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The efficacy of *Chondrostereum purpureum* in sprout control of birch during mechanized pre-commercial thinning

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Abstract The efficacy of mechanized pre-commercial thinning (PCT) done by a lightweight mini-harvester Tehojätkä together with the *Chondrostereum purpureum* (Pers. ex Fr.) Pouzar fungal treatment (dilutions 1:100, 1:200, 1:400) and control (cutting only) was studied for three years. The efficacy of the fungal treatment was defined as capability to prevent sprouting of birch (*Betula pendula* Roth. and *B. pubescens* Ehrh.). The fungal treatment resulted in higher stump mortality and lower number of sprouts but it did not have a clear effect on the maximum height of stump sprouts. However, mortalities obtained in this study (34.1%, 26.8%, and 25.6% for dilutions 1:100, 1:200, and 1:400, respectively) were notably lower compared to previous studies which indicate that the accuracy of the spreading mechanism was not satisfactory. We conclude that it is possible to decrease stump sprouting with the fully mechanized fungal treatment but putting this implementation into practice needs more testing to increase efficacy.

Keywords Biological control · Vegetation management · Silviculture · Mechanization · Stump sprouts · *Betula* spp.

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Introduction

After artificial forest regeneration the natural regeneration of pioneering deciduous species creates a need for young stand management (Huuskonen and Hynynen 2006; Uotila et al. 2012). Removing unwanted deciduous tree species, mostly silver birch (*Betula pendula* Roth.) and downy birch (*Betula pubescens* Ehrh.), assures growth of commercially valuable conifers and decreases competition between conifers and faster growing deciduous species (Lindholm and Vasander 1987; Vanha-Majamaa et al. 1996; Gobakken and Næsset 2002; Huuskonen and Hynynen 2006; Uotila et al. 2012; Äijälä et al. 2014).

Conventionally, young stand management is done motor-manually by cutting competing (deciduous) trees to assure the development of target (conifer) trees. However, cutting young deciduous trees is a quite ineffective method since it stimulates vigorous regrowth whereby most of the stumps produce several new sprouts (Kauppi et al. 1987; Johansson 1992, 2008). Thus, young stand management is usually done in two phases. First, early cleaning (EC) is performed about five years after regeneration, when the height of conifer saplings is ca. 1 m. Second, when pines are from five to seven meters and spruces from 3 to 4 m in height, it is time for the pre-commercial thinning (PCT): spruce-dominated stands are thinned to the density of 1800–2000 and pine-dominated to 2000–2200 saplings per hectare (Huuskonen et al. 2008; Pettersson et al. 2012; Fahlvik 2005; Äijälä et al. 2014; Uotila 2017). Pine-dominated stands are grown in denser spacing to ensure high-quality timber by branch mortality and natural pruning (Mäkinen 1999; Varmola and Salminen 2004). Cleaning of deciduous saplings also decreases the risk of moose browsing in pine stands (Härkönen 1998). Although repeated cuttings increase the total cost of young stand management, it considerably enhances the diameter development of target trees and is therefore desirable (Huuskonen and Hynynen 2006; Uotila 2017).

The cost-efficiency of young stand management could be improved if repeated cuttings were not needed. Here, the use of chemical herbicides would be efficient, but this is restricted by forest certification (PEFC 2017). Therefore, mechanical cutting combined with the use of a white-rot fungus, *Chondrostereum purpureum* (Pers. Ex Fr.) Pouzar, as a biocontrol agent has been studied (e.g. Wall 1986; Gosselin et al. 1999; Setliff 2002; Vartiamäki 2009; Hamberg et al. 2015). This is an environmentally friendly alternative to chemical herbicides. The idea is to apply *C. purpureum* inoculum on freshly cut stumps to suppress re-sprouting (Wall 1990). *C. purpureum* is a lignicolous, basidiomycete fungus occurring naturally worldwide in temperate and boreal vegetation zones (Wall 1990; Setliff 2002; Vartiamäki et al. 2008). It invades woody tissue through fresh wounds, e.g. via cut surfaces, causing discoloration, decay, and even death of the host (Wall 1990; Hintz 2007; Vartiamäki 2009). However, it has been shown not to cause disease in non-targeted healthy trees, so its use as a biocontrol agent does not pose the risk of disease epidemics (Gosselin et al. 1999; De Jong 2000).

The use of *C. purpureum* has been promising in field tests even though there is variation in results due to timing of the treatment, the accuracy of the spreading mechanism, the basal area of the stump, and tree species (Wall 1986; Setliff 2002; Vartiamäki et al. 2009; Roy et al. 2010; Hamberg et al. 2015, 2017; Hamberg and Hantula 2016, 2018). As a method, applying *C. purpureum* inoculum manually on cut surfaces is challenging due to the high number of stumps within regeneration areas. Also, motor-manually using a clearing saw, takes 2.6 times longer to perform the fungal treatment compared to cutting only (without fungus), mainly due to the additional operations and the weight of the equipment needed for the application (Roy et al. 2010).

There are mechanical solutions available for young stand management, but currently less than 1% is done fully mechanically in Finland (Strandström 2016; Luke 2018). Even though the main target of mechanization is to improve the cost-efficiency of young stand management through higher productivity, clear cost-savings have not been achieved compared to the use of a clearing saw (Mattson and Westerberg 1992; Strandström 2016). The use of *C. purpureum* in sprout control may provide an opportunity to improve the cost-efficiency of mechanical solutions since machines could easily carry the additional weight required by *C. purpureum* inoculum. However, there is no previous research combining the fungal treatment with mechanized young stand management (cutting excess deciduous saplings), although this method likely decreases the need for the subsequent PCT.

In this study, the aim was to measure the efficacy of a lightweight mini-harvester Tehojätkä (Usewood Ltd., Finland) application of *C. purpureum* inoculum to freshly cut stumps in order to control competition from deciduous trees in juvenile conifer stands. The hypothesis was that mechanized pre-commercial thinning together with the fungal treatment is more effective compared to the control without a fungal treatment (cutting only). The efficacy was defined as (1) increased stump mortality, (2) decreased number of sprouts on a stump, and (3) shorter length of sprouts. In this study, the young stand management method is called "early PCT", with the idea that EC and PCT are combined into one young stand management method without repetitive operations.

Materials and methods

Stands, machines and treatments

Early PCT was done between June and September 2014 on eleven juvenile forest stands, 7 ± 0.6 years after regeneration (mean ± SE) (Table 1). Stands were regenerated either to spruce ($n = 7$) or pine ($n = 4$) and they were located in eight geographically separate areas in central Finland. Every stand included 1–3 different fungal treatments: dilution 1:100 ($n = 8$), 1:200 ($n = 5$), 1:400 ($n = 7$), and one control treatment (cutting only) ($n = 11$) (Table 1). Due to practical arrangements at stands, all treatments were not repeated on each stand but the control was included in each stand.

The work was done by a lightweight mini-harvester Tehojätkä (Usewood Ltd., Finland) equipped with a boom-mounted UW40-cleaning head (Supplementary Figure S1). The Tehojätkä weighs 1800 kg, and is 3.8 m in length and 1.5 m in width (Usewood Ltd., Finland). Horizontal boom reach is 3.8 m. The UW40-cleaning head (no longer in production) is especially designed for small-diameter stems. It has either a cutting (for stems < 40 mm in diameter) or a sawing function (for stems 20–90 mm in diameter), depending on the rotation direction of the blade. The cleaning head weighs 90 kg and the speed of rotation is one cycle per second. The UW40-cleaning head has active tilt, i.e., the cutter may be tilted and locked during the cutting.

The basal suspension of *C. purpureum* (provided by Verdera Ltd.) included the fungal strain R5 (Hamberg et al. 2015) containing a minimum of 10^6 colony forming units (Gonzáles 1996). It was diluted with tap water just before the treatments in the field (dilutions 1:100, 1:200 or 1:400). Tehojätkä machines were equipped with tanks (capacity of 200 l) for applying liquid suspension of *C. purpureum* mycelium onto freshly cut stump surfaces. Dilutions were conducted through a hose along the boom to the cleaning head. There were three different Tehojätkä machines with two different dosing methods (Table 1). In the standard dosing method, used by two machines, *C. purpureum* inoculum was dosed to the upper side of the cutting blade from which it flowed through holes, made in the blade, onto the surface of cut stumps. In the third machine, *C. purpureum* suspension was dosed straight to underside of the blade through a nozzle. In our final models (see below), we did not find any differences between the dosing methods ($p > 0.05$), and therefore all Tehojätkä machines were treated as one group.

The control treatments (cutting only, without the fungus) were performed using either the Tehojätkä machines or motor-manually with a clearing saw (Table 1). There was no statistically significant difference in stump mortality between the controls done either by the Tehojätkä machines or a clearing saw ($p > 0.05$), and therefore the control treatments were not treated separately in the statistical analysis.

Table 1 Description of the study design of eleven stands located in eight geographically separate areas in central Finland: number of sample plots ($n = 480$), regenerated tree species and year, the fungal treatments (*Chondrostereum purpureum* dilutions 1:100, 1:200 or 1:400), dosing method to apply *C. purpureum* inoculum (standard/nozzle) and the number of machines used within a stand as a superscript (1–3), the method used for the control (cutting only: CS clearing saw, UW Usewood Tehojätkä), timing (the number of calendar week when the treatment was done), and mean dampness of the stand six-level classification based on the evaluation of cover of bryophytes

Stand	Regene-ration year	Tree species	Number of plots	Fungal treatment			Dosing method	Control method	Timing (work-week)	Damp-ness
				1:100	1:200	1:400				
1.1	2005	Pine	30		×		Nozzle[1]	UW	24	3.4
1.2	2005	Pine	30			×	Nozzle[1]	CS	24	2.9
1.3	2005	Pine	30	×			Nozzle[1]	CS	24	2.8
2.1	2007	Spruce	30			×	Nozzle[1]	CS	28	2.9
2.2	2003	Spruce	30	×			Nozzle[1]	CS	29	2.6
3.1	2009	Spruce	60	×	×	×	Standard[2]	UW	24–26	4.2
4.1	2008	Pine	60	×	×		Standard[2]	UW	27–28	2.5
5.1	2008	Spruce	60	×	×	×	Standard[2]	UW	29–30	3.3
6.1	2009	Spruce	45	×		×	Standard[2]	UW	30–32	3.4
7.1	2008	Spruce	60	×	×	×	Standard[3]	CS	37–39	2.9
8.1	2008	Spruce	45	×		×	Standard[2]	UW	40	2.9

Fieldwork

In years 2015, 2016 and 2017, i.e., 1–3 years after the treatments, inventories in the field were done between September and November. Inventories were carried out by measuring a systematic, regularly shaped grid of 15 circular sample plots (r = 1.0 m) per treatment (control and fungal treatments), except that, in stand 4.1, altogether 30 plots were measured for the control (cutting only). The distance between the plots was determined according to the area (0.3–0.7 ha) excluding a buffer zone of 10 m between the treatments and from trees of neighboring stands to avoid their immediate effects on sprouting (Hamberg et al. 2015). Altogether, the data consisted of 480 sample plots, but some plots were not found during the study, and, therefore, the final data consisted of 470 sample plots: 116 for the *C. purpureum* dilution 1:100, 73 for 1:200, 102 for 1:400, and 179 for the control (Table 1).

In every sample plot, all stumps (diameter > 0.5 cm at ground level) and saplings (height > 0.5 m) were measured in order to evaluate the efficacy of the fungal treatments. However, we present here results only for birch stumps (*Betula pendula* and *B. pubescens*) since they were the most common tree species in investigated stands (71% of all stumps), and since *C. purpureum* is especially efficient in birch (Hamberg et al. 2017). This provided us with a good basis for our efficacy investigations in mechanized fungal treatments. When stumps were investigated, tree species, the diameter of the cut surface (mm), the height of the stump (cm), the number and maximum height of stump sprouts (cm from the ground), and the presence of fruiting bodies of *C. purpureum* on a stump (0 = fruiting bodies not found, and 1 = fruiting bodies found) were recorded. Furthermore, on every plot, the dampness of the ground was evaluated based on the cover of bryophytes commonly found in mires (*Sphagnum* and *Polytrichum commune*) using a six-level classification (1 = 0%, 2 = 0.1–1%, 3 = 1–10%; 4 = 11–25%, 5 = 26–50%, 6 = > 50%, Tamminen and Mälkönen 1999).

Statistical analysis

In data analysis, we concentrated on the efficacy of different treatments (control vs. fungal treatments), i.e., the mortality of stumps and the ability to alleviate sprouting (number and maximum height of sprouts) after the treatments. Mortality means that a stump had no sprouts and was therefore considered dead. Silver (*Betula pendula*) and downy birches (*B. pubescens*) were not separated in the analyses since they have been shown to respond similarly in these treatments (Hamberg et al. 2015). The data used in the analysis consisted of 1436 birch stumps in 2015 and 2017, but, in 2016, only 1371 stumps were found and measured.

The statistical program R was used in the analyses (R Core Team 2018). The mortality of stumps (0 = stump is alive, 1 = stump is dead), the presence of fruiting bodies on a stump, and the number of sprouts on a living stump were investigated with generalized linear mixed models (GLMMs) using the function *glmer* in the library *lme4* (Bates et al. 2015). In the mortality and the fruiting body models, a binomial distribution with logit link function was used, whereas in the number of sprouts model, a Poisson distribution with log link function was used. The maximum height of a sprout in different treatments was investigated with linear mixed models (LMMs), using the *lme* function in the *nlme* library (Pinheiro et al. 2018). All birch stumps were included in the mortality models, but only living stumps were included in the stump sprout models (number and height). Models were estimated separately for each year.

Models for mortality, sprout number, and the maximum height of the sprout included the following explanatory variables: (1) treatment (a factor with four levels: control, and three different *C. purpureum* dilutions 1:100, 1:200, and 1:400), (2) timing (the number of calendar week when the treatment was done), (3) dampness of the ground (scale 1–6), (4) stand density (the number of saplings on the plot before the early PCT), and (5) the diameter of a stump (mm). The fruiting body models included the same variables as above, except that the control treatment was excluded since no fruiting bodies were found from the control sample plots. Correlations between the explanatory variables were < 0.35. As we wanted to separate the treatment effects from the other effects (affecting mortality, and the number and height of stump sprouts), explanatory variables 2–5 were included in the final models regardless of whether they were statistically significant or not (see Hamberg et al. 2015). Stand and sample plot were included as nested random factors as conditions within the same stand and sample plot may be more similar than on a randomly selected stand or a sample plot. Residual plots were inspected after each model to identify outliers and to check that the variances of residuals are homogenous (O'Hara and Kotze 2010; Warton and Hui 2011). Overdispersion was also inspected by including observation-level random effect (OLRE) (Harrison 2014).

Results

Before the early PCT, the densities of coniferous and deciduous saplings were 5067 ± 582 and 15,497 ± 1527, respectively (mean ± SE). The early PCT lowered the density of deciduous trees by ca. 87% to the densities 4324 ± 520 and 2029 ± 227 ha^{-1}, respectively. The mean height of conifers after the early PCT in 2014 (measured from remaining saplings in 2015) was 130.4 ± 3.7 cm. The mean diameter and height of cut birch stumps was 12.9 ± 0.2 mm and 33.0 ± 0.4 cm, respectively.

Mortality

Mortality was higher on the fungal treated stumps than on the control stumps (cutting only) one, two and three years after the early PCT ($p < 0.001$) (Table 2; Fig. 1a). Mortality increased with increasing *C. purpureum* concentration (1:400 < 1:200 < 1:100) and time lag after the treatments (year 2015 < 2016 < 2017). After three growing seasons, the mortality of birch stumps was 34.1, 26.8, and 25.6% for the *C. purpureum* dilutions 1:100, 1:200, and 1:400, respectively (predicted mean value based on GLMM). Stump mortality on the control stands (cutting only) was 11.5%.

Timing of the treatment (i.e., the number of calendar week when the treatment was performed) affected the mortality of birch stumps ($p < 0.001$): when the early PCT was performed later in the growing season, the mortality decreased (Table 2; Fig. 2). Mortality was ca. 60% in the fungal treatment (dilution 1:100) when performed in the middle of June (calendar week 25), ca. 35% in the end of July (calendar week 30), and no more than ca. 10% in the beginning of October (calendar week 40). In the other dilutions (1:200 and 1:400) and the control, the mortality was lower, but the trend was similar: the mortality of birch stumps was lower later in the

Table 2 The effects of (1) the treatment (the control vs. the fungal treatments with the *Chondrostereum purpureum* dilutions 1:100, 1:200 or 1:400), (2) timing of the treatment (the number of calendar week when the treatment was done), (3) dampness of the ground, (4) the number of saplings on the plot before the early pre-commercial thinning, and (5) the diameter of an investigated stump (mm) on the mortality of birch stumps (0 = alive, 1 = dead) one (2015), two (2016), and three years (2017) after the treatments (generalized linear mixed models)

Explanatory variables	Mortality in 2015 n = 1436				Mortality in 2016 n = 1371				Mortality in 2017 n = 1436			
	Coeff. ± SE	DF	z	p	Coeff. ± SE	DF	z	p	Coeff. ± SE	DF	z	p
Intercept	3.137 ± 1.175	1280	2.669	**0.008**	3.419 ± 0.909	1215	3.763	**< 0.001**	2.472 ± 0.827	1280	2.987	**0.003**
C. purpureum treatment												
1:100	2.021 ± 0.271	1280	7.461	**< 0.001**	1.672 ± 0.233	1215	7.157	**< 0.001**	1.380 ± 0.200	1280	6.890	**< 0.001**
1:200	1.282 ± 0.290	1280	4.414	**< 0.001**	1.352 ± 0.258	1215	5.246	**< 0.001**	1.031 ± 0.227	1280	4.531	**< 0.001**
1:400	1.244 ± 0.276	1280	4.511	**< 0.001**	1.313 ± 0.228	1215	5.752	**< 0.001**	0.970 ± 0.191	1280	5.061	**< 0.001**
Timing	− 0.252 ± 0.036	1280	− 6.906	**< 0.001**	− 0.215 ± 0.027	1215	− 8.013	**< 0.001**	− 0.169 ± 0.023	1280	− 7.393	**< 0.001**
Dampness	0.061 ± 0.119	1280	0.509	0.610	− 0.094 ± 0.104	1215	− 0.908	0.363	− 0.022 ± 0.102	1280	− 0.213	0.831
Density (saplings per plot)	0.009 ± 0.012	1280	0.734	0.463	0.009 ± 0.011	1215	0.790	0.430	0.019 ± 0.011	1280	1.832	0.067
Stump diameter (mm)	0.050 ± 0.010	1280	4.836	**< 0.001**	0.047 ± 0.009	1215	0.009	**< 0.001**	0.035 ± 0.008	1280	4.109	**< 0.001**

Coefficients and their standard errors (SE), degrees of freedom (DF), associated Wald's z-score (= coeff./SE) and significance level p when all coefficients in the models are presented. Statistically significant p values ($p < 0.05$) are in bold. See also Fig. 1a

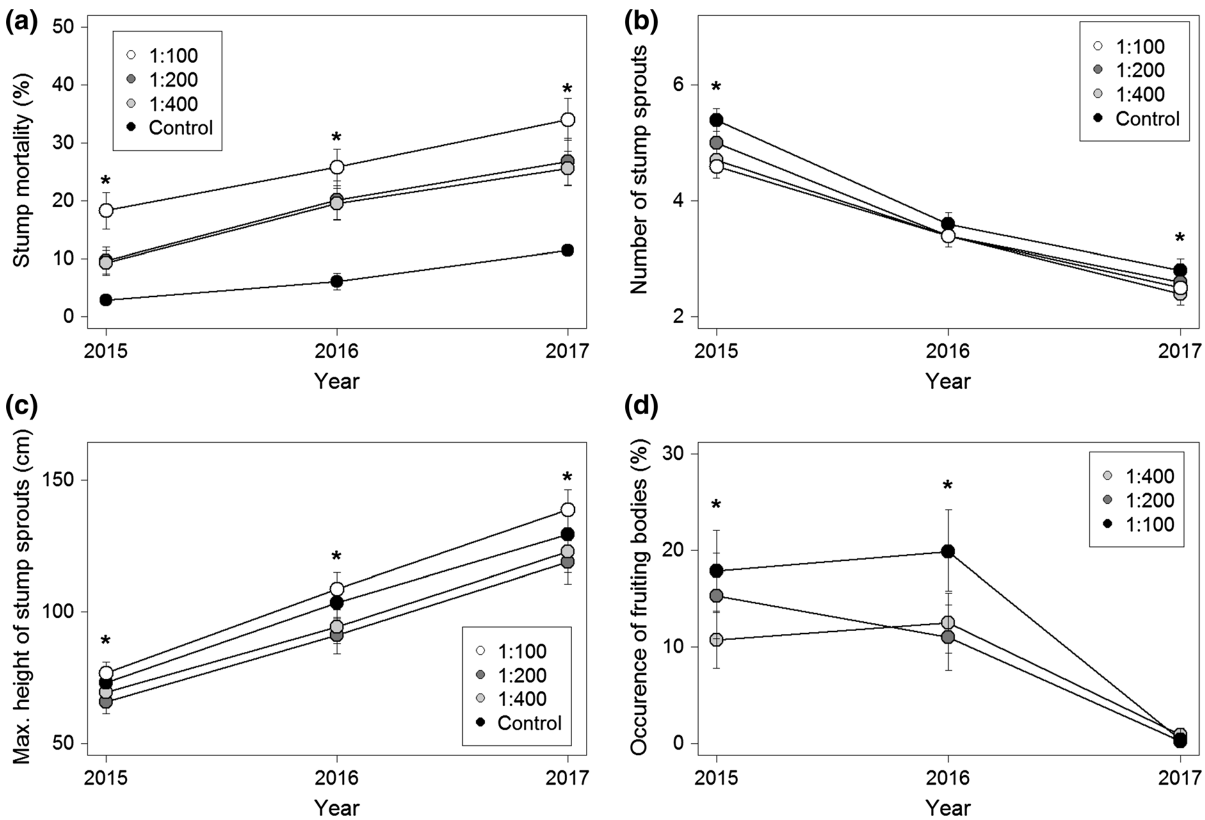

Fig. 1 The effects of the control (cutting only) and the fungal treatments (*Chondrostereum purpureum* dilutions 1:100, 1:200, and 1:400) on **a** the mortality of birch stumps, **b** the number of sprouts per stump, **c** the maximum height of sprouts per stump, and **d** the presence of fruiting bodies (only for the fungal treatments) one, two and three growing seasons after the early pre-commercial thinning. Means with SE are presented. Figures have been drawn based on the predicted values of the generalized linear or linear mixed models. Statistically significant difference ($p < 0.05$) between the control and at least one of the fungal treatments is indicated with an asterisk. The asterisk relates to the specific year in the x-axis. See Tables 2, 3, 4, and 5

growing season the treatment was done. Furthermore, mortality was higher for larger diameter stumps than for those with smaller diameters ($p < 0.001$).

Number of sprouts

The number of sprouts in living birch stumps was lower in the fungal treatments compared to the control (cutting only) (Table 3; Fig. 1b). The *C. purpureum* dilutions 1:100 ($p = 0.047$) and 1:400 ($p = 0.019$) differed from the control (cutting only). In stumps, the number of sprouts decreased every year (2015 > 2016 > 2017). Three years after the early PCT, the predicted mean number of sprouts per stump was 2.8 for the control, and 2.5, 2.6, and 2.4 for the *C. purpureum* dilutions 1:100, 1:200, and 1:400, respectively. The density of saplings (per plot) ($p < 0.001$) and the diameter of a stump ($p < 0.001$) affected the number of sprouts per birch stump. When the number of saplings increased on a plot before the early PCT, the number of sprouts decreased. The number of stump sprouts increased with increasing diameter of stumps. One and two years after the treatment, timing of the treatment (i.e., the number of calendar week when the treatment was done) affected the number of sprouts ($p < 0.001$): when the early PCT was performed later in the growing season, the number of sprouts increased. Dampness increased the number of sprouts one year after the treatments ($p = 0.004$).

Maximum height of sprouts

The fungal treatments did not have a clear effect on the maximum height of sprouts as it had on the mortality

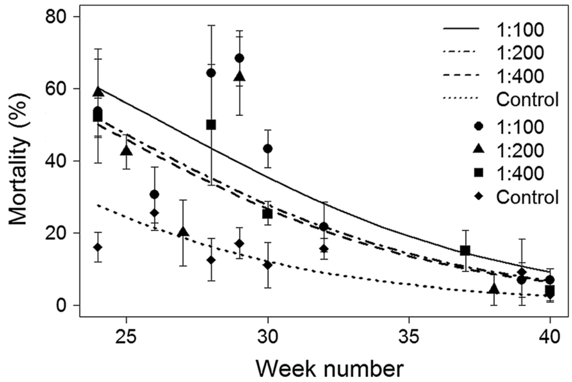

Fig. 2 Mortality of birch stumps in the fungal (*Chondrostereum purpureum* dilutions 1:100, 1:200, and 1:400) and the control treatments (cutting only) three years after the treatments by the timing of the treatment done in 2014 (week number). Values in the curves are based on the generalized linear mixed model (see Table 2). Values in points are average weekly mortality figures based on raw data (mean ± SE)

of stumps and the number of stump sprouts per living stump (Table 4; Fig. 1c). The *C. purpureum* dilution 1:200 decreased ($p = 0.030$) the maximum height of sprouts whereas the dilution 1:100 increased ($p = 0.008$) it. Three years after the early PCT, the maximum height of sprouts was 129.3 cm in the control treatment whereas in the *C. purpureum* dilutions 1:100, 1:200, and 1:400, the maximum heights were 138.8, 118.8, and 122.8 cm, respectively (predicted mean values based on LMM). The maximum height of sprouts increased with the increasing diameter of a stump ($p < 0.001$).

Fruiting bodies

The presence of fruiting bodies on birch stumps treated with *C. purpureum* inoculum decreased with time (year 2015 > 2016 > 2017) (except that dilutions 1:100 and 1:400 had a minor increment from 2015 to 2016) and increased with increasing *C. purpureum* concentration (1:400 < 1:200 < 1:100) (Table 5; Fig. 1d). One year after the treatments, fruiting bodies were present on 17.9, 15.3, and 10.4%, for dilutions 1:100, 1:200, and 1:400, respectively. Three years after the treatments the corresponding figures were only 0.4, 0.2, and 0.9%, respectively. Stump size affected the presence of fruiting bodies so that the presence was higher on larger stumps ($p < 0.001$)

Discussion

Based on our results, mechanized pre-commercial thinning together with the *Chondrostereum purpureum* treatment was more effective compared to the control without fungal treatment (cutting only), resulting in increased stump mortality and decreased number of sprouts. However, the fungal treatment did not have a clear effect on the maximum height of stump sprouts as on stump mortality and the number of stump sprouts. The mortality of birch stumps increased with the increasing concentration of *C. purpureum* inoculum.

This was one of the first studies presenting the results of mechanized biocontrol treatment using *C. purpureum* inoculum. However, mortalities obtained in this study were lower compared to previous studies. In our study, the same *C. purpureum* strain R5 was used as in Hamberg et al. (2015) where the mortality of birch stumps was 78% after three growing seasons. Also, in other studies, the mortality of stumps has been more than 75% for different birch species and the difference between the control and the fungal treatments has been notable (Wall 1990; Roy et al. 2010; Vartiamäki 2009; Lygis et al. 2012).

In earlier studies, the suspension of *C. purpureum* has been inoculated manually, for example via a plastic squirt bottle, to ensure high accuracy (Hamberg et al. 2015; Vartiamäki et al. 2009). Even though during the early PCT operation, an application of *C. purpureum* inoculum on the surface of fresh stump surfaces is technically feasible with Tehojätkä, the accuracy of the spreading mechanism seemed not to be satisfactory. There may have been application malfunctions resulting in the low mortality figures obtained in this study (we do not have any exact data of the accuracy of the Tehojätkä spreading mechanism revealing whether the *C. purpureum* inoculum reached the surface of the stump or not).

Timing of the early PCT application affected stump mortality. The fungal treatment performed in June resulted in promising sprout control efficacy since mortality was relatively high (60%) three years after the treatment. Similar findings of the fungal treatment being more effective in the beginning and the middle of the growing season have previously been reported (Vartiamäki et al. 2009; Lygis et al. 2012).

C. purpureum treatment affects sprouting for a relatively long time as mortality usually increases

Table 3 The effects of (1) the treatments (the control vs. the fungal treatments with the *Chondrostereum purpureum* dilutions 1:100, 1:200 or 1:400), (2) timing of the treatment (the number of calendar week when the treatment was done), (3) dampness of the ground, (4) the number of saplings on the plot before the early pre-commercial thinning, and (5) the diameter of an investigated stump (mm) on the number of sprouts in a birch stump one (2015), two (2016), and three years (2017) after the treatments (generalized linear mixed models)

Explanatory variables	Number of sprouts in 2015 n = 1244				Number of sprouts in 2016 n = 1093				Number of sprouts in 2017 n = 1064			
	Coeff. ± SE	DF	z	p	Coeff. ± SE	DF	z	p	Coeff. ± SE	DF	z	p
Intercept	1.067 ± 0.186	1091	5.743	**< 0.001**	0.917 ± 0.195	940	4.699	**< 0.001**	1.020 ± 0.300	914	3.400	**< 0.001**
C. purpureum treatment												
1:100	− 0.151 ± 0.038	1091	− 4.031	**< 0.001**	− 0.065 ± 0.048	940	− 1.373	0.170	− 0.108 ± 0.054	914	− 1.991	**0.047**
1:200	− 0.081 ± 0.053	1091	− 1.523	0.128	− 0.082 ± 0.054	940	− 1.271	0.204	− 0.055 ± 0.072	914	− 0.763	0.445
1:400	− 0.137 ± 0.036	1091	− 3.792	**< 0.001**	− 0.081 ± 0.045	940	− 1.803	0.071	− 0.121 ± 0.051	914	− 2.342	**0.019**
Timing	0.026 ± 0.005	1091	5.343	**< 0.001**	0.014 ± 0.005	940	3.009	**0.003**	0.005 ± 0.009	914	0.585	0.559
Dampness	− 0.071 ± 0.025	1091	− 2.865	**0.004**	− 0.019 ± 0.028	940	− 0.691	0.490	− 0.059 ± 0.031	914	− 1.873	0.061
Density (saplings per plot)	− 0.015 ± 0.003	1091	− 5.539	**< 0.001**	− 0.018 ± 0.003	940	− 5.725	**< 0.001**	− 0.013 ± 0.003	914	− 4.075	**< 0.001**
Stump diameter (mm)	0.019 ± 0.001	1091	14.722	**< 0.001**	0.018 ± 0.002	940	10.336	**< 0.001**	0.017 ± 0.002	914	8.275	**< 0.001**

Coefficients and their standard errors (SE), degrees of freedom (DF), associated Wald's z-score (= coeff./SE) and significance level p when all coefficients in the models are presented. Statistically significant p values ($p < 0.05$) are in bold. See also Fig. 1b

during the first three years after the treatment (Hamberg et al. 2015; Vartiamäki et al. 2009). This was also shown in our study, as the mortality of stumps increased annually from 2015 to 2017. However, mortality increased for the control as well, but clearly less than in the fungal treatments. Also, the diameter of stumps affected mortality, being lower for smaller stumps as was also shown by Hamberg et al. (2015). Most likely, the increasing stump diameter increased the possibility of *C. purpureum* inoculum to hit the target and improved application accuracy. However, in larger stumps, it has also been observed that after one growing season, mortality does not necessarily increase with increasing stump diameter (the most resistant stumps were 13 cm in diameter), and in some cases, almost all stumps may die regardless of the stump diameter (Hamberg and Hantula 2018).

Even though the fungal treatment did increase the mortality of stumps and decreased the number of sprouts, the maximum height of sprouts was not as clearly affected. Similar findings have been observed in earlier studies (Vartiamäki et al. 2009; Roy et al. 2010; Hamberg et al. 2015). Yet, the diameter of the stump was related both to the number and the maximum height of the sprouts, so that larger stumps had more and taller sprouts (see also Hamberg et al. 2015). Also, density (the number of saplings per plot) was related to the decreasing number of sprouts on a stump, similar to earlier studies (Hamberg et al. 2015). This is mostly due to shading and competition of neighboring trees causing shoot bud death (Jones and Harper 1987). The early PCT, especially together with the fungal treatment, provides more space and light for stumps still living in a stand (Roy et al. 2010). This may have caused even an increase in the number and maximum height of sprouts, as was seen in our study for the maximum height. In our study, the differences in the number of sprouts between treatments were small.

Solutions, such as the fungal treatment, are needed in order to improve the cost-efficiency of young stand management by removing the need for repeated operations. In another method, unwanted deciduous saplings are uprooted mechanically to prevent sprouting (Strandström 2016; Hallongren and Rantala 2013; Saksa et al. 2018). If the later PCT is not needed after uprooting, the costs are at the same level or 6–28% lower than summed costs of two motor-manual operations done by clearing saw, depending on stump

Table 4 The effects of (1) the treatments (the control vs. the fungal treatments with the *Chondrostereum purpureum* dilutions 1:100, 1:200 or 1:400), (2) timing of the treatment (the number of calendar week when the treatment was done), (3) dampness of the ground, (4) the number of saplings on the plot before the early pre-commercial thinning, and (5) the diameter of an investigated stump (mm) on the maximum height of the sprout in birch stumps one (2015), two (2016), and three years (2017) after the treatments (linear mixed models)

Explanatory variables	Max. stump sprout height in 2015 n = 1244				Max. stump sprout height in 2016 n = 1093				Max. stump sprout height in 2017 n = 1064			
	Coeff. ± SE	DF	t	p	Coeff. ± SE	DF	t	p	Coeff. ± SE	DF	t	p
Intercept	56.751 ± 19.326	1091	2.936	**0.003**	76.489 ± 29.867	940	2.561	**0.011**	62.714 ± 36.513	914	1.718	0.086
C. purpureum treatment												
1:100	3.924 ± 1.936	1091	2.026	**0.043**	5.287 ± 2.849	940	1.856	0.064	9.495 ± 3.566	914	2.663	**0.008**
1:200	− 7.168 ± 2.579	1091	− 2.780	**0.006**	− 12.348 ± 4.018	940	− 3.073	**0.002**	− 10.494 ± 4.818	914	− 2.178	**0.030**
1:400	− 3.546 ± 1.912	1091	− 1.854	0.064	− 9.081 ± 2.823	940	− 3.217	**0.001**	− 6.475 ± 3.504	914	− 1.848	0.065
Timing	0.297 ± 0.623	1091	0.477	0.634	1.218 ± 0.966	940	1.261	0.208	2.302 ± 1.178	914	1.955	0.051
Dampness	− 0.631 ± 1.164	1091	− 0.543	0.588	− 2.813 ± 1.722	940	− 1.633	0.103	− 2.857 ± 2.170	914	− 1.317	0.188
Density (saplings per plot)	− 0.205 ± 0.115	1091	− 1.786	0.074	− 0.302 ± 0.187	940	− 1.615	0.107	− 0.332 ± 0.217	914	− 1.525	0.128
Stump diameter (mm)	0.691 ± 0.085	1091	8.177	**< 0.001**	0.894 ± 0.121	940	7.401	**< 0.001**	1.218 ± 0.153	914	7.986	**< 0.001**

Coefficients and their standard errors (SE), degrees of freedom (DF), t value and significance level p when all coefficients in the models are presented. Statistically significant p values ($p < 0.05$) are in bold. See also Fig. 1c

Table 5 The effects of (1) the fungal treatments (*Chondrostereum purpureum* dilutions 1:100, 1:200 or 1:400 as a reference), (2) timing of the treatment (the number of calendar week when the treatment was done), (3) dampness of the ground, (4) the number of saplings on the plot before the early pre-commercial thinning, and (5) the diameter of an investigated stump (mm) on the presence of fruiting bodies in birch stumps (0 = no fruiting bodies, 1 = fruiting bodies found) one (2015), two (2016), and three years (2017) after the treatments (generalized linear mixed models)

Explanatory variables	Presence of fruiting bodies in 2015 n = 907				Presence of fruiting bodies in 2016 n = 898				Presence of fruiting bodies in 2017 n = 907			
	Coeff. ± SE	DF	z	p	Coeff. ± SE	DF	z	p	Coeff. ± SE	DF	z	p
Intercept	2.655 ± 1.592	779	1.668	0.095	− 0.234 ± 1.459	770	− 0.160	0.873	− 1.019 ± 2.508	779	− 0.406	0.685
C. purpureum treatment												
1:100	0.598 ± 0.242	779	2.476	**0.013**	0.552 ± 0.260	770	2.123	**0.034**	− 0.943 ± 0.590	779	− 1.597	0.110
1:200	0.411 ± 0.280	779	1.470	0.142	− 0.152 ± 0.343	770	− 0.443	0.658	− 1.423 ± 0.881	779	− 1.616	0.106
Timing	− 0.198 ± 0.050	779	− 3.949	**< 0.001**	− 0.103 ± 0.041	770	− 2.516	**0.012**	− 0.020 ± 0.058	779	− 0.336	0.737
Dampness	− 0.103 ± 0.143	779	− 0.720	0.472	− 0.075 ± 0.174	770	− 0.428	0.668	− 0.777 ± 0.442	779	− 1.758	0.079
Density (saplings per plot)	0.012 ± 0.014	779	0.905	0.366	0.015 ± 0.018	770	0.801	0.423	− 0.091 ± 0.058	779	− 1.575	0.115
Stump diameter (mm)	0.117 ± 0.014	779	8.281	**< 0.001**	0.122 ± 0.163	770	7.463	**< 0.001**	0.064 ± 0.023	779	2.813	**0.005**

The control treatment (cutting only) was not included in the models. Coefficients and their standard errors (SE), degrees of freedom (DF), associated Wald's z-score (= coeff./SE) and significance level p when all coefficients in the models are presented. Statistically significant p values ($p < 0.05$) are in bold. See also Fig. 1d

diameter of the removed saplings (Strandström 2016). Although no cost-efficiency estimations were included in our study, at least the same cost savings can be expected when the fungal treatment is used to suppress re-sprouting.

In conclusion, it is evident that the fungal treatment decreases stump sprouting. However, potential future implementations of the mechanized fungal treatments require more testing relating to the accuracy and the reliability of applying this method. If repeated cuttings are not needed, cost savings may be achieved.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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