Logging Operation Damage to Roots of Clear-felled *Picea abies* and Subsequent Spore Infection by *Heterobasidion annosum*

Jonas Rönnberg

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Two studies were carried out to examine the effects of clear-felling operations on stump roots of Norway spruce (*Picea abies* (L.) Karst.). In study I, the number of cases and the degree of damage to stump roots of Norway spruce were investigated on three clear-felled sites in northern and southern Sweden respectively. The cutting was done in winter or spring. A mean of 37 % of the stumps had signs of root damage caused by clear-felling operations. Study II was carried out on two sites in southern and two sites in northern Sweden. The trees were clear-felled in June or July. The frequency of natural infection by *Heterobasidion annosum* (Fr.) Bref. through damaged roots was compared to infection through stump surfaces. The total area of damage on roots was 88 % of the stump surface area. On average, 54 % of the stumps were infected through the stump surface and 19 % through locations of root damage. The root infections, however, were generally small in size as compared to stump surface infections. The study shows that damage to roots at clear-felling may be extensive, but this probably is not of great importance for the efficacy of stump treatment against *H. annosum*.

Keywords Butt rot, clear felling, logging damage, Norway spruce, root rot, stump root infection
Author´s address Swedish University of Agricultural Sciences, Southern Swedish Forest Research Centre, P.O. Box 49, SE-230 53 Alnarp, Sweden
Fax +46 40 462 325 **E-mail** jonas.ronnberg@ess.slu.se
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1 Introduction

Root and butt rot in Norway spruce (*Picea abies* (L.) Karst.) cause severe economic losses to forestry in Scandinavia. *Heterobasidion annosum* (Fr.) Bref. and *Armillaria* spp. are the most common species, of which the former causes the most severe damage (Yde-Andersen 1958, Holmsgaard et al. 1968, Johansson 1980). Establishment of *H. annosum* occurs by spores infecting fresh wounds (Isomäki and Kallio 1974) and stump surfaces (Rishbeth 1951a). The mycelia subsequently spread to healthy trees via root grafts or looser contacts between infected and uninfected roots (Rishbeth 1951a,b, Stenlid 1987). Further, transmission of genets of *H. annosum* between consecutive rotations (Stenlid 1987, Piri 1996) and the build up of infection incidence in subsequent rotations of Norway spruce have been reported (Jørgensen et al. 1939, Low 1958, Kramer 1966, Yde-Andersen 1978, Schönhar 1990, 1997).

Furthermore, Norway spruce stumps infected by spores of *H. annosum* after clear-felling may contribute to the transfer of *H. annosum* in the subsequent rotation (Yde-Andersen 1978). Since treatment of stumps with biological or chemical agents has been successful in preventing spore infection of stump surfaces (Korhonen et al. 1994, Pratt 1994, Brandtberg et al. 1996) and subsequent development of root rot, treatment of stumps at clear-felling may reduce the risk of infection in subsequent rotations. However, clear-felling operations may cause mechanical damage to stump roots, i.e. the exposure of unprotected wood on the roots of stumps. The risk for fungal infection in root wounds on living trees following thinnings has also been shown (Pawsey and Gladman 1965, Nilsson and Hyppel 1968, Dimitri 1969b, Schönhar 1975, 1979, 1995, Andersson 1984, el Atta and Hayes 1987). Numerous cases of damage to stump roots and frequent *H. annosum* spore infection at locations of damage may thus make stump treatment at clear-felling inefficient. No previous investigations, however, have shown the risk of natural spore infection by *H. annosum* on logging-damaged areas of the stump roots of clear-felled Norway spruce. Furthermore, no information on the frequency of logging damage to stumps roots at clear-felling is available.

Two studies were carried out to examine the potentially damaging effects of clear-felling operations on the stump roots of Norway spruce. The first study aimed at quantifying the amount, extension, and degree of logging damage on clear felled Norway spruce. The second study aimed at quantifying the risk of natural spore infection of *H. annosum* to the damaged parts of the stump roots created at clear-felling operations of Norway spruce.

2 Material and Methods

2.1 Study I

Six clear-felled sites were selected, three in southern Sweden (55°N, 13°E) and three in northern Sweden (63°N, 14°E) (Table 1). Norway spruce was the dominating tree species at all sites. The sites were clear-felled during the winter and spring of 1997. Damage to stump roots was caused by either the harvester or the forwarder. At the sites in southern Sweden, the harvesting of felling residues, i.e. the collection of treetops and branches, may have caused additional damage. The sites were investigated during the summer of 1997. At each site, two 40 × 40-meter plots were randomly chosen. Within each square all stumps from clear-felling were registered. The cases of damage were classified as being of a superficial type, in which the bark had been wrenched off the root with no rupture of the exposed outer surface of the wood; or as being of broken-tissue type, in which severe abrasion had lifted and split the wood fibres. The stumps were classified into four groups: (i) undamaged, (ii) less than 25 % of the visible root system with superficial damage, (iii) up to 60 % of the visible root system with superficial damage, or less than 25 % but broken-tissue damage, and (iv) the whole visible root system damaged with a varying degree of superficial and broken-tissue damage. The classification was made due to a supposed increasing risk of infection according to the extension and degree of damage to the root systems (Dimitri 1969a,b, Schönhar 1975). The number of investigated stumps after clear-felling, i.e. after harvesting and forwarding, varied between 53 and 188 stumps per plot (Table 1).

2.2 Study II

Four sites were selected, two in southern Sweden, Fulltofta (55°96'N, 13°39'E), and Maglasäte (55°95'N, 13°30'E), and two in northern Sweden, Fullsjön (63°29'N, 15°57'E), and Åskott (63°16'N, 14°41'E), both situated in forested areas. The soil type was a sandy loamy till, and Norway spruce was the dominating tree species at all sites. To get a heavy natural spore infection, clear-felling was carried out during summertime, i.e. in mid-June for the sites in northern Sweden and at the end of July for the sites in southern Sweden. At all sites the temperature was about 20 °C at the time of felling. The weather was scattered clouds with occasional showers. Damage to the roots was caused by the harvester and by the forwarder. The Fulltofta site in southern Sweden was clear-felled and sampled in 1996. The other sites were clear-felled and sampled in 1997. At each site, immediately after felling, 50 Norway spruce stumps were randomly chosen and marked. The stump diameters were measured. To distinguish natural spore infection on the stump surface from old infection already present in the tree at the time of felling, a disc was cut from the top of the stump immediately after felling. All discs were put in plastic bags and incubated in darkness at 20 °C for 10 days, after which *H. annosum* was identified on the discs by the presence of its conidial stage. Stumps with *H. annosum* were excluded from further studies.

Three months after clear-felling, a final sampling was carried out. Among the healthy stumps, i.e. stumps without infections at stump height at the time of clear-felling, 10 stumps with damage to their root systems were randomly chosen. From the stump surface, a two-centimetre-thick disc was cut. Sites of damage to root systems were carefully excavated and the roots thoroughly brushed. Damaged sections of the roots were cut using chain and hand saws. If the section of damage was greater than 30 cm in length, a 30-cm-long sample was cut from the centre of the area of damage. To ensure that roots were free from old infections and to distinguish old infections from possible new ones, 2-cm-thick control sample discs were cut from the roots 30 cm from each end of the area of damage. If the area of damage extended all the way to the butt, control samples were cut from the root outside the area of damage. All samples were immediately transferred into plastic bags after being cut.

At the laboratory, the damage samples were cut into discs two centimetres thick, using a band saw and transferred into new plastic bags. All sample discs in plastic bags were incubated in darkness at 20 °C for 10 days, after which *H. annosum* was identified by the presence of its conidial stage. If conidiophores of *H. annosum* were found on a control sample, the corresponding whole stump was excluded from the study. In total, three sampled stumps were excluded from the study. The sizes and location of colonies of *H. annosum* in relation to heart or sapwood, identified by the presence of its conidial stage, were registered. Stumps with infected root samples were classified into the damage classes described in study I. From conidiophores on five randomly-chosen disc samples from each site, isolations were made according to Swedjemark and Stenlid (1993). Identification of the isolated strains' intersterility group was made according to Korhonen (1978) and based on the isolated strain's ability to heterokaryotise homokaryotic strains of the S- and P-intersterility groups of *H. annosum*.

2.3 Statistics

In the statistical calculations, all stumps were regarded as independent of each other. Similarly, all cases of damage to roots were regarded as independent. To compare the difference in the number of damaged stumps between northern and southern Sweden, a t-test was carried out. To achieve normality and homogeneity of variance within the data material, i.e. the number of damaged stumps, frequencies were transformed before analysis. The dependent variable, i.e. the proportion X/n where X is the number of affected observations and n the total number of observations, was transformed by arcsine transformation (1) according to Zar (1984):

$$p' = 1/2\left(\arcsin\sqrt{X/(n+1)} + \arcsin\sqrt{X+1/(n+1)}\right) \quad (1)$$

where p' is the transformed frequency.

The difference in number of infected stump surfaces and infected sites of damage was analysed by a 95 % confidence interval. The 95 % confidence interval was calculated using independent samples when both populations have the same underlying variance. A Spearman rank correlation test was done to see if there were correlations between the frequency of infected cases of damage and the size of the damaged area, and between the frequency of infected cases of damage and the distance from the stump surface to the location of damage. The variables used were size and distance correlated with infection. Damage class was not used due to lack of original data for sample stumps with uninfected cases of damage to roots.

Table 1. Frequencies of damages among different damage classes of stumps of clear-felled Norway spruce. "i" is stumps without sites of damage to roots and "iv" is stumps with most severe and frequent sites of damage to roots.

Site	Stumps investigated, no. plot^{-1}	i %	Damage class ii %	iii %	iv %
Fjäl (n)[1]	110	66	18	12	4
Hindrik (n)	188	78	12	9.7	0.3
Skallsjön (n)	121	60	19	17	4
Dammv. (s)[1]	54	45	31	19	5
Enebacksv. (s)	56	44	37	16	3
Sjöbo ora (s)	53	43	38	19	0

[1] (n) or (s) is location of site in northern or southern Sweden

3 Results

3.1 Study I

Altogether, 63 % of the stumps were undamaged (class I). At the sites in northern Sweden 69 % of the stumps were undamaged, whereas at the sites in southern Sweden a significantly ($p < 0.02$) lower proportion (44 %) of the stumps were undamaged. Class II damage was the most common type of damage at all sites and class IV damage least common (Table 1). The frequency of stumps in damage class IV was less than 5 %. A higher frequency of damaged stumps did not lead to a higher frequency of severely damaged stumps.

3.2 Study II

In total, 37 stumps with 76 cases of root-damage were investigated. Mean stump diameter was 36 cm (Table 2). The size of the damage locations ranged between 5 cm^2 and 4320 cm^2. The total damaged area on roots exposed to spore infection by *H. annosum* was 88 % of the total stump surface area investigated.

Natural infection occurred at all sites. Mean infection frequency at stump height was 54 %. Colonies of *H. annosum*, i.e. conidiophores ag-

Table 2. Incidence of *H. annosum* spore infection in logging damage on stump roots of clear-felled Norway spruce. "Stumps" is the number of investigated stumps, where "tot." is the total number of stumps and "inf." is the number of stumps with infection by *H. annosum* spores at the stump surface. "Damage" is the number of investigated logging-damaged areas, totally, "tot." and infected, "inf." "Diameter" is the mean diameter of sampled stumps for the total sample, "tot.", and for stumps with infection in roots, "inf." "Size" is the mean size of the investigated sites of logging damages, totally, "tot.", and infected, "inf." "Distance" is the mean of distances between stump surface and end of damage for the total sample, "tot.", and for infected sites of damage, "inf."

Site	Stumps tot. no.	Stumps inf. no.	Damage tot. no.	Damage inf. no.	Diameter tot. cm	Diameter inf. cm	Size tot. cm^2	Size inf. cm^2	Distance tot. cm	Distance inf. cm
Fullsjön (n)[1]	9	6	17	2	29	31	624	429	70	93
Åskott (n)	10	4	22	2	31	21	557	1016	73	90
Fulltofta (s)[1]	8	8	17	4	45	53	374	77	41	41
Maglasäte (s)	10	2	20	0	40	–	776	–	108	–

[1] (n) or (s) is location of site in northern or southern Sweden

gregated in groups, were found in the outer part of discs, i.e. in the sapwood. The number of infections per stump disc varied between one and ten. Most conidiophore colonies covered an area of about one cm^2. The largest group of conidiophores covered an area of about 10 cm^2. Mean size of infection was 1.5 cm^2.

Infection frequency at logging damaged areas of stump roots was significantly lower (95 % confidence interval) than infection frequencies on stump surfaces, 11 % (Table 2), corresponding to 19 % of the investigated stumps. The Maglasäte site was free from root infection by *H. annosum*. All infections were restricted to one to three discs cut from the damaged area, i.e. approximately colonising a length of 1–5 cm of the site of damage. Mean length of infection in roots was 1.6 cm covering an area of about 0.8 cm^2 on the cross-sectional area of the discs. In all cases except one, a stump infected through root damage was also infected through the stump surface. Normally, infection by *H. annosum* was found in only one damaged root, even if several roots of the same stump were damaged. Only one stump was infected through two areas of root damage. Five of the stumps with infected root damage had damage corresponding to the second damage class, one to the third and one to the fourth class. Healthy stumps investigated for spore infection were distributed in damage classes equally to the stumps in study I. No exact figures were available though. None of the broken-tissue damage investigated was infected by *H. annosum*.

In comparing equal areas of stump surface and root damage, the relative number of infections was 1 on the stump surface and 0.45 on sites of root damage. An equal area exposed to spore infection by *H. annosum* on stump surfaces and locations of root damage would therefore correspond to 21 % of the investigated stumps with infection in cases of damage. Mean size of infection in root discs was 59 % of mean size infection on stump surface. The total area of infection on root discs was 5.9 % of total area of infection on stump surface. The number of *H. annosum* conidiophore colonies in roots was 10 % of that on stump surface. There was no correlation between the size of the damaged area, the distances from stump surface to the end of the damaged area, and spore infection by *H. annosum* in the damaged area ($r = -0.13$, $p = 0.27$ and $r = -0.057$, $p = 0.63$ respectively).

At the two sites in northern Sweden the S-type of *H. annosum* was present. In southern Sweden at the Fulltofta site the S-type of *H. annosum* was present, and at the Maglasäte site the P-type of *H. annosum* was present.

4 Discussion

The most important finding in this study is the difference in infection frequency between stump surfaces and root areas of Norway spruce damaged by logging. The present study implies that damaged root areas will be infected significantly less by spores of *H. annosum* than the surfaces of stumps at clear-felling. This may be an effect of different moisture content in stump surfaces and in locations of damage to roots caused by the felling operation (Meredith 1960). Bendz-Hellgren and Stenlid (1998) have shown that differences in moisture content in clear-felled Norway spruce stump surfaces have importance for successful germination of *H. annosum* spores. This is supported by results reported for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (Redfern 1993). High moisture content causes oxygen deficiency and a decreased ability for *H. annosum* to detoxicate phenolic compounds and utilise lignin (Cwielong et al. 1993). Accordingly, the most suitable place at the stump surface for germination is normally confined to the area between heart and sapwood. Therefore, it is possible that the superficial wood of root-damaged areas in this study had unsuitable moisture conditions. According to Nilsson and Hyppel (1968) and Dimitri (1969a), broken-tissue damage on roots made by an axe had a greater probability for a successful infection by *H. annosum* than superficial damage. This may have been due to more suitable moisture content in areas of defined broken-tissue damage. However, in this study, broken-tissue damage, caused by logging machines, was characterised by the splitting of wood fibres. It is likely that the moisture content in damage areas with split wood fibres will change rapidly, and therefore be unfavourable to the establishment of *H. annosum*. This might explain why no infections were found in broken-tissue damage.

It is also possible that the orientation of wood fibres and the germination of spores can explain the difference in spore infection frequency of the stump surface and sites of damage on roots. At the stump surface, after spores have germinated, *H. annosum* is able to grow along the wood fibres. In superficial sites of damage on roots, *H. annosum* has to grow across the fibre direction to get into the wood. The growth across the fibre direction is slow and may slow down the development of infection (Rennerfelt 1946). This possibly makes *H. annosum* vulnerable to competition from other fungi or to extreme climatic conditions.

The weather conditions were about the same at all sites at the time of clear-felling. However, differences in weather conditions during the months after felling may have caused differences in the establishment of *H. annosum* in locations of root damage. At the Maglasäte site in southern Sweden, where there were no infections in the damaged root areas, climate data for August 1997 indicated warmer and drier weather than average for the previous 30 years (SMHI 1997). It is possible that the weather conditions at the time caused low moisture content in stumps and thereby inhibited the establishment of *H. annosum*. For other sites, climatic data was about normal (SMHI 1996, 1997), and the climatic differences between sites were regarded as less important to the result.

In this study there was no correlation between the size of an area of logging damage on the stump root and the incidence of spore infection by *H. annosum* in it. According to Pawsey and Gladman (1965) and Schönhar (1975), there should be a greater risk for fungal infection in large areas of damage than in small ones. However, these studies were carried out on damaged areas of residual trees in thinned stands. Despite a lack of correlation between the size of damaged area and infection frequency, in this study most stumps with infected roots belonged to the second damage class. The damage class is, however, not only a description of the size of a damaged area but also of the number of areas of damage and their severity, i.e. superficial damage versus broken-tissue damage. Also, the number of stumps in different damage classes investigated for spore infection corresponds with the number of stumps in different damage classes in the field. According to study I only a few stumps got class four damage but numerous got class two damage. Therefore it seems most important to reduce the number of stumps with class two damage.

The number of stumps at clear-felling was higher in northern Sweden, but the number of damaged stumps was significantly higher in southern Sweden. The latter is most likely an effect of the harvesting of felling residues at the sites in southern Sweden. Furthermore, because the sites were clear-felled during winter and spring, the thicker snow cover in northern Sweden may have protected stumps from root damage.

Due to the great amount of damage to the stump roots of clear-felled Norway spruce, as shown in study I, and due to the 21 % risk of stump infection of *H. annosum* in logging-damaged areas, treatment of stumps without butt rot as a measure of preventing spore infection by *H. annosum*, and subsequent transfer of infection to the next rotation, can be questioned. However, not all areas of damage on infected stumps will get infected, and hence the possible infection source in the next rotation may be overstated. Additionally, in damaged root sections in this study, areas of infection were small and number of infections low. It is possible that infections of *H. annosum* in roots will die and not serve as a potential infection source in the next rotation (Dimitri et al. 1971). Furthermore, it is possible that infections by *H. annosum* will be unable to expand in the wood due to competition from later successional decomposing fungi (Rishbeth 1950, Käärik and Rennerfelt 1957, Holmer and Stenlid 1993, 1997). In comparison, infections at the stump surface were numerous and covered a relatively larger area. According to el Atta and Hayes (1987) and Schönhar (1995), *H. annosum* is seldom found in extraction wounds at thinnings. It is likely that the infection of stump surfaces is much more important than infection of logging-damaged areas in the build-up of a potential infection source for transfer of infection to the subsequent rotation. In conclusion, though spores of *H. annosum* infect some logging-damaged areas, treatment of stumps of clear-felled Norway spruce still seems effective in reducing the possible infection source of *H. annosum* to the subsequent tree rotation.

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