SILVA FENNICA

Silva Fennica 41(1) research articles

www.metla.fi/silvafennica · ISSN 0037-5330
The Finnish Society of Forest Science · The Finnish Forest Research Institute

Assessing the Incidence of Butt Rot in Norway Spruce in Southern Finland

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Mattila, U. & Nuutinen, T. 2007. Assessing the incidence of butt rot in Norway spruce in southern Finland. Silva Fennica 41(1): 29–43.

The aim of this study was to analyze the occurrence of butt rot damage to Norway spruce in different parts of southern Finland and to quantify the associated loss of quality. The data used in the study are from the 9th National Forest Inventory and consist of 5998 sample plots and 8007 spruce sample trees of saw-timber size. To predict the probability of damage to stands and trees, logistic regression models were constructed. Separate models were made for the whole study area, for the area where the general risk of *Heterobasidion* root and butt rot damage is high and for the area where the damage frequency is relatively low. In the high-risk area, the probability of damage decreased with increasing elevation and increased with increasing temperature sum. In addition, damage was more common on fertile sites and less common on peatlands; and thick peat layer decreased the risk of damage. The probability of damage was also higher in stands where special or selective cuttings had been carried out. In the sample tree data, the probability of damage increased slightly with increasing diameter and age of the tree. In the low-risk areas, elevation was the only variable that explained the probability of damage to a spruce tree. Site fertility and previous cuttings (more than ten years ago) explained the probability of damage to stands only weakly. For spruce damaged by butt rot, the saw-timber volume was reduced, on average, by 60% both in the high-risk area and in the low-risk area.

Keywords Butt rot, *Heterobasidion*, logistic regression, Norway spruce, quality loss
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Received 1 December 2004 **Revised** 24 October 2006 **Accepted** 10 January 2007
Available at http://www.metla.fi/silvafennica/full/sf41/sf411029.pdf

1 Introduction

According to the 8th National Forest Inventory (NFI8, 1986–1994), the total standing volume of trees in Finland was 1890 mill. m^3, of which pine made up 46 percent, spruce 36 percent and broadleaved species 18 percent (Tomppo et al. 2001). In recent years the market situation in Finland has favoured cutting of mature spruce stands. However, a considerable amount of overmature forest in southern Finland remains untouched; and many stands that are just reaching maturity have been regenerated (e.g. Korhonen et al. 2000a,b,c; Korhonen et al. 2006). As a result of increasing the amount of overmature spruce forest, the risk of losses due to decay has also increased. Consequentely, there is a need to predict the probability of damage to stands and to single spruce trees; and the associated loss of saw timber.

In southern Finland, *Heterobasidion* butt rot is the major cause of decay in Norway spruce (*Picea abies* (L.) Karst.) (Kallio and Norokorpi 1972, Hallaksela 1984, Piri et al. 1990). The second most important species of fungi that decay Norway spruce are *Armillaria borealis* Marxmüller and Korhonen and *A.cepistipes* Velenovský. In addition, *Stereum sanguinolentum* (Alb. & Schw.: Fr.) Fr., *Resinicum bicolor* (Alb. & Schw.: Fr.) Parm. and several other species can cause butt rot in spruce (Hallaksela 1984, Piri et al. 1990). By volume the proportion of decay caused by *Heterobasidion* is about 47–90% of the total rot volume in Norway spruce (Tamminen 1985). In addition to decay, *Heterobasidion* butt rot reduces the growth of spruce (Bendz-Hellgren and Stenlid 1995, Bendz-Hellgren and Stenlid 1997) and makes the trees vulnerable to wind damage. Two *Heterobasidion* species, *H. parviporum* and *H. annosum*, occur in Finland (Korhonen 1978, Niemelä and Korhonen 1998). About 90% of the *Heterobasidion* damage to Norway spruce in southern Finland is caused by *Heterobasidion parviporum* and 10% by *Heterobasidion annosum* (Korhonen 1978, Korhonen and Piri 1994).

In Finland, *Heterobasidion* butt rot is most abundant in southern and southwestern parts of the country, and the damage caused by the fungus becomes less common inland and towards the north (Laine 1976, Tamminen 1985, Korhonen and Piri 1994). *Heterobasidion* occurs at almost the northernmost limit of *Picea abies*; but in the northernmost forest, damage caused by the fungus is rare (Laine 1976, Norokorpi 1980, Korhonen and Piri 1994). Climate – in particular, cold and snowy winters – is considered to be the main factor limiting the occurrence of *Heterobasidion* butt rot in Finland. Compared to the forest vegetation zones, which have been defined on the basis of differences in vegetation due to temperature, either maritime or continental climate, and edaphic factors (Kalela 1961), *Heterobasidion* damage is most frequent in the hemi-boreal zone, and in about two of the sub zones of the south boreal zone, i.e. the narrow belt by the Gulf of Bothnia and the southwestern district of the south boreal zone.

Basidiospores of *Heterobasidion* root and butt rot are released into the air from perennial basidiocarps. When the air temperature is above zero, the spores disperse and infect fresh stumps and wounds (Kallio 1970). Human activities, such as thinnings and former land use are the most important factors that favour the spread of the disease (Stenlid 1987, Venn and Solheim 1994, Vollbrecht and Agestam 1995, Stenlid and Redfern 1998). Consequently, summertime cuttings predispose spruce stands to *Heterobasidion* butt rot and are known to promote the spread of the disease in Finland. After final cutting of a diseased stand, *Heterobasidion* butt rot can spread from old stumps to the subsequent tree stand (Stenlid 1987, Piri 1996, Piri and Korhonen 2001, Piri 2003). In old stumps, the mycelium of *Heterobasidion* may survive and produce basidiocarps for several decades (Laine 1976, Piri 1996).

Several properties of site and soil also affect the occurrence and severity of damage. In general, high risk of *Heterobasidion* damage has been associated with fast growth of trees and high fertility of the site, high pH and calcium content, low organic matter content and relatively high content of sand in the soil (Alexander et al. 1975, Laine 1976, Korhonen and Stenlid 1998, Stenlid and Redfern 1998, Gibbs et al. 2002). In addition, on peatlands and moist upland soils the risk is considered to be low (Laine 1976, Lindberg and Johansson 1992, Korhonen and Stenlid 1998, Stenlid and Redfern 1998). According to Kaarna-Vuorinen (2000), however, the relative frequency of butt rot is higher on drained peatland sites than on undrained sites. In addition, ditching of mineral soil sites increases the risk of *Heterobasidion* butt rot damage, possibly because the root systems suffer from occasional drought (Korhonen et al. 1998).

In Europe, several models of *Heterobasidion* root and butt rot have been developed. These models have been used in stand-level analyses of the incidence and severity of damage, the effects of thinnings on damage or the benefits of controlling the disease (Greig and Low 1975, Stenlid 1987, Pratt et al. 1989, Möykkynen et al. 1998). In addition, in Denmark and Sweden empirical models have been developed to predict the incidence of butt rot (Vollbrecht and Agestam 1995, Vollbrecht and Bilde Jorgensen 1995). Tamminen (1985) modelled the frequency of butt rot in Norway spruce using sample tree data from the 7th National Forest Inventory (NFI7) in the southern part and the west coast of Finland, where the frequency of butt rot is generally high. According to the model, the occurrence of butt rot in spruce trees was best explained by variables describing the geographical location of the trees (i.e. latitude, elevation and temperature sum), site variables such as paludification and fertility, and by the age of the stand. Tamminen (1985) used the model to estimate the frequency of butt rot throughout southern Finland. The model may, however, overestimate the frequency of rot outside the study area.

In Finnish National Forest Inventories, occurrence of decay in sample trees has been recorded since NFI7; but different classifications of the observed decay have been used in different inventories. Since the 8th inventory (NFI8, 1986–1994), observations on decay have also been made at stand level. There has, however, been no attempt to identify the decaying agents until the 9th National Forest Inventory (NFI9) carried out in 1996–2003.

The aim of this study was to analyze the factors associated with the occurrence of butt rot damage in Norway spruce stands and spruce trees in different parts of southern Finland. Models were constructed to predict the probability of damage to stands and to single spruce trees using the NFI9 data. In addition, the proportion of saw timber lost due to decay in trees classified as damaged by *Heterobasidion* butt rot was quantified.

2 Material and Methods

2.1 Data from the National Forest Inventory

The data used in this study are from the 9th National Forest Inventory (NFI9), measured in the years 1996–2000 in southern Finland (roughly between latitudes 60ºN–64ºN). In the data, southern Finland included the eleven southernmost forest districts, namely Åland, Rannikko, Lounais-Suomi, Häme-Uusimaa, Kymi, Pirkanmaa, Etelä-Savo, Etelä-Pohjanmaa, Keski-Suomi, Pohjois-Savo and Pohjois-Karjala (Fig. 1). The NFI data were measured in clusters that were situated systematically 7 kilometers from each other in both south–north and east–west directions (Metsäntutkimuslaitos 1996). Every fourth measured cluster is permanent, and the others were temporary. The temporary clusters contained 18 sample plots, the distance between neighboring sample plots being 300 meters. The data recorded from temporary sample plots include observations of the forest stands and sites as well as observations of sample trees. The sample trees were selected from the sample plots with a relascope. If a sample plot was situated in more than one stand, each stand was measured and described separately. For this study, only data from stands on temporary sample plots that contained spruce sample trees of saw-timber size were selected. Consequently, the data used here consist of 5998 stands and 8007 spruce sample trees of saw-timber size.

In addition to measurements of tree, stand and site characteristics (Table 1), the data contain observations of abiotic and biotic damage within the stand and in the sample trees. Decaying agents are divided into groups: "*Heterobasidion* butt rot", "other identified wood-decaying fungi" and "unidentified fungi". The occurrence of *Heterobasidion* butt rot in a sample tree was determined visually from a bore core taken at breast height. If there was evidence of other wood-decaying pathogens or stem or root injuries in a tree, it was not classified as damaged by *Heterobasidion*. Recordings of *Heterobasidion* within a stand were based on visual observations of bore cores and also on observations of other symptoms of *Heterobasidion* within the stand, e.g. fruiting bodies of

Table 1. Description of the variables that significantly explained the probability of butt rot.

Variable	Description	Scale
Site type	Mineral soil site types and corresponding peatland classes	
Grove		0/1
Herb-rich		0/1
Mesic		0/1
Sub-xeric		0/1
Xeric		0/1
Peatland	1 if the organic layer on the mineral soil is peat or if more than 75% of the ground cover consists of marsh vegetation, else mineral soil.	0/1
Organic layer	1 if the thickness of the organic layer on the ground is more than 30 cm, otherwise 0	0/1
Thin peat layer	1 if the thickness of the organic layer on a peatland is not over 30 cm, otherwise 0	0/1
Thick peat layer	1 if the thickness of the organic layer on a peatland is more than 30 cm, otherwise 0	0/1
Ditching	1 if the site has been ditched, otherwise 0	0/1
Special cutting	1 if cutting aiming at, for example, cleaning of road or ditch banks or removing of damaged or dying trees, has been carried out in the stand during the past ten years, otherwise 0	0/1
Selective cutting	1 if selective cutting, i.e. removing single trees from the upper tree layer, has been carried out in the stand during the past ten years, otherwise 0	0/1
Time from cutting	1 if more than ten years has elapsed since the last cutting, otherwise 0	0/1
Elevation	Elevation above sea level, m	m
Temperature sum	Effective temperature sum: sum of daily average temperatures above +5°C	°Cday
$d_{1.3}$	Diameter of a sample tree at 1.3 height,	mm
Age	Age of a sample tree, observed from increment cores taken at the 1.3 height.	years

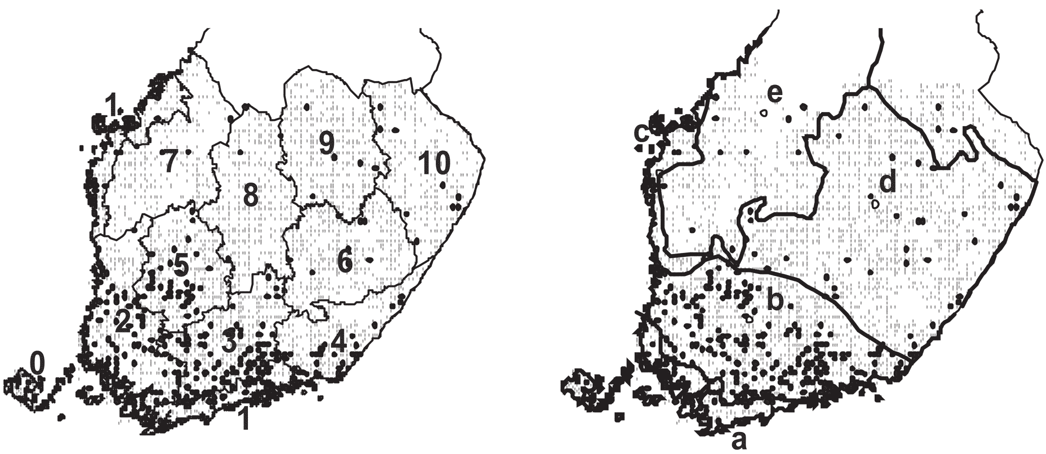

Fig. 1. Inventoried spruce stands and forestry districs and forest vegetation zones. Black dots: stands damaged by *Heterobasidion*. High-risk area: forestry districts 1–5; low-risk area: forestry districts 0, 6–10. Forestry districts: **0**: Åland, **1**: Rannikko, **2**: Lounais-Suomi, **3**: Häme-Uusimaa, **4**: Kymi, **5**: Pirkanmaa, **6**: Etelä-Savo, **7**: Etelä-Pohjanmaa, **8**: Keski-Suomi, **9**: Pohjois-Savo and **10**: Pohjois-Karjala. Forest vegetation zones: **a**: Hemiboreal; **b**: South boreal, southwestern area; **c**: South boreal, coastal area; **d**: South boreal, lake area; **e**: Middle boreal, Ostrobothnia.

Table 2. Site characteristics in the studied stands.

	Undamaged	Butt rot	Total	Butt rot %
MINERAL SOIL	4777	376	5153	7.3
ditched	431	28	459	6.1
non-ditched	4346	348	4694	7.4
thick organic layer	27	1	28	3.6
thin organic layer	4750	375	5125	7.3
organic, rock, cliff	87	5	92	5.4
clay, silt, fine sand	910	103	1013	10.2
coarse sand,	3690	264	3954	6.7
coarse gravel	90	4	94	4.3
groves	162	7	169	4.1
herb rich	2063	216	2279	9.5
mesic	2428	150	2578	5.8
sub-xeric	114	3	117	2.6
xeric	10	0	10	0.0
PEATLAND	817	28	845	3.3
ditched	673	20	693	2.9
non-ditched	144	8	152	5.3
thick organic layer	433	9	442	2.0
thin organic layer	384	19	403	4.7
groves	24	3	27	11.1
herb rich	248	9	257	3.5
mesic	500	16	516	3.1
sub-xeric	43	0	43	0.0
xeric	2	0	2	0.0

the pathogen and occurrence of butt rot in thinning stumps.

In the NFI9 sample tree data, the standing stems were classified into timber assortments, and the length and location of each assortment were recorded. The parts of the stems with saw-timber dimensions (with spruce, minimum length of 40 dm and minimum upper diameter of 16 cm) had to fulfill the saw-timber qualifications. If a part of a stem had saw-timber dimensions but did not fulfill the saw-timber qualifications, it was placed either into the pulpwood or the wastewood assortment, and the length of the part and the cause of the quality defect were recorded. One of the reasons for decreased timber quality was decay in the stem; the occurrence of decay and the length of decayed part of a spruce stem was assessed based on increment cores taken at 1.3 m height, occurrence of polyporus in the stems or leaking of resin from the stem.

In the sites studied, the elevation above sea level varied from 0.7m to 280 m; and the approximate

Table 3. Cuttings in the studied stands during the past ten years.

	Undamaged	Butt rot	Total	Butt rot %
No cuttings	3694	260	3954	6.58
Tending of seedling stands	63	0	63	0.00
Standard removal	19	1	20	5.00
First commercial thinning	326	17	343	4.96
Other thinning	1351	97	1448	6.70
Artificial regeneration	3	0	3	0.00
Natural regeneration	34	3	37	8.11
Selective cutting	15	4	19	21.05
Special cutting	89	22	111	19.82

effective temperature sum, calculated with the model of Ojansuu and Henttonen (1983), varied from 953°Cday to 1371°Cday. Decay classified as *Heterobasidion* butt rot occurred in 7.3% of the spruce stands on mineral soils and on 3.3% of the stands on peatlands. On peatlands, the proportion of stands damaged by *Heterobasidion* rot was highest on the most fertile sites; whereas on mineral soils, the proportion of damaged stands was highest on herb-rich forest types (Table 2). During the past ten years, in 65.9% of the studied stands no cuttings had been carried out. Frequency of damage caused by *Heterobasidion* rot was highest in spruce stands where there had been special or selective cuttings (Table 3).

The mean age of the sample trees, observed from the increment cores taken at breast height, was 68.8 years (min 17 years, max 322 years). The height of the trees varied from 9.8 m to 35.4 m (mean 21.3 m) and the diameter at breast height from 16.5 cm to 62.4 cm (mean 27.83).

2.2 Modelling the Probability of Butt Rot

The probabilities of butt-rot damage that was classified as caused by *Heterobasidion* were modelled with multiple logistic regression using SPSS software (Hosmer and Lemeshow 1989, Collet 1991). Logistic regression is commonly used in modelling the probability of an event, and it has also been widely used in analyzing factors affecting the risk of forest damage (e.g

Valinger and Fridman 1997, Jalkanen and Mattila 2000, Morrison et al. 2000). In logistic regression, a logit transformation is used to make the relationship between the response probability and the explanatory variables linear. The multiple logistic regression model is expressed as:

$$\text{logit}(p) = \ln[p/(1-p)] = \beta_0+\beta_1 x_1+\beta_2 x_2+\ldots+\beta_n x_n$$

where p is the probability that an event occurs and $x_1 \ldots x_n$ are the variables explaining the probability. The predicted probabilities are calculated by transforming back to the original scale: $p = \exp(\text{logit}(p)) / [1 + \exp(\text{logit}(p))]$.

The relative effects of the explanatory variables on the probability of damage were studied on the basis of the odds ratios for the variables (Breslow and Day 1980). The odds ratio approximates how many times the damage is more (or less) likely to occur when the factor affecting the probability of damage increases by one unit. In logistic regression, the odds ratios can be calculated by taking exponents of the estimated coefficients for the explanatory variables into the model (Hosmer and Lemeshow 1989).

Preliminary selection of variables was based on univariate logistic regression; all variables that, according to the Wald test, significantly ($p < 0.05$) explained the damage probabilities in the univariate models were selected for further analyses. For final selection of variables, the preliminary variables were included in stepwise (both forwards and backwards) logistic regression.

In order to determine whether the variables that account for the incidence of damage differ in different parts of the study area, models were made separately for the whole inventoried area, for the area where the general risk of *Heterobasidion* damage to spruces is known to be high and for the area where *Heterobasidion* damage occurs, but the frequency of damage is relatively low. The high-risk area was defined as including coastal areas and the southern and southwestern parts of the study area (Rannikko, Lounais-Suomi, Häme-Uusimaa, Kymi, Pirkanmaa forest districts). In the high-risk area, the number of stands was 3035 and the number of sample trees was 4075. The low risk area, which included Åland, Etelä-Savo, Etelä-Pohjanmaa, Keski-Suomi, Pohjois-Savo and Pohjois-Karjala forest districts (Fig. 1), contained 2963 stands and 3932 sample trees.

The fit of the models was studied using the Hosmer-Lemeshow goodness-of-fit test (Hosmer and Lemeshow 1989). The test statistics summarizes the differences in the observed frequencies and predicted probabilities in risk deciles of the data, and the test statistics is then compared to χ^2-distribution with eight degrees of freedom. The model fit was also studied graphically by comparing the mean observed frequencies of damaged stands or damaged trees and the mean predicted probabilities. To do this, probability estimates were calculated for every stand and every tree in the data. The mean predicted probabilities for forest districts were then compared to the observed frequencies. In addition, the strength of the association of the explanatory variables with the probability of damage was studied based on Nagelkerke's pseudo R-square (Nagelkerke 1991). The spatial distribution of the observed damage frequencies and the model residuals in the data were represented as surfaces (maps) produced by using the Ordinary Kriging interpolation procedure of the ArcGis-software.

2.3 Modelling the Reduction for the Saw-Timber Volume Due to Decay

The data were augmented by the reduction indices for the saw-timber volume of the trees of saw-timber size, which were calculated in the study of Mehtätalo (2002). The theoretical saw-timber volume and the volumes of different timber, pulpwood and wastewood assortments were calculated from NFI9 data using the volume functions and taper-curve models of Laasasenaho (1982). The theoretical saw-timber volume was defined as the volume of that part of the stem whose diameter exceeds the minimum diameter required for the particular tree species (in Finland, for spruce 16 cm). The total reduction index was calculated by dividing the volume of timber that was not accepted as saw timber due to stem defects or due to dimensions by the theoretical saw-timber volume of the stem. Correspondingly, the reduction index due to decay was calculated by dividing the volume of timber that was not accepted as saw timber due to decay by the theoretical saw-timber volume of the stem.

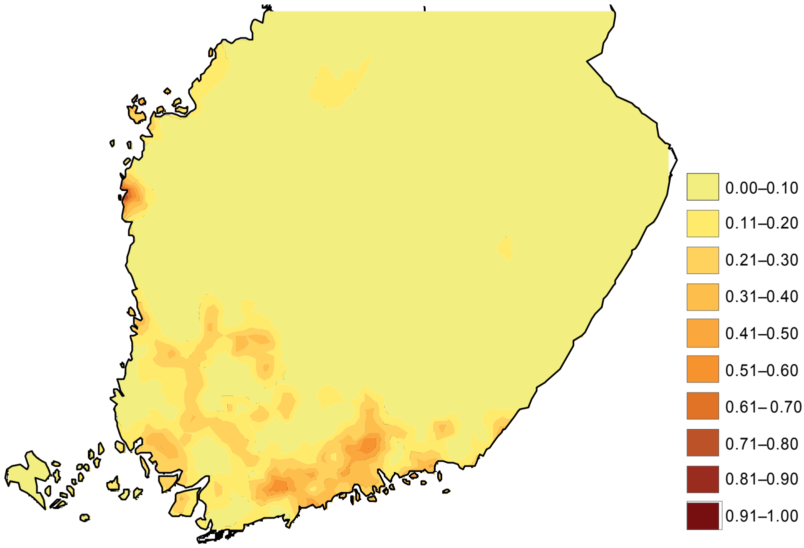

Fig. 2. Relative frequency of butt rot according to the NFI9 data. The map is based on the ordinary kriging algorithm of ArcMap™ 8.3.

Multiple linear regression was used to study the reduction in saw-timber volume due to decay in trees recorded as damaged by *Heterobasidion* butt rot. The reduction index due to decay is the proportion of decayed timber of the theoretical saw-timber volume of a tree. To keep the predicted values of the reduction between 0 and 1, a logit transformation,

$$\text{logit}(R) = \ln[R/(1 - R)]$$

was calculated for the reduction index (R). The NFI9 data contain trees recorded as damaged by *Heterobasidion* but whose saw-timber volume has not decreased due to decay. The data also include such infected trees whose reduction index is estimated to have a value 1. Because the logit transformation is, however, not defined if R = 1 or R = 0, these values in the data were replaced with 0.9999 and 0.0001, respectively.

3 Results

3.1 Distribution of Butt Rot in Spruce Stands and Trees

The overall proportion of spruce stands in which butt-rot damage occurred was 6.7%, and the proportion of damaged sample trees was 3.3%. In the area defined as a high-risk area, the proportion of damaged stands was 12.2% and the proportion of damaged sample trees 5.8%. The damaged stands were, however, rather unevenly distributed within the high-risk area (Fig. 2). Based on spatial interpolation of the observed damage, the high-risk area included local disease centers. In the worst centers the predicted frequency of stands damaged by butt rot exceeded 80%. In addition, in the east and in the coastal area of the Gulf of Bothnia, the borders of the most heavily infested areas were distinct. In the low-risk area, the overall proportion of damaged stands was 1.1%, and the proportion of damaged sample trees was 0.7%.

Table 4. Logistic regression models for the probability that butt rot occurs in a spruce stand. *= p<0.05, **= p<0.01, ***= p<0.001.

Variable	Whole data		High-risk area		Low-risk area	
	Estimate	Odds ratio	Estimate	Odds ratio	Estimate	Odds ratio
Constant	–11.496***		–7.286***		–5.390**	
Elevation	–0.010***	0.990	–0.008***	0.992		
Temperature sum	0.008***	1.008	0.004***	1.004		
Grove	–	–			1.512**	4.537
Herb-rich	0.426***	1.531	1.481***	4.396		
Mesic	–	–	1.118**	3.059		
Organic layer	–0.741*	0.477				
Ditching	–0.474**	0.622				
Thin peat layer			–0.605**	0.546		
Thick peat layer			–1.129*	0.323		
Special cutting	1.075***	2.931	0.991***	2.694		
Selective cutting	1.458*	4.299	1.526*	4.599		
Time from cutting					1.089*	2.972

3.2 Probability of Butt-Rot Damage to a Spruce Stand

In the model estimated using data for the whole of southern Finland, elevation above sea level, effective temperature sum, site fertility, variables describing bog formation on the site, and selective and special cuttings that had been carried out in the stand best accounted for the probability that butt-rot damage had occured in the spruce stand. The same factors also explained the probability in the high-risk area, except that slightly different variables were used to describe bog formation on the site (Table 4). The Nagelkerke pseudo R square of the whole data model was 0.157 and for the high-risk area model 0.085. In both models, elevation and effective temperature sum accounted for most of the variation in the occurrence of damage; the Nagelkerke pseudo R squares for the models containing only elevation and temperature sum as independent variables were 0.134 (whole data) and 0.045 (high-risk area). According to the models, the probability of damage decreases with increasing elevation and increases with increasing temperature sum.

In the model estimated using data for the low-risk area (Table 4), the only variables explaining the probability of damage were site fertility and time elapsed since the last cutting. The probability was higher in stands situated in groves and in stands that had not been cut during the past ten years.

Based on the odds ratios for site fertility in the model estimated from the data for high risk area, the relative effect of site fertility on the probability of damage was rather strong; on mesic sites the risk was three-fold and on more fertile herb-rich sites 4.4-fold compared to other site types (sub-xeric and poorer sites) and, on the other hand, compared to the most fertile sites, i.e. groves (Table 4). In the low-risk area, however, the probability of damage was higher in groves than in other site types. On peatlands with a thin peat layer, the risk of damage was about half the risk on mineral soils (odds ratio 0.546). If the peat layer was over 30 cm thick, the risk was less than one third the risk on minerals soils (odds ratio 0.323). The results for the whole data suggest that drainage of the site is also associated with the probability of damage; ditching of the site reduced the risk.

Both special and selective cuttings carried out in a stand strongly increased the probability of damage (Table 4). In these data, however, both cutting methods were quite rare: in the high-risk area, special cutting had been carried out in 67 stands and selective cuttings in 11 stands. In data for the low-risk area, the risk of damage was three-fold in stands where cuttings had not been carried out during the past ten years (odds ratio 2.972).

According to the Hosmer-Lemeshow test, the overall fit of both the model estimated using the whole set of data (χ^2=6.545, df =8, p=0.586) and

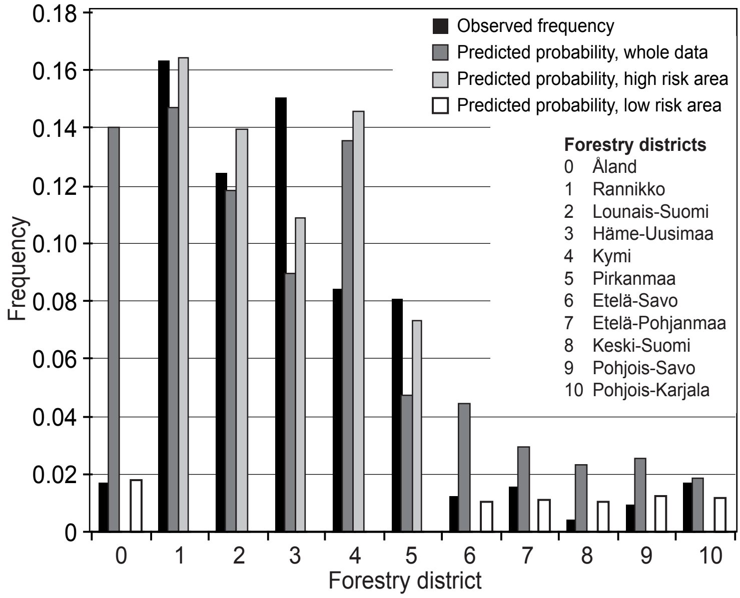

Fig. 3. Observed and predicted damage frequencies in forestry districts. Predictions are made using separate models for the whole study area and for high- and low-risk areas.

the model estimated using data for the high-risk area (χ^2= 3.755, df=8, p= 0.879) was good; i.e. the difference between predicted probabilities and observed frequencies was not significant. However, in such districts where the damage frequency is low, the model calculated from the whole set of data overestimated the probability of damage and in other districts mainly underestimated the risk (Fig. 3). Better predictions were obtained by using different models for the high- and low-risk areas (Fig. 3). The residual variation, however, remained high; and the residuals seemed to be spatially autocorrelated, especially in districts where the local infection centers were situated (Fig. 4).

3.3 Probability of Butt Rot Damage to a Spruce Tree

According to the Hosmer-Lemeshow test, the tree-level model estimated using data for the whole of southern Finland did not fit the data well (χ^2=19.07, df=8, p=0.014). In the model for the high-risk area, the predictions corresponded to the observed frequencies (χ^2=9.574, df=8, p=0.296). The residuals of the model seemed to be spatially autocorrelated.

In the high-risk area, the site variables that accounted for the occurrence of butt rot in spruces were mainly the same as those in the stand-level model (Table 5). However, thickness of the organic layer was not significant, and the probability of damage to a tree was higher only on herb-rich sites. In addition, special cuttings did not affect the probability of damage, whereas selective cuttings made in the stand significantly increased the risk.

The tree-level variables tested here included age, diameters at heights of 1.3 m ($d_{1.3}$) and 6 m (d_6) and diameter ($d_{1.3}$) growth. The probability of damage increased with increasing age of a tree (Table 5). The effect was, however, minor. Based on the odds ratio for tree age, a 50-year increase in tree age increases the probability of damage 1.49-fold. In relascope sampling, the probability of a tree to be selected as a sample tree depends on its diameter. Therefore, although it was not significant (p=0.069), tree diameter was included in the model.

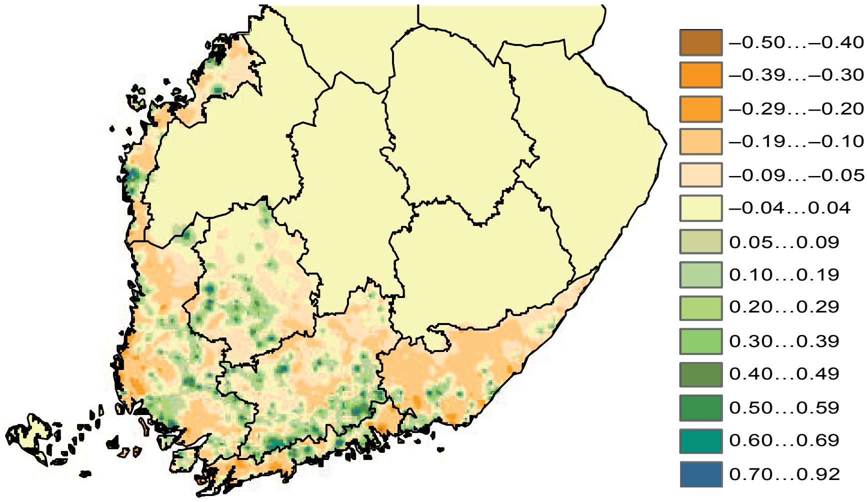

Fig. 4. Residuals of the model for the probability of *Heterobasidion* damage in stands in the high-risk area.

Table 5. Logistic regression models for the probability that butt rot occurs in a spruce tree.
* = p<0.05, ** = p<0.01, *** = p<0.001.
$d_{1.3}$ (whole data): p = 0.105;
$d_{1.3}$ (high risk area data): p = 0.069.

Variable	Whole data		High-risk area		Low-risk area	
	Estimate	Odds ratio	Estimate	Odds ratio	Estimate	Odds ratio
Constant	–11.349***		–7.255***		–3.607***	
Elevation	–0.013***	0.987	–0.012***	0.988	–0.011**	0.989
Temperature sum	0.006***	1.006	0.003**	1.003		
Herb-rich	0.333*	1.395	0.334*	1.397		
Peatland	–0.857**	0.425	–1.102***	0.332		
Selective cutting	1.528*	4.611	1.719*	5.579		
$d_{1.3}$	0.016	1.016	0.019	1.019		
Age	0.009***	1.009	0.008**	1.008		

In the low-risk area, elevation above sea level was the only variable that accounted for the probability that butt rot will occur in a spruce tree (Table 5). However, if the island of Åland, where all sample trees were growing in stands situated less than 50 m above sea level, was removed from the data, this variable was no longer significant.

3.4 The Saw-Timber Percentage of Spruce Classified as Damaged by *Heterobasidion*

In the whole set of sample-tree data, on average, 26.3% of the volume of saw timber was estimated to be reduced due to quality defects. The reduction due to decay in a stem was low, 3.5%. In spruce recorded as damaged by *Heterobasidion*, the relative reductions of the timber volume were, however, considerably higher; both in the high-

Table 6. Model for the reduction of the saw-log volume due to decay in trees damaged by *Heterobasidion* butt rot.

Variable	β	p
Constant	7.192	0.000
$d_{1..3}$	–0.182	0.000
Mesic	3.939	0.035
Sub-xeric	–1.280	0.027

risk area and in the low-risk area, the estimated total reduction for the saw-timber volume averaged 72% and the reduction due to decay 60%. The diameter of the tree and the site fertility accounted for the logit transformed reduction index due to decay (Table 6). The model could, however, explain only 9% of the variation in the reduction index (adjusted R square 0.093). According to the model, the reduction was higher on subxeric sites and lower on mesic sites than in groves and on herb-rich sites. The reduction index also decreased with increasing tree diameter.

4 Discussion

Both in the model estimated using the whole set of data and in that estimated using data for the high-risk area, elevation and effective temperature sum were the most important factors accounting for probability of butt rot damage to spruce stands and trees. In the low-risk area, however, these factors were not important. This result suggests that these factors approximate the location of the most heavily infected areas. In coastal areas, long periods of infection with *Heterobasidion* due to maritime climate favor the spread of *Heterobasidion*. In the models, elevation may reflect the effect of proximity of the sea on weather conditions in a stand. In Finland, the highest effective temperature sums accumulate and the longest growing periods (air temperature above +5°C) occur in the area where *Heterobasidion* damage is most abundant.

To obtain better predictions of the occurrence of butt rot damage in Southern Finland, division of the data into low- and high-risk areas seems to be reasonable. In the present study, this division was made using the borders of forest districts that are mainly administrative units. A better definition of the areas might be obtained, for example, using the borders of the vegetation sub-zones that are defined by the effects of climate conditions and edaphic factors on the vegetation cover. On the other hand, the outline of the high-risk area based on forest districts is rather similar to that based on the forest vegetation sub-zones, excluding Kymi and Pirkanmaa districts, whose northern parts are less fertile watershed areas. It should, however, be noted that the division into high- and low-risk areas is based on prevailing conditions. Consequently, the border may change if the circumstances that have affected the abundance of *Heterobasidion* butt rot change. These circumstances include, for example, changes in cutting methods, changes in controlling the spread of the disease and also possible climate change.

The risk of butt rot increased with increasing site fertility, which is in line with the results of studies concerning the effect of site fertility on *Heterobasidion* butt rot (Korhonen and Stenlid 1998). However, in the high-risk area, the probability of damage in the most fertile sites, i.e. in groves, was lower than on less fertile herb-rich sites. In the high risk area, *H. parviporum*, which infects mainly Norway spruce, dominates (Korhonen 1978, Korhonen and Piri 1994). The observed lower risk in groves may be a consequence of a possible higher proportion of deciduous trees in stands that are situated in groves compared to other stands. In the low-risk area, where *H. annosum*, which often also infects deciduous trees, becomes more common (Korhonen 1978, Korhonen and Piri 1994), groves were at higher risk of damage than were the other site types.

According to the results, the probability of butt rot on peatlands with a thick peat layer is lower than on peatlands with a thin peat layer. On peatlands the risk of *Heterobasidion* butt rot damage is often considered to be minor (Laine 1976). Such damage, however, also occurs on peatlands. Contrary those of Kaarna-Vuorinen (2000), some of our results also suggest that the risk of damage decreases if the site is drained. In Finland, however, ditched forest sites (considered suitable for wood production and associated cutting operations) include mainly peatlands with a thin peat layer. Consequently, drainage and thickness of the organic layer on the soil may be confounding factors.

Human activities are known to be the most important factors predisposing stands to butt rot, and the increased risk due to cuttings should be included in models for predicting the probability of butt rot in spruce (Möykkynen et al. 2000). In our study, however, customary thinnings did not explain the risk of butt rot. This is probably because the decay, which had, after thinning operation, originated from the stumps and grown through root contacts into new stems, cannot in ten years be detected at breast height. The risk of damage due to *Heterobasidion* butt rot caused by thinnings can be reduced by delaying the thinnings, by preferring wintertime thinnings or by using stump treatments. The NFI9 data, however, include no information on timing of the cuttings (winter vs. summertime) or stump treatment. On the other hand, in Finland, stump treatments have not been common until the past ten years.

Selective cuttings strongly increased the probability of butt rot both to the stands and to the sample trees, while special cuttings affected only the occurrence of damage at the stand level. Special cuttings include cuttings that are carried out for a wide range of reasons. Most of the special cuttings are, however, for the purpose of removing dead, dying or damaged trees, including windthrows, from the stand. The primary reason for wind damage may, in fact, have been decay in stems or in roots. In the inventory, there may also be difficulties to distinguish special and selective cuttings from each other, and some of the cuttings that have been recorded as selective cuttings may originally have been aimed at selecting damaged trees. Both selective and special cuttings may thus be merely the consequences of butt rot that had originated much earlier, rather than factors predisposing the trees to damage. However, both cutting methods may, for example, due to lack of strip roads, easily cause mechanical damage to the remaining trees, thus predisposing them to butt rot.

In the low-risk area, the probability of damage increased if cuttings in the stand had been carried out more than ten years previously. In principle, the more time that has elapsed since the stand or tree was infected, the easier it is to detect butt rot in the increment core of spruce taken at breast height. In the low-risk area, however, such stands where cuttings had not been made during the past ten years were, on average, older than other stands. Consequently,"time since cuttings" may refer to the effect of stand age on the probability of damage. In the high-risk area, an increase in the age of a sample tree slowly increased the probability of butt rot in spruce.

Reduction of saw-timber volume in a tree is affected by the size of the tree. For example, it is clear that in the smallest trees of saw-timber size the decay observed at breast height leads to a 100% reduction in the saw-timber volume. On the other hand, decay that had not yet reached breast height was not recorded in the inventory. This method leads to underestimation of the loss of saw-timber volume due to decay. If a tree was classified as damaged by *Heterobasidion*, however, reductions in saw-timber volume were high in both the high- and low-risk areas; but only a little of the variation in the indices could be explained by the tree dimensions or the site variables.

The most important factor affecting the reliability of the results of this study is the uncertainty related to the recordings of butt rot, especially in sample trees. Decay in the stem of a living tree is difficult to detect. Even more difficult is to define correctly the damaging agent, unless there are basidiocarps of the fungus present. It has been estimated that only 50% of root and butt rot can be found by boring at breast height (Kallio and Tamminen 1974, Stenlid and Wästerlund 1986). In NFI7, 55% of spruce trees with butt rot, caused by different damaging agents, were detected from the increment cores taken at breast height (Tamminen 1985). These trees, however, accounted for 87% of the total volume of wood affected by rot. According to Hallaksela (1984), *Heterobasidion* was the decaying agent in 38–56% of the butt rot spruce in southern and southwestern parts of Finland. It is obvious that also in NFI9 much rot has not been detected, and in some cases the causal agent has not been correctly identified.

These results suggest that in Finland there are two types of spatial variation in the occurrence of butt rot in Norway spruce stands. Firstly, there is a trend approximately from south-west to north-east or from the coast inland. This trend is most likely a consequence of change in climatic conditions. Secondly, the data included local disease centers; and the residuals of the models seemed to be spatially autocorrelated, especially close to the centers. These centers may arise from the established occurrence and relatively slow spatial spread of the damaging agent, which in most cases has probably been *Heterobasidion*. The results also suggest that although some site factors in the models were significant, their ability to predict butt-rot damage is limited. In addition, information on former land use and forest management in the NFI data does not allow us to take into account the effects of cuttings on the occurrence of butt rot. Consequently, the best way to improve predictions of butt-rot damage is probably to take into account the spatial variation in the occurrence of butt rot, i.e. by using spatial logistic models.

Acknowledgments

The study is related to the project "A forestry model for the national level analysis of forest management strategies in Finland" funded by the Academy of Finland (Project no. 202831) as a part of the Wood Material Science Research Programme. We would like to acknowledge also the Finnish National Forest Inventory, which provided the NFI sample plot and tree data, two anonymous referees for their constructive comments, and Dr. Joann von Weissenberg for checking the language of this manuscript.

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