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Research article

Success of mechanical application of *Chondrostereum purpureum* by two different cutting heads

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ABSTRACT

In young boreal forests, naturally grown hardwoods are usually abundant, restricting the growth of cultivated conifers. Cutting only is inefficient due to quick resprouting of hardwoods, and therefore biological sprout control by using a decay fungus *Chondrostereum purpureum* (Pers. Ex Fr.) Pouzar has been investigated to provide a better option for young forest management. Due to the high number of hardwood saplings, fully mechanized methods are needed in the biocontrol instead of manual treatments. We investigated the ability of two different cleaning heads to prevent sprouting of naturally grown silver and downy birches (*Betula pendula* Roth. and *B. pubescens* Ehrh.) in young Norway spruce (*Picea abies* (L.) H. Karst.) dominated forests. Hardwood saplings were cut, and their stumps treated with an inoculum containing hyphae of a decay fungus *C. purpureum*. Three growing seasons after the treatment, birch stump mortality was 80 % and 47 % in the tested cleaning heads. In living stumps, the number of saplings was lower in the fungal treatment than in the cutting only. The diameter and height of stumps, and competition from surrounding saplings and trees regulated the success of the cleaning heads in preventing sprouting. The spreading mechanics of the devices should be developed further to increase their performance.

1. Introduction

In young boreal commercial forests, naturally regenerated hardwood trees compete with cultivated conifers [1]. This competition causes substantial delays for the growth of conifers and decreases the quality of timber [2]. Hardwood saplings are cut to provide more growing space for cultivated tree species. However, cutting only is an inefficient method since hardwood trees can reproduce quickly by resprouting [3,4]. Therefore, hardwood removal should usually be done twice, which increases the costs for the management of young forests [1].

In recent years, the use of biological sprout control has been investigated to provide an alternative, more ecologically sustainable method for the management of young forests and other areas where controlling the growth of fast-growing hardwood species is desirable [4,5]. In this method, inoculum, containing fungal hyphae of a decay fungus *Chondrostereum purpureum* (Pers. Ex Fr.) Pouzar, is spread on freshly cut stumps immediately after cutting. This has been shown to kill saplings and prevent resprouting of hardwood trees better than only cutting, when the fungal treatment has been implemented manually [3,4]. After fungal treatment, high mortality (ca. 80–100 %) was achieved in silver and downy birches (*Betula pendula* Roth. and *B. pubescens* Ehrh.), European aspen (*Populus*

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tremula L.) and grey alder (*Alnus incana* (L.) Moench), and to a lesser degree (ca. 50 %) in rowan (*Sorbus aucuparia* L.) in young Finnish forests [5,6]. The efficacy is based on the quick growth of the fungus within treated stumps resulting in decay and mortality of the stumps and roots – preventing the regrowth of new sprouts [5]. Because the method is based on the biological decay process, the mortality of treated stumps usually increases with time and concentration of fungal inoculum [7].

Chondrostereum purpureum is a common fungal species in the boreal and temperate vegetation zones worldwide [3,5,8]. Thus, it can be considered as an environmentally friendly alternative to synthetic herbicides used in sprout control [3,4,9]. This fungal species is slightly pathogenic and slightly saprotrophic in wounded hardwood species having fresh wood tissue available [10]. For unwounded hardwood trees, it is not harmful. *Chondrostereum purpureum* is not known to cause disease in living conifers, but it can rarely be found on dead conifer wood as a saprophyte [10,11].

In addition to decay, *C. purpureum* causes silver-leaf disease to trees [10]. Infection always starts from a wound in a tree, and the fungus can infect the whole tree: roots, stem and branches. *Chondrostereum purpureum* establishes early in the wood, and mycelium grows more quickly both up and down from the wound than in a lateral direction. Yet the fungus does not thrive if the substrate is already colonized by other fungi. Young fruiting bodies of *C. purpureum* are purple, but they become dingy when they age (Fig. 1). The upper surface of the fruiting body is grey or brown and hairy, and the lower surface is purple or lilac and covered by basidiospores. The fungus has an extraordinary capacity for spore production, especially in autumn after rains. This is the reason why *C. purpureum* is so common and can easily infect wounded trees.

Young coniferous forests may include tens of thousands of naturally grown hardwood saplings per hectare [12,13]. Therefore, it is almost impossible to treat all cut stumps with the fungus manually. Different motor-manual clearing saw options have been tested in biological sprout control, but their ability to restrict the growth of new saplings has been rather low with a maximum birch stump mortality of 36 % [13]. Adding a spreading system to a clearing saw increases its weight, and inoculum needs to be transported to the site in addition to gasoline. Yet this method enables the biocontrol fungus to reach stump surfaces immediately after cutting. The first fully mechanized method tested for biological sprout control was an UW40 cleaning head (Usewood Forest Tec Ltd., Finland) with the ability to spread fungal inoculum immediately after cutting to stump surface. After the fungal treatment, stump mortality was only 16 % [13], and in the subsequent tests, mortality was higher but still relatively low, i.e., 34 % [7,14]. MenSe RP6L cutter (Mense Ltd., Finland) with a simultaneous fungal application was slightly better with 42 % stump mortality [14]. Also, the first tests with a cleaning and spreading head Cutlink (Kesmac Ltd., Finland) yielded rather low overall stump mortality of 40 % after the fungal treatment [12].

Fig. 1. Fruiting bodies of a decay fungus *Chondrostereum purpureum* on a birch stump. Photo: Leena Hamberg.

In these investigations, dilution of inoculum medium varied from 1:10 to 1:100 (from strong to more diluted), and therefore, it is hard to evaluate whether the low efficacy values result from poor efficacy of the devices or excessive dilution or both. Yet a clear benefit of mechanized methods is that cleaning and spreading heads are attached to booms of mini-harvesters or tractors that can carry the weight of inoculum medium, and that an inoculum medium can be immediately applied to freshly cut stump surfaces.

In order to be an effective option, a fully mechanized method should cut hardwood saplings near cultivated conifers without causing harm to the conifers. Saplings should be cut to short stumps with no branches or green leaves that can provide resources for saplings to continue photosynthesizing, since this clearly decreases the efficacy of the fungal treatment [12]. Furthermore, it should be able to spread fungal inoculum on stump surfaces immediately after cutting, since a delay in application decreases the efficacy of the fungus to kill treated stumps [5].

Although the fungal species prevents sprouting when done manually [5], no effective mechanized methods for sprout control are available. Therefore, in this study, we investigated the efficacy of two different cleaning and spreading heads in young Norway spruce dominated forests including a large quantity of silver and downy birches – species that often form the highest proportion of hardwood saplings in young coniferous forests in Finland [7]. We tested whether fully mechanized methods can reach the same stump mortality as that achieved in the most successful sprout control studies done manually [5]. Therefore, we used the same dilution as in the manual treatments (1:10).

2. Material and methods

2.1. Cleaning and spreading heads

Two different cleaning and spreading heads – Cutlink (Kesmac Ltd., Kitee, Finland) and Vihtoja (Aurinkoinen Työ Ltd., Kuhmoinen, Finland) – were tested to find out their efficacy in biological sprout control. The Cutlink cleaning head was designed for clearing all types of small-diameter stems in young stands (Fig. 2a). Cutlink consisted of three rotating spire screws that force the stems of seedlings against fixed blades. The inoculum medium of *C. purpureum* is sprayed simultaneously with the cutting operation onto stump surfaces from the underside of the blades. The tank of inoculum medium was mounted to the cleaning head. A standard fuel pump for cars with 5 bar pressure was used with spray painter nozzles (model 317). Cutlink was attached to the 8.5 m boom produced by Kesla (model 305 T). The base machine was a Valtra N174 tractor with 200 l min^{-1} hydraulic pump. In this construction, the spraying of inoculum medium could be controlled by the operator through the pedal attached to the cabin floor to regulate the amount of medium.

The Vihtoja cleaning head was designed for mechanized early cleaning of young stands. The cogged collecting blades gather the stems of saplings for the fixed cutting blade (Fig. 2b). As the blades are closed, they will remain 15 mm apart from each other vertically, providing more room for inoculum media to be sprayed. In addition, the collecting blades draw the cleaning head forwards from stem to stem. At maximum, the diameter of stems cut may be 15 cm if the cutting is carried out from two directions. The spreading nozzles spray the inoculum medium on the upper surface of the collecting blades. The size of the spraying nozzle was 1.5 mm, and the Droppen pump used in Komatsu Forest harvesters was utilized. The boom, to which the cleaning head was attached, and the tractor that was used as the base machine were similar to the ones that was used in the case of Cutlink.

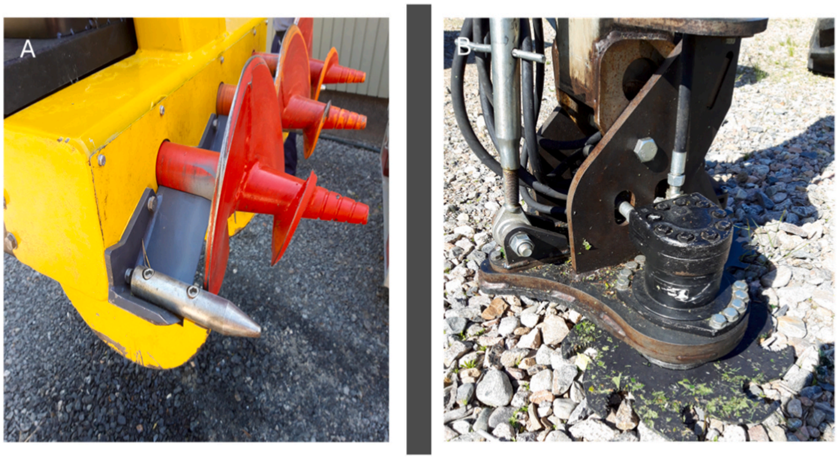

Fig. 2. Cleaning and spreading head options investigated in this study. (A) In the Cutlink head, red rotating spire screws force the stems of seedlings against fixed grey blades, and the inoculum medium of *Chondrostereum purpureum* is sprayed from the underside of the blades. Yellow side walls prevent inoculum from spreading further from the locations it has been spread. (B) In the Vihtoja head, cogged collecting blades gather the stems of saplings for the fixed cutting blade, and the spreading nozzles spray the inoculum medium on the upper surface of the collecting blades. Photos: Leena Hamberg.

2.2. Field experiment

Experiments were performed in forest regeneration areas of spruce (*Picea abies* (L.) H. Karst.), on mineral soils (Table 1). Cutlink sites were established in the eastern part of Finland, in the municipalities of Rääkkylä and Tohmajärvi (mean temperature 3.7 °C and precipitation 57.3 mm per year [15]). Vihtoja sites were located in Jämsä and Juupajoki, in the middle part of Finland (mean temperature 4.7 °C and precipitation 59.3 mm per year [15]). Five sites per device were chosen. Within each site, one cutting only, and one fungal treatment sample plot – each 10 m × 10 m in size – were located next to each other ca. five meters apart. All sites included plenty of naturally grown silver and downy birches (*Betula pendula* and *B. pubescens*). Birch species were not investigated separately since no clear difference in their responses to the fungal treatment has been found [7].

Basal solution of *Chondrostereum purpureum* was prepared in spring 2021 by Verdera Ltd., Finland, a couple of weeks before the treatments, stored in plastic bottles and kept at +4 °C. Fungal strain R5 of Finnish origin was used in the study [5]. The same fungal strain was also used in the most effective manual fungal treatments done previously [5]. The basal solution included 10^6 colony forming units per gram (CFU g^{-1}) [16]. Fungal inoculum was prepared just before the treatments by diluting the basal solution of *C. purpureum* with tap water (1:10). Blue stain was added to the inoculum to observe the success of the devices in spreading inoculum. The viability of the inoculum was tested before and after the fungal treatment by applying it to potato dextrose agar Petri plates. Agar plates were visually inspected to verify the presence of viable *C. purpureum* hyphae indicating that the fungal hyphae were also viable within inoculum.

Cutlink sample plots were treated on the 7th-8th of June 2021, and Vihtoja sample plots on the June 14, 2021. Weather was warm and sunny on each day: in Cutlink sites, mean temperature was 15.6 °C (maximum ca. 22.0 °C), and in Vihtoja sites 15.3 °C (maximum ca. 21.9 °C) [17]. In the cutting only sample plots, naturally grown hardwood trees were cut by using a cleaning head (either Cutlink or Vihtoja) but without spreading fungal inoculum on stump surfaces. In the fungal treatment, hardwood trees were cut similarly as in the cutting only treatment but at the same time, fungal inoculum was spread on fresh stump surfaces. In each Cutlink site, the cutting only sample plot was treated first, and after that the fungal treatment sample plot before moving to the next site. In Vihtoja, all cutting only sample plots were treated first, since the sites were located close to each other. Cut saplings were removed from the sample plots. Time used for treatments was recoded for each sample plot.

After the treatments, we marked and numbered 20 birch stumps, at least 0.5 cm in diameter, within each sample plot (altogether 100 stumps per treatment per device) to be investigated after one, two and three growing seasons. To account for variation in stump size and competition around investigated stumps, we measured the diameter of stumps (mm) at the height of 20 cm, the height of each stump (cm), and counted the number of competing saplings around each investigated stump within a circular sample plot 0.5 m in radius (Table 2). Competing saplings were birches, rowan, Norway spruces or pines (*Pinus sylvestris* L.) with the same age and size as investigated birches. Most of the competing saplings were cut, but some could not be cut in the treatments, and some were intentionally left to form new tree generation. Trees at least 5 cm in diameter at breast height (DBH, at the height of 1.3 m) were measured around each investigated stump within a circular sample plot 10 m in radius. In practice, these trees were located outside of the treated sample plots. The volume of trees per hectare around each stump was calculated by using equations for Norway spruce, Scots pine and silver birch [18].

To evaluate the success of the devices in sprout control, different indicators were used and measured. We investigated whether blue stain could be seen on the surfaces of birch stumps immediately after the treatments to determine whether fungal inoculum was spread successfully on freshly cut stump surfaces. The occurrence of old branches in stumps decreases the efficacy of *C. purpureum* in sprout control [12]. Therefore, we investigated whether old branches were still attached to target stumps after cutting. Damage to all cultivated Norway spruces was investigated (proportion of cut and damaged spruces) within a circular sample plot, 4 m in radius (center point in the middle of a sample plot 10 m × 10 m in size). Also, areas surrounding spruce were investigated within smaller circular sample plots (0.5 m in radius) to determine the occurrence of hardwood saplings that could not be cut in the treatments. After one, two and three growing seasons (in September or late August 2021–2023), we investigated stump mortality (no stump sprouts),

Table 1
Young Norway spruce (*Picea abies*) forests (sites) included in the study, their location, geographical coordinates (WGS84) and year when spruces were planted in the clear-cut areas. Proportion of birches represent the share of silver and downy birch (*Betula pendula* and *B. pubescens*) out of all broadleaved saplings within each site. In the Cutlink site 2, spruces were naturally regenerated, i.e., grown from adjacent mature spruce trees (the site was cut in 2013).

Site	Location	Coordinates	Spruces planted (year)	Proportion of birches (%)
Cutlink				
Site 1	Rääkkylä	N 62°23,287′, E 29°50,406′	2014	95
Site 2	Rääkkylä	N 62°17,991′, E 29°34,570′	–	90
Site 3	Rääkkylä	N 62°18,445′, E 29°24,979′	2014	85
Site 4	Tohmajärvi	N 62°22,085′, E 30°00,769′	2011	45
Site 5	Tohmajärvi	N 62°22,147′, E 30°00,330′	2011	50
Vihtoja				
Site 1	Jämsä	N 61°50,324′, E 24°51,184′	2015	80
Site 2	Jämsä	N 61°50,014′, E 24°51,357′	2015	90
Site 3	Juupajoki	N 61°51,583′, E 24°35,076′	2015	100
Site 4	Juupajoki	N 61°51,574′, E 24°35,227′	2015	100
Site 5	Juupajoki	N 61°51,587′, E 24°35,524′	2015	100

Table 2

Diameter and height of silver and downy birch (*Betula pendula* and *B. pubescens*) stumps, the number of competing saplings and total volume of trees around investigated birch stumps when the cleaning and spreading heads of Cutlink and Vihtoja were used in sprout control. Number of observations (*n*) and mean values with standard deviations (SD) are presented. Minimum and maximum values are provided within the parentheses.

		Stump diameter (mm)	Stump height (cm)	Number of competing saplings around[a]	Total volume of trees (m^3 ha^{-1})
	n	Mean (min-max) ± SD	Mean (min-max) ± SD	Mean (min-max) ± SD	Mean (min-max) ± SD
Cutlink					
Cutting only	100	19.9 (8.0–55.0) ± 8.9	39.2 (20.0–80.0) ±11.9	6.8 (0–25) ± 4.8	7.7 (0–44.3) ± 12.6
Fungal treatment	100	20.6 (8.0–50.0) ± 9.1	39.1 (15.0–72.5) ± 11.0	6.4 (0–22) ± 4.0	18.1 (0–81.7) ± 28.5
Vihtoja					
Cutting only	100	16.5 (6.0–41.0) ± 7.7	35.9 (15.5–64.0) ± 10.9	7.6 (0–40) ± 7.5	0.1 (0–0.8) ± 0.3
Fungal treatment	100	15.6 (6.0–33.0) ± 5.8	36.8 (20.0–73.0) ± 9.5	7.1 (0–27) ± 6.2	1.4 (0–12.4) ± 2.3

[a] Measured within a circular sample plot 0.5 m in radius.

and we recorded the number of stump sprouts and the height (cm) of investigated birches and whether fruiting bodies of *C. purpureum* could be found on investigated stumps. The birch height was measured from soil surface upwards.

2.3. Statistical analyses

Statistical models were used to investigate and compare the efficacy of the cleaning heads in sprout control. The efficacy is defined here as an ability of a cleaning head to kill treated saplings and to prevent sprouting. Since the treatments could not be performed in the same sites, we controlled the variation in sites statistically (see below). Effects on stump mortality, and the number of stump sprouts and the height of birches were investigated separately for each year (2021, 2022 and 2023).

Generalized linear mixed models (GLMMs) with a function *glmer* in the library *lme4* in statistical programme R were used to estimate the mortality models (binomial distribution with a logit link function [19,20]). All stumps were included in the stump mortality models. As a response we had stump mortality (a factor with two levels: 0 = a stump is alive, 1 = a stump is dead). Explanatory variables in the models were 1) clearing and spreading head (a factor with two levels: Cutlink or Vihtoja), 2) treatment (a factor with two levels: 1 = fungal treatment, 2 = cutting only), 3) an interaction term between clearing and spreading head, and the treatment, 4) stump diameter (mm), 5) stump height (cm), 6) competition around each investigated sapling (number of other saplings around, circular sample plot 0.5 m in radius), and 7) volume of trees around each investigated sapling (m^3 ha^{-1}). Explanatory variables 4–7 were included in the models to account for variability within these variables (see Table 2), and because they may affect sprouting. Site was included in the models as a random factor, as saplings within one site are more similar than randomly collected saplings.

Only living stumps were included in stump sprout models. The same explanatory variables – and a random factor – were included in the number of stump sprout models as were included in the mortality models. GLMMs with a function *glmer.nb* in the library *lme4* were used (negative binomial model with a log link function [19,20]).

Birch height models for living stumps were estimated using linear mixed models (LMMs) and function *lme* in the library *nlme* (normal distribution [21]). The height of birches (cm) was as a response variable in the models, but otherwise the same explanatory variables and a random factor were included as in the mortality models.

We checked that the models satisfied assumptions of normality of residuals and whether potential outliers can be found by inspecting diagnostic plots. Function *bootMer* in *lme4* package and package *AICcmodavg* were used when predicted values with standard error of mean values were calculated based on the models [19,22]. Packages *ggplot2* and *gridExtra* were used to draw figures [23,24].

Table 3

Occurrence of blue stain and old branches on investigated birch (*Betula pendula* and *B. pubescens*) stumps, cut and damaged Norway spruces (*Picea abies*), and uncut hardwood saplings around cultivated Norway spruces (%) in Cutlink and Vihtoja sample plots immediately after the treatments. Values are presented for all sample plots except for blue stain that is presented for both the cutting only and the fungal treatment sample plots separately. Number of observations (*n*) per cleaning and spreading head are presented.

Indicator	*n*	Cutlink (%)	Vihtoja (%)
Blue stain on birch stumps			
• Cutting only	100	14[b]	0
• Fungal treatment	100	87	94
Old branches in birch stumps	200	4	28
Cut Norway spruces	10[a]	1	14
Damaged Norway spruces	10[a]	5	4
Uncut hardwood saplings around Norway spruces	10[a]	45	28

[a] Proportion of investigated spruces within each sample plot was as an observational unit.

[b] Traces of blue stain from the Cutlink cleaning and spreading head (all cutting only plots could not be treated before the fungal treatment plots).

3. Results

3.1. Performance of devices

Treatment time per sample plot (10 m × 10 m in size) was ca. 40 and 14 min for Cutlink and Vihtoja, respectively. In the Cutlink sample plots, there were no interruptions after the first fungal treatment sample plot, where nozzles should be replaced due to clogging. In each Vihtoja site (except one), the device had to be cleaned at least once since it got stuck by cut saplings. Cutlink used ca. 6.55 L and Vihtoja 3.44 L fungal inoculum per fungal treatment sample plot.

Immediately after the fungal treatments, blue stain was observed frequently on birch stumps treated by Cutlink and Vihtoja (Table 3). Old branches and unintentionally cut Norway spruces were found more frequently in Vihtoja sample plots relative to those found in Cutlink plots, whereas uncut hardwood saplings were more frequent in close proximity to cultivated Norway spruces in Cutlink versus Vihtoja sample plots.

3.2. Occurrence of fruiting bodies

No fruiting bodies were found before the treatments. In the fungal treatment, fruiting bodies of *C. purpureum* were observed already after the first growing season (Table 4). They were more frequent in Cutlink than Vihtoja sites. Fruiting bodies were most frequent after the second growing season, and in the last inventory they could be found only on some stumps. In the cutting only, fruiting bodies were found infrequently.

In the fungal treatment, the occurrence of fruiting bodies seemed to relate to stump mortality in the first two study years (Table 5). In stumps without visible fruiting bodies, stump mortality increased from the first to the last inventory year. The occurrence of fruiting bodies seemed to be associated with larger and higher stumps but with lower competition by the surrounding saplings and trees.

3.3. Effects of treatments on sprouting

Birch stump mortality was statistically significantly higher in the fungal treatment performed by the Cutlink cleaning and spreading head than that by the Vihtoja head ($p < 0.018$, Table 6, Fig. 3a). Furthermore, mortality was higher in the fungal than in the cutting only treatment of Cutlink throughout the investigated years ($p < 0.001$), whereas for Vihtoja, this difference was not as pronounced. In the fungal treatment of Cutlink, mortality of stumps was already 39 % after the first growing season in 2021, and it increased to 79 % after the second growing season and stayed at that level also in the last inventory in 2023. In the cutting only treatment, mortality stayed at a low level. In Vihtoja plots, stump mortality was ca. 8, 39 and 47 % in the fungal treatment after one, two and three growing seasons, whereas in the cutting only, stump mortality stayed at a low level throughout the years.

In the fungal treatment, there were no differences in the number of stump sprouts and in the height of birches between the cleaning and spreading heads Cutlink and Vihtoja ($p > 0.100$, Table 6, Fig. 3b). In Cutlink, the number of stump sprouts was lower in the fungal than in the cutting only treatment after the first and second growing seasons ($p < 0.050$). In Vihtoja, the number of stump sprouts was only slightly lower in the fungal treatment than in the cutting only treatment. In Cutlink, birches were shorter in the fungal than in the cutting only treatment after the second and third growing season ($p = 0.031$ and 0.060, difference in height was 15 and 22 cm, respectively) whereas in Vihtoja, only small differences between the treatments were found (Fig. 3c).

3.4. Effects of stump diameter and height, and growing space

Large birch stumps had a higher mortality rate than small ones ($p = 0.015$ three growing seasons after the treatments, Table 6). When stump diameter increased from less than 10 to 55 mm, mortality increased from 70 to 95 % (Fig. 4a). In large stumps, there were also more stump sprouts than in small stumps ($p = 0.002$ three growing seasons after the treatments). When stump diameter increased from less than 10 to 55 mm, the number of stump sprouts increased from 2 to 4 (Fig. 4b). Birches were almost two times taller in large than small stumps ($p < 0.001$, Fig. 4c). Stump height was not associated to stump mortality, but an increase in stump height was associated negatively with the number of stump sprouts ($p = 0.072$), and positively with the height of birches ($p = 0.044$). When the height of stump increased from 15 to 80 cm, the height of birches increased from 105 to 140 cm (Fig. 4d).

Table 4
Occurrence of fruiting bodies in treated birch (*Betula pendula* and *B. pubescens*) stumps in different treatments performed by the cleaning and spreading heads of Cutlink and Vihtoja one, two and three growing seasons after the treatments (2021, 2022 and 2023, respectively).

		Occurrence of fruiting bodies (%)		
	n	2021	2022	2023
Cutlink				
Cutting only	100	0	7	2
Fungal treatment	100	45	68	16
Vihtoja				
Cutting only	100	0	1	1
Fungal treatment	100	12	46	15

Table 5

Associations between the occurrence of fruiting bodies of a decay fungus *Chondrostereum purpureum* on birch (*Betula pendula* and *B. pubescens*) stumps and variables measured from the study sites two growing seasons after the fungal treatment (year 2022). Treatments were performed by the cleaning and spreading heads of Cutlink and Vihtoja.

Fruiting bodies	Stump mortality (%)			Stump diameter (mm)	Stump height (cm)	Competition[a]	Volume of trees (m^3 ha^{-1})
	2021	2022	2023				
Cutlink							
No	18	50	77	16.4	37.5	6.8	23.1
Yes	64	84	63	22.6	39.9	6.2	15.7
Vihtoja							
No	3	17	25	14.1	35.7	8.0	1.4
Yes	42	72	63	17.2	38.1	6.0	1.3

[a] Number of other saplings around an investigated birch stump within a circular sample plot 0.5 m in radius.

An increase in competition around investigated saplings decreased stump mortality ($p = 0.060$) and decreased the number of stump sprouts and the height of birches ($p = 0.063$ and $p = 0.003$, respectively, Table 6). When the number of other saplings around an investigated birch stump increased from 0 to 40, the height of birches decreased from 95 to 65 cm (Fig. 4e). An increase in the volume of trees was negatively associated with stump mortality ($p = 0.064$) and the number of stump sprouts ($p = 0.009$). When the volume of trees increased from 0 to 80 m^2 ha^{-1}, the number of stump sprouts decreased from 7 to 5 (Fig. 4f).

4. Discussion

4.1. Biocontrol efficacy

Our results showed that biological sprout control can be performed effectively by using mechanized application. The treatment by the cleaning and spreading head Cutlink yielded high stump mortality, ca. 80 % – similar to the mortality rate found with manual treatments in previous studies [e.g., 4,25]. The cleaning and spreading head Vihtoja also performed well since stump mortality was 47 %, but there was large variation in mortality in different sample plots (25–70 %), possibly because saplings blocked the blades more in some sample plots than others. This may be one reason why the stump mortality remained at lower level than in the Cutlink sample plots.

The difference in the way inoculum was spread on stump surfaces may partly explain differences in efficacy between Vihtoja and Cutlink. In the case of Vihtoja, inoculum is spread from upper side of the cutting blade similarly to UW40 [14] – both yielding rather low final efficacy in causing tree mortality with the fungal treatment. In the case of Cutlink, inoculum is squirted below the cutting blade and side walls of the device restrict the area inoculum can land after spread from nozzles. This feature may help in concentrating inoculum on freshly cut stump surfaces.

The benefit of using a spreading device attached to the cleaning head enables spreading fungal inoculum immediately to the fresh stump surface which is one of the most important factors affecting the sprout control efficacy [5]. This is beneficial when there are tens of thousands of hardwood saplings to be cut and treated within a forest site.

4.1.1. Cutlink

Our results revealed that the cleaning head of Cutlink was more effective than the Vihtoja head in biological sprout control. The most noticeable finding was that stump mortality was high, ca. 40 %, already after the first growing season (three months after the treatment). This was similar to the mortality of the most successful fungal treatments performed manually [6]. After the second growing season, mortality increased to ca. 80 %.

In the spreading system of the Cutlink cleaning head, the amount of inoculum could not be adjusted to a specific level. Inoculum was spread only when the operator used a pedal manually. Therefore, a high amount of inoculum was used in this study (655 l ha^{-1}). In earlier experiments, the consumption has been lower: in the case of the UW40 cleaning head, 399 l ha^{-1}, and in the case of the Cutlink head, 580 l ha^{-1} (see Table 7, [12,13]).

Inoculum used in this study was diluted 1:10 with tap water, and therefore the amount of basal solution used, 65.5 l ha^{-1}, was high (Table 7). However, the structure of the cleaning head of Cutlink seems to work. In the previous Cutlink test, where 1:100 dilution was used with a consumption of basal solution 5.8 l ha^{-1}, stump mortality was ca. 60 % after three growing seasons when no old branches were left on stumps after cutting (Table 7, [12]). It seems that the side walls surrounding rotating screws restricts inoculum to a limited area, thus forcing it to land on stump surfaces that were freshly exposed.

The 1:10 dilution and high consumption of basal solution yielded very quick and effective sprout control. Such an excessive use of basal dilution is not needed in practice. Even moderate sprout control efficacy may be enough to avoid the second sprout control round. In the previous study [7], the fungal treatment implemented through a cleaning head UW40, the stump mortality was only 34 % three growing seasons after the fungal treatment. Still, after couple of years, it seemed that in the sites treated by using the UW40 [7], there is no need to repeat sprout control since cultivated conifers had outcompeted hardwood saplings and started to grow better than conifers in the cutting only sample plots [25]. However, the results of the present study show that the Cutlink cleaning head used in this study may provide better growing space for cultivated conifers and better economical revenue in the future than other spreading heads tested

Table 6

Results of the experiment when the cleaning and spreading heads of Cutlink and Vihtoja were used to control the sprouting of silver and downy birches (*Betula pendula* and *B. pubescens*). Generalized linear and linear mixed model results after each growing season are presented, except for the mortality model after the first growing season (mortality was too low for modelling). Mortality models include all investigated stumps, and stump sprout and birch height models living stumps only. Model coefficients (Coeff.) and confidential intervals (CI) are in bold when $p < 0.05$ and underlined when $0.05 \leq p < 0.10$. See Fig. 3.

Model		Intercept	Spreading head Vihtoja[a]	Cutting only[b]	Spreading head Vihtoja:Cutting only[c]	Stump diameter (mm)	Stump height (cm)	Competition[d]	Volume of trees (m^3 ha^{-1})
	n	Coeff. (CI)	Coeff. (CI)	Coeff. (CI)	Coeff. (CI)	Coeff. (CI)	Coeff. (CI)	Coeff. (CI)	Coeff. (CI)
Mortality									
After 1. season	400	–	–	–	–	–	–	–	–
After 2. season	400	1.778 (1.797)	**−1.774 (1.262)**	**−3.938 (1.082)**	**1.426 (1.362)**	0.035 (0.039)	−0.013 (0.027)	−0.059 (0.061)	−0.023 (0.024)
After 3. season	398	0.609 (1.633)	**−1.457 (1.192)**	**−3.224 (0.892)**	0.943 (1.162)	**0.045 (0.037)**	−0.002 (0.025)	0.011 (0.051)	−0.014 (0.022)
Number of stump sprouts									
After 1. season	348	**1.797 (0.304)**	0.070 (0.178)	**0.192 (0.167)**	−0.111 (0.220)	**0.017 (0.008)**	−0.003 (0.004)	−0.005 (0.010)	**−0.006 (0.004)**
After 2. season	268	**1.207 (0.437)**	0.241 (0.323)	**0.273 (0.272)**	−0.100 (0.325)	0.007 (0.010)	−0.002 (0.006)	−0.011 (0.012)	<0.001 (0.006)
After 3. season	250	**0.850 (0.472)**	0.139 (0.341)	0.168 (0.310)	0.085 (0.370)	**0.015 (0.010)**	−0.006 (0.008)	−0.010 (0.014)	−0.003 (0.006)
Height of birches[e]									
After 1. season	348	**3.508 (0.265)**	−0.015 (0.247)	0.089 (0.118)	−0.077 (0.153)	**0.009 (0.006)**	**0.006 (0.004)**	−0.007 (0.006)	0.002 (0.004)
After 2. season	268	**4.205 (0.274)**	−0.029 (0.253)	**0.163 (0.147)**	−0.097 (0.178)	**0.009 (0.006)**	**0.005 (0.004)**	**−0.010 (0.006)**	0.001 (0.004)
After 3. season	250	**4.388 (0.325)**	0.011 (0.280)	0.174 (0.180)	−0.131 (0.220)	**0.014 (0.006)**	**0.004 (0.004)**	−0.007 (0.010)	−0.001 (0.006)

[a] Performance of the cleaning and spreading head of Vihtoja compared to the cleaning and spreading head Cutlink in the fungal treatment.

[b] Difference between the fungal treatment and the cutting only in Cutlink.

[c] Interaction term between the cleaning and spreading heads (Cutlink or Vihtoja) and the treatments (fungal treatment or cutting only).

[d] Number of other saplings around an investigated birch stump within a circular sample plot 0.5 m in radius.

[e] Responses were log transformed, i.e., results are in log scale.

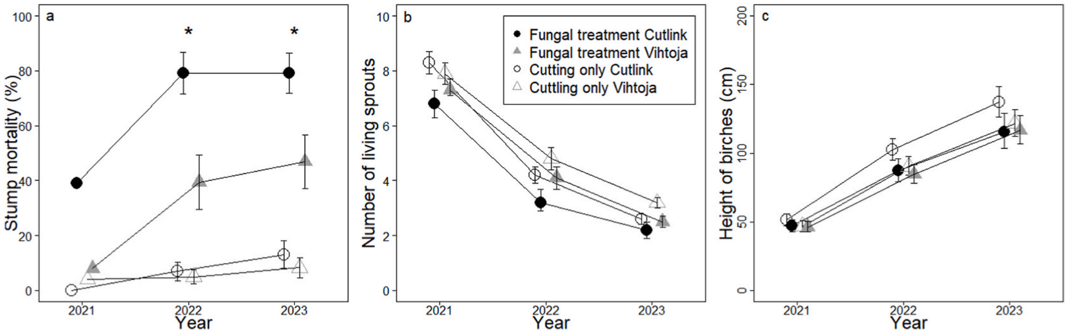

Fig. 3. Stump mortality (a), and the number of stump sprouts (b) and the height of young birches (*Betula pendula* and *B. pubescens*) (c) after they were cut or cut and treated with the decay fungus *Chondrostereum purpureum* by using the cleaning and spreading head of Cutlink or Vihtoja. Results are shown one, two and three growing seasons after the treatments (2021, 2022, 2023, respectively). Predicted values and standard errors of means based on the estimated generalized linear or linear mixed models are presented, except for mortality in 2021 since no model could be estimated due to low mortality. Asterisks show statistically significant differences ($p < 0.05$) between the cleaning and spreading head of Cutlink or Vihtoja in the fungal treatment. See Table 6.

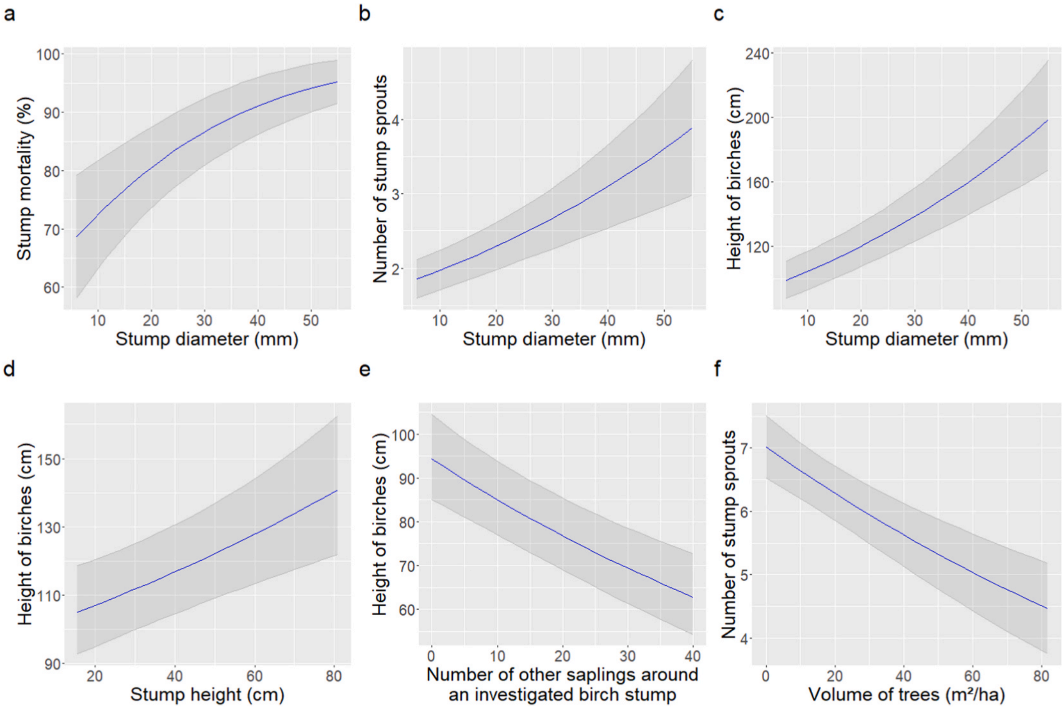

Fig. 4. Associations between (a) stump diameter and mortality ($n = 400$), (b) stump diameter and the number of stump sprouts ($n = 250$), (c) stump diameter and the height of birches ($n = 250$), (d) stump height and the height of birches ($n = 250$), (e) the number of other saplings around an investigated sapling and the height of birches ($n = 268$), and (f) the volume of trees and the number of stump sprouts ($n = 348$). Predictions are based on the estimated generalized or linear mixed models. Predicted values were calculated for the fungal treatment done by the cleaning and spreading head Cutlink. Predicted values with the standard errors of means are presented for the data collected three (a–d), two (e) or one (f) growing seasons after the treatment. See Table 6.

so far. However, in order to be a cost-efficient method, the efficacy of Cutlink should be verified by using an automated spreading system with a weaker solution of 1:100 targeting 300 L consumption (i.e., 3 L basal solution) per hectare.

Cutlink treatments took almost three times longer than Vihtoja treatments (Table 7). The operator explained that it was hard to see properly from a high tractor where the cultivated spruces were located. The operator was also very careful, and therefore the occurrence of old branches in investigated birch stumps, and the proportion of cut cultivated Norway spruces were low, but at the same time, this increased time used to treat the sample plots. Thus, balance between the use of time and efficacy should be found. Otherwise, the treatment is not cost efficient.

Table 7
Consumption of diluted fungal inoculum and basal solution (*Chondrostereum purpureum*), time used for the treatment, and stump mortality of silver and downy birches (*Betula pendula* and *B. pubescens*) after the fungal treatment for different cleaning heads equipped with spreading application. Note that stump mortality was investigated two to four growing seasons after the treatment.

	Dilution	Consumption (l/ha)	Basal solution used (l/ha)	Time used for the fungal treatment (h/ha)	Stump mortality (%)	Growing seasons
Tehojätkä UW40[a]	1:10	399.4	39.9	29.0	16	2
Tehojätkä UW40[b]	1:100	–	–	–	34	3
Tehojätkä UW40[c]	1:100	–	–	–	34	4
Mense RP6L[c]	1:100	–	–	–	42	4
Cutlink[d]	1:100	580.0	5.8	–	40	3
Old branches		–	–	–	18	3
No old branches		–	–	–	59	3
Cutlink[e]	1:10	655.0	65.5	65.0	79	3
Vihtoja[e]	1:10	344.0	34.4	25.0	47	3

[a] Based on the study by Laine et al. [13].
[b] Based on the study by Laine et al. [7].
[c] Based on the study by Laine et al. [14].
[d] Based on the study by Hamberg et al. [12].
[e] This study.

4.1.2. Vihtoja

In the fungal treatment of Vihtoja, stump mortality was low after the first growing season, but one year later, it increased to 40 %. However, interestingly, mortality did not increase much during the last study year, and remained at rather low level (47 %), similar to that observed in the Mense RP6L cleaning head and in the first Cutlink tests [12,14].

Blue stain (indication of the success in spreading fungal inoculum on stump surfaces) was found frequently on the treated stumps, and therefore, we expected to see higher stump mortality after the third growing season. Stump surfaces were partly stained by oil used in the blades of the Vihtoja. Therefore, the results regarding the frequency of blue stained stumps should be interpreted cautiously. Low occurrence of fruiting bodies in stumps seems to reveal that the fungal treatment was not as effective as it was in the Cutlink treatment. However, the consumption of inoculum was almost half of that used in the Cutlink treatment, i.e., 344 l ha^{-1}, since the amount of inoculum could be adjusted before the treatments.

Treatments were done quickly by the Vihtoja cleaning and spreading head, ca. within 14 min. This may explain why old branches were found frequently on cut stumps. Old branches have a clear decreasing effect on stump mortality [12]. It has been suggested that photosynthesis in old living branches could strengthen treated stumps against *C. purpureum*, and therefore, stump mortality is low. More than 10 % of the cultivated Norway spruces were accidently cut. The Vihtoja cleaning head swung unintentionally during the treatments, which may explain this result. Another deficiency related to its performance in cutting was that cut saplings often blocked the blades and thus prevented them from rotating which interrupted the work regularly. However, when these deficiencies are fixed and a better spreading method added, the device may show better efficacy.

4.2. Number of stump sprouts and birch height

The fungal treatments done by using the Cutlink and Vihtoja cleaning and spreading heads decreased the number of sprouts and the height of birches in living stumps. Decrease in sprout numbers has been observed also in earlier studies but seldom in birch height [e.g., 4,6,25]. Statistically significant difference in birch height was observed in the Cutlink sample plots. This may be because fungal inoculum was successfully spread on stump surfaces, and therefore, the height of birches was significantly lower than in the cutting only treatment.

The diameter and height of stumps, and competition around investigated saplings had pronounced effects on the mortality of stumps, the number of stump sprouts and the height of birches. In both the Cutlink and Vihtoja sites, the larger stump diameter was the more stump sprouts and taller birches were found, similarly as has been observed in earlier studies [7,26]. Taller stumps had fewer sprouts, but the birches were taller. Taller stumps may include more old branches (see Ref. [12]) which may diminish the growth of new sprouts. Occurrence of fruiting bodies indicates stump mortality [this study, [27]]. Interestingly, in the present study, those birch stumps that had fruiting bodies were higher than stumps where fruiting bodies could not be found after the second growing season. This result reveals that low stump height may not be as important factor as earlier considered for successful sprout control [12].

Surprisingly, competition from surrounding saplings and trees located outside the sample plots was negatively associated with stump mortality. Competition usually decreases the ability of birches to cope with fungal infections [5]. This competition between plants also negatively affected the occurrence of fruiting bodies of *C. purpureum*, suggesting that environmental conditions influence the ability of the fungal species to spread within stumps, to produce fruiting bodies and finally to kill the stump. Yet as expected, competition from surrounding saplings decreased both the number of sprouts and the height of birches (see also [7,28]).

4.3. Implications for forest management

This study showed that sprout control by using a decay fungus *C. purpureum* is a promising method in young forest management when mechanized methods are used. An especially important feature is the ability of the cleaning and spreading heads to spread fungal inoculum on fresh stump surfaces immediately after cutting. This increases the probability of the fungus infecting the treated stump and killing it. Yet, in the future, the cost-efficiency of the heads should be investigated to find out the most optimal consumption of an inoculum medium in relation to stump mortality and spruce growth. In the fungal treatment, the effects of additional operations on worker productivity should also be investigated [26]. Also, time used for the fungal treatment should be adjusted to achieve the best cost-efficiency. So far, no commercial cleaning and spreading heads nor fungal inoculum are available in Europe, and therefore, such development is needed so that this method can be used in young forest management.

5. Conclusions

This study showed that biological sprout control by using a decay fungus *C. purpureum* can be implemented effectively in a mechanized method, yielding 80 % stump mortality in treated silver and downy birch (*Betula pendula* and *B. pubescens*) thickets within young Norway spruce (*Picea abies*) forests. In particular, the Cutlink cleaning head could spread fungal inoculum more effectively than the Vihtoja head on stump surfaces. Future development should include adjustment of the amount of fungal inoculum and time used for the treatment. At the same time, the final stump mortality and spruce productivity should be taken into account in order to be a cost-efficient option in young stand management.

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CRediT authorship contribution statement

Leena Hamberg: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ville Kankaanhuhta:** Writing – review & editing, Writing – original draft, Resources, Project administration, Funding acquisition, Conceptualization.

Data availability statement

Research data can be found in the Dryad database https://doi.org/10.5061/dryad.vt4b8gv0s.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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