Height Distributions of Scots Pine Sapling Stands Affected by Retained Tree and Edge Stand Competition

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The paper focused on the height structure of Scots pine saplings affected by (1) retained solitary pine trees or (2) a pine-dominated edge stand. The study material in (1) and (2) consisted of ten separate regeneration areas in southern Finland. In (1) 2-m radius study plots were located at 1, 3, 6 and 10 m distances from 10 systematically selected, solitary retained trees in each stand. In (2) the study plots were systematically located within 20 m from the edge stand. Competition of the individual trees was modelled using ecological field theory. The 24th and 93rd sample percentiles were used for estimating the height distribution using the two-parameter Weibull function. The models incorporated the effect of varying advanced tree competition on the predicted percentiles. Competition free dominant height was used as a driving variable for the developmental phase. Competition resulted in retarded height development within a radius of about 6 m from the retained tree, while it extended up to roughly half of the dominant height of the edge stand. The height distribution without external competition was relatively symmetrical, but increasing competition resulted in a more peaked and skewed distribution. Slight differences were found between northern sunny and southern shaded stand edges, while the least retarded height occurred at the north-western edge receiving morning sunlight. Kolmogorov-Smirnov goodness-of-fit tests showed acceptable and equal fit for both data sets; 2% and 8% of the distributions did not pass the test at the alpha 0.1 level when the Weibull distribution was estimated with the observed or predicted percentiles, respectively.

1   Introduction

Retention of trees is currently practiced in commercial forestry in the Nordic countries. Its primary purpose is the creation of structurally more complex stands in order to maintain specific ecological processes and recreational and aesthetical values. The adopted practices include retention of solitary trees, tree groups, patches and zones on and adjacent to regeneration areas. Specific valuable habitats, combining particular site conditions and vegetation types, are conserved and protected by means of small-scale buffer zones wherever encountered. Aesthetical and recreational values are mainly promoted by reducing clearcut size and utilizing irregular shaped regeneration areas. The retention practices were adopted in the 1990s and little attention was paid to the potential consequences for forest regeneration, productivity, and profitability in the absence of solid evidence concerning the benefits to biodiversity (See e.g. Annila 1998, Larsson and Danell 2001, Vanha-Majamaa and Jalonen 2001, Kuuluvainen et al. 2002, Ruuska et al. 2006).

Many of the structural retention practices tend to increase the length of the stand edges bordering regeneration areas, resulting in an increase in the area influenced by the stand edges. As a shade intolerant species, Scots pine (*Pinus sylvestris* L.) appears to be particularly susceptible to edge effects (de Chantal et al. 2003). According to Niemistö et al. (1993), Scots pine seed trees have an effect on the structure of pine seedlings, their spatial pattern and size distribution. Height development, as well as the density of the seedlings, decreased near to the seed trees. A similar decrease in seedling density was also found by Pukkala and Kolström (1992). The height reduction in the vicinity of seed trees reported by Pukkala and Kolström (1992) was steeper than that found by Niemistö et al. (1993). Nevertheless, these studies did not give any detailed description of the height distributions.

The height distribution is of prime importance from the point of view of the quality and quantity of a seedling stand and its future development. The height distribution can be depicted in a number of ways. In addition to flexible probability density functions, like beta (Loetsch et al. 1973, Päivinen 1980), Weibull (Bailey and Dell 1973), or Johnson's S_B (Johnson 1949, Hafley and Schreuder 1977) functions, non-parametric methods are also available (Silverman 1986, Droessler and Burk 1989). Non-parametric distributions are the most flexible as they include the ability to describe bi- and multimodality. However, they are usually impossible to apply for prediction purposes (e.g. Kernell-smoothing). One exception to this is the percentile-based prediction method for a distribution-free model (Borders et al. 1987, Maltamo et al. 1999).

The Weibull function has many advantages even though it is not the most flexible parametric distribution. The simplicity in mathematical derivation, low number of parameters required and its analytical cumulative function, are some of the properties that have made the Weibull function widely used. Maximum likelihood estimators are generally considered the best, but the percentile estimators are also applicable and easy to compute due to the analytical form of the cumulative Weibull distribution (Bailey 1973). The two-parameter Weibull function, especially, makes percentile estimation convenient.

The purpose of this study is to construct height distributions models for Scots pine sapling stands by incorporating the competition effect of i) solitary retained trees and ii) edge stand trees. Competition is assumed to have an effect on the selected two percentiles of the saplings' height distribution. Thus, percentile prediction of the two-parameter Weibull function should enable illustration of the effect of varying competition phases on the height distribution of the seedlings.

2   Material and Method

The studied stands were located in southern Finland (between 60°00´–62°45´N and 23°00´–28°45´E), at an altitude of below 200 m a.s.l, and covered the potential site range for managed Scots pine stands on mineral soil sites ranging from xeric (*Calluna* type, CT) to sub-mesic (*Myrtillus* type, MT) heaths (Cajander 1925). The site index at age 100 yrs (H_{100}) varied from 15 to 26 m. The original study material has been presented in more detail by Valkonen et al. (2002) and by Ruuska et al. (2006).

2.1 Retained Trees

The retained tree-study material consisted of ten Scots pine regeneration areas, in which mature Scots pine trees were retained for 8 to 18 years. Each stand represented the solitary retention pattern. On the average, the number of retained trees was 64 trees ha^{-1} with 22-m dominant height and basal area of 6.3 m^2 ha^{-1}. Three of the stands were planted and the rest were naturally regenerated. The 2-m radius study plots were located at distances of 1, 3, 6 and 10 m, alternatively to the north and south or to the east and west, from 10 systematically selected retained trees (i.e. sample of 10 stands × 10 retained trees × 8 plots). Thus, a total of 80 main crop pine saplings per stand were systematically sampled, mapped and measured for their dimensions (dbh, base diameter and height, h) as well as a number of other characteristics (e.g. branches, growth, crown dimensions) that are not discussed in this paper. All the other saplings located within a 2-m radius were measured for dimensions and distance from the main crop tree in order to measure the competition between the saplings. For the other stand characteristics, see Table 1.

2.2 Edge Stands

The edge-stand study material consisted of ten planted Scots pine sapling stands. The Scots pine-dominated edge stands had a dominant height of at least 15 m. On the sapling stand site, two square blocks (20 m × 20 m) were mainly situated on the opposite sides of the clearcut edges. In this data set green retention within the sapling stands was not accepted. A total of 32 main crop pine saplings were systematically sampled from each block and were mapped and measured for dbh and h (i.e. sample of 10 stands × 2 blocks × 32 plots). The other measured tree characteristics are not discussed in this paper. A circular sample plot (r = 2 m) was established around each selected main crop tree, which formed the midpoint of the plot. An additional sample of five dominant height saplings was selected subjectively in each sapling stand to represent the potential dominant height development in the absence of edge stand competition. The average height of these five dominant

trees is denoted as H_{dom}. The edge-stand sample plot was located 40 m along the border and 10 m towards the stand interior. All trees with dbh ≥ 5 cm in the edge stand were mapped and measured for species, dbh, and h. The average characteristics of the edge stands were a density of 570 ha^{-1}, dominant height of 20 m, and basal area of 21 m^2 ha^{-1}. The most important stand characteristics of the data are shown in Table 2.

2.3 Competition

Competition from the retained trees and between the saplings was described using widely applied ecological field theory (e.g. Wu et al. 1985, Kuuluvainen and Pukkala 1989). In Valkonen et al. (2002) and Ruuska et al. (2006), the competition index, influence potential (IPOT), was divided into the share of saplings and the share of the retained/edge trees, respectively. In this paper, IPOT characterized the share of the retained trees and edge trees only, i.e. an external competition factor from the saplings' standpoint. In previous simulation studies (Valkonen et al. 2002, Ruuska et al. 2006), IPOT was derived from the stump height diameters because seedlings less than breast height were also included in the study material (see Appendix). The same calculated IPOT values were used in the present study. The competition was dependent on the retained/edge tree dimensions, density ha^{-1}, and their spatial pattern. All these factors have an impact on how many individual trees have an effect on the resources at the particular calculation point (e.g. the plot midpoint).

2.4 Height Distributions

Combining the most similar sample plots (similar distance and competition status from the retained tree or stand edge) within a stand (and a block in the stand edge data) was essential in order to increase the number of observations for fitting and modelling the height distributions of the Scots pine saplings. At least two plots were aggregated. Saplings that originated from planting or natural regeneration were not separated. The planting density commonly used in commercial forestry is 2000 ha^{-1}. Thus, a considerably high number of

Table 1. Stand characteristics of the ten sapling stands including 346 height distributions for pine saplings formed from the retained tree data [a].

Variable	Mean	STD	Min	Max
Sapling stands				
$T_{(ret)}$, yrs	11.7	3.5	8	18
H_M, m	2.49	0.73	1.66	3.75
H_{dom}, m	3.89	1.26	2.11	6.65
N, ha^{-1}	6153	4518	2986	18477
h_{24}, m	1.43	0.83	0.31	4.64
h_{93}, m	3.15	1.49	0.66	11.5
IPOT	0.251	0.208	0.000	0.772
N_{plot}, ha^{-1}	6120	5903	1194	56102
Retained trees				
T_{rt}, yrs	114	23	75	150
H_{dom_rt}, m	22.1	2.04	17.6	24.3
N_{rt}, ha^{-1}	63.6	25.1	32	117

[a] $T_{(ret)}$, retention period; H_M, median height and H_{dom}, dominant height of pine saplings; N, mean number of seedlings in a stand; h_{24} and h_{93}, 24th and 93rd height percentiles of pine saplings; IPOT, competition index of old trees based on ecological field theory; N_{plot}, mean number of saplings in stand plots; T_{rt}, mean age of retained trees; H_{dom_rt}, dominant height of retained trees and N_{rt}, number of retained trees.

Table 2. Stand and plot characteristics of the ten stand and 243 height distributions formed from the edge stand data [a].

Variable	Mean	STD	Min	Max
Sapling stands				
T, yrs	12.6	4.3	7	23
H_M, m	2.39	0.92	1.12	5.86
H_{dom}, m	4.10	1.28	2.04	5.86
N, ha^{-1}	6226	2635	2671	10874
h_{24}, m	1.62	0.90	0.34	3.91
h_{93}, m	3.48	1.54	0.82	7.31
N_{plot}, ha^{-1}	6816	3979	1273	25464
IPOT	0.0145	0.0446	0.000	0.300
Edge stands				
T_{es}, yrs	86	29	40	135
H_{dom_es}, m	19.7	3.95	15.0	25.0
N_{es}, ha^{-1}	572	215	213	875

[a] For definitions of abbreviations see Table 1. T_{es}, mean age of edge stand; H_{dom_es}, dominant height of edge trees; N_{es}, number of stems in the edge stand.

the saplings, average about 4000 ha^{-1} in the edge stand data, were naturally regenerated (Table 2). The final competition factors affecting the height distribution were calculated as the mean distance and mean competition index of the combined sample plots. A total of 346 height distributions were included in the retained tree stand data and 243 distributions in the edge stand data.

The two-parameter Weibull function was selected for describing the height distributions of the pine saplings. The probability density function (pdf) of the two-parameter model for the Weibull random variable x, using the notation by Dubey (1967) is:

$$f(x) = \frac{c}{b}\left(\frac{x}{b}\right)^{c-1} \exp\left\{-\left(\frac{x}{b}\right)^c\right\};\tag{1}$$

$x \geq 0,\ b > 0,\ c > 0$

The Weibull distribution is characterised by the scale parameter b and the shape parameter c. The analytic cumulative distribution (2) makes the percentile method easy to compute (e.g. Bailey 1973).

$$F(x) = 1 - \exp\left(-\left(x/b\right)^c\right)\tag{2}$$

Two percentiles with a known value of the random variable and two unknown parameters can be solved using the system of equations. The value x_α of x is defined such that a randomly chosen observation has the probability α of being less than or equal to x_α. The two ordered percentiles were denoted as $\alpha 1$ and $\alpha 2$ ($\alpha 1 < \alpha 2$), and the corresponding values of the random variable as $x_{\alpha 1}$, and $x_{\alpha 2}$. Systems of equations were solved for parameters b and c. Using the symbols k and m, the parameter estimates took the simple form shown in Eq. 3 and 4 (see Dubey 1967, Bailey 1973).

$$\hat{b} = \exp\left(\frac{m}{k}\right)\tag{3}$$

$$\hat{c} = \frac{k}{\ln\left(x_{\alpha 1}/x_{\alpha 2}\right)}\tag{4}$$

where

$$k = \ln\left\{-\ln\left(1 - \alpha 1\right)\right\} - \ln\left\{-\ln\left(1 - \alpha 2\right)\right\}$$

and

$$m = \ln\{-\ln(1-\alpha1)\}\ln x_{\alpha2} - \ln\{-\ln(1-\alpha2)\}\ln x_{\alpha1}$$

The selected estimators, 100-times the pth percentiles, were the 24th and 93rd. They are the most efficient and asymptotically normal percentile estimators when both of the parameters, b and c of the Weibull function, are unknown (Dubey 1967).

The variation in these percentiles and the most important stand variables from height distribution modelling standpoint are given in the Table 1 for the retained tree data and in Table 2 for the edge stand data. The density is divided into stand level (N) and plot level (N_{plot}) number of saplings per hectare. Dominant height (H_{dom}) is a stand level variable describing sapling stand developmental phase without any external competition effects.

The analytic cumulative distribution (2) of the Weibull function makes the calculations convenient. For example, the conditional height with respect to a given percentile (p) could be calculated as:

$$h_p = b\left[-\ln(1-p)\right]^{1/c} \tag{5}$$

Eq. 5 was used e.g. for calculating the median height, h_{50}.

2.5 Model Formulation and Validation

Median height and dominant height are common stand characteristics and thus they were candidate explanatory variables for the two sample percentiles. Although both the median or dominant height without competition could represent the developmental phase of a stand, dominant height is more stable one. Another advantage of using H_{dom} is related to the known dominant height

development (e.g. Gustavsen 1980, Varmola 1993), which can be utilized when simulating stand development (e.g. Ruuska et al. 2006). Thus, H_{dom} was chosen as an explanatory variable for the model application in connection with the simulation studies and the reference value measured in the absence of the edge effect.

The height percentiles were assumed to be a multiplicative function of the sapling stand's developmental phase (H_{dom}), and to vary locally as a function of the external competition from the growth resources (IPOT) by advanced trees. Additionally, the edge effect was simply assumed to be a function of edge stand height (H_{dom_es}), distance (s) and direction (θ) to the nearest edge stand because of asymmetric radiation in the northern hemisphere. Finally, sapling stand density, denoted as the variation of the relative density within a stand (N_{plot}/N), may have an effect on the height structure (i.e. differences in the internal competition phase may affect the shape of the distribution). This candidate response was formulated so that the target plot density had no effect when it equalled the stand average density (i.e. when $N_{plot} = N$, then $\ln(N_{plot}/N) = \ln(1) = 0$).

The hierarchical structure of the data and the correlation between the estimated height percentiles were taken into account using an hierarchical multivariate model in MLwiN package (Rasbash et al. 2004). The multiplicative model was linearized using a logarithmic transformation. Thus, the model for height percentiles (h_p) for plot j in a stand k including competition from the retained trees had the following form:

$$\ln\left(h_{p(jk)}\right) = a_0 + a_1 \ln\left(H_{dom(k)}\right) - a_2 \ln\left(IPOT_{jk} + 1\right)$$
$$- a_3 \ln\left(N_{plot(jk)}/N_k\right) + \beta_k + \varepsilon_{jk} \tag{6}$$

while the model for the height percentiles in the vicinity of the edge stand was given the form:

$$\ln\left(h_{p(jk)}\right) = a_0 + a_1 \ln\left(H_{dom(k)}\right) - a_2 \ln\left(IPOT_{jk} + 1\right) - a_3 \ln\left(N_{plot(jk)}/N_k\right)$$
$$- a_4 H_{dom\_es(k)} / \left(s_{jk} + \cos\left(\theta_{jk}\right) - \sin\left(\theta_{jk}\right)\right) + \beta_k + \varepsilon_{jk} \tag{7}$$

where
s = distance from the edge, m
θ = direction from the stand plot to the nearest edge, radians

H_{dom} = dominant height of the sapling stand, m
H_{dom_es} = dominant height of the edge stand, m
IPOT = competition index of the retained/edge trees according to ecological field theory

N_{plot} = number of pine saplings per hectare on the stand plot

N = mean number of pine saplings per hectare in the whole stand

β_k = random parameter for stand k

$a_0–a_4$ = estimated fixed parameters of the models

ε_{jk} = plot level random error

When assuming the residual errors of the models to be multinormally distributed, half of the variance ($s_e^2/2$) had to be added into intercept in order to avoid bias when transforming back into original scale. In Eq. 7 the direction to the edge (i.e. orientation) was first examined independently as the north-south aspect (sunny vs. shaded) including $\cos(\theta)$, and secondly as the east-west aspect (evening vs. morning sun) including $\sin(\theta)$. Finally, when they both proved to be significant factors, they were combined as shown in Eq. 7 that resulted in an improved statistical fit. The total effect of orientation was symmetrical in the way that a positive effect of a particular direction resulted in a negative effect of the same extent in the opposite direction. It was also obvious that the effect of orientation had to be diminishing with respect to distance (s) from the edge. Also, the extent of the edge effect was assumed to correlate with the edge stand height, H_{dom_es}.

The approximate extent of the edge effect could be defined in numerous different ways with respect to biotic and abiotic factors. In this study interest was focused on height development adjacent to the edge. Thus, the extent of the edge effect was defined as the distance within which the stand-plot dominant height reached the respective competition free stand dominant height. The 97th percentile (h_{97}) was found to represent well the sapling stand H_{dom}. Thus, the approximate extent of the edge effect was defined as the distance within which h_{97}, defined with Eq. 5, coincided with the given H_{dom}, e.g. H_{dom} of 4 m of the sapling stand. The orientation was taken into account, but the density was fixed to the average stand density in order to prevent its effect on the calculations.

When assessing model validity, the logical behaviour of the models was checked using Math-Cad (MathCad… 2001). Calculation of the competition (IPOT) would require mapping of the trees together with their dimensions. However, when focusing the model behaviour, the IPOT values were averaged using equation $IPOT = H_{dom\_es}/35$ $\exp(-(1/0.4\ H_{dom\_es})s^2)$ according to Kuuluvainen and Pukkala (1989).

The fitted and predicted height distributions were tested with the Kolmogorov-Smirnov (KS) one sample goodness-of-fit test at the alpha = 0.1 level. In this study, the fitted distributions were solved using Eq. 3 and 4 with i) the observed height percentiles (h_{24} and h_{93}), while the predicted distributions were solved from ii) the predicted height percentiles ($\hat{h}_{24}$ and $\hat{h}_{93}$ using Eq. 6 and 7). Thus, the difference in the goodness-of-fit reflected the impact of generalizing the underlying phenomenon with the models.
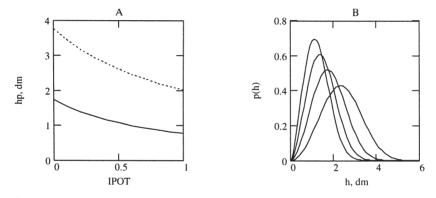
3 Results

3.1 Models for Sapling Height Percentiles

The estimated models (6) for retained tree stands (Table 3) showed that the predicted percentiles were lower than the dominant height (H_{dom}) of the sapling stand. Even if the within-stand average density was not related to the advanced tree competition (correlation coefficient between N_{plot} and IPOT was only 0.03), the relative density, i.e. the ratio between plot level density and stand average density, had only a slight influence on the higher percentile – increasing the plot density (i.e. increased competition between saplings) resulted in a decreasing h_{93}. According to the variance-covariance matrix, the total cross-model correlation was relatively high, namely 0.604.

The models (7) for the height percentiles influenced by the edge effect had much in common with previous models constructed for the retained tree effect. However, the edge effect was evidently stronger, and thus the resource competition factor IPOT alone could not explain it. Furthermore, the distance to the edge (s), the height of the edge stand (H_{dom_es}) and the orientation as the direction to the nearest edge (θ) proved to have an effect on the height structure. As in the case of the retained trees, the average density of the sapling stand was not influenced by the edge stand either, but the within-stand variation in the saplings' relative density (N_{plot}/N) explained some of

Table 3. Estimated fixed parameters, standard deviations of random parameters and residual errors for equations (6) and (7). For fixed parameters, the standard errors of the estimates are given in parentheses.
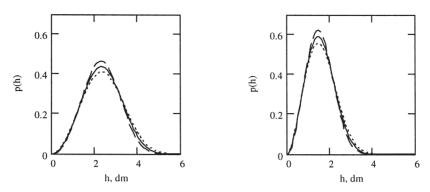
Model	Dependent variable	Fixed parameters					Random β_{jk}	Residual ε_{jk}
		a_0	a_1	a_2	a_3	a_4		
(6)	$\ln(h_{24})$	–0.744	0.926	–1.171			0.243	0.374
		(0.321)	(0.237)	(0.127)				
	$\ln(h_{93})$	–0.055	0.982	–0.895	–0.054		0.105	0.302
		(0.152)	(0.112)	(0.102)	(0.026)			
(7)	$\ln(h_{24})$	–0.882	1.073	–2.467	–0.173	–0.280	0.202	0.298
		(0.298)	(0.210)	(0.627)	(0.047)	(0.035)		
	$\ln(h_{93})$	0.068	0.947	–2.535	–0.111	–0.186	0.221	0.226
		(0.316)	(0.224)	(0.476)	(0.035)	(0.026)		

Fig. 1. The predicted height percentiles h_p (h_{24}=solid line and h_{93}=dash line) as a function of competition index (IPOT) (Fig. A). Corresponding height distribution related to the competition factor, IPOT=0.0 (widest distribution; no competition), 0.3, 0.6, 0.9 (Fig. B). Dominant height was fixed to 4 m.

the variation in the modelled height percentiles. The cross-model correlation coefficient was as high as 0.60. All the estimated parameters were highly significant except a_3 for relative density (p=0.006) in model (6) (Table 3).

3.2 Model Behaviour in the Retained Tree Stands

The behaviour of the models for the height percentiles are illustrated conditional to a dominant height of 4 m and as a function of retained tree competition ($0 \leq \text{IPOT} \leq 1$) (Fig. 1). Both percen-

tiles behave relatively similarly with respect to the competition index. When the relative density was one, h_{93} was proved to be considerably lower (3.7 m if IPOT=0) than the given dominant height $H_{\text{dom}}=4$ m which, in turn, coincided with the 97th percentile, whereas the maximum sapling height was practically 5.0 m (99.9% of the cumulative distribution) (Fig. 1B). The corresponding median height of the distributions decreased from 2.4 m without competition to only 1.2 m with a competition index of 0.9. Note that considerable competition occurs within a 6-m radius from a retained tree (see Valkonen et al. 2002).

The curve for h_{93} was slightly steeper than

Fig. 2. The effect of within-stand density variation on the height distribution. Stem number of the stand plot was fixed to 2000 (- - -), 4000 (—), 8000 (– – –) ha^{-1} without retained tree competition (left) and with competition IPOT = 0.5 (right) when the average density was set to 4000 ha^{-1} and H_{dom} 4 m.

that for h_{24}, and thus the difference between the percentiles decreased with increasing competition (Fig. 1A). Increasing competition resulted in a more peaked distribution but, according to Fig. 1B, skewness to the right (a longer tail towards taller trees) slightly increased as well. When the model behaviour was focused more widely, the height distributions without competition (IPOT = 0) resulted in a relatively symmetrical height distribution regardless of the median or dominant height (e.g. within range $3 < H_{dom} < 6$ m).

The differences in plot density only slightly affected the height distribution. Increasing density resulted in a more narrow distribution, and decreasing density in wider distributions. For example, an average density of 4000 ha^{-1} and a plot density of 8000 ha^{-1} resulted in an h_{93} of 3.6 m, and a plot density of 2000 ha^{-1} resulted in an h_{93} of 3.8 m. The corresponding effect on height distribution was relatively slight (Fig. 2).

3.3 Model Behaviour at the Vicinity of the Edge Stand

The edge effect was studied with respect to the distance and orientation. Fig. 3A shows the effect of the direction to the edge (northern sunny edge; direction = 0 or 360° (i.e. 0 or 2π radians), southern shaded edge; direction = 180° (i.e. π radians)

on the height percentiles h_{24} and h_{93}. Furthermore, the diminishing extent of the edge effect could be seen, with respect to evenly increased distance from the edge ($s = 3$, 6 and 9 m), as an uneven change in the predicted percentiles. As an example, the height percentiles at 3-m distance were about 50% of that at 9-m distance from the edge stand of 20 m H_{dom} (Fig. 3A). On the other hand, if 15 m is assumed as the H_{dom} of the edge stand, then the proportion of heights at the respective distances was about 65%. In order to simplify the analyses the competition (IPOT) was generalized using the equation presented by Kuuluvainen and Pukkala (1989), in which the distance from a competitor represented the distance from the edge. Thus, in the case of the example of $H_{dom\_es} = 20$ m, IPOT varied from 0.19 to a negligible value of 0.00002 on moving from a distance of 3 m to 9 m.

The relatively symmetrical height distributions, when only slightly affected by the edge stand competition, became more and more skewed to the right along with increasing edge effect (Fig. 3B, 4B). The differences in the height distributions were at their greatest between south-eastern and north-western sides of the clearcut. The difference between these positions was relatively obvious when focusing the distributions at the edge vicinity, but they logically diminished with increasing distance (Fig. 4). At 12-m distance the difference was relatively marginal. The difference
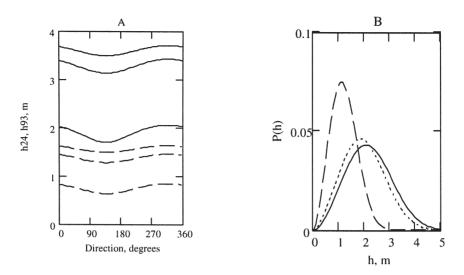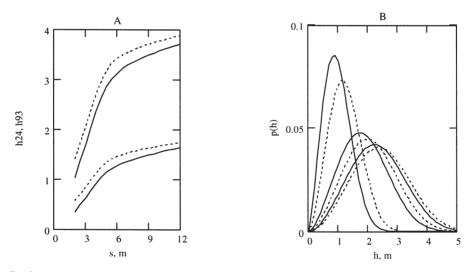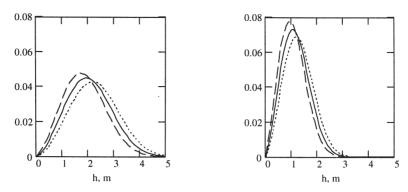
Fig. 3. The predicted 24th (– –) and 93rd (—) height percentiles with respect to distance (i.e. 3, 6, and 9 m distances) and the direction (degrees) to the nearest edge (A). Height distributions at the corresponding distances (3 m (– –), 6 m (· · ·), and 9 m (—)) from the edge on the north-eastern side (i.e. effect of direction on height percentiles is 0) of the clearcut (B). The dominant heights were set to 4 m and 20 m for sapling and edge stands, respectively.

Fig. 4. The differences in height percentiles (A) and height distributions (B) between south-eastern (solid lines) and north-western (dotted line) sides of a 4-m H_{dom} sapling stand. The height distributions are illustrated at 3, 6 and 12-m distance from an edge stand of 20 m H_{dom}.

in the predicted h_{93} on the south-eastern and north-western sides was less than 6% at a distance of above 9 m, but more than 9% below 6 m and more than 20% below 3 m. The difference in h_{24}

was even greater, namely 9%, 14%, and 33%, at the respective distance thresholds.

The differences in plot density (within-stand variation) clearly affected the height distribution

Fig. 5. The effect of within-stand density variation on the height distribution. Stem number of the stand plot was fixed to 2000 (- - -), 4000 (—), 8000 (− − −) ha^{-1} at 9-m distance (left) and 4-m distance (right) from the edge of 20 m H_{dom}, when the average sapling stand density was set to 4000 ha^{-1} and H_{dom} to 4 m.

(Fig. 5). Increasing density resulted in a more narrow distribution, and decreasing density in wider distributions. For example, an average density of 4000 ha^{-1} and a plot density of 8000 ha^{-1} resulted in a median height of 1.9 m, while a plot density of 2000 ha^{-1} resulted in a median of 2.4 m.

3.4 Extent of the Competition Effect

The extent of the effect of the retained tree on seedling height and height growth can be simply analysed on the basis of the competition index (see Appendix). Valkonen et al. (2002) showed that the effect of a solitary retained tree was negligible above 6-m distance. The approximate extent of the edge effect was defined as the distance within which the height percentile h_{97} coincided with H_{dom}. This was performed by calculating the h_{97} values (Eq. 5) of the predicted height distributions as a function of distance and two directions, the least affected north-western and the most affected south-eastern part of the opening adjacent to the edges. When assuming a dominant height of 25 m for the edge stand, the edge effect extended up to 10 m at the north-western part and 13 m at the south-eastern (shaded) part of the opening. The respective effect was found to vanish at a distance of 6 and 8.5 m if the edge stand dominant height was set to 15 m. Thus, on the average the edge effect extended up to a distance that corresponded to about half the dominant height of the edge stand.

3.5 Evaluation of the Height Distribution Models

The data for the model evaluation were generated using the presented models. The required input data for predicting the height distributions, i.e. the dominant height without competition (H_{dom}) and the competition index (IPOT), were extracted from the data (as if the retained trees were the same). A total of 6 fitted and 28 predicted height distributions showed a lack-of-fit out of the 346 height distributions of the retained tree data. In the case of the edge effect study, 5 fitted and 20 predicted Weibull distributions did not pass the KS test out of the total of 243 distributions. This result can be regarded as acceptable because the proportion of failures (0.08) of the predicted distributions in both cases was slightly below the risk level of 0.1.

4 Discussion

When both parameters, b and c, of the Weibull function are unknown, the most efficient percentiles are the 24th and 93rd (Dubey 1967). These percentiles were modelled with the dominant height of the sapling stand (H_{dom}). This was a practical solution, because the known development of H_{dom} (Gustavsen 1980) was applied as a driving variable in the simulations (Ruuska et al.

2006). It is obvious that H_{dom} could give a more reliable estimate for the 93rd percentile, but also a less accurate estimate for the 24th percentile than the alternative median height.

The competition index was determined on the basis of the retained trees and edge trees according to their size and spatial distribution using ecological field theory. Thus, it is a tree- or point-specific measure. In this study, the competition index was calculated for the plot midpoint in which the main crop tree was located. Some of the small sample plots had to be combined in order to increase the number of observations for studying the height distributions. It was obvious that the combination of small sample plots could be achieved without losing substantial information due to the relatively small variation in competition indices among the aggregated plots. Surprisingly, a considerably higher maximum competition index value was found close to a solitary retained tree (0.77) than close to the stand edge (0.30) where several trees could have an effect on the value of the index. One explanation is that, in the case of solitary retained trees the given distance was an absolute measure but, in the case of a stand edge, the distance was defined in respect to the nearest schematic stand edge line formed from the outer trees. In addition, solitary retained trees were older and larger on the average than the edge stand trees.

Competing big trees, either solitary retained trees or edge trees, had no significant effect on the average sapling stand density (see Valkonen et al. 2002, Ruuska et al. 2006). This was in line with the results earlier reported for shade tolerant species (Hughes and Bechtel 1997, Acker et al. 1998), but quite the opposite to the results of Niemistö et al. (1993) in northern Finland. Nevertheless, within-stand random variation in the density of the saplings was relatively wide and had some effect on the height distribution. A higher local density moved the distribution to the left, towards shorter trees, while a lower density moved the distribution towards taller trees. In terms of the estimated parameter, this effect was considerable in the vicinity of the edge stand, but rather negligible in the vicinity of the retained trees. Furthermore, the effect of the relative density on the lower percentile (h_{24}) in the retained tree stands proved to be insignificant.

Competition, described according to ecological field theory, was found to be an important characteristic when modelling the height structure of a pine sapling stand. In the case of the retained trees, it was the driving variable characterizing the within-stand differences in height distribution. The main factor behind this phenomenon may be the competition for light, but below-ground competition is also significant, especially in the case of solitary or grouped retained pines where the light interception of pine is relatively low (Kuuluvainen and Pukkala 1989). Competition proved to be meaningful within a distance of 6 m from a solitary retained tree. This is in line with the results of the study by Jakobsson and Elfving (2004) in Sweden, even though defined differently, through stand volume analysis.

Edge stand competition seemed to extend up to a distance of approximately half the dominant height of the edge stand. The effect is nonlinear due to a rapid increase in competition close to the edge (see Gagnon et al. 2003). In a study carried out by Jakobsson and Nilsson (2005), the volume of the seedling stand was significantly lower in the nearest 0–5 m zone from an edge stand with a mean height of 18 m, while the gradual increase in the volume of the zones located further away was insignificant. They also found that the volume and basal area in the nearest zone was only about 10% of that at a distance of 35 m. Such a reduction could be partly due to decreased seedling density (see Niemistö et al. 1993), but unfortunately this was not analysed by Jakobsson and Nilsson (2005). In the study carried out by de Chantall et al. (2003), pine seedlings showed retarded growth within a distance of about 10 m to 30 m depending on the direction to the edge (about 20-m mean height). Also, the biomass and height in the vicinity of the southern edge was about 30% and 70% of the maximum two growing seasons after sowing, respectively. Huggard and Vyse (2002) concluded that the effect of an edge stand on various biotic and abiotic factors generally extended over a distance of less than 20 m into the opening in high-elevation forests in British Columbia. However, the five-year height growth of planted spruce seedlings showed no edge effect on the north edge, but there was reduced height growth within at least 20 m from the south (shaded) edge.

Light interception tends to be much higher near

edge stands. Drever and Lertzman (2002) showed a clear nonlinear relationship between wide gradient of retained tree structure and understorey light. Due to the high latitude and low solar angle in Finland, the southern edge received only about 40% of the maximum radiation, which was equal to the radiation received under the canopy (about 10 metres from the edge) on the northern edge (de Chantal et al. 2003). Approximately the same result was found in British Columbia by Burton (2002). Both north-south (i.e. sunny vs. shaded) and east-west (i.e. afternoon sun vs. morning sun) aspects were examined and found to have a significant effect on the height distribution. The present model was formulated so that the 'positive effect' of a particular direction resulted in a similar 'negative effect' at the opposite side (Zheng and Chen 2000). In the present study, an edge stand on the south-western side of the opening seemed to have the strongest retarding influence on the saplings' height development. A north-eastern edge stand resulted in the least reduction in sapling height, respectively. Thus, the spatial pattern of tree size did not coincide exactly with the spatial pattern of radiation. Instead, the height development of Scots pine seemed to favour the morning sun compared to the afternoon sun. This may be related to the generally more favourable conditions during earlier sun in the west, i.e. a lower air temperature and higher relative humidity (see Wayne and Bazzaz 1993). Even if the difference between the directions was only rather small, the result was very much the same as that found by de Chantal et al. (2004) in similar geographical conditions but with considerably younger pine seedlings. Similar to the present study, tree height at the north-western part of the opening was about 20% higher than in the south-eastern part within a zone a few meters from the edge. In the study carried out by York et al. (2003), the northern part of the opening was found to be more favourable for seedling development than the southern part but there were only negligible differences favouring west compared to east. However, the fact that a number of different species were included in the same analysis may have lost some information about this effect. In fact, de Chantal et al. (2003) found relatively different responses with shade intolerant Scots pine and shade tolerant Norway spruce (*Picea abies* (L.) Karst.) to a light resource gradient.

The models presented in this study for the retained tree effect were further developed from the previously presented model in Valkonen et al. (2002). The present formulation is compatible with the models concerning edge effect, i.e. having H_{dom} as a measure for the successional stage and taking into account the correlation between the models and the hierarchical structure of the data. The distribution models required spatial calculations only for the stand plot midpoints. However, simulation of the sapling growth required spatial calculations for all the trees, saplings, retained trees, and edge stand trees (Valkonen et al. 2002 and Ruuska et al. 2006).

Acknowledgements

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Appendix

Competition index, IPOT

A growth potential (GPOT) value of 1 at a point in a stand indicated full availability of growth resources with no tree interference, and a value of 0 indicated the minimum level where no growth resources are available. The influence of a tree on GPOT was described by a single function, which was assumed to summarize the tree effects as a function of tree size and distance:

$$\varnothing_i(s) = \varnothing_i(o)\exp(-b_i s^2)$$

where

$\varnothing_i(s)$ = effect of tree i on the growth potential at distance s (m)

s = distance from tree i to the calculation point p

$\varnothing_i(o)$ = effect of tree i at the location point of a tree

b_i = parameter

Parameter $\varnothing_i(o)$ was dependent on tree size as follows:

$$\varnothing_i(o) = d_k/60 \text{ and}$$
$$b_i \quad = (0.4h)^{-1}$$

where d_k is stump diameter (cm), h is tree height (m), 60 is reference diameter, $d_{k(\max)}$ and 0.4 comes from previous studies by Kuuluvainen and Pukkala (1989), and Valkonen et al. (2002).

The maximum effect 1 was achieved at the location of a tree of $d_k = 60$ cm. The Growth Potential (GPOT) at point p was obtained by reducing its initial value of 1 by the effect of all the trees (n) around it ($\varnothing_i(s_i(p)) > 0.01$)

$$\text{GPOT}_i(p) = \prod_{i=1}^{n}\left[1 - \varnothing_i\big(s_i(p)\big)\right]$$

The competition index was the Influence Potential (IPOT) of all trees at point p:

$$\text{IPOT}_i(p) = 1 - \text{GPOT}_i(p)$$