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Treatment of *Picea abies* and *Pinus sylvestris* Stumps with Urea and *Phlebiopsis gigantea* for Control of *Heterobasidion*

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Abstract: *Heterobasidion* spp. root rot causes severe damage to forests throughout the northern temperate zone. In order to prevent *Heterobasidion* infection in summertime cuttings, stumps can be treated with urea or *Phlebiopsis gigantea*. In this study, the consumption of stump treatment materials and the quality of stump treatment work were investigated. A total of 46 harvesters were examined in May–November 2016 in Finland. The average stem size of softwood removal and softwood removal per hectare explained the consumption of stump treatment material. The quality of stump treatment work was good in the study. The best coverage was achieved with the stumps of 20–39 cm diameter at stump height (d_0). It can be recommended that the harvester operator self-monitors and actively controls his/her treatment result in cutting work and sets the stump treatment equipment in a harvester if needed. The results also suggested that when cutting mostly small- and medium-diameter ($d_0 \leq 39$ cm) conifers, the stump treatment guide bars with relatively few (<18) open holes are used, and at the harvesting sites of large-diameter trees, the guide bars with a relatively great (>27) number of open holes are applied.

Keywords: root rot; biotic factor; forest health; tree growth; stump protection; wood harvesting

1. Introduction

The root and butt rot fungus *Heterobasidion annosum* sensu lato (Fr.) Bref. is widely distributed in coniferous forests of the Northern Hemisphere, especially in Europe, North America, Russia, China and Japan [1]. There are three native *Heterobasidion annosum* species in Europe: (1) *Heterobasidion annosum sensu stricto* (*s.s.*) has a wide range of hosts and causes mortality to pines (*Pinus* spp.), especially Scots pine (*Pinus sylvestris* L.), and root and butt rot to Norway spruce (*Picea abies* (L.) Karst.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.). (2) *Heterobasidion parviporum* Niemelä and Korhonen causes root and butt rot to Norway spruce, and (3) *Heterobasidion abietinum* Niemelä and Korhonen causes disease to several Abies species in southern Europe [1,2].

Heterobasidion spp. root rot causes severe damage to forests throughout the northern temperate zone: In the European Union, annual losses attributed to growth reduction and degradation of wood are estimated at approximately €800 million [3,4]. In Finland, the damage caused by *Heterobasidion* spp. root rot for Norway spruce has been estimated to be approximately €40 million year^{-1} and some €5 million year^{-1} for Scots pine [5,6]. Climate change is thought to favor the living conditions and the spread of *Heterobasidion* spp. root rot [7,8]. In addition, shortening of winter lengthens the infection time of the spores of *Heterobasidion* spp. root rot and increases the proportion of summertime cuttings. Consequently, the prevention of *Heterobasidion* spp. root rot, as well as the obstruction of the spread of

Heterobasidion spp. root rot can be considered among the most significant challenges facing the modern forestry sector [9].

The pathogen of *Heterobasidion* spp. root rot infects fresh stumps after thinning and clear-cutting operations and spreads to neighboring trees via root-to-root contacts. In order to prevent *Heterobasidion* spp. root rot infection in summertime cuttings, stumps can be treated with urea that increases the pH of the stump surface, making it unsuitable for spore germination and preventing *Heterobasidion* spp. root rot from getting deeper into coniferous wood [10–16]. Alternatively, the stump surface can be covered with large amounts of the antagonistic fungus *Phlebiopsis gigantea* (Fr.) Julich, to prevent any pathogen spores that subsequently land on the stump surface to germinate [17–24].

According to the Plant Protection Product Register [25], four urea products are used in Finland: Moto-urea (license number: 3069), PS-kantosuoja-2 (1949), Teknokem Kantosuoja (3124) and Urea-kantokate (2928). Currently, the trademarks of biological control agents are Rotstop® (1648) and Rotstop® SC (2939) on the market in Finland [25]. The stump treatment areas have been annually 45,000–117,000 hectares in the 2010s in Finland [26,27].

The stump treatment with both urea and Rotstop reduces the basidiospore infection of *Heterobasidion* spp. root rot by an average of over 90% (cf. [28–33]). Achieving good pesticide efficacy requires careful treatment in order to wet the surface of the whole stump by spreading [31,34–37]. The effectiveness of prevention is reduced in relation to the uncovered area on the surface of the stump. Thus, the good coverage of stumps is an absolute prerequisite for high-quality stump treatment work [9].

According to the Government decree on the prevention of damage by *Heterobasidion* spp. root rot [38], *Heterobasidion* spp. root rot has to be prevented in mineral soils when the share of Norway spruce and Scots pine (i.e., conifers) of the total initial stand volume is more than 50% before wood harvesting operation and in peatland forests if the share of Norway spruce of the total initial stand volume is more than 50% before logging operation in Finland. In accordance with the Forest damage prevention act [39], the prevention of *Heterobasidion* spp. root rot must be carried out in thinnings and regeneration fellings in the risk zone of *Heterobasidion* spp. root rot between the beginning of May and the end of November in southern and central Finland (see Figure 1). Furthermore, the stump treatment has to be done for all conifer tree stumps of more than 10 cm in stump diameter (d_0) and the stump treatment material must cover at least 85% of the surface of each stump being treated [38]. Stump treatment is not required if any of the following conditions are met: (1) thermal growth season (i.e., the snow has melted in the opening places and the average daily air temperature has permanently raised more than +5 °C) has not started, (2) the air temperature of the wood harvesting day is below 0 °C, (3) there is a uniform snow cover on the ground, or (4) the lowest air temperature in the municipality of the harvesting site has been below 10 °C during the three-week period preceding the wood harvesting operation [38].

The stump treatment material is applied on the stump surface of coniferous trees using the harvester equipped with stump treatment facilities. Nowadays, the volumes of storage tanks in harvesters for the stump treatment material are typically around 100–150 dm^3. The stump treatment material is pumped from the storage tank of a harvester to the harvester head whence it is discharged onto the stump surface of the conifer tree via holes spaced along the underside of the guide bar. There are pre-drilled (but not totally open) holes at a distance of 12–13 mm in the new stump treatment guide bar. Before bringing a new guide bar into use, the desired number of holes in the guide bar is opened by drilling with a 1.5 mm drill bit or hitting with a small spike. The number of pre-drilled holes in a guide bar depends on the length of the guide bar. For instance, the stump treatment guide bar of 75 cm in length has around 40 pre-drilled holes. When the length of the guide bar is 60 cm, the number of pre-drilled holes is typically less than 30 holes, and when the length of the guide bar is 90 cm, there are more than 50 holes in the guide bar.

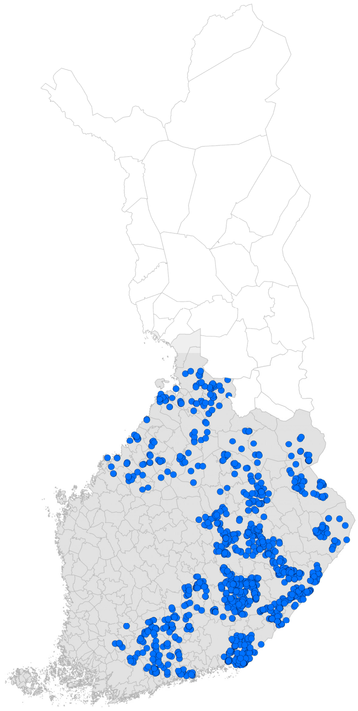

Figure 1. The distribution of harvesting sites (n = 1831) in the study. The gray color in the map displays the risk zone of the spread of *Heterobasidion* spp. root rot in Finland [39].

By means of the number and location of open holes in a guide bar and control systems for the treatment equipment of a harvester, the harvester operator can control the spraying of treatment material. Due to the variation in the stem size of removal in the forest stand, with smaller trees, some of the treatment materials often pass through the stump surface because the number of open holes in the guide bar usually has to be dimensioned according to the larger-diameter trees at a harvesting site [40].

There is only one report published in which the hectare-based consumption of stump treatment materials has been presented in Finland [41]. Mäkelä [41] estimated that the consumption of stump treatment material is around 40–60 $dm^3\ ha^{-1}$ in thinnings and approximately 50–90 $dm^3\ ha^{-1}$ in final cuttings. Mäkelä [41] forecasted his consumption figures of treatment product based on the number of stems cut and the total area of stump ends treated. The sales package labels of urea treatment products on the market promise that the consumption is 1.5–2.0 $dm^3\ m^{-2}$ of stump surface treated [42–45]. On the other hand, the sales package labels of Rotstop® and Rotstop® SC products give the following adequacy estimates: 0.33–0.68 $dm^3\ m^{-3}$ of softwood harvested or 25–150 $dm^3\ ha^{-1}$ [46,47].

Unfortunately, the current consumption figures presented in literature are not precise for using chemical and biological controls against *Heterobasidion* spp. root rot. Therefore, Stora Enso Wood Supply Finland (WSF) and the University of Eastern Finland carried out the study on stump treatment against *Heterobasidion* spp. root rot in Finland. The aims of the study were to produce more accurate information about stump treatment and to clarify the following:

- the consumption of stump treatment materials and
- the quality of stump treatment work (i.e., the coverage of stumps treated).

2. Materials and Methods

2.1. Data on the Consumption of Stump Treatment Materials

The consumption of stump treatment materials in 46 harvesters was collected in May–November 2016 in Finland at the harvesting sites of Stora Enso WSF. There were 25 Ponsse (Beaver, Ergo, Fox, Scorpion and Scorpion King), 14 John Deere (1070D, 1070E, 1170E, 1270D, 1270E and 1270G), 5 Komatsu/Valmet (901, 901TX, 901TX.1, 911.4 and 911.5), 1 Logset (8H GTE) and 1 ProSilva (810) harvesters in the study. Since the harvesters of the study did not have the technology to perform automatic measuring of the consumption of stump treatment material, the consumption of treatment materials was manually measured by the harvester operators with recording forms. The measurement methods used by the operator differed between the harvesters of the study: Some operators measured the consumption of treatment materials when filling up the storage tank of a harvester by measuring the amount of substance added by a flow meter or by the signs in the storage tank. Some operators used a dipstick. All methods aimed at a minimum accuracy of five dm^3 $measurement^{-1}$.

There were 40 harvesters which used only urea as a stump treatment product in the study and only Rotstop® SC suspension was used in four harvesters. Furthermore, both urea and Rotstop® SC were used in two harvesters. In total, the stump treatment materials were measured to spread 309,427 dm^3 during the study period. Of this volume, three urea products (i.e., Moto-urea, PS-kantosuoja-2 and Teknokem Kantosuoja) accounted for 272,754 dm^3 (88.1%) and the share of Rotstop® SC was 36,673 dm^3 (11.9%).

The harvesting site-specific harvester production data (i.e., prd files [48]) provided the stand information, which was collected from the enterprise resource planning (ERP) system of Stora Enso WSF. The prd files were received for a total of 1831 harvesting sites. The prd files included the volume, number and average stem size of removal by tree species, as well as a cutting method. In addition, the hectare-based consumption figures for harvesting sites were calculated using the harvesting instruction maps of logging areas. If there was some indication of an abnormality in the implementation of the harvesting site cut in the prd file, the hectare-based consumption was not calculated for such harvesting sites. The geographical distribution of harvesting sites in the study is illustrated in Figure 1.

The total removal volume of softwood trees at the harvesting sites of the study was 587,120 m^3 solid over the bark (later only: m^3). The share of Norway spruce removal was 320,257 m^3 (54.5%) and the share of Scots pine was 266,863 m^3 (45.5%), and a total of 2,413,256 softwood trees were cut. Most of the softwood volume was cut from clear cuttings (59.3%) and later thinnings (27.9%). From first thinnings, softwood was felled 5.8% of the total softwood volume, 4.5% from seeding fellings and 2.3% from other fellings (i.e., cuttings of hold-over stands, shelterwood fellings and special cuttings).

GB, Iggesund, John Deere, Komatsu, Oregon and Ponsse guide bars were used in the harvesters of the study. The most commonly used guide bar trademark was the Iggesund by which in total 51.9% of the total softwood volume harvested was cut. The share of GB guide bars was 23.8% and with Oregon bars it was 15.3% of the total softwood removal cut in the study. The length of guide bars varied between 50 and 95 cm. From the total softwood removal, the majority (71.8%) was cut by the guide bars of 75 cm in length. The average number of open holes in stump treatment guide bars was 22.5 holes with the variation range of 3–41 holes. The study also detected the effect of the number of open holes in a stump treatment guide bar on the consumption of stump treatment material. In total, the harvester operators recorded the number of open holes in the guide bar for 1808 harvesting sites on the data collection forms. The volumes of softwood cut with the different number of open holes are described in Figure 2.

Moreover, the influence of the adjustment habits by harvester operator on the consumption of stump treatment material was investigated. The options for adjusting the stump treatment equipment (i.e., timing and duration in spraying and spreading pressures) in the interviews of harvester operators were as follows:

- By harvesting site,
- By cutting method,
- After detecting weak stump coverage in spraying or
- Never.

All harvester operators of the study (n = 68) were interviewed at the beginning of the study period (May 2016) and at the end of the study (October–November 2016). The adjustment habits of the operators, as well as the other study experiences and observations (i.e., Was it easy to measure the consumption of stump treatment material? Did the operator achieve the target accuracy set in his consumption measurements? In what kind of harvesting sites were there lots of problems with the coverage of stump surfaces in the treatment work?) were asked in the operator interviews. If the adjustment habits of the operators at the same harvester differed from each other, the harvester was classified into a group based on the harvester operator's response to most adjustments. The number of harvesters and harvesting sites in different adjustment classes are given in Table 1.

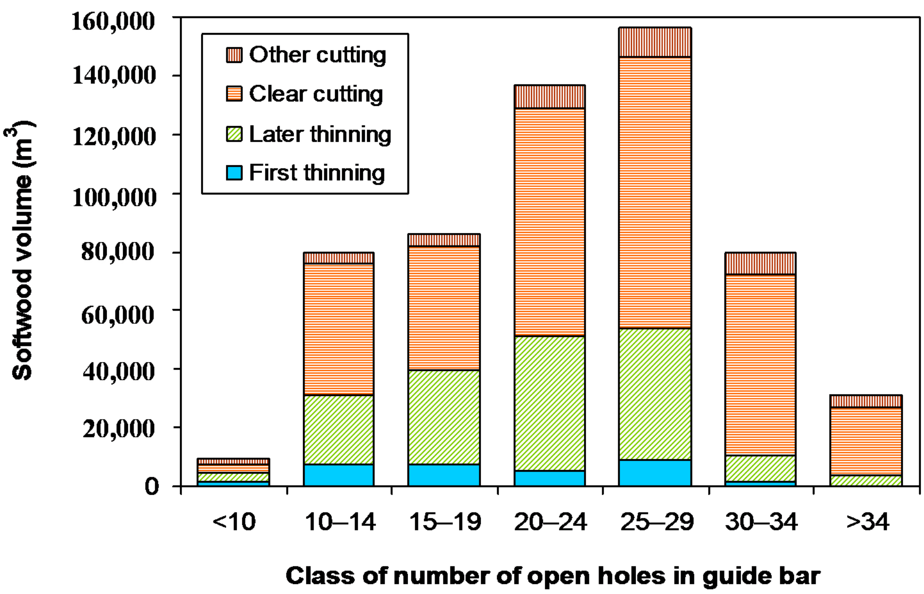

Figure 2. The distribution of the number of open holes in harvesters' stump treatment guide bars by cutting method in the study.

Table 1. The number of harvesters and harvesting sites in the different adjustment habit classes by harvester operator in the study.

Adjustment Habit Class	Number of Harvesters	Number of Harvesting Sites
By harvesting site	0	0
By cutting method	12	490
After detecting weak stump coverage in spraying	19	726
Never	15	615
Total	46	1831

2.2. Coverage Data

The quality of stump treatment work was evaluated with all harvesters of the study by inventorying the coverage of stump treatment on the stump surfaces of conifer trees cut after the stump treatment work. The goal was to make three coverage inventories for each harvester during the study period. Besides, the aim was to conduct one coverage inventory for each main cutting method (i.e., first thinning, later thinning and clear cutting) with each study harvester. The inventory of different cutting methods was done to ensure that the coverage of stump treatment would be valid on the stumps of different diameter within all harvesters involved in the consumption study.

The coverage of stump treatment material on the stump surface can be detected by the dye of the treatment material. The uncovered area of the entire stump surface by stump treatment material was estimated by using a transparent plastic measuring plate (Figure 3).

(**A**)

(**B**)

Figure 3. (**A**) A transparent measuring plate used in the study. By changing the distance of the transparent measuring plate above the stump, the focal length is selected by combining the edges of the stump and the ring of the measuring plate. Based on the relative proportions of the plate, it is possible to determine the relative proportion of the uncovered area of the stump surface. Photo courtesy of Uittokalusto Ltd. (**B**) The stump with the uncoverage rate of around 11–13% (not the blue area). Photo courtesy of Kalle Kärhä.

In each coverage inventory, the target was to measure 50 stumps [49,50]. In accordance with the Guidelines for inventorying the coverage of stump treatment prepared for the study, the stumps were measured via cluster sampling on the longest line of each logging area. From the line, the five closest conifer tree stumps were measured at the distance of ten meters from ten places, with a total sample size of 50 stumps. The stump diameter (d_0) and coverage percentage (i.e., coverage rate) of each stump selected for the inventory were recorded on the Inventorying form of the coverage of stump treatment (cf. [49,50]). The quality of stump treatment work was evaluated on the basis of the criteria of the Finnish Forest Centre [50], i.e., 85% or more of the stump surface of the approved stump should have been covered. Contrary to the consumption data, the quality inventories of stump treatment were carried out at a logging area-specific level (i.e., logging area may consist of one or several harvesting sites) instead of the harvesting site-specific measurements of consumption.

After inventorying the coverage of stumps, the percentages below 85% covered stumps were calculated on the form. When the sample was 50 stumps in the inventories, the deduction percentage was calculated by multiplying the number of uncovered stumps by two. The evaluation based on the deduction percentage was given to the quality of stump treatment work as follows:

- The deduction percentages of 0–9% marked a good level of coverage,
- 10–29% a satisfactory level and
- 30–100% marked an ineligible level of coverage [50].

The quality inventories of stump treatment were performed by a responsible wood harvesting officer at Stora Enso WSF for each study harvester. The quality inventories made by the harvester operators themselves were not used in the study. When all harvesters did not cut in the stands of all three main cutting methods (i.e., first thinning, later thinning and clear cutting), several inventories for the same cutting method were conducted with some harvesters. In total, 144 quality inventories (27 in first-thinning stands, 65 in later thinnings and 52 in clear cuttings) were carried out in the study. The final coverage data was 7042 stumps (Figure 4).

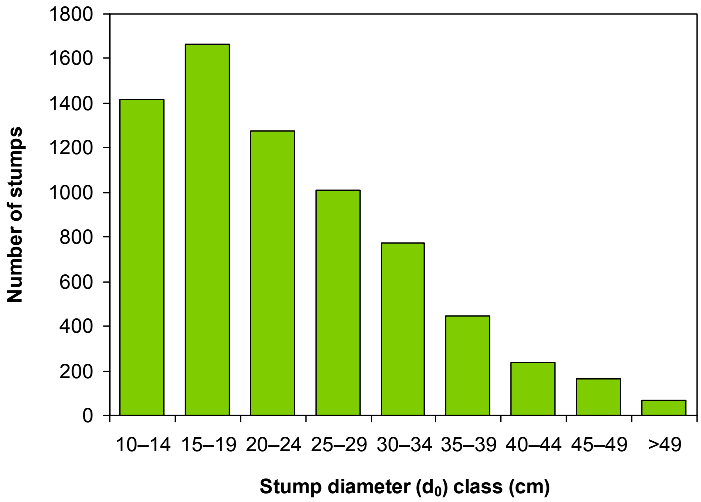

Figure 4. The frequency distribution of stumps (n = 7042) inventoried for the final coverage data of the study.

2.3. Analysis of Study Materials

The harvesting site-specific data on the consumption of stump treatment products, as well as the coverage data of the stumps inventoried were initially tested for normal distribution assumption by a Kolmogorv–Smirnov test. Based on the results of the test, the consumption and coverage data did not comply with normal distribution. Since the material was not distributed normally, the non-parametric methods were applied in the statistical analysis of the study. For a comparison of multiple samples in the study, a Kruskal–Wallis one-way ANOVA (χ^2) test was used and for comparison of two samples a Mann–Whitney (U) test was used.

The consumption (dm^3 m^{-3} of softwood, and dm^3 ha^{-1}) models of stump treatment material were formulated using regression analysis with the average stem size of softwood removal, softwood removal ha^{-1}, the density of softwood removal, treatment product dummy (1, if urea, 0, when Rotstop® SC), the number of open holes in a guide bar, and the dummy variables of operators' adjustment habits of treatment equipment (Adj_Dum_1: 1, if by cutting method, otherwise 0; Adj_Dum_2: 1, if after detecting weak stump coverage, otherwise 0; Adj_Dum_3: 1, if never, otherwise 0) as the independent variables. The different transformations and curve types were tested in order to achieve symmetrical residuals for the regression models and in order to ensure the statistical significance of the coefficients. All statistical analyses were conducted with IBM SPSS Statistics 21 software.

3. Results

3.1. Consumption of Stump Treatment Materials

The study results indicated that the consumption of stump treatment material depends significantly on the average stem size of softwood removal at the harvesting site (Figure 5). The consumption of stump treatment material was, on average, 1.09 dm^3 m^{-3} of softwood cut in first-thinning stands (the average stem size of softwood removal in the stand 83 dm^3), 0.72 dm^3 m^{-3} of softwood in later thinnings (154 dm^3), 0.39 dm^3 m^{-3} of softwood in clear-cutting stands (423 dm^3) and 0.43 dm^3 m^{-3} of softwood in other cuttings (i.e., seeding fellings, cuttings of hold-over stands, shelterwood fellings and special cuttings) (355 dm^3).

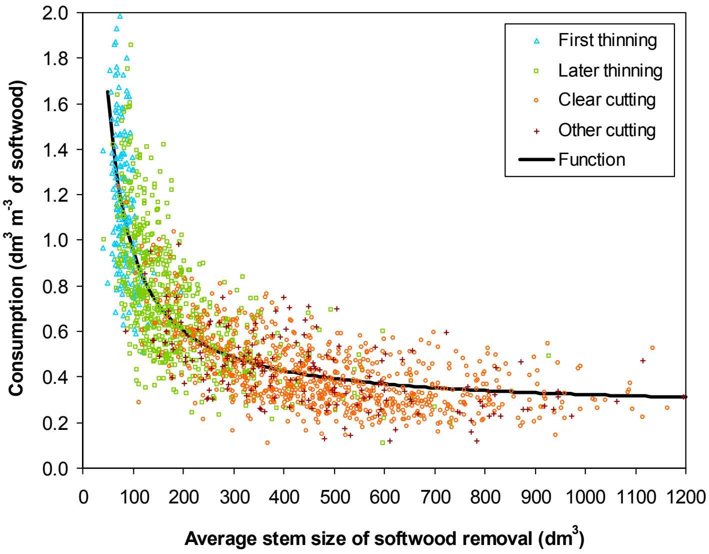

Figure 5. The consumption observations of stump treatment material as a function of the average stem size of softwood removal by cutting method, as well as the predicted consumption curve (cf. Table 2).

Table 2. Regression model for the consumption ($dm^3\ m^{-3}$ of softwood) of stump treatment material.

$y_1 = a + b/x_1$			
Adjusted R^2 = 0.625; *F* Value = 3056 *; Standard Error of the Estimate of the Model = 0.215**			
Coefficient	**Estimate of Coefficient**	**Standard Error of Estimate**	***t*-Value**
a	0.260	0.008	31.469 ***
b	72.019	1.303	55.279 ***

Note: y_1 = consumption ($dm^3\ m^{-3}$ of softwood); x_1 = average stem size of softwood removal (dm^3); a = constant; b = coefficient of the variable; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

In later thinnings and clear cuttings, the treatment product (i.e., urea and Rotstop® SC) used, the number of open holes in the stump treatment guide bar and the operators' adjustment habits of treatment equipment had a statistically significant effect on the consumption of stump treatment material in the study. The highest consumption was measured with urea, and when there were only a few open holes (<18 holes) in a guide bar and the harvester operator adjusted greatly (i.e., by cutting method) the stump treatment equipment in a harvester (Table 3). However, the impact of treatment product, the number of open holes, and the adjustment habits of operators on the consumption of treatment material was significantly lower than the influence of the average stem size and even lower than that of the cutting method (Figure 5, Table 3).

Table 3. The average consumption of stump treatment material by cutting method in the study.

Variable	Cutting Method			Statistically Significant Differences between the Variables by Cutting Method (FT, LT and CC)
	First Thinning (FT)	Later Thinning (LT)	Clear Cutting (CC)	
	Consumption (dm^3 m^{-3} of Softwood)			
Treatment product				
Urea	1.09	0.72	0.40	LT: *;
Rotstop® SC	1.14	0.71	0.31	CC: ***
Number of open holes in guide bars				
<18 (a)	1.11	0.82	0.41	LT: a–b ***, a–c ***;
18–27 (b)	1.06	0.68	0.41	CC: a–b *, a–c **
>27 (c)	1.31	0.64	0.35	
Adjustment habits by operator				
By cutting method (a)	1.13	0.80	0.40	LT: a–b **, a–c ***, b–c *;
After detecting weak coverage (b)	1.07	0.71	0.39	CC: a–c **
Never (c)	1.08	0.65	0.38	

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

When modelling the consumption (dm^3 m^{-3} of softwood) of stump treatment material, the average stem size of softwood removal in the stand best explained the consumption (Table 2). The coefficient of determination (adjusted R^2) of the consumption model was 62.5%. Other independent variables were also tested in the model, but they did not significantly increase the coefficient of determination of the consumption model (Table 2). The residuals of the model centered on zero and were symmetrical throughout the range of the average stem size observations.

The average hectare-based consumption of stump treatment material was 51.0 dm^3 ha^{-1} in first thinnings (the average softwood removal at the harvesting site 46 m^3 ha^{-1} and the average density of softwood removal 558 trees ha^{-1}), 44.6 dm^3 ha^{-1} in later thinnings (63 m^3 ha^{-1} and 402 trees ha^{-1}), 80.8 dm^3 ha^{-1} in clear cuttings (210 m^3 ha^{-1} and 491 trees ha^{-1}) and 58.9 dm^3 ha^{-1} in other cuttings (140 m^3 ha^{-1} and 409 trees ha^{-1}) (Figure 6).

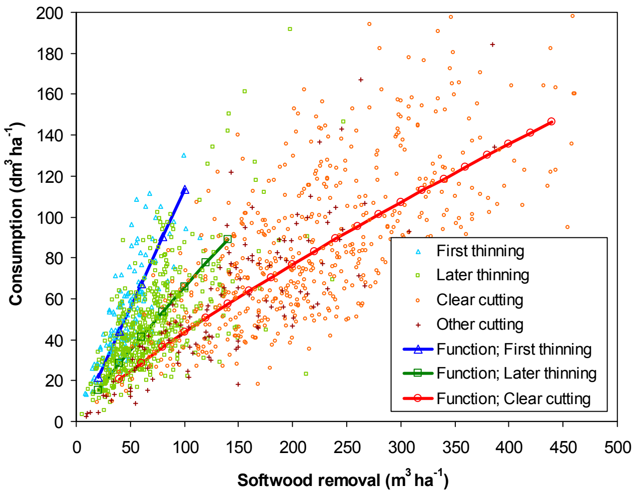

Figure 6. The hectare-based consumption observations of stump treatment material as a function of softwood removal per hectare and the predicted consumption functions by cutting method (cf. Table 4).

Table 4. Regression models for the hectare-based consumption of stump treatment material.

$y_2 = x_2^b$			
FT: Adjusted R^2 = 0.628; *F* Value = 226 *; Standard Error of the Estimate of the Model = 0.312**			
LT: Adjusted R^2 = 0.469; *F* Value = 446 *; Standard Error of the Estimate of the Model = 0.397**			
CC: Adjusted R^2 = 0.529; *F* Value = 625 *; Standard Error of the Estimate of the Model = 0.342**			
Cutting Method/Coefficient	**Estimate of Coefficient**	**Standard Error of Estimate**	***t*-Value**
FT/b	1.027	0.007	145.803 ***
LT/b	0.909	0.004	213.822 ***
CC/b	0.819	0.003	302.811 ***

Note: y_2 = consumption (dm^3 ha^{-1}); x_2 = softwood removal (m^3 ha^{-1}); b = coefficient of the variable; FT = first thinning; LT = later thinning; CC = clear cutting; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

The best hectare-based consumption models of stump treatment material by cutting method were achieved when the softwood removal hectare^{-1} was the independent variable in the models (Table 4). The residuals of the hectare-based consumption models also distributed symmetrically.

3.2. Quality of Stump Treatment Work

The coverage inventories showed that the quality of stump treatment work was good in the study: 72.2% of the coverage inventories indicated that the work quality was good. Correspondingly, 26.4% of stump treatment work was classed as satisfactory. Only 1.4% of the total stump treatment work inventories provided an ineligible result.

The proportion of less than 85% covered (i.e., not approved) stumps measured in the total coverage data was 6.6% and the proportion of 85% or better covered stumps was 93.4%. When analyzing the coverage by stump diameter class, it could be noted that the highest coverage was achieved with the stumps of 20–39 cm (Figure 7). The coverage of the smaller- (<20 cm) and larger-diameter (>39 cm) stumps inventoried was significantly lower (χ^2 = 35.5; $p < 0.001$) than the stumps of 20–39 cm.

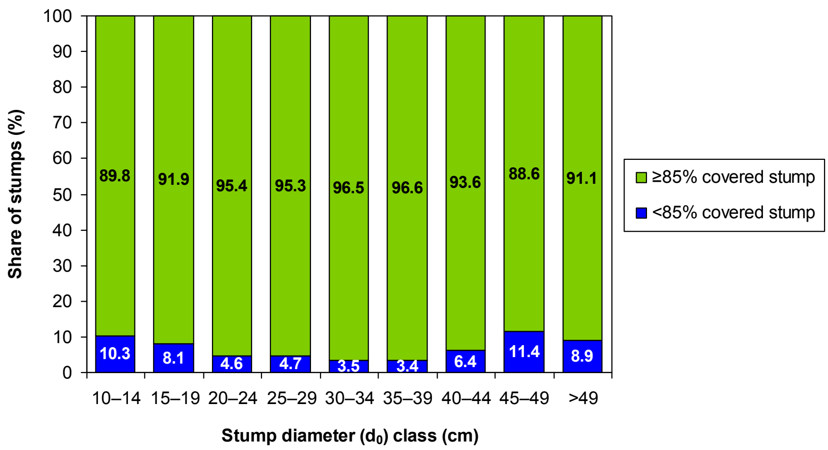

Figure 7. The shares of <85% and ≥85% covered stumps inventoried by stump diameter class.

In this study, the average coverage rate (i.e., the coverage percentage of all stumps inventoried) was 94.9% in first thinnings, 94.3% in later thinnings, and 95.1% in clear-cutting stands. The cutting methods differed significantly in the quality of stump treatment work for unequal stumps: In clear cuttings, the coverage rate with small-diameter (<20 cm) stumps was significantly lower (90.7%) than in first and later thinnings (94.4% and 93.8%, respectively) (Table 5). Correspondingly, in first-thinning stands, the coverage rate of stumps treated was good with both small (<20 cm) and medium-sized

(20–39 cm) stumps. With the larger-sized (>39 cm) stumps, the coverage rate was the highest (93.9%) in clear cuttings (Table 5).

Table 5. The average coverage rates by stump diameter class in the study.

Variable	Stump Diameter (d_0) Class (cm)			Statistically Significant Differences between the Variables by Stump Diameter Class (S, M and L)
	10–19 ("Small")	20–39 ("Medium")	>39 ("Large")	
	Coverage Rate (%)			
Cutting method				
First thinning (a)	94.4	96.8	-	S: a–c ***, b–c ***;
Later thinning (b)	93.8	95.1	91.2	M: a–b ***, b–c ***;
Clear cutting (c)	90.7	96.4	93.9	L: b–c **
Treatment product				
Urea	93.5	95.8	93.3	
Rotstop® SC	94.7	96.4	95.8	
Number of open holes in guide bars				
<18 (a)	93.9	96.5	92.5	M: a–b ***, a–c **;
18–27 (b)	93.3	95.3	91.5	L: a–c *, b–c **
>27 (c)	93.2	95.8	94.9	
Adjustment habits by operator				
By cutting method (a)	94.1	96.1	92.7	S: a–b ***, a–c ***, b–c ***;
After detecting weak coverage (b)	91.9	95.5	95.8	M: a–b **, b–c ***;
Never (c)	95.4	96.0	91.3	L: a–b ***, b–c ***

Note: S = "Small"; M = "Medium"; L = "Large"; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

When clarifying the effect of the number of holes in a guide bar on the quality of treatment work, the best coverage rate was obtained with small- and medium-sized stumps when the guide bar was perforated with relatively few (<18) open holes, and with larger-sized (>39 cm) stumps when the guide bar was equipped with a relatively great (>27) number of open holes (Table 5). When investigating the influence of the operator's adjustment habits of treatment equipment, it could be noticed that the highest coverage rate was achieved as follows:

- with small (<20 cm) stumps when the harvester operator did not adjust the stump treatment equipment of the harvester at all (95.4%),
- with medium-sized (20–39 cm) stumps when the operator adjusted the treatment equipment in the harvester by cutting method (96.1%) and
- with large-diameter (>39 cm) stumps when the operator sets the treatment equipment after detecting weak stump coverage in spraying (95.8%) (Table 5).

4. Discussion and Conclusions

The data for the consumption of stump treatment material was almost 0.6 million m^3 of softwood and more than 2.4 million softwood trees cut with 46 harvesters, and the stump treatment material was spread more than 300,000 dm^3. The consumption data was hence relatively large. The study produced fresh data on the consumption of stump treatment materials. Among other things, novel consumption information is needed to define the equitable payments of stump treatment work for forest machine contractors. Besides, our consumption figures can be utilized when estimating and modelling the profitability of stump treatment against *Heterobasidion* spp. root rot [51–55].

In the study, measurement of the consumption of stump treatment material was challenging, as there was no technology for automatically measuring the consumption of treatment product in the study harvesters. The consumption of treatment products was measured using many measuring methods according to the alternative options used in the harvesters of the study, as well as the preferences of the operators. All methods aimed at a minimum accuracy of five dm^3 per measurement. On the basis of operator interviews, each operator thought that he achieved a set target for the measurement accuracy. Nevertheless, in the near future, forest machine manufacturers should seriously consider equipping their harvesters with the automatic standard measurement system to verify the real-time and total consumption of stump treatment material at the harvesting site, as nowadays measuring the fuel consumption in modern harvesters is important.

Currently, the volumes of storage tanks in harvesters for the stump treatment material are typically 100–150 dm^3. The storage tanks are sufficient for a single work-shift cutting in thinnings and clear cuttings (Table 6). However, efficient cutting in a double work-shift system calls for continuous cutting work, without visiting the roadside landing to fill up the stump treatment tank of a harvester between work shifts. In thinnings, the stump treatment tank of a harvester must be around 150 dm^3 and in clear cuttings more than 150 dm^3 for double work-shift cutting work (Table 6). Hence, forest machine manufacturers should construct larger storage tanks for the stump treatment material in harvesters in the future.

Table 6. Calculation of the sufficient volumes of storage tanks for the stump treatment material in harvesters working in one and double work shifts by cutting method.

	First Thinning	Later Thinning	Clear Cutting
Consumption of stump treatment material (dm^3 m^{-3} of softwood) [1]	1.09	0.72	0.39
Cutting productivity (m^3 of softwood SMH^{-1})	7.5 [2]	12.5 [3]	28.5 [3]
Consumption of stump treatment material (dm^3)			
In one work shift [4]	57.2	63.0	77.8
In two work shifts [5]	114.5	126.0	155.6

Notes: [1] Average consumptions of stump treatment material in this study; [2] Cutting productivity in first thinnings = m^3 per scheduled machine hour (SMH) by Kärhä et al. [56]; [3] Cutting productivity in later thinnings and clear cuttings by Eriksson and Lindroos [57]; [4,5] It was assumed that there are 7.0 SMHs in one work shift and 14.0 SMHs in two work shifts.

The study results showed that the average stem size of softwood removal in the stand has a significant effect on the consumption (dm^3 m^{-3} of softwood) of stump treatment material. Furthermore, the softwood removal $hectare^{-1}$ by cutting method explained the hectare-based consumption of stump treatment material in the study. The average consumption of stump treatment material was 51 dm^3 ha^{-1} in first thinnings, 45 dm^3 ha^{-1} in later thinnings and 81 dm^3 ha^{-1} in clear cuttings. The results of the study were in line with the calculations by Mäkelä [41]: the consumption was 40–60 dm^3 ha^{-1} in thinnings and 50–90 dm^3 ha^{-1} in clear cuttings.

Many *Heterobasidion* researches [31,34–37] have pointed out that achieving good pesticide efficacy requires careful stump treatment in order to wet the surface of the whole stump by spreading, and the effectiveness of prevention work is reduced in relation to the uncovered area on the surface of the stump. Therefore, our target must invariably be a high-quality stump treatment. On the basis of the study results, it can be recommended that the harvester operator self-monitors and actively controls his/her treatment result in cutting work, especially operating in large-diameter forest stands, sets the stump treatment equipment in the harvester if needed, subsequently achieving a high-quality result in his/her stump treatment work.

It must be noted that, in this study, many harvester operators stated that they do not set stump treatment equipment in their harvesters at all. In fact, one-third of the harvesters were categorized in the group of "Never adjustments", i.e., no settings for the stump treatment equipment in a harvester (cf. Table 1). Thus, we need better education and communication concerning the significance of high-quality stump treatment work, active and continuous self-monitoring treatment result, and setting the stump treatment equipment of the harvester if needed. Oliva et al. [58] have underlined that it is essential to treat the large-sized stumps very carefully because the probability of stump-to-tree spread of *Heterobasidion* spp. root rot depends significantly on the diameter of the stump.

The coverage rate by cutting method was best in clear cuttings, but the difference between clear cuttings and thinnings was very small. Consequently, the stump treatment work can be considered successful and uniform with all cutting methods in the study. There was no significant difference between biological (Rotstop® SC) and chemical (urea) controls used in the coverage rates of stump treatment work. However, it must be noted that there were only six Rotstop® SC harvesters of the total 46 harvesters in the study, and from the total softwood volume cut in the study the proportion of Rotstop® SC was only 12%.

According to the statistics of the Finnish Forest Centre, the shares of good logging areas related to stump treatment work have been annually 73.9–76.7% in the coverage inventories in 2012–2016, and the shares of satisfactory and ineligible results in stump treatment work have been 17.1–24.3% and 2.9–7.1%, respectively [59]. In this study, the distribution of the treatment work results was as follows: good 72.2%, satisfactory 26.4% and ineligible 1.4%. Hence, in this study, the proportions of good and ineligible results were slightly lower and on the other hand the share of satisfactory logging areas was higher compared to the figures of the whole of Finland by Leivo [59] in coniferous forests in recent years.

Correspondingly, in this study, the share of less than 85% covered (i.e., not-approved) stumps measured was 6.6%. The Finnish Forest Centre has reported that the share of not-approved stumps of the total stumps inventoried was, on average, 10.2% in 2014 and 9.2% in 2015 in Finland [60,61]. Thus, the share of not-approved stumps in this study was smaller to the whole of Finland.

Based on the study results, the quality of stump treatment work can be found to be the best with the medium-sized (20–39 cm) stumps, and the coverage rate with the smaller (<20 cm) and larger (>39 cm) stumps was slightly lower than with the medium-sized stumps. The number of open holes in stump treatment guide bars had an impact on the quality of treatment work when cutting different sized coniferous trees. Accordingly, it can be concluded that in the stands of mostly small- and medium-diameter ($d_0 \leq 39$ cm) conifers, the treatment guide bars with relatively few (<18) open holes are used, and at the harvesting sites of large-diameter trees, the guide bars with a relatively great (>27) number of open holes are applied.

Several harvester operators interviewed underlined that the stump treatment is most difficult in the coniferous stands in which there is great variation in the stem size of removal. Especially in the case of larger-diameter clear cuttings, the stump treatment of small-sized stumps is very challenging. To sum up, since the adjustments of the controlling system of treatment equipment and the open holes in the treatment guide bar have to be decided in accordance with the dominant trees in the stand, nowadays there are difficulties to spray the divergent stumps perfectly. In the future, forest machine manufacturers could develop more advanced controlling systems of stump treatment for their harvesters, for instance self-adaptive spraying systems according to the stem size to be felled. This kind of self-adaptive spraying system requires, however, machine vision or mobile laser scanning systems on the harvesters to inform the controlling stump treatment system of the size of the next tree to be cut (cf. [62–65]).

Because the consumption data was measured as harvesting site-specific and the coverage data as logging area-specific, there were no possibilities to merge the materials and to compare more comprehensively the consumption and coverage data in the study. Consequently, a further study on the consumption and coverage could be performed to optimize the consumption of stump treatment material subjected to the high-quality coverage rate in the coniferous forests.

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