Is stump removal for bioenergy production effective in reducing pine weevil (*Hylobius abietis*) and *Hylastes* spp. breeding and feeding activities at regeneration sites?

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Abstract

Stump harvesting can help in managing forest pests, improve site preparation, and provide a source of bioenergy. However, stump removal does not remove all the roots from clear-cut areas. To investigate whether stump removal helps to manage forest pests, the effect of stump removal and its timing on the breeding and larval feeding activities of pine weevil (*Hylobius abietis*) and *Hylastes* spp. was studied. In eastern Finland, 16 commercial regeneration sites dominated by Norway spruce (*Picea abies*) (eight control areas, eight stump removal areas) were selected. Stumps were harvested in 2011, within the year following logging in three of the stump removal sites (short delay extraction), and in the second year after logging at five of the stump removal sites (long delay extraction). Root samples were excavated from sites three years after logging to examine the amount of roots, gnawing intensity, and density of larvae. In the control plots, gnawed root surface areas were 24% and 50% greater than those in long delay and short delay stump removal sites, respectively. After timing treatment, the estimated larval densities of both species were lower than the estimated larval densities in the control sites. In conclusion, the timing of stump extraction may partially regulate the breeding material and abundance of *Hylobius* and *Hylastes.* However, it is probable that this effect is not strong enough to substantially limit the future damage on planted seedlings.

Key words: Logging; Stump removal; Roots; Forest pests; Larvae.

1. Introduction

Tree stumps from forest regeneration areas are potentially an important source of raw material for bioenergy production because stumps offer more biomass than logging residues (Egnell et al., 2007). As well, stump harvesting may open new opportunities for managing forest pests and diseases and improve quality in site preparation (Saarinen 2006). However, stump harvesting can also adversely affect soil carbon stores, increase soil erosion and compaction, reduce soil nutrient stocks, and cause valuable habitat loss for mosses, fungi, insects, etc. (Walmsley and Godbold, 2010).

Previous studies focused on the effects of stump harvesting on species dependent on dead wood (Work et al., 2016; Victorsson and Jonsell, 2016; Shevlin et al., 2017). However, few studies have focused on the effects of stump harvesting on pest populations, especially on the *Hylobius* genus (Coleoptera: Curculionidae), one of the most common and abundant economic pests in conifer seedling stands in Europe (Långström and Day, 2004). *Hylobius* breeds in conifer stumps and roots, and hampers the restocking of regeneration sites. In addition, larvae of *Hylastes cunicularius* Er., and *Hylastes brunneus* Er., another potential but poorly studied pest group in conifer seedlings, and longhorn beetles (Cerambycidae), often exist both in pine and spruce stumps and roots (Victorsson and Jonsell, 2016).

In a fresh clear-cut area, stumps and logging residues emit volatile compounds (e.g. several monoterpenes and ethanol) that attract potentially harmful insects to the site, including pine weevil (*Hylobius abietis)*, (Nordlander, 1987; Brattli et al., 1998) and *Hylastes* spp. (Joseph et al., 2001) which reproduce in the stumps and roots of logged trees. Pine weevils lay their eggs in the soil and bark of the roots (Nordlander et al., 1997) and *Hylastes* spp. also lay their eggs in recently clear-cut stumps (Lindelöw et al., 1993). *Hylastes cunicularius* Er. breeds mainly in Norway spruce and

Hylastes brunneus Er. breeds mainly in Scots pine. After hatching, pine weevil larvae overwinter in stumps, feeding under the bark of stumps and roots, and pupate in the following summer (Nordenhem, 1989). New adult weevils emerge in autumn of the year following clear-cutting. In this way, pine weevil breeding continues actively for a few successive years after clear-cutting has occurred.

Pine weevils and *Hylastes* spp. preferentially feed on the thin bark of coniferous tree species (Manlove et al., 1997; Leather et al., 1999; Löf et al., 2005; Wallertz et al., 2014). Pine weevils feed on the roots and branches of mature trees and on the stems of seedlings. Both *Hylastes* species feed on the roots of mature trees, and on the roots and at the stem base of seedlings, but just on the basis of feeding marks it is impossible to separate the species. In boreal forest regeneration sites, pine weevil feeding can cause the death of 60–80% of planted coniferous seedlings (Örlander and Nilsson, 1999). Sustained pine weevil feeding on seedlings can last at least three consecutive years (Långström, 1982). Most serious economic damage due to pine weevil feeding occurs at newly planted coniferous regeneration sites where previous stands have been clear-cut coniferous forests (Långström and Day, 2004).

In theory, the rapid harvesting of stumps and coarse logging residue after clear-cutting might effectively reduce the amount of volatile compounds, which lure new adults to the clear-cut area. In addition, it could also reduce the amount of suitable breeding material available and decrease the subsequent larval population. Consequently, stump removal might reduce the feeding damage caused by pine weevil and *Hylastes* spp. on planted seedlings. Thus, stump removal might function as a silvicultural method in the integrated management of root-feeding pests However, immediate and total stump removal may not be possible in practical forestry management terms. In practice, in stump harvesting, an excavator uproots the main tree root system, but many side roots and rotten roots remain in the soil. Silvicultural instructions recommend to leave at least 25 stumps ha^{-1} for biodiversity and to prevent erosion (Koistinen, 2016). Moreover, stumps less than 20 cm in diameter are often left due to the high cost of excavation (Kärhä, 2012).

The pine weevil has a strong ability to dig in the soil and lay eggs in small roots (Nordlander et al., 1997). *Hylastes* spp. also can dig up to 100 cm in the soil to enter buried roots (Lindelöw, 1992). Furthermore, if stump removal is delayed for a long time and done after arrival of pine weevils and *Hylastes* spp. in clear-cut areas, then they have already succeeded in colonising the stump and root system. This may compromise the potential pest control effect of stump removal. Therefore, it is necessary to know how many roots are left for breeding substrate and how the timing of stump removal in clear-cut areas contributes to the reproduction potential of *Hylobius abieti*s and *Hylastes* spp.

The concerns about the relationship of pine weevil and *Hylastes* spp. with stumps in clear-cut areas are as follows: 1) both species feel attraction to stumps, and immigrate to clear-cut areas in early summer; 2) weevils and *Hylastes* both breed in stumps and roots, and after completion of the larval stage, emergence can take more than two years after immigration for young adult pine weevils, and more than one year for *Hylastes* spp. in eastern Finland; 3) normally, stump removal will be carried out in clear-cut areas after pest insect immigration. With this knowledge, theoretically, it can be assumed that early stump removal might decrease the amount of breeding material and the abundance of pine weevil and *Hylastes* spp. in the regeneration site. To determine how stump removal and its timing affect the breeding and abundance of pine weevils and *Hylastes* species, we studied the effects of stump removal on the amount of coniferous root material remaining in clear-cut areas available for *Hylobius* and *Hylastes*. We also tested short delay (within a year of clear-cut) versus long delay (the year following clear-cut) stump removal on the populations of *H. abietis* and

Hylastes spp. by measuring their larval feeding intensities on roots. *Hylastes* spp. and pine weevil feeding intensities in the remaining roots were compared between control sites (with no stump removal) and sites with stump removal.

2. Material and methods

2.1. Study sites and experimental design

In this study, 10 and 6 regeneration sites, logged in 2009 and 2010, respectively were selected in eastern Finland (Table 1). The sites were dominated by Norway spruce (*Picea abies* L.). Typically, in January and July, the mean temperature is -16°C and +17°C, respectively, in North Karelia (data from Finnish Meteorological Institute). In this experiment, sites were clear-cut in the previous winter season and fresh stumps were available for insect colonisation in the following spring. The experiment had a paired-site design: the 16 sites were paired, so that each pair consisted of a control site (stumps left intact) and a stump removal site. Control and stump removal sites were paired based on approximately equal volumes of standing stock before final logging. Because of the time lag between logging and stump extraction, stump extraction sites were classified in either the short delay or long delay category. The five pairs logged in 2009 (stump extracted 2010) were those with a long delay and the three pairs logged in 2010 (stump extracted 2010) were those with a short delay between the logging and stump harvest.

Stump removals were performed on all experimental sites in 2010 according to the normal commercial practices and instructions approved by good silvicultural practise for energy wood harvest (Koistinen et al., 2016). According to the instructions, more than 25 stumps of various tree species ha^{-1} (over 15 cm in diameter), all rotten stumps, and stumps less than 20 cm in diameter, should be left. Each site had been mounded by an excavator and planted with Norway spruce seedlings according to normal local forestry practices. All study sites were located on mineral soil.

The dominant late-successional forest floor species was *Vaccinium myrtillus* L. (mesic, *Myrtillus* forest-type) for all sites except the Kermansalo and Jalaslampi sites, which had an herb-rich forest type (*Oxalis-Myrtillus* type) (Cajander, 1949).

In the middle of each regeneration site, 20 sample plots were established. Sample plots were 1 m^2 each and arranged along two lines, each line containing 10 sample plots. Sample plots had a minimum distance of five meters between them. If the central point of the root extraction plot and control site contained a big stone or stump, the sample plot was moved forward.

2.2. Root sampling

All roots of each sample plot were excavated manually in the autumn of 2012 (logged in 2009) and 2013 (logged in 2010). Litter, branches, and visible deciduous roots were removed from the sample plot before excavation. Roots clearly identified in the field as belonging to a deciduous tree species were ignored. All excavated conifer roots were put in plastic bags in the field, frozen in the laboratory, and later identified in the laboratory. If pieces of bark from the roots fell off during digging, the bark samples were put in the same bag as the root sample and was also examined later for traces of insects, but generally, root decomposition had not progressed to the point that it would have been disturbed by root sampling. Pits in the sampling plots were dug to the depth at which no roots could be found. Roots that extended outside of the sample plot were cut exactly from the border line of the plot with secateurs or a saw. In this study, sampled roots diameter was short delay 6.5 ± 4 cm (mean ± SD), long delay 6.6 ± 4.6 cm, and control 9.8 ±12.8 cm and the length short delay 22 ± 11 cm, long delay 29 ± 15 cm, and control 32 ±14 cm. However, in control plots there were a few roots with root neck and part of the stump attached. The number of very large roots in control plots were so small that it has no effect on results.

In the laboratory, the length and diameter of the root samples were measured from both ends of each root. The root surface area was calculated using the formula $2[\pi r^2] + [2 \pi r] \times h$ cm^2, where r is the mean radius of the sample root and h is the length of the sample root. The amount of feeding by both *Hylobius* and *Hylastes* species was estimated for each root. Both species mine larval tunnels in the phloem of the roots. *Hylobius* larval tunnels are about 5 mm wide. *H. cunicularius* and *H. brunneus* tunnels cannot be separated from each other, they are too narrow, and occur mostly in wood; thus the two species were grouped in this study. All discovered adult insects, larvae, and pupal chambers were counted and identified. Gnawed root surface areas were calculated by [surface area of each root × 100]/gnawed (%) for each root. The total root surface area and gnawed root surface areas were calculated for each plot. The fungal coverage of root samples was estimated.

In total, 8 891 coniferous root samples were examined. In this experiment, it was estimated by assuming that one gnawed root indicated the presence of one larva. Total gnawed roots were counted for each sample plot. To obtain the larval density ha^{-1}, we calculated the average number of larvae present in the control, short delay stump removal, and long delay stump removal plots. Each treatment averages were multiplied by 10 000 to obtain the per-hectare value of larval density.

2.3. Statistical analysis

Before statistical analyses, dependent variables were transformed by log 10+1 to reduce non-normality. We developed a mixed linear model in the following form:

$$\text{Log } Y_{ij} = \log \beta_1 + \log \beta_2 T_{ij} + \log \beta_3 \delta_{ij} + \log \beta_4 \theta_{ij} + \varepsilon_{ij}.$$

In the model, β_1 is constant, and β_2, β_3, and β_4 are the coefficients of the corresponding variables. T_{ij} is the treatment as $T \in$ (control [no stump removal], SR [stump removal]), δ_{ij} is the treatment × time (short, long), θ_{ij} is the stand volume, i is the site, j is the paired sites (control, stump removal), and ε_{ij} is the error in the model.

In the model, the total root surface area, gnawed root surface area, and larvae density were dependent variables, the treatment and stump removal time difference were set as factors, and the previous stand volume was considered as a covariate. Further, the treatment, time, treatment × time interaction, and stand volume were set as fixed effects. Sites and paired sites were set as random effects. Significance levels were set at $p < 0.05$. In SPSS 17 statistical software, analyses of variance were performed using a general linear mixed model.

3. Results

3.1. Stump removal and availability of feeding resources

In control sites, the mean root diameter was 34% larger than that of the stump removal sites (Table 2). There were significant variations in the root surface area between the control and stump removal sites, and between the timing of the stump harvest (Table 3). Control sites had, respectively, 44% and 64% greater mean root surface areas than the long delay (following year of clear-cut) and short delay (within year of clear-cut) stump removal sites. Short delay stump removal sites had less root surface area remaining than long delay removal sites, and control sites also showed the same pattern (Fig. 1). The logging volume of the previous stand had no significant influence on the remaining root surface area (Table 3), because sites were paired with corresponding volumes of the previous stand as part of the experimental design.

3.2. Effect of stump removal on number of larvae

The total number of pine weevil pupal chambers found in the roots was 226, which is 2.5 % of the total roots collected from all study sites (Fig 2.). Pupal chambers were more frequent in the control sites (Fig. 2). Most pine weevil larvae (187) were also found in control sites, and only one pine weevil larvae was found from a stump removal site (Fig. 2). In the stump removal sites, we estimated the pine weevil larval density to be 78 780 and 35 700 larvae ha^{-1} on the basis of the root feedings, which were 6% and 48% lower than the estimated larval densities in the control sites in long delay and short delay stump removal respectively (Fig 3). Stump extraction had a significant effect on the larval density (Table 4). There was also a significant difference in pine weevil larval density between treatment and time interaction (Table 4). Stump removal sites also had 21% fewer *Hylastes* spp. feeding than control sites, and stump removal significantly reduced *Hylastes* spp. feeding (Fig. 4) (Table 4).

3.3. Effect of stump removal on feeding

In stump removal sites, the gnawed root surface areas by *H. abietis* and *Hylastes* were 24% and 50% lower in the long delay and short delay plots than those in the control plots, respectively, and the differences were significant (Fig. 5) (Table 5). Gnawed root surface areas were greater in the long delay than short delay stump removal sites. In general, the gnawed root surface area in the control areas was 34% larger than that in the stump removal sites.

In control sites, pine weevils gnawed 17% of roots; in stump harvesting sites, pine weevils gnawed 11% of roots. Pine weevils gnawed 38% more root surface area in control sites compared to stump removal sites (Fig. 6). In addition, the area gnawed by *Hylastes* species was 26% larger in the control sites than in the stump removal sites. Pine weevil gnawed more root surface area compared to *Hylastes* spp. in both the control and stump removal sites (Fig. 6). In the mixed model, both species each showed significant differences based on stump extraction treatments, but did not exhibit significant differences based on time, treatment × time interaction, and logging volume (Table 6). Traces of fungal growth were found in 3% of roots.

4. Discussion and conclusion

Our study showed that removal of stumps from clear-cut areas reduced the amount of suitable breeding material with significant effect on the size of both pest populations in regeneration sites. However, in the current stump harvesting practice it is not possible to eradicate root dwelling pests completely from a clear-cut area. It was established in our study for the first time, that approximately 35 700–78 780 pine weevil and 33 250–67 660 *Hylastes* spp. larvae ha^{-1}, or more, were present in the remaining roots after stump removal. Because we used very strict criteria, that a root with signs of feeding indicates the presence of only one larva, these values more likely are closer to the minimum population densities than the maximum population densities.

Roots infected by certain fungi can be totally devoid of insect larvae (Skrzecz, 2017). Here, however, only a very small proportion of roots were infected by fungi, and it seemed that fungal decomposition had not yet destroyed the traces of larval tunnels or pupal chambers. Thus, the timing of the root sampling fitted well to the local development phase of the pine weevils. The number of pine weevil larvae found supported this, and gave justification to the estimation method for determining pine weevil larval density.

Previously, Moore et al. (2004) have estimated that in Scotland, in areas where stumps were left intact, the larval population of *H. abietis* was between 46 000–170 000 larvae ha^{-1}. Our estimate of the larval population size on the control sites fits well within these limits. To our knowledge, there are no other estimates of the larval population size of *H. abietis*, and no studies on the effect of stump removal on it, excluding one older study performed in Sweden and published in Swedish (see Långström and Day, 2004). Further, our results support the earlier speculation that the role of *Hylastes* as a pest in conifer regeneration sites might be underestimated (Lindelöw, 1992). Recently, Nordlander et al. (2017) provided that clear-cut sites on seedling mortality caused by

Hylastes spp. (mean 4 %) and *Hylobius* (mean 29 %) after two seasons. It is also important to mention that less research has been carried out on *Hylastes* spp. compared to that on *Hylobius abietis.* After all, it seems that the population density of *Hylastes* spp. is not much smaller than that of *H. abietis*.

We found that the reducing effect of stump removal was more effective when stump extraction was carried out with only a short delay after logging than if it was delayed for a longer time (extraction in following year after clear-cut). A long delay between logging and stump extraction leads to only a minor decrease in the number of roots with signs of feeding by larvae. In stands with a long delay extraction treatment, higher amounts of stumps and roots were available for a longer time, which allows a longer window of opportunity for colonisation and the spread of larvae into the root systems of logged trees than in stands with a short delay stump extraction treatment. A short delay between logging and the removal of fresh stumps may reduce the amount of attractive volatiles emitted from the stand, and shorten the period when root dwelling pests are attracted to a clear-cut area for breeding.

In addition to the timing of stump extraction, differences in the weather conditions between years and sites might have some unknown effects on these results. The summer 2010 was extremely hot, with an all-time summer temperature record of + 37°C in eastern Finland. Moreover, the sites logged in winter 2010 (short delay sites) had a slightly more southern location than the sites logged in 2009 (long delay sites). However, the weather-related factors probably have no major effect on the results. The hot summer in 2010 affected all sites, and the cumulative temperature sums of the three subsequent summers was almost the same between the periods 2009–2012 and 2010–2013; it was only 72 degree days higher in the first period than in the second (data from Joensuu Airport weather station, in the middle of the study areas; Finnish Meteorological Institute).

Although the reduction in size of estimated larval populations was significant in the short delay stump extraction treatment, the size of estimated larval population still remained at a very high level. These remaining larvae will mature and likely cause seedling damage during their emerging period from the roots. Accordingly, parent pine weevils and new-born weevils may remain in high numbers for some consecutive years following clear-cutting of a particular site (von Sydow 1997; Örlander et al., 1997). Pine weevils have the ability to emerge from even four-year-old roots (Nordenhem, 1989). Additionally, *Hylastes* species can remain for four to six years in clear-cut areas and cause seedling damage (Lindelöw, 1992). However, if the stump harvesting operation can be carried out before migration of adult pests into the clear-cut area, then pine weevil and *Hylastes* spp. abundance might be minimised. To do this, forest managers must make proper decisions about stump harvesting time.

Our study showed that there are a substantial number of *Hylastes* spp. present both in stump extracted and control sites, but it seems that the stump removal had a more pronounced effect on the pine weevil larvae populations than on populations of *Hylastes*. In control sites, *Hylastes* spp. exhibited less root-feeding activity than pine weevils. However, after stump removal treatment, pine weevil root feeding was reduced more than feeding by *Hylastes* species. This may be because *Hylastes* utilizes recently died and dying roots for breeding (Ehnström and Axelsson, 2002) and can be more abundant in mature forests than pine weevil (Heikkala, 2016). Moreover, pine weevil may exhibit life cycle and behaviour that is strongly related to fresh clear cuts, and, therefore, stump extraction reduced significantly pine weevil's attraction to harvested sites of this study. Whereas *Hylastes* species were less affected because it was already present in logged stands.

Although it could be assumed that after clear-cut, *Hylastes* spp. and pine weevil larvae compete food resources, we found that there were plenty of roots available for larval feeding for both species. Large amounts of roots without signs of gnawing indicated that the competition pressure on root dwelling larval populations was generally at a low level.

According to our results, stump removal reduces the amount of resources available for root feeding pests and the size of the larval population. However, the critical question is that is this reduction enough to diminish the size of the adult population, which causes the seedling damage, so that the risk of future damage to seedlings would be considerably lower. In our study, it was estimated that approximately 89 090 to 100 840 pine weevil larvae and 77 280 to 81 850 *Hylastes* spp. larvae were still present in the clear-cut area. When long delay and short delay treatments were applied, then 78 780 and 35 700 pine weevil larvae, and 67 660 and 33 250 *Hylastes* spp. larvae survived, respectively. According to Moore et al. (2004), 40–80% of pine weevil larvae survived to become adults in traditional regeneration sites. If we follow their lowest survival rate estimation (40%), then in our stump extracted site the number of emerging pine weevil adults ha^{-1} will be 31 512 in long delay and 14 280 in short delay sites. In addition, the number of emerging adults of *Hylastes* spp. will be 27 064 (long delay sites) and 13 300 (short delay sites) ha^{-1}.

We have previously found that traditional regeneration sites, there was more seedling damage caused by pine weevil than in sites with the stumps extracted (Rahman et al., 2015). In fresh clear-cut areas, it has been estimated that 14 000 adult immigrant weevils ha^{-1} can cause damage to 82% of seedlings (Nordlander et al., 2003). Based on this finding and our calculations above, it is not justified to conclude that the reduction in population size of weevils resulting from stump removal is sufficient significantly to reduce the damage level to coniferous seedling stocks. Therefore, it appears that stump extraction is not a very effective method to control damage caused by *Hylobius* and *Hylastes*. Only if the stump extraction is performed without delay will there be a good possibility of reducing the population size, and enhancing the impact of other first-line control methods.

After all, in addition to pest damage control, stump removal has a multitude of other silvicultural and ecological effects, which must be considered. Stump harvesting reduces the amount of ground vegetation such as cowberry and bilberry (Andersson et al., 2016), and partially reduces moss cover (Hyvönen et al., 2016). Several studies have suggested that intensive stump harvesting is a threat to forest biodiversity, especially for species dependent on wood (Jonsell and Schroeder, 2014; Victorsson and Jonsell, 2016; Shevlin et al., 2016). Potentially, stump wood for bioenergy is beneficial to mitigating CO_2 emissions (Ortiz et al., 2016) but there are also reports claiming that the opposite is the case (Mäkipää et al., 2015). In addition, in the field of forest protection, stump harvesting has the potential to reduce infections of the root rot fungus *Heterobasidion* by 20–72% in the next generation trees (Cleary et al., 2013). Theoretically, stump harvesting can reduce pine weevil damage and lower the rate of root rot fungus infection. However, for practical applications and to balance the expense of stump harvesting, forest managers have to make proper decisions and identify suitable sites for stump harvesting for better forest management.

In the existing forest management system, it is not possible to reduce the breeding material and size of weevil populations sufficiently with stump harvesting. It seems that by adjusting the time lag between logging and stump extraction, it is possible to some extent to regulate the amount and quality of remaining roots and thus reduce breeding material for pine weevil. The total elimination of root material suitable for the breeding of root dwelling pests is technically difficult and not possible with current stump extraction methods. Total removal of the roots would be highly expensive and ecologically problematic. Instead of this unrealistic method, the rapid removal of cut stumps might be applied to support other control methods for root-feeding pests. It is already well established, and it has also been recently suggested that seedlings planted on mineral soil are relatively safe from weevil damage (Luoranen et al., 2017). Additionally, as the seedlings grow, having large stem diameters reduces pine weevil feeding damage (Nordlander et al., 2011). Recently, Viiri and Luoranen (2017) suggested that deep planted seedlings can reduce pine weevil feeding damage. If stump removal remains the forest manager's methodology in the future, it should be studied whether it is possible to reduce weevil damage more effectively by combining fast stump removal and choosing the planting spots with optimal conditions for seedling survival and growth.

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Figure captions

Fig 1. Estimated marginal means (±S.E.) of the available surface area of roots in stump removal and control sites with long delay and short delay time lag difference between logging and stump extraction.

Fig. 2. Total identified and counted (±S.E.) pupal chambers, larvae of *H. abietis* during laboratory assessment of the roots collected from stump removal and control sites.

Fig 3. Estimated marginal means (±S.E.) of pine weevil larval density in stump removal and control sites with long delay and short delay time lag difference between logging and stump extraction.

Fig 4. Estimated marginal means (±S.E.) of *Hylastes* spp. larval density in stump removal and control sites with long and short delay time lag difference between logging and stump extraction.

Fig 5. Estimated marginal means (±S.E.) of the gnawed area of roots (Long delay and short delay time lag difference between logging and stump extraction x Treatment interaction) by *Hylastes* spp. and *Hylobius abietis.*

Fig 6. Estimated marginal means (±S.E.) of the gnawed area of roots in stump removal and control sites independently by *Hylastes* spp. and *Hylobius abietis*.

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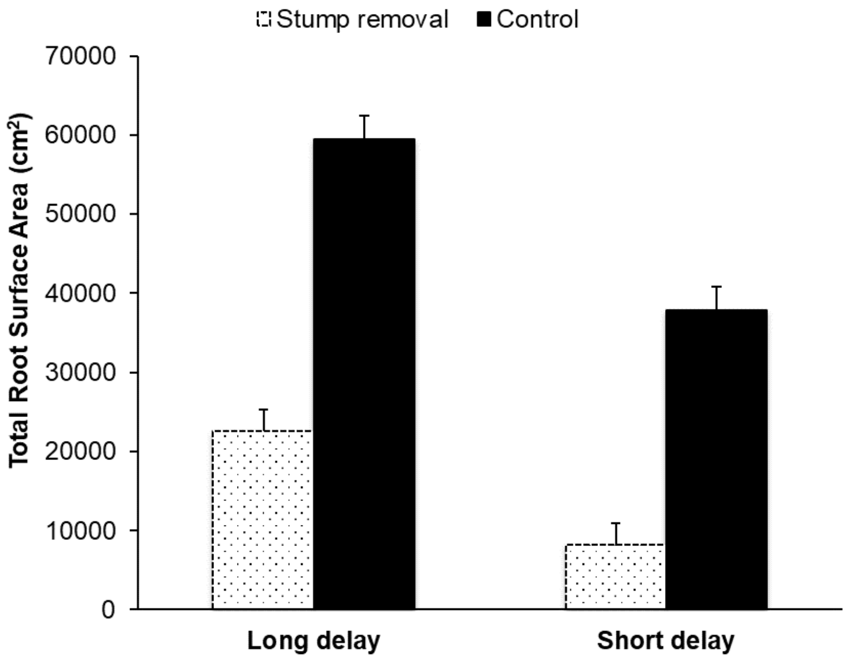
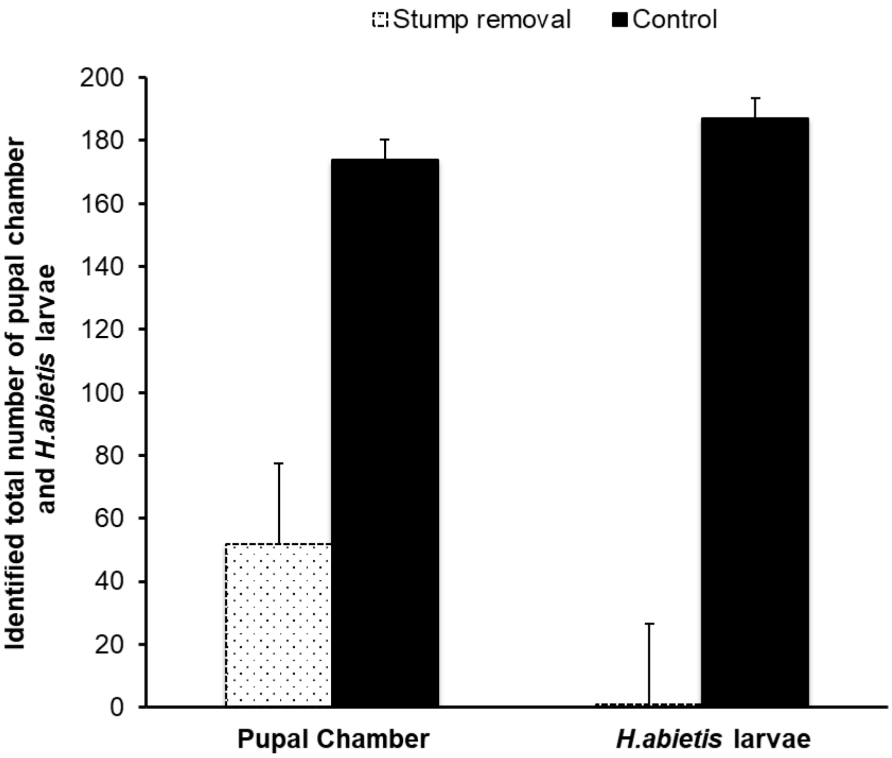
1



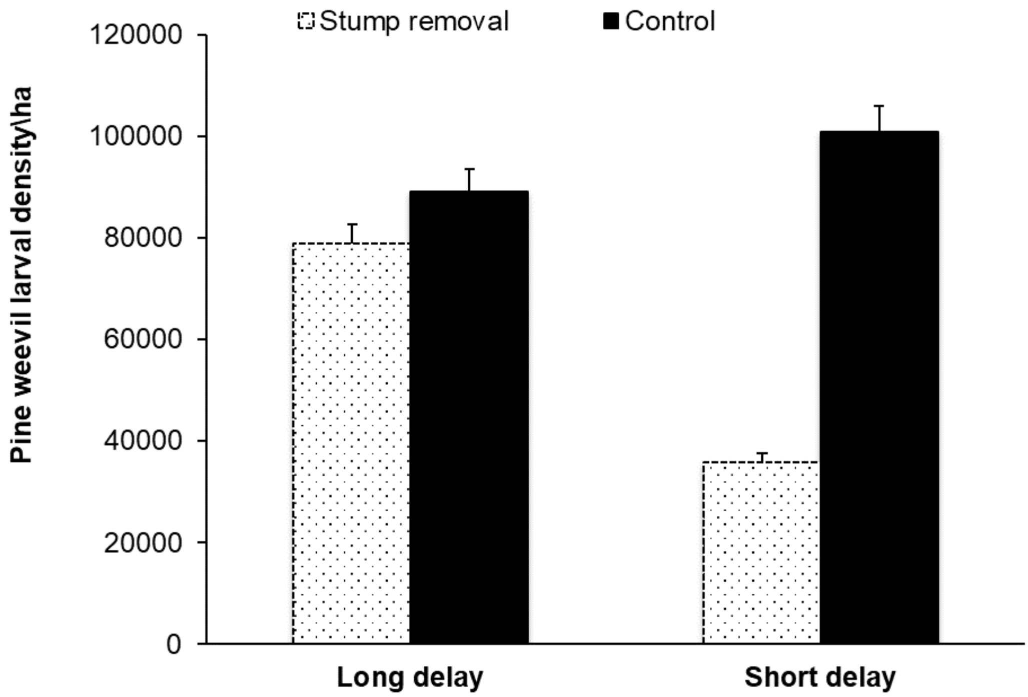
Stump removal
Control
70000
60000
50000
40000
30000
20000
10000
0
Total Root Surface Area (cm²)
Long delay
Short delay

Fig 2



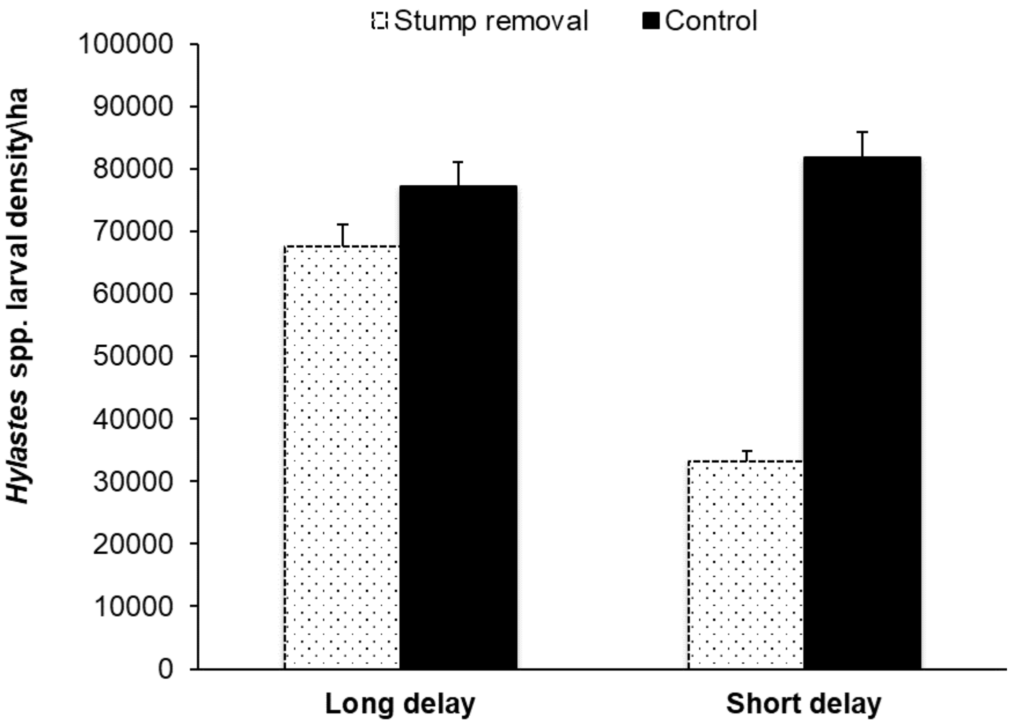
Stump removal
Control
Identified total number of pupal chamber and H.abietis larvae
200
180
160
140
120
100
80
60
40
20
0
Pupal Chamber
H.abietis larvae

3



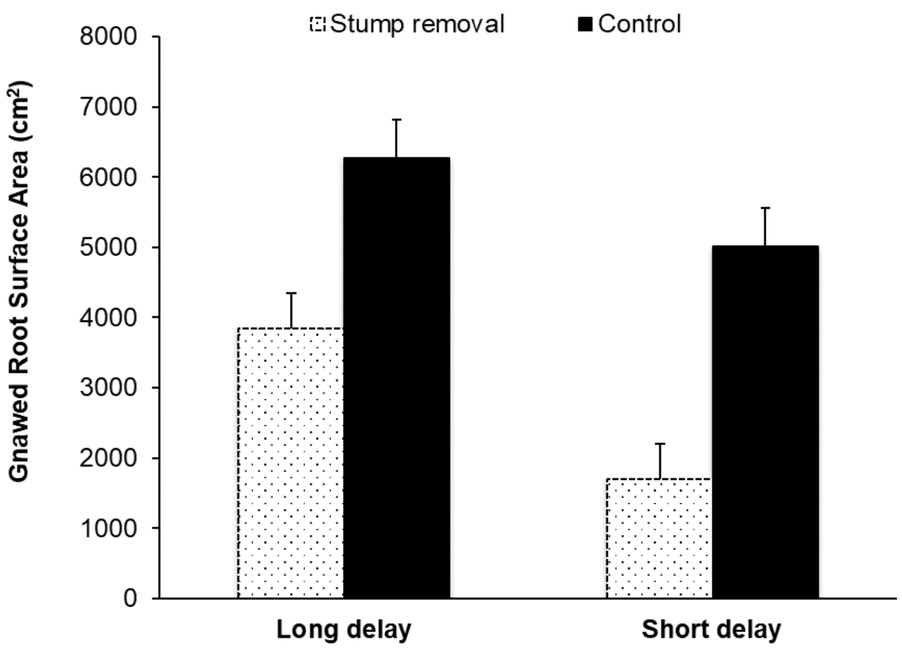
Stump removal
Control
120000
100000
80000
60000
40000
20000
0
Pine weevil larval density\ha
Long delay
Short delay

4



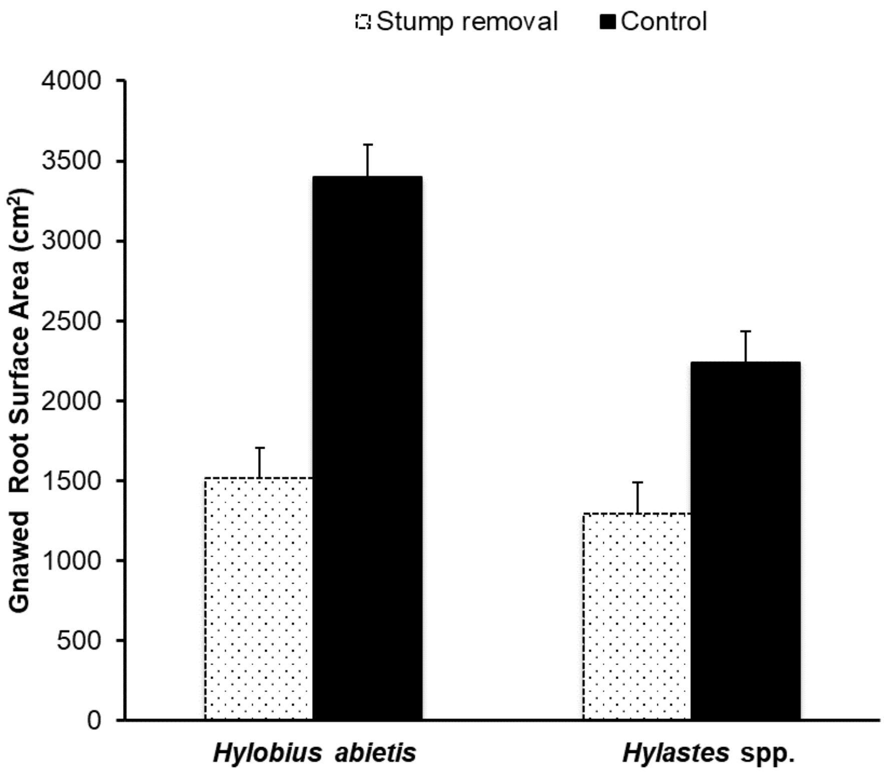
Stump removal
Control
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Hylastes spp. larval density\ha
Long delay
Short delay

Fig 5



Stump removal
Control
Gnawed Root Surface Area (cm²)
8000
7000
6000
5000
4000
3000
2000
1000
0
Long delay
Short delay

6



Stump removal
Control
4000
3500
3000
2500
2000
1500
1000
500
0
Gnawed Root Surface Area (cm²)
Hylobius abietis
Hylastes spp.

Table 1

Description of study sites and temperature sum, dd ºC (threshold > +5 ºC).

Site name	Pair code	Distance between pair sites (km)	Logging volume(m³/ha)	Coordinates	Area, ha	Site type	dd	Logged	Stump extraction	Root sampling date
Uimaharju	P1	35	223	62°56' 30.24", 30° 19' 28.239"	0.73	Damp (*Myrtillus type*)	1066	2009	No	9.–20.8.2012
Katajavaara	P1		237	62°51' 33.396", 29° 50' 32.868"	0.89	Damp (*Myrtillus type*)	1043	2009	2010	8.–16.8.2012
Korpivaara,	P2	55	260	62°50' 22.696", 30° 42' 24.108"	0.91	Damp (*Myrtillus type*)	1026	2009	No	21.–24.8.2012
Havukkavaara 1	P2		287	62°36' 59.054", 30° 9' 35.772"	2.95	Damp (*Myrtillus type*)	1017	2009	2010	6.–14.8.2012
Kokonsalmi	P3	85	234	62°26' 2.793", 28° 52' 58.572"	0.70	Damp (Myrtillus type)	1172	2009	No	31.8.–5.9.2012
Havukkavaara 2	P3		244	62°36' 50.369", 30° 9' 39.412"	3.42	Damp (*Myrtillus type*)	1020	2009	2010	7.–13.8.2012
Rempsu	P4	20	256	62°26' 4.524", 28° 53' 54.41"	1.97	Damp (*Myrtillus type*)	1167	2009	No	11.–14.9.2012
Juurikka	P4		260	62°32' 3.482", 28° 50' 50.81"	1,12	Damp (*Myrtillus type*)	1141	2009	2010	31.8.–5.9.2012

Petrumansalo	P5	15	294	62°26' 34.754", 28° 53' 22.978"	2.93	Damp (*Myrtillus type*)	1154	2009	No	20.–25.9.2012
Juurikkajärvi	P5		298	62°32' 10.792", 28° 51' 0.221"	2.07	Damp (*Myrtillus type*)	1143	2009	2010	17.–19.9.2012
Polvijärvenniemi	P6	30	304	62°24' 44.94", 28° 19' 22.589"	0.92	Damp (*Myrtillus type*)	1215	2010	2010	4.–9.9.2013
Jalaslampi	P6		301	62°23' 10.059", 28° 47' 24.971"	1.19	Rich (*Oxalis-Myrtillus type*)	1179	2010	No	27.9.–2.10.2013
Polvijärvensalmi	P7	30	262	62°24' 45.805", 28° 19' 9.735"	2.23	Damp (*Myrtillus type*)	1215	2010	2010	11.–13.9.2013
Kermansalo	P7		258	62°23' 39.13", 28° 47' 31.512"	0.95	Rich (*Oxalis-Myrtillus type*)	1173	2010	No	19.–26.9.2013
Valkeinen	P8	40	267	62°23' 14.925", 28° 48' 46.041"	0.43	Damp (*Myrtillus type*)	1169	2010	No	9.–14.10.2013
Arhinmäki	P8		265	62°36' 34.767", 28° 39' 37.257"	3.43	Damp (*Myrtillus type*)	1122	2010	2010	15.–18.10.2013

Table 2

Summary of the different root parameters in control, short delay and long delay stump extraction plots

	Control	Short delay stump extraction	Long delay stump extraction
Number of roots/ha (± S.E.)	322 900±1.11	133 600±0.88	292 700±1.60
Diameter of roots cm/ ha, mean(± S.E.)	10.4±0.35	6.7±0.25	6.8±0.19
Surface area of roots cm^2/ ha, mean(± S.E.)	51 546±2615.9	8 001±658.1	22 412±1426.7

Table 3

Results of general linear mixed model analysis of the effect of stump removal on root surface area in soils of forest regeneration sites. Parameters of the model were Treatment (Control, Stump removal), Time lag of stump extraction (Long, short), their interaction term Treatment*Time lag and Logging Volume of total root surface area as continuous covariate of the model

	Df	F-value	P-value
Treatment	11	170.2	0.001
Time lag	11	53.4	0.001
Treatment*time lag	11	9.87	0.009
Logging volume	11	0.58	0.461

Table 4

Results of general linear mixed model analysis of the effect of stump removal on larvae density of *Hylobius abietis* and *Hylastes* spp. Parameters of the model were Treatment (Control, Stump removal), Time lag of stump extraction (Long, short), their interaction term Treatment*Time lag and Logging Volume of total root surface area as continuous covariate of the model

	Pine weevil larvae			*Hylastes* spp. larvae		
	Df	F-value	P-value	Df	F-value	P-value
Treatment (Control, Stump removal)	11	5,6	0.002	11	9,8	0.009
Time lag (Long, short)	11	17	0.108	11	2,2	0.164
Treatment*time	11	3.06	0.014	11	3,8	0.076
Logging volume	11	0.006	0.940	11	0.001	0.970

Table 5

Results of general linear mixed model analysis of the effect of stump removal on total root surface gnawed area by *Hylobius abietis* and *Hylastes* spp. Parameters of the model were Treatment (Control, Stump removal), Time lag of stump extraction (Long, short), their interaction term Treatment*Time lag and Logging Volume of total root surface area as continuous covariate of the model

Total Root Gnawed area			
	Df	F-value	P-value
Treatment (Control, Stump removal)	6.2	32.48	0.001
Time lag (Long, short)	6.6	3.8	0.096
Treatment*time	6	6.1	0.049
Logging volume	10.4	0.6	0.452

Table 6

Results of general linear mixed model analysis of the effect of stump removal on root surface gnawed area separately by *Hylobius abietis* and *Hylastes* spp. Parameters of the model were Treatment (Control, Stump removal), Time lag of stump extraction (Long, short), their interaction term Treatment*Time lag and Logging Volume of total root surface area as continuous covariate of the model

	Root surface area gnawed by Pine weevil			Root surface area gnawed by *Hylastes* spp.		
	Df	F-value	P-value	Df	F-value	P-value
Treatment (Control, Stump removal)	6.1	21	0.004	5.4	14.6	0.011
Time lag (Long, short)	6.6	3.1	0.125	5.9	4.3	0.084
Treatment*time	6.1	3.8	0.099	5.5	2.6	0.160
Logging volume	9.9	0.78	0.398	9.9	0.66	0.435