factors affecting in results, for example; stand, method of early PCT, different mixing ratios, timing, so the efficacy of the *C. purpureum* treatment diminishes. However, it is clear that *C. purpureum* treatment increased mortality of stumps. Possible future implementation of *C. purpureum* treatment in practice requires also proper work instructions so that the efficacy of the treatment does suffer from the methods used. Treatment suits the best for large enough birch stumps done at the summer.

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