Stump Removal to Control Root Rot in Forest Stands. A Literature Study

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Tree stumps are expected to be increasingly used for energy production in Fennoscandia, thus environmental consequences of stump removal from forest land must be assessed. Aim of this work was to compile available data on the efficacy of stump removal in eradication of root rot fungi (*Heterobasidion*, *Armillaria*, and *Phellinus*), and to review its potential impacts on establishment and productivity of next forest generation. Site disturbance and some technical and economical aspects are discussed, and needs for future research outlined in northern European context. The review demonstrates that stump removal from clear-felled forest areas in most cases results in, a) reduction of root rot in the next forest generation, b) improved seedling establishment, and c) increased tree growth and stand productivity. Observed disturbances caused to a site by stumping operations are normally acceptable. The available data strongly suggests that possibly many (if achievable, all) rot-containing stumps must be removed during harvesting of stumps. Provided equal availability, the priority should be given for stump removal from root rot-infested forest areas, instead of healthy ones. As most studies were done in North America and Britain, several questions must be yet answered under Fennoscandian conditions: a) if and to which extent the conventional stump removal for biofuel on clear-felled sites could reduce the occurrence of *Heterobasidion* and *Armillaria* in the next forest generation, b) what impact is it likely to have on survival of replanted tree seedlings, and c) what consequences will there be for growth and productivity of next forest generation.

Keywords *Armillaria*, biofuel, forest disturbance, *Heterobasidion*, *Phellinus weirii*, stand growth
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1 Introduction

In Finland and Sweden, biomass from forests has been one of the main sources for renewable fuel. Until recently, mainly the residues from forest industries (e.g. sawdust, bark and black liquor) and logging residues (e.g. branches, tops and damaged wood) were increasingly being used for energy production (Saarinen 2006, Egnell et al. 2007). As the growing market is expected to consume even more biomass in the future, during the last years large interest has been addressed to stumps, which at harvested forest sites offer biomass resource equally large or larger than the logging residues (von Hofsten 2006, Egnell et al. 2007). Yet, the environmental consequences of stump removal must be assessed and evaluated, which might be both negative and positive. Sanitation of forest sites from root rot and improved growth conditions for the newly established plantations could be among the potentially positive consequences, which could also affect the cost effectiveness of stump harvesting. The aim of the present work was to compile available quantitative data on the efficacy of stump removal in eradication of root rot fungi (e.g. *Heterobasidion*, *Armillaria*, and *Phellinus*) from infested forest sites, and to review the potential impacts it might have on site quality, including establishment and productivity of replanted stand of next generation. In addition, some technical and economical aspects are discussed, and needs for future research are outlined, particularly in a northern European context.

2 Biology of Root Rot Fungi and Stump Removal

Forest areas infested by root rot fungi *Armillaria* spp., *Heterobasidion* spp. and *Phellinus weirii* (Murr.) Gilb. (the latter absent from Europe) comprise millions of hectares around the world, consisting of chronically and progressively diseased stands, where these fungal pathogens each year reduce timber production by millions of cubic meters of wood and represent a major strategic problem for the practical forestry on a world-wide scale (Morrison et al. 1991, Shaw and Kile 1991, Thies and Sturrock 1995, Woodward et al. 1998). Apart from wood production, root disease fungi also influence other stand management objectives, such as stability, wildlife, water, recreation, or viewscapes. Yet, in many areas today forest management practices have increased the incidence and severity of the root diseases to levels above those that might be acceptable for sustainable forestry (Sturrock 2000).

Although those fungi represent different species, their biology and ecology are in essential parts similar, and their spread is to a large extent enhanced by forest management. In particular, tree stumps, cut during forestry operations, play the major role in life cycles of the pathogens: 1) the stumps are primarily infected by airborne basidiospores and/or soilborne mycelium of the fungi; 2) fungal mycelia colonise stumps and grow out from those infecting the neighbouring trees, thus establishing expanding disease centres; 3) in stumps and root systems, the fungi remain viable for decades, thus transferring the root rot to subsequent forest generations, either via direct contact of roots or via increased infection risk due to presence of sporocarps; 4) the combined effect of 1, 2 and 3 leads to constant build up of the inoculum on infested sites and increase of root rot in newly grown stands; 5) on the diseased stumps, the sporocarps of the pathogens are frequently developed, and produce vast amounts of basidiospores for subsequent airborne spread and potential infections both locally and over large (up to 10–100 km) distances (Morrison et al. 1991, Shaw and Kile 1991, Thies and Sturrock 1995, Woodward et al. 1998).

Consequently, over the years stump removal, or “stumping” (Thies and Sturrock 1995), was suggested worldwide in numerous texts on forest pathology as a measure for control of root rot diseases caused by *Heterobasidion* spp., *Armillaria* spp., *Phellinus weirii* (in North America) and, to less extent, *Inonotus tomentosus* (Fr.) Karst. (in North America), even without presenting any quantitative evaluation of the efficacy of the method (Hartig 1878, Rostrup 1880, 1883, 1902, Sauer 1917, Anderson 1921, 1924, Belyaev 1939, Ankudinov 1951, Klyuschnik 1955, Sokolov 1964, Vasiliauskas 1970, Pawsey 1973, Kuhlman et al. 1976, Morrison 1976, 1981, Wallis 1976, Roth et al. 1977, 1980, Roth and Rolph

1978, Shaw and Roth 1978, 1980, Wargo and Shaw 1985, Shaw et al. 1989, Sturrock et al. 1994, Lewis et al. 2000). But in fact, the available comparative analyses of different root rot control methods (chemical, biological, integrated, silvicultural) did conclude, that stump removal, although expensive (but see Section 10 Economical Aspects), is the most effective method for control and eradication of *Heterobasidion*, *Armillaria* and *Phellinus* root rot on infested forest sites (Greig and McNabb 1976, Shaw and Roth 1978, 1980, Greig 1980, Thies 1984, van der Pas and Hood 1984, Morrison et al. 1991, Thies and Sturrock 1995, Sturrock 2000, Greig et al. 2001, Gibbs et al. 2002).

3 Root Rot Incidence in the Next Forest Generation

Table 1 summarises available studies on root rot (*Armillaria*, *Heterobasidion*, and *Phellinus weirii*) incidence in the next forest generation planted on stumped sites. The studies represent wide variety of geographic areas, site conditions, stand types, experimental design, techniques and equipment. Despite that, the results are to large extent consistent and demonstrate clearly that the stump removal has, to various extent, reduced the occurrence of root rot in the next forest generation (Figs. 1, 2 & 3). Thus, among a total of eighteen trials for reduction of *Armillaria*, in fifteen stump removal had considerably decreased the incidence of the pathogen in next rotation stand, while in three it had low or no impact (Table 1). Among a total of ten trials for reduction of *Phellinus weirii*, in nine stump removal has decreased its incidence in next rotation, and in only one of those it had no impact, as the disease was not observed neither on treated nor on control plots (Table 1).

For *Heterobasidion*, among a total of 32 trials investigated, nineteen reported the decrease of the pathogen in next rotation, in ten there was low or no impact, but three trials showed the increase of the disease following stump removal (Table 1). Yet, among those thirteen trials described to have negative, low or no impact, twelve represent an early 1914 experiment by Bornebusch and Holm (1934) (Table 1, Fig. 2), in which stump removal was done manually and the considerable portion of large decayed roots might have been left in the soil, thus contributing to persistence and subsequent transfer of the pathogen (Yde-Andersen 1970). In addition, no stump treatment was done as this aspect of the infection biology of *H. annosum* was not yet clear. Thus the effect of stumping

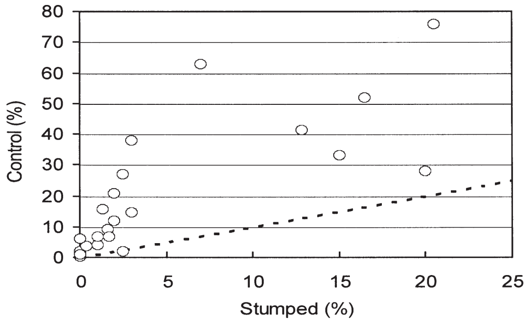

Fig. 1. Impact of stump removal on incidence of *Armillaria* root rot in next forest generation. Each circle shows the proportion of infected trees on stumped vs. control plots, observed in trials that are presented in the Table 1. Dotted line indicates level of infection at which stumping effect on disease incidence equals zero.

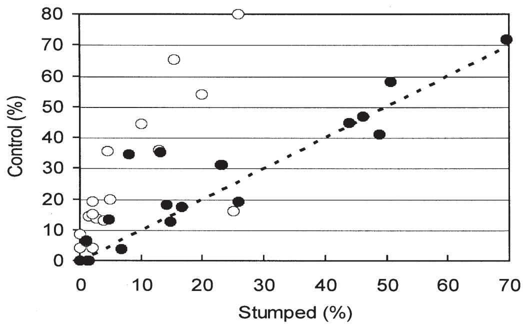

Fig. 2. Impact of stump removal on incidence of *Heterobasidion* root rot in next forest generation. Each circle shows the proportion of infected trees on stumped vs. control plots, observed in trials that are presented in the Table 1. Filled circles represent early experiment by Bornebusch and Holm (1934), where the stumps were dug out manually. Dotted line indicates level of infection at which stumping effect on disease incidence equals zero.

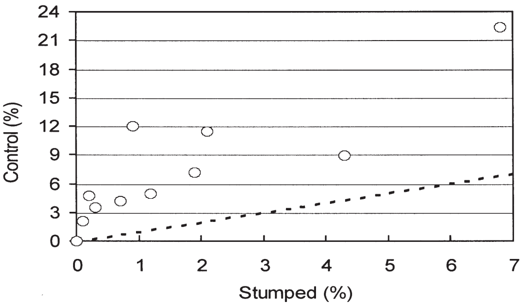

Fig. 3. Impact of stump removal on incidence of *Phellinus weirii* root rot in next forest generation. Each circle shows the proportion of infected trees on stumped vs. control plots, observed in trials that are presented in the Table 1. Dotted line indicates level of infection at which stumping effect on disease incidence equals zero.

may have been partly off set by establishment of the pathogen on stumps of the new generation. But even so, the results for *Picea abies* and *Pinus sylvestris* showed considerable disease reduction, from 31.2% to 23.3%, and from 34.5% to 8.5%, respectively (Bornebusch and Holm 1934, Table 1). Moreover, also the last trial with negative results for next generation *Larix* sp. (Peace 1954, c.f. Hyppel 1978, Table 1) was known for crude removal, which might be the reason also for comparatively high infection rates observed in next generation of *Pinus sylvestris* (Phillips 1963, Greig and Burdekin 1970, Greig and Low 1975, Table 1; see Section 4 Thoroughness of the Removal).

However, when data in the Table 1 reflects tree mortality (in brackets) it must be remembered that this demonstrates only the lowest limit of the occurring infections on a given site, as there will always be a portion of trees that are infected, but not killed by the disease. In particular, this is shown by the study of Self and MacKenzie (1995), where the numbers of *Armillaria*-killed and *Armillaria*-infected trees on de-stumped sites differed 7- to 50-fold, and on control sites, 3- to 8-fold (Table 1). The similar trend was observed for both *Armillaria* and *Heterobasidion* in experimental trials conducted by Greig et al. (2001). For example, mortality of 18–20 year-old *Picea sitchensis* and *Pseudotsuga menziesii* from *Heterobasidion* on sites with no removal was 1% and 2%, but actual infection rates at those sites comprised 15% and 13%, respectively (Table 1). This clearly indicates that also in other related studies real infection rates (checking those would be highly labour consuming) are much higher than the actually observed mortality. Moreover, as the experiments summarised in the Table 1 cover only a fraction of stand rotation time (2–30 years) one might expect that the infections will increase in later stages of stand development.

It is obvious from the studies that stump removal does not result in the complete eradication of any of the root rot fungi (Table 1). Yet, Greig (1980) pointed out that the object of stumping is not to completely eradicate root disease, but to reduce its effect to a level that can be tolerated. As the managed stands are known otherwise to steadily accumulate the infection potential of *Armillaria*, *Heterobasidion* and *Phellinus weirii* in root systems and stumps (Shaw and Kile 1991, Thies and Sturrock 1995, Woodward et al. 1998), stump removal therefore seems to be an effective preventive measure against the build-up of infections of the root rot fungi, and can be considered as a long-term management strategy of forest land.

In order to illustrate this, we compared mean root rot incidence percentages on stumped and control sites from all available trials (Table 1) using paired t-tests. Thus, mean (± sd) incidence of *Armillaria* spp. in control non-stumped sites was 21.1 ± 21.5%, while in stumped sites only 5.2 ± 6.9%, and the t-test between the two values was significant at $p = 0.0002$. Mean incidence of *Heterobasidion* spp. in non-stumped sites was 24.9 ± 21.5%, and on control sites 14.5 ± 17.2%, the t-test being significant at $p = 0.00009$ (this despite the highly variable results from the early trials by Bornebusch and Holm (1934)). For *Phellinus weirii*, the respective values on stumped and control sites were 7.4 ± 6.2% and 1.7 ± 2.1%, and the t-test was significant at $p = 0.002$. The overall effect of stump removal on root rot on disease occurrence, based on mean incidence on stumped and control sites, and calculated as,

$$\text{Effect} = [\text{Control} - \text{Stumping}] / \text{Control} \times 100 \qquad (1)$$

comprised 75.3% for *Armillaria* spp. (after 2–31 years; Table 1), 41.8% for *Heterobasidion* spp.

Table 1. Impact of stump removal on root rot incidence in the next forest generation.

Clear-felled stand		Next generation stand				Location	Source
Species	Infection (mortality)%	Species	Age, years	Infection (mortality) %, site stumped	non-stumped		
		***Armillaria* spp., incidence decreased**					
Picea sitchensis (Bong.) Carr.	80	*Abies procera* Rehd.	18–20	(2) 2	(8) 12	Wales	Greig et al. 2001
	Same trial, follow up		30–31	1	4		
Pseudotsuga menziesii (Mirb.) Franco	n.a. a)	*Larix occidentalis* Nutt.	19	(2.5)	(27.0)	British Columbia	Morrison et al. 1988
Pseudotsuga menziesii	n.a.	*Picea engelmannii* Parry ex Engelm.	19	(1.6)	(9.4)	British Columbia	Morrison et al. 1988
Picea sitchensis	80	*Picea sitchensis*	18–20	(2) 7	(28) 63	Wales	Greig et al. 2001
	Same trial, follow up		30–31	20	28		
Picea sitchensis	80	*Pinus contorta* Dougl. ex Loud.	18–20	(2) 3	(34) 38	Wales	Greig et al. 2001
	Same trial, follow up		30–31	1	7		
Pseudotsuga menziesii	n.a.	*Pinus contorta*	19	(1.3)	(15.8)	British Columbia	Morrison et al. 1988
Pinus ponderosa Dougl. ex Laws.	n.a.	*Pinus ponderosa*	21	2.5–23	34–49	Washington	Roth et al. 2000
Beilschmiedia tawa (Hook. f.) Kirk.	n.a.	*Pinus radiata* D.Don	2	15	33	New Zealand	Shaw and Calderon 1977
Native hardwoods	n.a.	*Pinus radiata*	4	(2)	(19–23)	New Zealand	van der Pas and Hood 1984
Pinus ponderosa	(8)	*Pinus radiata*	4	(0–5) 10–31	(10–22) 67–85	New Zealand	Self and MacKenzie 1995
Indigenous forest	n.a.	*Pinus radiata*	5	(12–21)	(52)	New Zealand	van der Pas 1981
Pseudotsuga menziesii	n.a	*Pseudotsuga menziesii*	14	(1.7)	(6.7)	British Columbia	Thies and Russell 1984
Pseudotsuga menziesii	n.a.	*Pseudotsuga menziesii*	19	(3.0)	(14.8)	British Columbia	Morrison et al. 1988
Pseudotsuga menziesii	n.a.	*Thuja plicata* Donn. ex D.Don	19	(0.0)	(2.1)	British Columbia	Morrison et al. 1988
Conifers	n.a.	conifers	19	(<0.5)	(3.6)	British Columbia	S.Zeglen, c.f. Sturrock 2000
		***Armillaria* spp., low or no impact**					
Pseudotsuga menziesii	n.a.	*Betula papyrifera* Marsch.	19	(0.0)	(0.4)	British Columbia	Morrison et al. 1988
Pseudotsuga menziesii	n.a	*Pseudotsuga menziesii*	10	(2–3)	(2)	British Columbia	Wass and Smith 1997
Picea sitchensis	80	*Pseudotsuga menziesii*	18–20	(0) 0	(5) 6	Wales	Greig et al. 2001
	Same trial, follow up		30–31	0	1		

Table 1 continued.

Clear-felled stand		Next generation stand				Location	Source
Species	Infection (mortality)%	Species	Age, years	Infection (mortality) %, site stumped	non-stumped		
		***Heterobasidion* spp., incidence decreased**					
Picea abies (L.) H.Karst.	74	*Abies concolor* Lindl. ex Hildebr.	11–19	4.7	13.3	Denmark	Bornebusch and Holm 1934
Picea abies	74	*Abies grandis* (Dougl. ex D.Don) Lindl.	11–19	13.2	35.1	Denmark	Bornebusch and Holm 1934
Picea sitchensis	80	*Abies procera*	18–20	(1) 1	(5) 6	Wales	Greig et al. 2001
	Same trial, follow up		30–31	2	4		
Picea abies	74	*Fagus sylvatica* L.	11–19	1.1	6.5	Denmark	Bornebusch and Holm 1934
Picea abies	74	*Larix decidua* Mill.	11–19	50.8	58.1	Denmark	Bornebusch and Holm 1934
Picea abies	74	*Picea abies*	11–19	8.1	34.5	Denmark	Bornebusch and Holm 1934
Picea abies	17–84	*Picea abies*	25–28	1–2	12–17	Sweden	Stenlid 1987
Pinus sylvestris L.	n.a.	*Picea sitchensis*	11	2.6	13.8	England	Peace 1954; c.f. Hyppel 1978
Picea sitchensis	80	*Picea sitchensis*	18–20	(0) 2	(1) 15	Wales	Greig et al. 2001
	Same trial, follow up		30–31	2	19		
Picea abies	74	*Pinus contorta*	11–19	22.9	31.2	Denmark	Bornebusch and Holm 1934
Picea sitchensis	80	*Pinus contorta*	18–20	(0) 0	(1) 4	Wales	Greig et al. 2001
	Same trial, follow up		30–31	1	6		
Pinus sylvestris	17	*Pinus nigra* J.F.Arnold	18	(15.4)	(65.2)	England	Greig and Low 1975
P.sylvestris, P.nigra	n.a.	*Pinus nigra*	20	(2–7)	(18–53)	England	Gibbs et al. 2002
Pinus sylvestris	n.a.	*Pinus nigra*	30	(10)	(37–52)	England	Gibbs et al. 2002
Pinus sylvestris	17	*Pinus sylvestris*	6	(13)	(36)	England	Phillips 1963
	Same trial, follow up		11	(20)	(54)		Greig and Burdekin 1970
	Same trial, follow up		18	(23.8) 25.8	(58.9) 79.9		Greig and Low 1975
Pinus sylvestris	n.a.	*Pinus sylvestris*	8	(0.0)	(0.5–16.9)	Ukraine	Belyi and Alekseyev 1980
Picea abies	74	*Pinus sylvestris*	11–19	23.2	31.2	Denmark	Bornebusch and Holm 1934
Pinus sylvestris	n.a.	*Pinus sylvestris*	27–30	(0.0–2.2)	(0.0–12.7)	Belarus	Raptunovich 1988
Picea sitchensis	80	*Pseudotsuga menziesii*	18–20	(1) 4	(2) 13	Wales	Greig et al. 2001
	Same trial, follow up		30–31	5	20		

Table 1 continued.

Clear-felled stand		Next generation stand				Location	Source
Species	Infection (mortality)%	Species	Age, years	Infection (mortality) %, site stumped	non-stumped		
		***Heterobasidion* spp., incidence increased**					
Pinus sylvestris	n.a.	*Larix* sp.	11	(25)	(16)	England	Peace 1954, c.f. Hyppel 1978
Picea abies	74	*Pinus nigra*	11–19	25.9	19.3	Denmark	Bornebusch and Holm 1934
Picea abies	74	*Pseudotsuga menziesii*	11–19	48.8	41.1	Denmark	Bornebusch and Holm 1934
		***Heterobasidion* spp., low or no impact**					
Picea abies	74	*Abies alba* L.	11–19	1.4	0.0	Denmark	Bornebusch and Holm 1934
Picea abies	74	*Abies nordmanniana*	11–19	0.0	0.0	Denmark	Bornebusch and Holm 1934
Picea abies	74	*Betula pubescens* Ehrh.	11–19	16.7	17.4	Denmark	Bornebusch and Holm 1934
Picea abies	74	*Betula pendula* Roth.	11–19	14.8	12.6	Denmark	Bornebusch and Holm 1934
Picea abies	74	*Larix leptolepis* (Sieb. & Zucc.) Gordon	11–19	46.2	46.9	Denmark	Bornebusch and Holm 1934
Picea abies	74	*Picea sitchensis*	11–19	69.6	71.8	Denmark	Bornebusch and Holm 1934
Picea abies	74	*Pinus ponderosa*	11–19	14.2	18.1	Denmark	Bornebusch and Holm 1934
Picea abies	74	*Populus canescens* (Aiton) Sm.	11–19	44.0	44.8	Denmark	Bornebusch and Holm 1934
Picea abies	74	*Quercus rubra* L.	11–19	6.7	3.6	Denmark	Bornebusch and Holm 1934
Picea abies	74	*Quercus robur* L.	11–19	1.2	0.0	Denmark	Bornebusch and Holm 1934
		***Phellinus weirii*, incidence decreased**					
Pseudotsuga menziesii	n.a.	*Pseudotsuga menziesii*	14	(0.1)	(2.1)	British Columbia	Thies 1984
Pseudotsuga menziesii	60–70	*Pseudotsuga menziesii*	19	(0.2)	(4.7)	British Columbia	Morrison et al. 1988
Pseudotsuga menziesii	n.a.	*Pseudotsuga menziesii*	10	(1.2)	(5.0)	Oregon	Thies et al. 1994
	Same trial, follow up		23	(2.1)	(11.4)		Thies and Westlind 2005
Abies grandis	n.a.	*Pseudotsuga menziesii*	23	(0.7)	(4.2)	Oregon	Thies and Westlind 2005
Pseudotsuga menziesii	n.a.	*Pseudotsuga menziesii*	23	(0.3)	(3.5)	Oregon	Thies and Westlind 2005
Pseudotsuga menziesii	n.a.	*Pseudotsuga menziesii*	25	(1.9)	(7.2)	Oregon	Thies and Westlind 2005
Pseudotsuga menziesii	n.a.	*Pseudotsuga menziesii*	27	(6.8)	(22.3)	Washington	Thies and Westlind 2005
Conifers	n.a.	conifers	19	(3.6–5.0)	(8.2–9.6)	Washington	K.Russell, c.f. Sturrock 2000
Conifers	n.a.	conifers	21	(0.9)	(12.0)	British Columbia	Sturrock 2000
		***Phellinus weirii*, low or no impact**					
Pseudotsuga menziesii	60–70	*Pinus contorta*	19	(0.0)	(0.0)	British Columbia	Morrison et al. 1988

a) Quantitative data not available, but in most cases the infection levels were classed as "heavy".

(after 6–31 years), and 66.1% for *Phellinus weirii* (after 10–27 years).

To date, the most comprehensive research on root rot management by stump removal has and is being done in conifer forests of northwestern USA and British Columbia, and in pine plantations in New Zealand and Great Britain (Table 1). In Britain, root rot management by stump removal has been mainly focused on eradication of *Heterobasidion* root rot in stands of *Picea sitchensis*, *Pinus sylvestris* and *Pinus nigra*. There, after a series of long-term experiments it was concluded that only through stump removal the adequate control of the pathogen can be achieved in second rotation plantations (Greig and Burdekin 1970, Greig and Low 1975, Greig and McNabb 1976, Greig 1980, 1984, Gibbs et al. 2002). Although the studies in other part of Europe are scarce, those are in good agreement with the British studies. Thus, in Ukraine and Belarus the stump removal in *Heterobasidion* infested sites consistently resulted in decrease of root rot in subsequent generations of *Pinus sylvestris* (Belyi and Alekseyev 1980, Raptunovich 1988), and the similar was observed in the only Swedish trial with *Picea abies* (Stenlid 1987).

4 Thoroughness of the Removal

During many studies in Canada and north-western USA extracted stumps were not removed from the sanitised sites, but left up-ended in or close to stump craters to dry out, as this was effective to eradicate from the substrate such pathogens as *Armillaria*, *Phellinus weirii* and *Inonotus tomentosus* (Thies 1984, Bloomberg and Reynolds 1988, Thies 1987, Thies and Nelson 1988, Smith and Wass 1989, 1991, 1994, Hedin 1993, Thies et al. 1994, Woods 1996, Thies and Westlind 2005). Moreover, this was preferred to windrowing and even recommended in order to reduce machine travel over the ground and, consequently, site disturbance (Smith and Wass 1991, 1994, Wass and Smith 1997; see Section 5 Site Disturbance).

By contrast, lifting, turning upside-down, and leaving on clear-felled sites *Heterobasidion*-infested stumps had no effect on the occurrence of the disease in the next generation of conifers as compared with control sites where stumps were left intact (Kurkela 2000). Moreover, as the fungus following felling produces sporocarps on stumps (Vasiliauskas et al. 2002) and cull pieces of infested trunks, this can considerably increase local production of airborne spores of the pathogen (Müller et al. 2007). It is known that primary infection by *Heterobasidion* in a particular stand to a large extent depends on the frequency of its sporocarps in the neighbouring forests (Woodward et al. 1998). Therefore, differently from other root rot fungi, the collecting and removing of *Heterobasidion*-infected stumps and other aboveground logging residues from the harvested forest areas would always be advisable unless thorough stump treatment was carried out at all thinnings and clearcuts of the new stands.

According to Morrison et al. (1991), inoculum longevity and infection potential of *Armillaria* and *Phellinus weirii* are greatest in the lower part of the stump and large diameter roots near the stump. Bloomberg and Reynolds (1982) demonstrated that the larger diameter roots transfer *Phellinus weirii* infection more efficiently. This indicates that even crude removal of infected stumps should be effective for control of the diseases.

In fact, the complete removal is seldom or never achieved in practice, and the removal of already decayed stumps and roots usually results in larger portion of their biomass being left in the soil, as compared with the healthy stumps (Hyppel 1978, Sturrock et al. 1994, Omdal et al. 2001). Despite that, machines designed to remove *Armillaria*-, *Heterobasidion*- and *Phellinus weirii*-infected conifer stumps in Canada and USA were shown to be highly efficient, and to remove 83–94% of the estimated belowground biomass (Bloomberg and Reynolds 1988, Omdal et al. 2001). Furthermore, over 80% of root remnants left in the soil were less than 5 cm in diameter (Sturrock et al. 1994, Omdal et al. 2001).

Numerous observations in stumped forest areas of North America (in particular, infested by *Armillaria* and/or *Phellinus weirii*) provided evidence that although initially decayed root remnants often have sufficient potential to kill young regeneration trees which contact them, they seldom constitute a long-term threat. This is because the viability of the pathogens in their saprotrophic survival is limited by small substrate size and by their having been disturbed, broken and exposed to invasion by soil saprophytes. Therefore, subsoil root remnants on stumped sites are usually exhausted by the pathogens, which lose viability in the time it takes roots of replanted trees to contact them (Bloomberg and Reynolds 1982, Thies 1984, Thies and Russell 1984, Morrison et al. 1988, 1991, Sturrock et al. 1994, Thies and Sturrock 1995, Omdal et al. 2001). Consequently, significant reduction of root rot has been achieved in trials where following stump removal no secondary effort was made to remove severed roots from the soil (Thies 1984, Thies and Nelson 1988, Thies et al. 1994, Thies and Westlind 2005).

On the other hand, Thies and Hansen (1985) provided evidence, which to some extent contradicts the results of field studies cited above. They demonstrated that 8 years after the burial of over 100 *Pseudotsuga menziesii* root pieces infected with *Phellinus weirii*, the pathogen remained viable in 46% of those, and the smallest piece was 1.3 cm in diameter. Corresponding quantitative data on *Armillaria* spp. and *Heterobasidion* spp. are not yet available.

Despite that in certain cases even crude stumping was demonstrated to be satisfactory for stand sanitation, several authors suggested that more thorough removal of stumps and roots would reduce losses more significantly, in particular when dealing with *Heterobasidion* and *Armillaria* (Yde-Andersen 1970, Shaw and Calderon 1977). Thus by excavations in England, *Heterobasidion* infection and subsequent mortality of young *Pinus sylvestris* was traced to contacts with small broken segments of roots, measuring 15 × 1–2 cm, that were not removed, but left in the soil (Greig and McNabb 1976, Greig 1980). Moreover, the improved methods of extraction reduced losses from *Heterobasidion* in the next pine generation from 20% to 10% (Greig 1984, Gibbs et al. 2002). When following stumping the soil was rootraked, leaving no roots thicker than 5 mm – this drastically reduced *Heterobasidion* root rot in the next generation of *Picea abies* (Stenlid 1987; Table 1).

In an experiment by Greig and Low (1975), small pine stumps from first thinning left in situ although deteriorating rapidly, yet to some extent contributed to *Heterobasidion*-caused mortality of *Pinus sylvestris* crops in the next rotation: after 18 years the mortality on plots where first thinning stumps were removed together with stumps of cut living trees was 23.8%. On plots where first thinning stumps were left intact and only freshly cut stumps were removed mortality was 26.5%. Considerably larger impact was observed on similar sites with the next generation of *Pinus nigra*, where the respective mortality was 15.4% and 24.0%. When stump removal operations did not remove all the roots, those and broken pieces left in the ground served as infection sources causing the mortality of around 25%. These rather high losses reflect the relatively inefficient methods of extraction used in described experiment (Greig and Low 1975).

More recently, Roth et al. (2000) in their long-term trial demonstrated that more thorough removal of root residuals on *Armillaria*-infested sites did reduce mortality caused by the fungus in the next forest generation of *Pinus ponderosa*. Four treatments of different thoroughness were investigated after trees and stumps were pushed out and removed from the site: 1) maximum removal of roots by machine, visible remaining roots picked out by hand; 2) maximum removal of roots by machine; 3) large stumps left on the site, otherwise maximum removal of roots by machine; 4) no further removal of roots. After 21 year following natural regeneration, infections by *Armillaria* were observed on 2.5–12%, 8.4–23%, 18–26.2% and 18–41% of the area on each of the treated sites, respectively. The infection levels on control sites, where stumps were retained, comprised 34–49% (Roth et al. 2000).

In the study by Morrison et al. (1988), root raking was shown not only to collect infected root pieces from a site, but the operation also altered the distribution of residual roots in the upper 60 cm of a soil, bringing larger amounts of infested small diameter roots to the 0–30 cm zone. This might have a positive effect on eradicating of the pathogens, as several studies had demonstrated that the replacement of root rot pathogens from infected substrates proceeds faster in upper soil layers. Thus, Rishbeth (1951) reported that the replacement of *Heterobasidion* by soil saprotrophic fungi from *Pinus sylvestris* roots proceeds faster in the upper layers of a soil (8 cm) than in more deep layers (20 cm). Nelson (1967) reported that also *Phellinus weirii* in soil-buried *Pseudotsuga menziesii* wood survived longer at 25–50 cm depth than at 1.5–7.5 cm depth. In the study by Munnecke et al. (1976), numerous observations of root excavations showed that *Armillaria* mycelia were killed in exposed roots, and *Trichoderma* usually was observed sporulating on wood infected by the pathogen. Another study provided evidence that soil-borne *Trichoderma* spp. readily invade buried wood blocks colonised by *Phellinus weirii* (Nelson 1964).

Yet, little is known regarding the mechanisms underlying those observations. To investigate the replacement of root rot fungi in residual roots by soil fungi on stumped forest sites in relation to substrate size, quality and environmental conditions would be of interest for future research, in particular encompassing wider range of host-pathogen systems and geographic areas (e.g. *Heterobasidion–Picea abies* in North Europe, also see Section 10 Economical Aspects, and Section 11 Concluding Remarks and Research Needs).

5 Site Disturbance

Possible site disturbance is one of the potential negative aspects in root rot control by stumping, and practical recommendations for reducing negative effects on site quality while combating the disease are available (Thies 1987, Smith and Wass 1991, Sturrock et al. 1994, Wass and Senyk 1999, Sturrock 2000; see also part 9 Equipment and techniques). Thies and Sturrock (1995) pointed out that stump removal can disturb, but also that it may only appear to disturb the site. The disturbance categories occurring on stumped sites are essentially the same as those resulting from a variety of forestry operations (Wass and Senyk 1999). Comparative analysis of available studies clearly indicates that impact on site to large extent depends on stumping method. The least disturbance occurs when following the uprooting, stumps are left upended near or at the extraction holes, and here negative impacts on both soil characteristics and seedling performance could be even lower than after conventional harvesting (Smith and Wass 1994). Whole tree harvesting with a single stand entry (push-falling) was also shown to result in rather low damage, and following that operation only 50.6% of the site was occupied by disturbed soils, with stumped spots and skid trails the most significant categories (Sturrock et al. 1994).

Transportation or piling of extracted stumps resulted in more severe impacts on a site, which usually exceeded those that occur during conventional harvesting (Smith and Wass 1989, 1991, Wass and Smith 1997). Thus, stump removal trials in British Columbia led to disturbance of 72–85% of the area (Smith and Wass 1994, Wass and Smith 1997); out of a total 85%, 74% of disturbance was caused by the stump removal, and only 11% by harvesting (Wass and Smith 1997). In another experiment, all stumping treatments resulted in mineral soil exposure on 100% of surface area, and on harvested but non-stumped sites of initially similar properties, soil compaction in all cases was significantly lower than on stumped sites and within acceptable limits (Smith and Wass 1991). Roth et al. (2000) reported that despite thorough ripping and movement following the removal of stumps and roots, soil on all treated sites was significantly more dense after 10 years than was soil on sites where stumps had not been removed.

Available studies demonstrate clearly that impact on site during stumping operations to a large extent is dependant on soil properties, and on sensitive sites the impacts following stump removal are more severe (in particular when stumps are removed from the site or piled in windrows). For example, in British Columbia stumping on initially dense, less penetrable and more moist (gleyed) soils resulted in severe compaction (except for soil scalps), exceeding soil bulk density threshold level detrimental for tree growth (1.4 Mg/m^3). When similar stumping operations were conducted on relatively loose, dry gravelly sandy loam, the negative impact in this case did not exceed the threshold level (Smith and Wass 1991). In another similar study on a gravely sandy loam, impact of stump removal operations on soil density was insignificant, and soil penetrability was even increased by the stump uprooting disturbance. Low impacts on soil density and increased soil penetrability were largely attributed to low site sensitivity to compaction (Wass and Smith 1997).

It is therefore known that stump removal is best suited on high quality sites with a slope of less than 35%, on light sandy soils, and should preferably be conducted when soil moisture is low (Thies and Sturrock 1995, Sturrock 2000). However, in study by Thies et al. (1994) even on a silty clay loam stump removal with a bulldozer increased soil bulk density only 7% as measured 10 years after treatment. Moreover, the subsequent recovery was relatively fast: after 12 years on stumped sites bulk density was 3% higher than on non-stumped plots and the difference was not statistically significant. Repeat measurements on the same plots after another 2 years showed that the stumped and non-stumped sites were similar in soil bulk density (0.97 and 0.96 g/cm^3), and were similar to the surrounding undisturbed forest land (Thies and Westlind 2005). In other related work, although some differences between pre- and post-stumping soil bulk density were found to be statistically significant, the observed changes in total bulk densities were relatively minor and were consistent with expectation (Sturrock et al. 1994)

In addition to soil compaction, other investigated impacts of stump removal on a site include soil displacement, changes in microrelief, chemical properties and impact on vegetation cover. According to Smith and Wass (1989), soil displacement on stumped sites can be characterised as gouges (channel, deep track), deposits (piled soil) and surface mixing. They demonstrated that during stump removal the amounts of very deep soil displacement can be large (26–41%) and exceeded maximum limits for harvesting operations (12%), e.g. suggested in British Columbia (Smith and Wass 1989).

In the same study, stump removal increased the proportion of soil disturbance classified as deposits. This increase in deposits was reflected in a decline of about 10% in the average bulk density found in the top 20 cm of mineral soil after stumping (Smith and Wass 1989). In a later trial they found out that the area disturbed by the stump uprooting operation, about equally divided between gouges (mainly tracks) and deposits. Consequently, the top 20 cm of soil in tracks was on average 23% denser and 68% less penetrable than the equivalent layer of undisturbed mineral soil. In contrast, deposits were about equal in density to undisturbed soil and, at depths of 15 and 20 cm, were about half as resistant to penetration (Smith and Wass 1994). Consequently, the impacts on soil microrelief that result from stumping operations were reported as significant, although this was not considered a serious problem for a future replanting of the sites (Smith and Wass 1989).

Whereas physical properties of soils on sensitive sites were significantly affected by the stumping operations, changes in chemical properties in initial studies were not so clearly evident (Smith and Wass 1991). Yet, a later work, Smith and Wass (1994) reported that the presence of free carbonates in the surface mineral soil on stumped sites increased with increasing depth of disturbance from 2% of spots sampled in undisturbed soils to 41% of spots with very deep (>25 cm) gouges or deposits. In addition, the disturbed mineral soil displayed higher organic carbon and higher C:N ratios than undisturbed soil but differences were not significant (Smith and Wass 1994). More recently it was found that soil on other stumped sites had a significantly lower concentration of organic carbon and total nitrogen, and significantly higher pH than undisturbed soil for the 0–10 cm layer, although there were no significant differences for any of the soil chemical parameters for the 10–20 cm layer (Wass and Smith 1997).

In whole-tree harvesting trials in Sweden, the extent of soil damage was estimated directly as the extent of loss of ground vegetation. Here, after one year stump and slash removal has resulted in loss of ground vegetation on 67.5% of a harvested area, whereas on control sites (stems removed, – stumps and slash left) the vegetation was absent only on 6.7% of the harvested area (Kardell 1992). However, the vegetation on disturbed sites recovered quickly, and already after 6 years the corresponding figures were 16.1% and 9.1% (Kardell 1992). After 22–28 years the difference between the whole-tree harvested and control sites was even less significant, as the loss of ground vegetation on stumped and control sites was 4.4% and 3.6% (Kardell 2007).

The development of vegetative cover on stumped sites might be dependent on type of disturbance. Thus, Smith and Wass (1994) reported that vegetation recovered more slowly on tracks than on deposits and included a number of species not frequently found on deposits or undisturbed ground. Other stump removal trials demonstrated that vegetation development was either not greatly dissimilar between disturbed and undisturbed soil (Wass and Smith 1997), or vegetative cover remained less on stumped sites than on non-stumped clearcuts during 3–5 subsequent years (Smith and Wass 1991).

In conclusion, impacts on a site, although in some cases significant, were not regarded as dramatic. Below, it will be demonstrated that site disturbance due to stumping cannot be equated with site degradation, and on the contrary, in many cases it was shown to be beneficial for establishment and growth of a subsequent stand (e.g. Kardell 1992, 1996, 2007, Sturrock 2000).

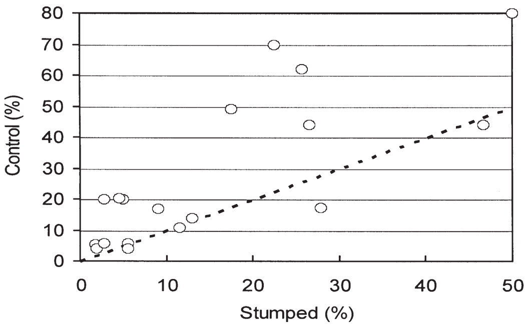

Fig. 4. Impact of stump removal on seedling survival. Each circle shows the proportion of planted seedlings remaining alive on stumped vs. control plots, observed in trials that are presented in the Table 2. Dotted line indicates level of seedling survival that would be equal on both stumped and control sites.

6 Seedling Survival

Extensive long-term whole-tree harvesting trials in Sweden clearly demonstrate that removal of stumps and slash from clear-felled sites has a strong positive impact on natural forest regeneration. Thus, after 7 years number of naturally regenerated trees on sites with stump removal was by 10% higher, and on sites with combined stump and slash removal, by 51% higher than on control sites with stumps and slash left intact (Kardell 1992). In northern Sweden, after 11 years the number of naturally established trees on stump removal and stump/slash removal sites was about twice as high than on control sites (Kardell 1996). In central Sweden, stump and slash removal resulted in up to 82% surplus of self-regenerated trees after 13–17 years (Kardell 2007). Results from Finland indicate that stump and slash removal could improve productivity and quality of subsequent re-planting of harvested forest sites (Saarinen 2006).

In agreement to whole-tree harvesting trials, the majority of available studies on root rot control also demonstrate that subsequent afforestation is more successful on sites where the stumps have been removed than on sites where the stumps were left intact. Thus, out of eighteen available trials, nine reported positive impact of stumping on seedling survival, in eight the survival was about the same both on stumped and non-stumped sites, and only one showed decreased survival (Table 2, Fig. 4). The latter was noted for *Larix occidentalis* (Morrison et al. 1988, Table 2), but it must be noted here that in a subsequent study the opposite results were reported (increased survival) for the same tree species in the same geographic area (Smith and Wass 1991, Table 2). Importantly, the data in the Table 2 reflect seedling mortality in early stages after re-planting, and was attributed to other causes than the root rot fungi *Armillaria*, *Heterobasidion* or *Phellinus weirii*.

In order to analyse the impact of stump removal on the survival of re-planted seedlings, we compared their average mortality on stumped and control sites from all available trials (Table 2) using paired t-tests. Mean (± sd) incidence of mortality in non-stumped sites was $27.4 \pm 23.8\%$, while in stumped sites only $15.6 \pm 15.0\%$, and the t-test between the two values was significant at $p = 0.005$. The overall effect of stump removal on seedling mortality, based on mean values on stumped and control sites, and (calculated using Eq. 1), comprised 43.1%.

Morrison et al. (1988) reported that the survival of *Pseudotsuga menziesii*, *Pinus contorta*, *Betula papyrifera*, *Larix occidentalis*, and *Picea engelmannii* seedlings planted on sites with stump

Table 2. Impact on stump removal on survival of seedlings and trees planted on clear-felled forest sites. Data reflect mortality due to other causes than *Armillaria*, *Heterobasidion* or *Phellinus weirii*.

Seedlings (trees) Species	Age, years	Mortality % on sites stumped	Mortality % on sites non-stumped	Location	Source
		Survival increased			
Betula papyrifera	3–5	50.8	80.4	British Columbia	Morrison et al. 1988 [a)]
Larix occidentalis	4	20–25	70	British Columbia	Smith and Wass 1991
Picea engelmannii	3–5	25.7	62.0	British Columbia	Morrison et al. 1988 [a)]
Pinus contorta	4	2–12	20	British Columbia	Smith and Wass 1991
Pinus radiata	2	9	17	New Zealand	Shaw & Calderon 1977
Pinus sylvestris	7–10	2.5–3.1	20	Sweden	Kardell 1996 [a,b)]
Pseudotsuga menziesii	3–5	4.5	20.2	British Columbia	Morrison et al. 1988 [a)]
Pseudotsuga menziesii	4	10–45	40–58	British Columbia	Smith and Wass 1991
Pseudotsuga menziesii	5	14–39	44	British Columbia	Smith and Wass 1994
		Survival decreased			
Larix occidentalis	3-5	27.9	17.2	British Columbia	Morrison et al. 1988[a)]
		Low or no impact (<5% difference, or statistically insignificant)			
Picea abies	1–5	1–2.3	5.3	Sweden	Kardell 1992[a,b)]
Picea abies & *Pinus sylvestris*	10	2–24	2–28	Sweden	B.Leijon, c.f. Egnell et al. 2007 [a,b)]
Pinus contorta	3–5	5.6	5.6	British Columbia	Morrison et al. 1988 [a)]
Pinus contorta	5	5–18	10	British Columbia	Smith and Wass 1994
Pinus sylvestris	1–5	1.7–2.1	4	Sweden	Kardell 1992 [a,b)]
Pinus sylvestris	7–10	2.1–3.3	5.8	Sweden	Kardell 1996 [a,b)]
Pseudotsuga menziesii	10	4–7	4	British Columbia	Wass and Smith 1997
Thuja plicata	3–5	46.6	43.9	British Columbia	Morrison et al. 1988 [a)]

[a)] Data reflect lowest limits of mortality, as it is based on seedling survival following replacement of initially planted but dead seedlings.
[b)] "Whole-tree harvesting" trials, not aimed to control root rot.

and root removal after first year was 85%, while only 42% of those survived in the untreated plots. The corresponding figures for *Thuja plicata* were 23% and 4%. After those sites were replanted with the similar planting stock during the two subsequent years, yet another seedling inventory after another three years revealed that: 1) the establishment of *Pseudotsuga menziesii*, *Betula papyrifera* and *Picea engelmannii* seedlings was markedly higher on sites with stump and root removal, as compared with untreated sites; 2) the removal had little or no impact on the establishment of *Thuja plicata* and *Pinus contorta*; 3) the removal had certain negative impact on survival of *Larix occidentalis* although it was rather high on both treated and untreated sites (Morrison et al. 1988, Table 2) During this period, no mortality due to root rot disease was observed, and on the sites without stump removal the mortality was attributed mainly to competition from herbs and shrubs (Morrison et al. 1988). This repeatedly indicates, that stumping significantly reduces the presence of ground vegetation competing with the replanted growing stock (see Section 4 Site Disturbance).

Also Shaw and Calderon (1977) suggested that stump and root removal is beneficial to vigour and survival of seedlings subsequently planted on clear-felled and stumped sites, and mainly due to soil disturbance. Their experiment in New Zealand *Pinus radiata* plantation has shown that seedling mortality due to other causes than *Armillaria* root rot on site without stump removal was 17%, as compared with 9% on site where stumps and roots were removed (Table 2).

Positive impact by stump removal on seedling survival was reported in Canadian study – the mortality of 4 year-old *Pseudotsuga menziesii*, *Larix occidentalis* and *Pinus contorta* seedlings on stumped sites was 10–45%, 20–25% and 2–12%, while on sites where the stumps were retained, the corresponding values were 40–58%, 70% and 20%, respectively (Smith and Wass 1991, Table 2). However, in the subsequent trials the differences in seedling survival on stumped vs. non-stumped sites were not so clearly pronounced (Smith and Wass 1994, Wass and Smith 1997, Table 2). Soil compaction and stagnant water were deemed as the main reasons for occasionally observed lower survival (Smith and Wass 1991).

Bloomberg and Reynolds (1988) reported long-term effect of stump removal on the survival of planted trees. In their study, stump uprooting did not reduce *Pseudotsuga menziesii* seedling mortality in the first few years after planting, but subsequent mortality has declined during 14 years in the stumped areas while continuing to rise in non-stumped areas. However, the observed results could most likely be attributed to increased infections by *Phellinus weirii* in later stages of stand development, and the corresponding data for this is provided in the Table 1. In large Swedish field experiments of whole-tree harvesting, followed up to 10 vegetation seasons, stump removal in most cases had no effect on survival of seedlings (except for one area where the impact was positive) in comparison with traditional forest management, or with removal of only logging residues (Kardell 1992, 1996, 2007, Egnell et al. 2007).

7 Tree Growth and Stand Productivity

The available data demonstrate that in most cases tree growth and stand productivity on stumped sites is either significantly higher or does not differ significantly from sites were stump removal was not conducted (Table 3, Figs. 5, 6, 7). Consequently, the results from a total of the available 29 trials could be divided into three categories: a) growth increase, reported from thirteen (45%) trials with six tree species from western North America and Europe, observed up to 30 years following stump removal, b) low or no impact on tree growth, reported from ten (34%) trials with six tree species from western North America and western and northern Europe, observed up to 21 year, and c) growth decrease, reported from six (21%) trials with three tree species from western North America, observed up to 8 years (Table 3).

In Swedish "whole-tree harvesting" trials, height increment of planted *Picea abies* and *Pinus sylvestris* after 7 years was, respectively, by 40–70% and by 15–20% higher on sites where stumps, and stumps and slash were removed, than on control sites with conventional stem harvesting (Kardell 1992). After 22–27 years, volume of self-regenerated trees (mainly *Betula* spp. and *Picea abies*) on stump/slash removal sites was higher than that on sites with conventional harvesting (Kardell 2007). Other studies reported "normal" growth of forest plantations, established on areas with stump removal without presenting any quantitative data. Thus, according to van der Pas and Hood (1984), growth of *Pinus radiata* trees planted on stumped plots in New Zealand was as vigorous as in the other plots. In western North America, planted *Pseudotsuga menziesii* trees after 14 years were so far showing good growth, indicating no major reduction in site productivity (Bloomberg and Reynolds 1988).

We analysed the whole data pool in the Table 3 by calculating and comparing mean height, diameter and volume values on stumped and control sites. Thus, mean (± sd) height of trees growing on stumped sites was 4.40 ± 4.37 m, while in non-stumped sites it was somehow lower, comprising 4.10 ± 3.95 m. Yet the t-test between the two values was significant at $p = 0.01$, demonstrating that trees planted on sites following stump removal exhibit generally better height increment. The positive impact of stumping was noted also for the stand volume, and the corresponding figures for stump removal and conventional harvesting sites were 117 ± 75 m^3/ha, and 96 ± 66 m^3/ha, respectively. The t-test was significant at $p = 0.027$, indicating generally higher productivity of stands established on sites from which stumps have been removed. By contrast, the available data did not reveal any impact of stumping on tree diameter growth, which was almost even on both stumped and control sites (respectively, 5.38 ± 4.03 cm and 5.40 ± 3.85 cm; t-test, $p = 0.9$). Consequently, the effect of stump removal (calculated accordingly Eq. 1) on height and volume growth was 7.3% and 21.9%, but for diameter growth it was close to zero.

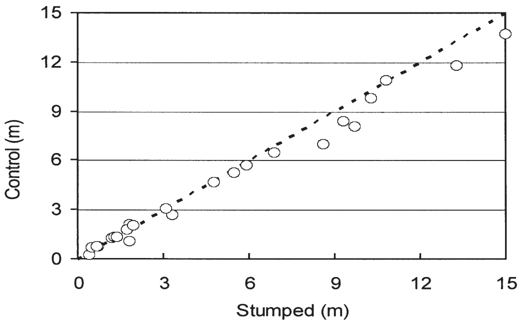

Fig. 5. Impact of stump removal on height growth of trees in next forest generation. Each circle shows average height of trees growing on stumped vs. control plots, observed in trials that are presented in the Table 3. Dotted line indicates tree height that would be equal on both stumped and control sites.

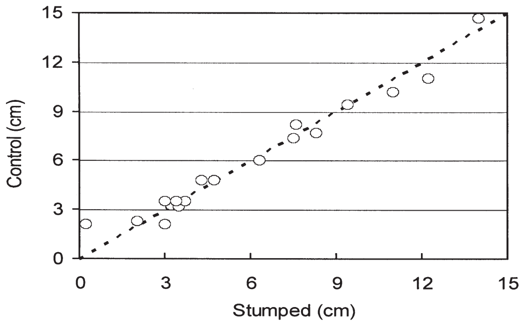

Fig. 6. Impact of stump removal on diameter growth of trees in next forest generation. Each circle shows average diameter of trees growing on stumped vs. control plots, observed in trials that are presented in the Table 3. Dotted line indicates tree diameter that would be equal on both stumped and control sites.

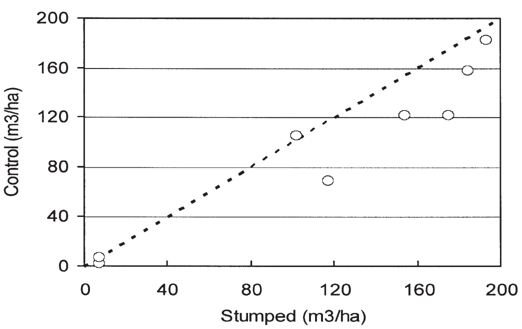

Fig. 7. Impact of stump removal on stand volume in next forest generation. Each circle shows volume of a stand growing on stumped vs. control plots, observed in trials that are presented in the Table 3. Dotted line indicates stand volume that would be equal on both stumped and control sites.

The positive effects on tree growth on stumped sites to certain extent should be attributed to improved performance of planted trees during the early phases of establishment (e.g. Table 2), but also to reduced infections of root rot fungi due to the removal of inoculum (Table 1). Some studies pointed out that trees planted on areas following stump removal exhibited increased growth due to reduced vegetative competition, soil mineralization and increased soil penetrability (Burdekin and Greig 1972, Morrison et al. 1988, Wass and Smith 1997). Under such circumstances trees achieve larger dimensions, and such trend might persist over the years. Thus, in north-western USA, height and diameter growth of *Pseudotsuga menziesii* planted on stumped sites after 8 years was by 23% and 43% higher, than on sites where stumps were left intact (Thies and Nelson 1988, Table 3). In this trial, the positive impact of stump removal on height growth did persist during the subsequent 15 years, and after 27 years trees on stumped sites were still significantly higher than those growing on control sites (Thies and Westlind 2005, Table 3).

Consequently, the faster tree growth results in higher standing volume. For example, in the British study by Greig and Low (1975), *Pinus sylvestris* trees were larger on stumped plots after 18 years, and at this stage the mean volume of stump-removal plots was approaching twice that of the control plots (Table 3). In 20 year-old plantations of *Pseudotsuga menziesii*, *Picea sitchensis* and *Pinus contorta*, established on sites with stump removal, standing volume was by 5%, 16% and 43% higher respectively, than on sites where stumps were not removed (Greig et al. 2001, Table 3). Results from the oldest North American stump removal trials provided convincing evidence that stumping on *Phellinus weirii* infested stands of *Pseudotsuga menziesii* at the age of 23–27 years has increased volume

Table 3. Growth of trees planted on stumped and non-stumped sites.

Tree species	Age, years	Mean growth characteristics of trees on stumped (–) and non-stumped (+) sites: Height, m –	Height, m +	Diameter, cm –	Diameter, cm +	Volume, m^3/ha –	Volume, m^3/ha +	Location	Source	Remarks on planting conditions on a stumped site
Growth increased										
Larix occidentalis	19	13.3	11.8	14.0	14.7			British Columbia	Morrison et al. 1988	Root-raked 45 cm deep
Picea sitchensis	20					184	158	Wales	Greig et al. 2001	
Pinus contorta	19	8.6	7.0	11.0	10.2			British Columbia	Morrison et al. 1988	Root-raked 45 cm deep
Pinus contorta	20					175	122	Wales	Greig et al. 2001	
Pinus nigra	3	0.38	0.27					England	Burdekin and Greig 1972	
Pinus sylvestris	18	9.3	8.38			117	69	England	Greig and Low 1975	
Pinus sylvestris	30	10.8	10.9	7.6	8.2	154	122	Belarus	Raptunovich 1988	Ploughed in (-) and (+)
Pinus sylvestris	10	1.77	1.06			7.2	2.4	Sweden	Kardell 1996[a)]	
Pseudotsuga menziesii	10	6.87	6.45	8.3	7.7			British Columbia	Wass and Smith 1997	Planted on tracks
Pseudotsuga menziesii	19	9.7	8.1	12.2	11.0			British Columbia	Morrison et al. 1988	Root-raked 45 cm deep
Pseudotsuga menziesii	20					193	183	Wales	Greig et al. 2001	
Pseudotsuga menziesii	23	10.32	9.79					Oregon	Thies and Westlind 2005	Not root-raked
Pseudotsuga menziesii	8	3.26	2.65	3.0	2.1			Washington	Thies and Nelson 1988	Not root-raked
Same trial, follow up	27	14.98	13.73						Thies and Westlind 2005	
Growth decreased										
Pinus contorta	8	1.19	1.25	3.2	3.3			British Columbia	Smith and Wass 1991	Planted on tracks
Pinus contorta	8	1.81	2.06	4.3	4.8			British Columbia	Smith and Wass 1994	Planted on tracks
Pinus monticola Dougl. ex D.Don.	3	0.51	0.49	1.62	1.81			Idaho	Page-Dumroese et al. 1998	
Pseudotsuga menziesii	3	0.43	0.52	0.11	0.14			Idaho	Page-Dumroese et al. 1998	
Pseudotsuga menziesii	8	0.46	0.70	0.17	2.1			British Columbia	Smith and Wass 1991	Planted on tracks
Pseudotsuga menziesii	8	1.16	1.34	3.0	3.5			British Columbia	Smith and Wass 1994	Planted on tracks
Low or no impact (<5% difference, or statistically insignificant)										
Abies procera	20					102	105	Wales	Greig et al. 2001	
Larix occidentalis	8	1.72	1.81	3.5	3.2			British Columbia	Smith and Wass 1991	Root-raked
Picea abies and *Pinus sylvestris*	11–16	3.1	3.1			7.1[b)]	7.1[b)]	Sweden	B.Leijon, c.f. Egnell et al. 2007[a)]	
Picea engelmannii	19	5.9	5.7	7.5	7.4			British Columbia	Morrison et al. 1988	Root-raked 45 cm deep
Pinus contorta	8	1.35	1.33	3.7	3.5			British Columbia	Smith and Wass 1991	Root-raked
Same study, different planting		1.29	1.33	3.7	3.5					Not root-raked
Pinus contorta	8	1.96	2.06	4.7	4.8			British Columbia	Smith and Wass 1994	Planted on deposits
Pinus ponderosa	21	4.75	4.69	9.4	9.4			Washington	Roth et al. 2000	Partly root-raked
Pseudotsuga menziesii	8	0.69	0.75	2.2	2.3			British Columbia	Smith and Wass 1991	Root-raked
Same study, different planting		0.65	0.75	1.9	2.3					Not root-raked
Pseudotsuga menziesii	8	1.36	1.34	3.4	3.5			British Columbia	Smith and Wass 1994	Planted on deposits
Pseudotsuga menziesii	10	5.49	5.28	6.3	6.0			Oregon	Thies et al. 1994	Not root-raked

[a)] "Whole-tree harvesting" trials, not aimed to control root rot.
[b)] Sum of base-square (m^2/ha).

by 25.4% (Thies and Westlind 2005). Moreover, there was no difference in volume between stands growing on stumped infested sites, and stands growing on non-stumped healthy areas. The only evidence of a negative impact on tree growth from stumping was a slight decrease in current volume increment observed in one of five trials, but it was deemed by authors as insignificant in a long-term perspective of a final stand volume.

On the other hand, cases are known when size of the trees was similar on stumped and control sites, but increased productivity was achieved solely by the root rot reduction. For example, Raptunovich (1988) reported that the average volume of 27–30 year-old plantations of *Pinus sylvestris* established on sites with stump removal was by 26.2% higher than in controls without stump removal (Table 3). Here, although diameter and height of the trees on both sites were rather similar, the overall increase in stand productivity was achieved due to reduced mortality from *Heterobasidion* root rot on de-stumped sites.

Some studies demonstrated that growth response on sites following stump removal might be a dynamic character and change in a course of time. Thus, Wass and Senyk (1999) followed up the trial by Smith and Wass (1991), and reported that during the first 10 years after uprooting trial, established *Pseudotsuga menziesii*, *Pinus contorta* and *Larix occidentalis* exhibited faster growth on treated sites, by 15 years, volumes for trees on uprooted sites were significantly reduced, and in several treatments had fallen below those recorded on control plots. Out of five long-term *Pseudotsuga menziesii* stump removal trials studied by Thies and Westlind (2005), after 23–25 years significant impact of the treatment on height growth was observed only in two, while in the rest three no significant height differences were observed between trees growing on stumped and non-stumped sites.

However, in some situations stump removal may have detrimental effect on tree growth (Sturrock 2000), and such negative effects were attributed in part to altered soil conditions, in particular to compaction of initially dense, less penetrable and moister (gleyed) soils (Smith and Wass 1991, 1994). As obvious from the Table 3, in all four experiments with reported decreased growth, the trees were planted on tracks, thus growing under conditions of severely compacted soil. However, following planting of trees on deposits (no compaction), neither height nor diameter growth differed from undisturbed conditions in the same trials and sites (Smith and Wass 1991, 1994, Table 3). Other studies in plantations established following stump removal also reported slow tree growth on tracks as compared with rapid growth on scalped spots of soil (Wass and Senyk 1999), and it was noted that the negative impact is correlated with the severity of compaction (Smith and Wass 1994).

8 Fertilization

Fertilizers are likely to be applied on forest sites following whole-tree harvesting. Studies on fertilization impacts for tree growth and root rot incidence in next generation stands are scarce, and only *Phellinus weirii–Pseudotsuga menziesii* system in western North America has been extensively investigated (Thies and Nelson 1988, Thies et al. 1994, Thies and Westlind 2005). It was hypothesised that fertilization effects following stumping are twofold: a) it has a positive impact on subsequent growth of replanted trees, and b) it enhances the eradication of root rot pathogens from subsoil residues of infected wood, thus contributing to site sanitation.

As expected, fertilization of site with ammonium nitrate following stump removal produced increases of 13% in height and 17% in diameter at breast height (d.b.h.) in replanted *Pseudotsuga menziesii* after eight growing seasons (Thies and Nelson 1988), and in another study significant increase in height and diameter growth was observed after nine seasons (Thies et al. 1994). More recent work demonstrated positive residual effect of nitrogen fertilizer can be apparent for at least 23 years (Thies and Westlind 2005).

Early studies provided evidence that the displacement of *Phellinus weirii* from infected roots might be accelerated by applying high levels of nitrogen (N) fertilizer. In laboratory tests, N applied as either ammonium chloride or sodium nitrate dramatically reduced the viability of *Phellinus weirii* in buried wood cubes (Nelson 1970), and in field tests, applying urea reduced survival of the fungus in wood (Nelson 1975). Reduced survival of *Phellinus weirii* was later correlated with increased populations of *Trichoderma* spp. (Nelson 1976). However, field trial fertilization with ammonium nitrate following stump removal did not have a detectable effect on development of the pathogen in planted *Pseudotsuga menziesii* during a ten-year period (Thies et al. 1994). The authors speculated that in this study the application of fertilizer could have been better timed to reduce the occurrence of the disease in the next stand, and if fertilizer had been applied at a time when significant precipitation would carry it into the soil, the influx of available N might have stimulated the soil microorganisms antagonistic to *Phellinus weirii*, making them better able to quickly invade residual roots. Yet, subsequent long-term trials on stumped sites did not reveal any effect of fertilization on occurrence of *Phellinus weirii* in replanted *Pseudotsuga menziesii* (Thies and Westlind 2005).

The impact of fertilization on survival and persistence of *Armillaria* and *Heterobasidion* in wood residues in soil has not been investigated. However, Vasiliauskas et al. (2004) demonstrated that the application of urea to *Picea abies* stumps strongly promoted wood colonization by *Ascomycetes* and *Deuteromycetes*, and almost completely eliminated wood-decay *Basidiomycetes*, including *Heterobasidion* spp. and *Armillaria* spp. Therefore, the possibility can not be excluded that under different ecological conditions nitrogen fertilization of stumped forest sites might promote the establishment of soil microfungi in diseased residual roots and enhance replacement of the pathogens (also, see Section 4 Thoroughness of the Removal). Further investigations in this field might be of interest, and if a synergistic effect of stumping / fertilization would be apparent, this might be useful in developing a strategy to reduce losses from root rot agents in a wide range of intensively managed forest ecosystems.

9 Equipment and Techniques

In first stump removal experiments to eradicate the pathogens, stumps were dug out manually (Bornebusch and Holm 1934, Yde-Andersen 1970), or were removed by winching (Phillips 1963, Greig and Low 1975, Greig and McNabb 1976), and it was anticipated that much infested root material had remained in the soil (see Section 3 Root-rot Incidence in the Next Forest Generation). To date, equipment and techniques for stump removal to control root rot (in particular *Phellinus weirii*) have been mostly investigated in western North America (Oregon, Washington, and British Columbia), and reviews are available where those developments are analysed from the historical perspective (Thies 1984, Thies and Russell 1984, Thies and Sturrock 1995, Sturrock 2000). Scandinavian whole-tree harvesting trials in this respect were reviewed by von Hofsten (2006).

During early trials, stumps were removed by using a bulldozer with a solid blade (Roth and Rolph 1978, Roth et al. 1980, Thies and Russell 1984, Thies 1984, Thies and Nelson 1988, Thies et al. 1994, Thies and Westlind 2005), which moved more soil than was desirable. Large holes were created and topsoil was mixed with subsoil. Then, a bulldozer with a toothed (brush) blade was demonstrated to successfully remove stumps with less movement and mixing of soil and leaving fewer large holes and where necessary allowing a final root-raking with a brush blade to bring more of the broken roots to the surface (Smith and Wass 1991, 1994). More recent work with log forks on a bulldozer has done even better. After the forks are pushed into the soil on either side of a stump, the stump can be pushed or pried from the soil. As the stump is lifted, much of the soil clinging to the roots falls back into the hole. Leverage gained from the forks permits use of a much lighter bulldozer than is otherwise required. Forks produced smaller holes, moved and mixed less soil, and were deemed to remove more infested roots than did blades (Thies 1984, Thies and Russell 1984, Thies and Sturrock 1995, Sturrock 2000).

Subsequently, a concept was developed in stump removal with a vibrating stump puller. The puller combined lift and vibration to separate the stump and root system from the soil with a minimum of site disturbance and has been successful at removing stumps up to 50 centimeters in diameter (Arnold 1981, Schultz and Bennet 1994, Omdal et al. 2001). More recently, excavators with a standard bucket and a hydraulically operated gripping thumb have been recommended for stump removal, due to their maneuverability, low impact to site and the ability to extract even the most severely infected stumps, and stumps of large diameter (>76 cm) (Bloomberg and Reynolds 1988, Thies 1987, 1995, Smith and Wass 1989, 1991, 1994, Morrison et al. 1991, Schultz and Bennet 1994, Sturrock et al. 1994, Woods 1996, Wass and Smith 1997, Omdal et al. 2001). Stumps are extracted by grabbing the stem portion above ground between the rake and the thumb attachment. The stump was then lifted from the ground and shaken to remove soil from the roots (Woods 1996). This equipment can dig or lift stumps while its tracks remain stationary, thereby causing less compaction and disruption than equipment that relies on a pushing force. Much of the site and soil damage caused by a bulldozer resulted from tracks moving and slipping when the force necessary was applied to push the stumps out (Smith and Wass 1989, 1994, Thies and Sturrock 1995, Wass and Smith 1997; see Section 5 Site Disturbance). It is anticipated that successful stumping operations require an excavator that is large enough to easily undermine root system, has the ability to pull and lift a stump or stump sectors, and has tracks wide enough apart to provide a minimum of ground pressure (Thies and Sturrock 1995, Sturrock 2000).

Push-over harvesting, or push-falling, is an alternative to post-harvest stumping (Sturrock et al. 1994, Thies and Sturrock 1995, Sturrock 2000). Whole trees are pushed over either by bulldozers (Morrison et al. 1988, Roth et al. 2000) or by excavators (Hedin 1993), which causes root systems to be pulled from the soil, and harvesting and removal of diseased stumps and roots is thus achieved with one stand entry. Yet also in this instance the use of wide-tracked excavators to push-fall trees is a major advance over a bulldozer with brush blade, as the excavator removes more roots from the soil, does not miss stumps, and minimizes site degradation (Morrison et al. 1991). An excavator pushes a tree over and then shakes the root wad to remove soil, and then rakes the resulting hole to break up, expose, and remove residual root pieces. Finally, trees are bucked into logs and the root wads cut off either straight at the excavation site or at the landing. Push-falling of Douglas-fir up to 78 centimeters d.b.h. was both operationally effective and cost-effective for reducing *Armillaria* and *Phellinus weirii* inoculum on many sites in British Columbia (Morrison et al. 1991, Sturrock et al. 1994).

Similarly, in Great Britain and New Zealand, mechanized stump removal (to control *Armillaria* and *Heterobasidion* root rot in pine stands) was initially accomplished by using a bulldozer with a solid blade (Greig and McNabb 1976, Shaw and Calderon 1977, van der Pas 1981, van der Pas and Hood 1984, Self and MacKenzie 1995, Greig et al. 2001, Gibbs et al. 2002). In Britain, a wide range of machinery was subsequently tested for stump removal, including bulldozers and a wheeled tractor with the loading arm adapted to push over and harvest the whole trees, but machines utilizing some form of hydraulic lifting action have been shown to be most satisfactory, as this type of machine was found to remove more of the finer root system undamaged than for example did a bulldozer (Greig and McNabb 1976, Greig 1980). The current stump removal operation in Britain is a two-stage operation. Firstly, after the trees are felled and the timber cleared from the site, the stumps are individually removed by a hydraulic excavator fitted with a single tine and left in rows. When all the stumps have been excavated, they are pushed into rows by a large, wheeled tractor fitted with a seven-pronged blade (Greig 1984, Gibbs et al. 2002).

Since 1970s till present, in whole-tree harvesting trials in Scandinavia stumps are removed either by excavator (stump rake) or using special stump harvester Pallari KH-160 (Kardell 1992, von Hofsten 2006, Saarinen 2006, Egnell et al. 2007). The harvester is developed by Tervolan Konepaja Oy, and is specially designed for mounting on hydraulic excavators to break up, loosen and take apart all kinds of stumps and roots. When extracting, Pallari KH-160 harvester shakes the stumps to remove excess of soil and to reduce weight, and is equipped with splitting stump-root device, which cuts larger stumps and roots into smaller pieces to reduce size (for mode of action and technical characteristics, see Stumpharvester… 2003). Currently, Pallari KH-160 harvester is intended for continuous use in large-scale stump harvesting for biofuel in Finland and Sweden. Moreover, in Finland a conventional stump rake is being tested, that combines stump extraction and soil scarification (mounding), thus creating more favourable conditions for subsequent stand regeneration (von Hofsten 2006, Saarinen 2006, Egnell et al. 2007).

10 Economical Aspects

Sturrock (2000) pointed out that the removal of infested stumps and roots can result in incremental growth benefits equivalent to or greater than those derived from planting, site preparation, genetic improvement, or vegetation management, and that the successful treatment may restore stands to near optimal productivity in one treatment (see also Tables 1, 2 and 3).

Earlier studies stressed that stump removal, although highly successful in reducing inocula of root rot fungi, is a costly operation (Shaw and Calderon 1977, Thies 1984, Sturrock et al. 1994). Consequently, the practice was more often suggested for use on highly infested sites or commercial fruit orchards (Shaw and Kile 1991), but not for a large-scale control of root rot in forest stands (Greig 1984, Shaw et al. 1989, Greig et al. 2001). Forest managers were hesitant to conduct stump removal because they view it as an expensive investment with an unknown future rate of return (Sturrock 2000). Therefore in the past, the main challenge with disease control by stumping was to balance the quantity of inoculum that must be removed to sanitise given site, with the economic cost of stump removal that can be justified by the yield of a stand in a following forest generation (Shaw and Calderon 1977, Greig 1980, Shaw and Kile 1991). In a few cases, stump removal was included as a reducing factor of root rot disease incidence when modelling forest yield in relation to management strategies of *Phellinus weirii* and *Armillaria* (Bloomberg 1988, Marsden et al. 1993).

According to Wargo and Shaw (1985) the control of root rot by stump removal requires detailed information on disease behaviour and damage levels, accessible terrain, proper soil conditions, and a site of high enough quality to produce a reasonable timber volume after disease effects have been minimised. Moreover, it was emphasized, that the application of this method must be carefully planned and conducted to ensure that it does not need to be done repeatedly after the infested areas of the first rotation have been cleared (Gibbs et al. 2002). In conclusion, stump removal was recently deemed as a highly effective but at the same time exclusive method for root rot control in forest stands.

So far, in all available studies on root rot control, stumps and roots following the removal were either dropped directly near to extraction craters and left scattered over a site (see Section 4 Thoroughness of the Removal), or pushed and piled into rows at the edges or throughout the plots (van der Pas 1981, van der Pas and Hood 1984, Greig 1984, Smith and Wass 1989, 1991 1994, Self and MacKenzie 1995, Thies and Sturrock 1995, Wass and Smith 1997, Greig et al. 2001, Gibbs et al. 2002). Consequently, the most common practice to date was not to harvest and utilize the removed material, but instead leave it to dry out and decompose (or sometimes to burn it) in the forest. Yet, even then in certain cases the operation was found to be cost-effective (Shaw and Calderon 1977, Greig 1980, 1984, Russell et al. 1986, Morrison et al. 1988, Self and MacKenzie 1995, Gibbs et al. 2002). For example, Self and MacKenzie (1995) demonstrated that actual returns from *Armillaria* control by stump removal might be almost twice as high as the costs. Morrison et al. (1988) concluded that in their 20-year experimental trial on *Armillaria* and *Phellinus weirii* root rot control by stump removal, the additional costs of the treatment were justified and compensated by the reduced losses to root disease, improved tree growth and full, uniform stocking. Greig and McNabb (1976) demonstrated that stump removal in *Heterobasidion*-infested pine stands in England resulted in financial benefits due to reduced loss from the disease in the next forest generation.

Besides of control and eradicating of root rot diseases, removal of extracted stump and roots from a forest site might be beneficial in several other ways. For example, simultaneous reduction of competing vegetation is accomplished, providing improved conditions for subsequent re-forestation (Hakkila 1974, Saarinen 2006; Table 2; see Section 6 Seedling Survival). By removal of *Heterobasion*-infected stumps and roots, the substrate for its sporocarp formation is excluded thus restricting the potential for airborne infections (see Section 4 Thoroughness of the Removal). Also the piles with *Armillaria*-infected stumps in the forest were shown to contain infection potential and trees planted within 4 m of the windrow were more likely to die from the pathogen than trees further away (Self and MacKenzie 1995). Removing those will therefore decrease the risk for the soilborne *Armillaria* infections.

In addition, the stumping will reduce harvesting costs by eliminating the necessity of treating stumps with urea or the *Phlebiopsis gigantea* Rotstop® biological control agent; costs of the treatment at final felling are estimated to be 0.4 euro/m^3 (Thor 2003, 2005). Moreover, in certain cases windrows of piled stumps were estimated to cover considerable part (10–16%) of stumped area (Greig and McNabb 1976, Wass and Smith 1997). Planting trees on windrows and piles of stumps would be impossible and successful natural regeneration on these piles would likely be delayed for many years (Wass and Smith 1997). Studies in Britain had shown that when the distances between stump rows were increased from 40 m to 80 m intervals, this resulted in additional 6% of plantable land, which offset the additional operational costs (Greig 1984, Gibbs et al. 2002).

However, the main financial improvement of stumping operation could be achieved by commercially utilizing removed stumps and roots, which until recently was problematic (Hakkila 1974, Greig 1980, Gibbs et al. 2002). Yet, at present a new perspective has emerged in energy sector of, e.g. Sweden and Finland under which forestry products, including stumps and roots, are and will be increasingly used for biofuel (Björheden 2006, Saarinen 2006, von Hofsten 2006, Egnell et al. 2007). As a result, the interest in stump harvesting has recently increased and is due to become economically feasible and routine practice in clear-felled forest areas. Consequently, the conditions are becoming favourable for simultaneous considerable eradication of root pathogens and sanitation of large forest areas without additional cost. Moreover, as evident from the current review, the potential does seemingly exist for acquiring stumps for fuel under improved economical and environmental terms than initially anticipated.

11 Concluding Remarks and Research Needs

The present review demonstrates that stump removal in clear-felled forest areas in most cases results in, a) reduction of root rot in the next forest generation (Table 1, Figs. 1, 2, 3), b) improved establishment of replanted seedlings (Table 2, Fig. 4), and c) increased tree growth and stand productivity (Table 3, Figs. 5, 6, 7). Consequently, the observed disturbances caused to a site by stumping operations were in most cases acceptable from forest manager's point of view. Yet, the majority of studies on consequences of stump removal have been conducted and are underway in North America. More recently there, along with the newly started *Armillaria* and *Phellinus weirii* trials, the long-term stumping experiments for control of *Inonotus tomentosus* root rot have been established (Sturrock 2000).

In Europe, the investigations on impact of stump removal on root rot occurrence and growth of the next forest generation stand are relatively scarce, and the extensive in-depth studies on the subject have been and are being done almost exclusively in Great Britain, and are focused at the control of *Heterobasidion* (Tables 1 and 3). Related information from the other parts of the continent, although promising, is nevertheless fragmented, and to date documented *Heterobasidion* eradication trials are available only from East Europe and Scandinavia, and were conducted in stands of *Pinus sylvestris* and *Picea abies*, respectively (Tables 1 and 3). Yet, studies of whole-tree harvesting in Scandinavia (not aimed at root rot control) show that also there seedling establishment and growth on stumped sites is enhanced during the first decade, thus the expected long-term impact on stand productivity is likely to be positive (Kardell 1992, 1996, 2007, Egnell et al. 2006).

Root rot fungi *Heterobasidion* and *Armillaria* are among the most destructive forest pathogens in Fennoscandia (Wahlström 1992, Woodward et al. 1998). However, recently tree stumps came into focus as the source of renewable energy and the new perspective of their large-scale harvesting for biofuel is likely to become as a long-term strategy and routine practice, at least in Sweden and Finland. Therefore, the possibility has evolved with the same effort simultaneously to achieve the sanitation of forest areas, and probably even under improved economical terms. Yet, there is a need for clear and fundamental understanding on possibilities to influence sanitation of forested land in time perspective and to evaluate potential benefits. In order to do this, three main questions must be answered applicably to Fennoscandian conditions: a) if and to which extent the conventional stump removal for biofuel on clear-felled sites could reduce the occurrence of *Heterobasidion* and *Armillaria* in the next forest generation, b) what impact is it likely to have on survival of replanted tree seedlings, and c) will there be any, and what, long-term consequences for subsequent tree growth and stand productivity.

Therefore, stump removal experiments already existing in the region must be evaluated accordingly, including repeated evaluation of previously published experiments (e.g. Stenlid 1987). Moreover, new permanent replicated trials must be established, possibly encompassing higher diversity of native tree species. Of particular interest in north Europe would be to know: a) how many roots would remain in the soil during the removal of healthy and, respective, root rot infected stumps following conventional stump harvesting for biofuel, b) what is infection potential of the infested root remnants in relation to their size, depth and duration of occurrence in the soil, c) what soil fungi are involved in eventual displacing of *Heterobasion* and *Armillaria* from infected roots, and d) if and to which extent their activity is affected by a subsequent fertilization of a stumped site.

Finally, it should be remembered that during stump harvesting some companies might be reluctant to accept the rot-containing stumps for chip production due to, e.g. their lower quality as a fuel. Consequently, in such cases the danger exists of leaving diseased stumps untouched on forest sites, while removing only those containing apparently healthy wood. However, the data on this review strongly suggests that as many (if achievable, all) rot-containing stumps as possible must be removed during whole-tree harvesting. Moreover, provided equal access, resources and availability, the priority should be given for stumping of root rot-infested sites, instead of healthy ones. Therefore, in harvesting stumps for fuel, the interests of energy companies and forest owners must be harmonised, by aiming simultaneously at bioenergy production together with the sanitation of forest land from the root rot disease. This would be the most environmentally friendly solution.

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