Degree of Previous Cutting in Explaining the Differences in Diameter Distributions between Mature Managed and Natural Norway Spruce Forests

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The degree of naturalness was assessed in 37 mature (stand age 80–198 yrs) Norway spruce dominated stands located in southern Finland by measuring the number (0–610 ha^{-1}) and basal area (0–33 m^2ha^{-1}) of cut stumps. The Johnson's S_B distribution was fitted for living spruce trees to describe the dbh-frequency and basal area-dbh distributions. Regression models were constructed for predicting the parameters of the S_B distribution using traditional stand parameters (median diameter, basal area, stem number) and the cut stump variables (number, basal area). Stump variables improved the models and enabled to explain the differences in diameter distributions between stands with varying intensity of past cutting. Model for basal area-dbh distribution was more accurate than dbh-frequency model in terms of regression statistics, but less accurate in terms of generated stand variables. The number and basal area of cut stumps seem to be useful and simple measures of stand naturalness which have potential uses in stand modelling and biodiversity-oriented forestry planning.

Keywords naturalness, Johnson's S_B distribution, *Picea abies*, stand structure
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1 Introduction

The existing diameter distribution models in Finland have been developed to characterize mainly even-aged managed stands, and the shape of diameter distributions in uneven-aged managed or natural stands has received less attention. The beta distribution (Pukkala and Kolström 1988) or the negative exponential distribution (Kolström 1993) have been used to describe the initial diameter distributions when simulating uneven-aged, Norway spruce selection forests using a transition matrix. Maltamo et al. (2000) compared the Weibull distribution and percentile prediction

List of Symbols

Symbols concerning only living Norway spruce:

$\xi, \gamma, \delta, \lambda$	Parameters of the Johnson's S_B distribution
δ_G	Shape parameter of the basal area-dbh distribution
δ_N	Shape parameter of the dbh-frequency distribution
d_M	Median diameter at breast height (cm)
d_{gM}	Basal area median diameter at breast height (cm)
Md	Median in general. Md was either d_M of the dbh-frequency distribution or d_{gM} of the basal area-dbh distribution
D_q	Quadratic mean diameter at breast height (cm)
G	Basal area at breast height (m^2 ha^{-1})
N	Number trees (ha^{-1})
T	Stand age. Mean biological age of 10 dominant spruces (years)
V	Stem volume (m^3 ha^{-1})

Symbols concerning the whole stand (all tree species included):

G_{TOT}	Total basal area (m^2 ha^{-1})
N_{TOT}	Total number of trees (ha^{-1})
V_{TOT}	Total stem volume (m^3 ha^{-1})
G_S	Basal area of the cut stumps (m^2 ha^{-1})
N_S	Number of cut stumps (ha^{-1})
D_{qS}	Quadratic mean diameter of cut stumps (cm)

methods in describing the diameter distributions of Scots pine stands including both managed and natural forests. Siipilehto (2001) compared diameter distributions between natural and managed forest using the Johnson's S_B distribution. Nonparametric k-nearest-neighbor method (e.g. Haara et al. 1997) is an alternative approach if suitable data are available.

Completely untouched forests are rare in the boreal forests of Nordic countries. For example in eastern Finland, roughly half of the protected forests bore no witness of felling and were considered natural, whereas the other half, termed as seminatural, showed signs of light selective felling in the past (Uotila et al. 2002). This means that past treatments can still affect the present structure of seminatural, unmanaged stands.

Diameter distributions in natural or seminatural old-growth forests are often bimodal or multimodal (e.g. Kuuluvainen et al. 1996, Linder et al. 1997), but if different tree species are examined separately, the distributions are unimodal in most of the cases (Siipilehto 2001). Reverse J-shaped distribution is characteristic for natural late-successional spruce stands (Linder et al. 1997, Kuuluvainen et al. 1998). However, the shape of diameter distribution can also become more symmetrical along succession due to the mortality of smallest trees (Laiho et al. 1994, Linder 1998).

The objective of this study was to analyze whether knowledge on the degree of naturalness of mature, Norway spruce dominated stands, would be useful in predicting the diameter distribution of living spruce trees. The number and basal area of cut stumps originating from past cutting were used as measures of naturalness.

2 Material and Methods

2.1 Sample Plots

The study material consisted of 37 mature, Norway spruce dominated, *Myrtillus* type mesic heath stands (Cajander 1909). We used data from the 30 stands (including mature managed, over-

Table 1. Average, minimum and maximum values of the main stand variables for living Norway spruce in the study stands. The stands are grouped into three categories according to the basal area of cut stumps (G_s). Seminatural: $G_s \leq 2$ m^2ha^{-1} (number of stands n =12), slightly managed: $2 < G_s \leq 15$ m^2ha^{-1} (n = 13), intensively managed $G_s > 15$ m^2ha^{-1} (n = 12). For explanation of the variables see the list of symbols.

	Seminatural			Slightly managed			Intensively managed		
Variable	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Variables concerning living Norway spruce trees									
T, years	140	80	198	118	85	143	118	95	145
G, m^2ha^{-1}	22	7	33	22	6	32	24	15	57
N, ha^{-1}	747	482	1367	780	388	1434	465	240	880
V, m^3ha^{-1}	232	53	469	233	46	330	233	142	365
d_M, cm	17	10	23	18	10	24	25	17	32
d_{gM}, cm	26	16	38	24	14	31	29	21	37
D_q, cm	20	12	28	20	13	25	26	18	33
Variables concerning the whole stand									
G_{TOT}, m^2ha^{-1}	40	24	65	33	27	39	27	23	34
N_{TOT}, ha^{-1}	982	562	1633	1030	592	1860	550	324	1014
V_{TOT}, m^3ha^{-1}	449	226	720	339	270	479	294	234	409
N_S, ha^{-1}	5	0	22	159	25	371	420	179	610
G_S, m^2ha^{-1}	0.3	0	1	11	3	15	22	16	33
D_{qS}, cm	30*	24*	36	33	22	50	26	23	34

* Sample plots without cut stumps excluded

mature and natural stands) presented in Siitonen et al. (2000) and complemented the data with seven additional natural or seminatural stands, which were located in the same area and belonged to the same site type. Furthermore, measurements of both data sets were comparable (see Isomäki et al. 1998). Sample stands were located in southern Finland in the province of Pirkanmaa, ca. 62ºN 23º30'E. Relatively large sample plots were measured in all stands: 0.5 ha in the 30 stands in Siitonen et al. (2000) and 0.09–0.25 ha in the seven additional stands (Isomäki et al. 1998). Breast height diameters (dbh) were recorded for all living trees with dbh ≥ 5 cm. The number of measured Norway spruce trees per plot varied from 120 to 717.

The stand age (the mean age of ten dominant spruces cored at the root neck) varied between 80–198 yrs (Table 1). The stands had been managed with varying intensity. The number of cut stumps varied between 0–610 ha^{-1} and the corresponding basal area between 0–33 m^2ha^{-1} (Table 1). In practice, the stands formed a continuum from intensively managed stands to natural stands. Most of the natural and some of the managed stands originated from wildfires, as evidenced by frequent fire-scarred pines. Most of the managed stands had been treated with selective logging during the first half of 1900s, and thereafter with varying number and intensity of silvicultural thinnings.

The degree of previous cutting was estimated by counting the number of cut stumps ≥ 10 cm in diameter in 10 cm diameter classes (10–19, 20–29, ...) within an area of 1ha. The basal area of stumps was calculated based on the number of stumps in each diameter class and the median diameter of each class (15, 25, ...). Even very old (at least 50–100 years), completely moss-covered cut stumps could be separated from natural stumps on the basis of their uniform height, evenly cut surface, and lack of trunk remains next to the stump. We classified the stands into three categories according to the basal area of stumps: *intensively managed stands* in which $G_s > 15$ m^2ha^{-1}; *slightly managed stands* in which $2 < G_s \leq 15$ m^2ha^{-1}; and *seminatural stands* having $G_s \leq 2$ m^2ha^{-1}. Corresponding class limits in terms of number of stumps were about 250 ha^{-1} and 20 ha^{-1}. In six stands no signs of cutting were found. Stand characteristics are given in Table 1.

The average proportion of species admixture (Scots pine and broadleaved trees) was 20% and 30% in relation to the number or the basal area of living trees, respectively. The higher proportion of admixture in basal area was due to scattered large pine trees. The average total basal area was about 30 m^2ha^{-1} and average total volume of living trees was about 340 m^3ha^{-1} having an increasing trend from about 300 m^3ha^{-1} in the intensively managed stands to about 450 m^3ha^{-1} in the natural stands (Table 1). The same trend could be found in total basal area. For a more detailed description of the data see Siitonen et al. (2000).

2.2 Diameter Distribution

The breast-height diameter distributions for living Norway spruce, either as i) dbh-frequency distribution or ii) basal area-dbh distribution, were characterised with the Johnson's S_B distribution (1), which is based on transformation (2) to standard normality (Johnson 1949).

$$f(dbh) = \frac{\delta}{\sqrt{2\pi}} \frac{\lambda}{(dbh-\xi)(\xi+\lambda-dbh)} \exp\left(-0.5z^2\right) \quad (1)$$

where

$$z = \gamma + \delta \ln\left[\frac{dbh-\xi}{\lambda+\xi-dbh}\right] \quad (2)$$

z is standard normally distributed,
γ and δ are shape parameters,
ξ and λ are minimum and range parameters.

The three-parameter S_B distribution (ξ = 0) was fitted in the first step using the method of maximum likelihood presented by Schreuder and Hafley (1977) for dbh-frequency distribution, and by Siipilehto (1999) for basal area-dbh distribution. At the second step, the parameter λ (which was iteratively solved using maximum likelihood estimation) of the converged distributions was modelled with quadratic mean diameter of living spruces resulting in the Model 3.

$$\lambda = 24 + 1.6\, D_q \quad (3)$$

where
$D_q = 100\sqrt{4G/\pi\ N}$ (cm)
G = basal area of living spruces (m^2ha^{-1})
N = stem number of living spruces (ha^{-1})

The parameter λ (maximum dbh) was then set the value obtained by the Model 3. While both the endpoints are fixed, the maximum likelihood estimates for the shape parameter δ and γ have a closed solution (see Schreuder and Hafley 1977). The finite values were predetermined in order to diminish useless variation within the parameters of S_B distribution.

Regression models were constructed for predicting the parameter δ using traditional stand variables as predictors (Formulas 6 and 7 in Chapter 3.2). In addition to species-specific characteristics for living spruce trees (median diameter, basal area, stem number, stand age) also variables describing the entire stand (total stem number and basal area) and the proportion of admixture were optional predictors in the model. Cut stump variables (number, basal area) were included into the models to find out if they were significant predictors. In order to set the known median dbh for the predicted distribution, the parameter γ was solved using Formula 4.

$$\gamma = \hat{\delta} \ln(\lambda + \xi - Md) - \hat{\delta} \ln(\xi - Md) \quad (4)$$

where
Md is either median of the dbh-frequency distribution or median of the basal area-dbh distribution.

2.3 Assessment of the Model Fit

The behavior of the models was evaluated visually. The accuracy of the estimated and predicted distributions was tested using the Kolmogorov-Smirnov (K-S) goodness-of-fit test. In addition, relative biases (%) in basal area or in stem number were calculated when predicting the dbh-frequency or the basal area-dbh distributions, respectively.

$$bias = 100 \frac{1}{n} \sum_{i=1}^{n} \left[\left(Y_i - \hat{Y}_i \right) / \hat{Y}_i \right] \quad (5)$$

where
Y_i is the observed and
$\hat{Y}_i$ is the predicted stand characteristic.

Table 2. The Pearson correlation coefficients between the S_B distribution shape parameter of the dbh-frequency distribution (δ_N) or basal area-dbh distribution (δ_G), cut stump variables, and the main stand variables. Coefficients greater than 0.5 ($p < 0.005$) are indicated in **bold**. For explanation of the variables see the list of symbols.

	T	N	G	Md	Dq	N_S	G_S
δ_N	–0.206	–0.299	–0.141	0.428	0.260	**0.731**	**0.595**
δ_G	–0.134	–0.299	0.138	0.038	0.438	**0.794**	**0.648**
N_S	–0.272	–0.442	0.091	**0.637**	**0.528**	1.000	**0.915**
G_S	–0.320	–0.322	0.089	0.344	0.453	**0.915**	1.000

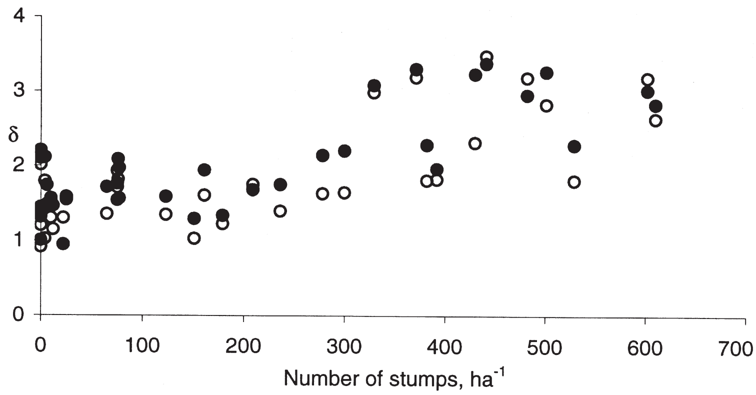

Fig 1. Relationship between the number of cut stumps and the S_B distribution parameter δ_N of the dbh-frequency (o) or δ_G of the basal area-dbh distribution (●).

3 Results

3.1 Relationships between Naturalness and dbh Distribution Characteristics

The mean stand age was the highest in the semi-natural stands. In spite of this, the intensively managed stands had, on the average, larger median diameter and larger basal area median diameter for Norway spruce (Table 1). In addition, the difference between these medians was the smallest in intensively managed stands indicating more symmetrical distributions. The number of spruce stems was clearly the smallest in the intensively managed stands. However, the basal area was about the same in all the three forest categories. The quadratic mean diameter of cut stumps was considerably larger in the slightly managed stands than in the intensively managed stands, indicating that the slightly managed stands had been selectively cut in the past.

High correlations ($r = 0.6–0.8$) were found between the value of S_B distribution parameter δ and the number of cut stumps and their basal area in a stand (Table 2, Fig 1). These correlations were considerably higher than those between δ and the living stand variables. The latter correlations were the highest between δ_N and the median diameter of the frequency distribution ($r = 0.428$), and between δ_G and the quadratic mean diameter ($r = 0.438$). The basal area of cut stumps was naturally highly correlated with their number.

3.2 Model Construction

The estimated prediction models for δ_N of dbh-frequency distributions (6) and δ_G of basal area-dbh distributions (7) were as follows (standard deviations of estimates in parentheses):

$$\ln\delta_N = \underset{(0.442)}{1.868} + \underset{(0.360)}{1.555} \ln d_M - \underset{(0.406)}{1.9816} \ln D_q + \underset{(0.0004)}{0.00179} N_s - \underset{(0.0085)}{0.0168} G_s \qquad (6)$$

$$\ln\delta_G = \underset{(0.252)}{1.140} - \underset{(0.214)}{2.160} \ln d_{gM} + \underset{(0.221)}{2.104} \ln D_q + \underset{(0.0002)}{0.00122} N_s - \underset{(0.0048)}{0.0165} G_s \qquad (7)$$

Logarithmic form for the dependent variable was used for homogenizing the variance as well as linearizing the relationships. In addition, it ensured the positive value for the parameter δ.

The standard errors of the models were 0.190 and 0.108, respectively. When predicting the values of $\ln\delta_N$, the degree of determination was 49% when median and quadratic mean diameters were the only predictors. However, the degree of determination increased to 70% when the number of cut stumps was added, and finally to 73% when both the number and the basal area of cut stumps were added into the model as predictors. When predicting $\ln\delta_G$, the respective degrees of determinations were 83%, 87%, and 91%.

Quadratic mean diameter of living spruce trees was used as a predictor. The ratio ln(G/N) could have been used as well, but D_q was in line with the determination of the maximum dbh, i.e. parameter λ. Also, we noticed that the estimated parameters of the models were less correlated than using both lnG and lnN as independent predictors. D_q of living trees was certainly highly correlated with d_M and d_{gM}. However, the two differently calculated mean values were excellent measures of the asymmetry (shape) of the distribution. Each of the mean characteristics alone could explain maximum of 18% of the variation in δ, while combining median and quadratic mean diameters, 49–83% of the variation was explained.

3.3 Model Evaluation

The behavior of the models was studied visually by predicting the distributions using the average stand characteristics for all the stands (i.e. $d_M = 20$ cm, $d_{gM} = 26$ cm, $G = 23$ m^{2}ha^{-1}, $N = 670$ ha^{-1}) but varying the number of cut stumps. Hypothetical stands used in the simulations were either 1) natural (no cut stumps), 2) slightly managed or 3) intensively managed, in which the cut stump variables corresponded to the averages shown in Table 1. Additionally, 4) a further hypothetical stand that had been thinned more intensively from below ($N_S = 600$ ha^{-1}, $G_S = 20$ m^{2}ha^{-1}, resulting in D_{qS} of stumps of 21 cm) was simulated using the models.

Slight management (selective cutting) caused only minor changes in diameter distributions as compared with the distributions in natural stand (Fig 2). This difference was hardly visible using Model 7, based on the basal area-dbh distribution. However, increasing the quadratic mean stump diameter from the average in the slightly managed stands (D_{qS} = 33 cm) skewed the distributions more to the right (longer tail). When D_{qS} was set to 40 cm, thinning would approach as selection of the thickest trees (Fig. 3). Decreasing mean stump size turned the distributions towards a symmetrical distribution i.e. shifted the mode to the right. Decreasing the mean size of cut stumps (D_{qS}) means that thinning is directed to smaller trees. In this case (example in Fig. 3), D_{qS} of 20 cm corresponds to thinning slightly below since the D_q of living trees (21 cm at breast height) means about 28 cm at stump height (Laasasenaho 1975). However, if we assume old stumps, even this thinning corresponds to selection from above.

In the intensively managed stand, the dbh distribution was more peaked and more symmetrical as compared with the distribution in natural stand (Fig. 2). Intensive thinning from below resulted in clearly the most peaked distributions. Applying the basal area-dbh model (7) seemed to cause the dbh distributions to become somewhat wider than applying the dbh-frequency model (6). The corresponding biases in stand characteristics are shown in Table 3. The clear underestimations in stem number when applying Model 7 for intensively managed stands or for even more intensive thinning from below indicated that these distributions were not peaked enough. Indeed, the extremely peaked dbh-frequency distributions with the same input variables (Fig. 2A) using Model 6 resulted in biases of only 0.4–2%.

The stands of the modelling data were generated using prediction models (6) and (7). The

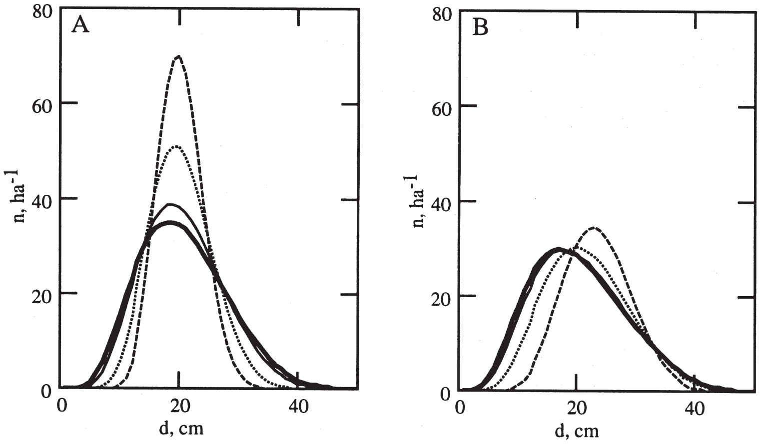

Fig. 2. The dbh-frequency distributions for Norway spruce predicted using dbh-frequency model (6) (Fig. A) or basal area-dbh model (7) (Fig. B) using the average stand characteristics, i.e. d_M = 20 cm, d_{gM} = 26 cm, G = 23 m^2ha^{-1}, N = 670 ha^{-1}. Natural stand with no cut stumps (▬) compared with three managed alternatives with varying cutting: slightly managed stand where the number and basal area of cut stumps were: N_s = 159 ha^{-1} and G_S = 11 m^2ha^{-1} (—); intensively managed: N_s = 420 ha^{-1} and G_S = 22 m^2ha^{-1} (...); and intensive thinning from below: N_s = 600 ha^{-1} and G_S = 22 m^2ha^{-1} (- - -).

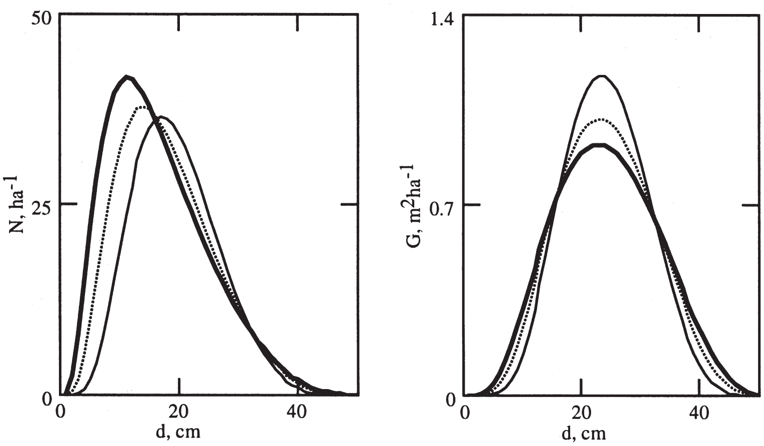

Fig. 3. The effect of the mean size of cut stumps on the shape of the dbh-frequency and basal area-dbh distributions for Norway spruce when predicted using basal area-dbh distribution model (7) and the average stand characteristics as in Fig. 2. The number of cut stumps = 160 ha^{-1} corresponds to average in the slightly managed stands while the quadratic mean diameter of stumps was set to 40 cm (▬), 33 cm (- - -) or 20 cm (–) using G_S of 20, 14 and 5 m^2ha^{-1}, respectively.

Table 3. Biases in the basal area (G) and stem number (N) when the average stand characteristics (d_M = 20 cm, d_{gM} = 26 cm, G = 23 m^2ha^{-1}, N = 670 ha^{-1}) and alternative numbers (N_S) and basal areas (G_S) of cut stumps were applied as input variables. The used stump parameters resulted in the shown quadratic mean diameters of the cut stumps (D_qs).

Management	N_S, ha^{-1}	G_S, m^2h^{-1}	D_qs, cm	Bias in G, %	Bias in N, %
Natural forest	0	0	0	–9.6	8.1
Slightly managed	160	11	30	–6.5	9.1
Intensively managed	420	22	26	–0.4	16.8
Cutting from below	600	20	21	2.1	25.1

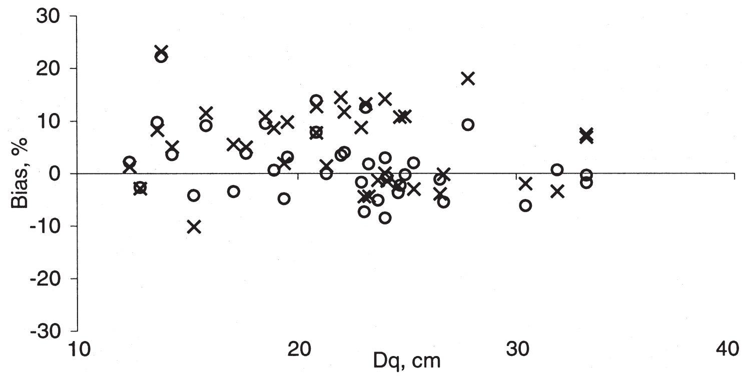

Fig 4. Bias in basal area (o) and in stem number (×) with respect to quadratic mean diameter of living Norway spruces, when modelling data was generated using Models 6 and 7, respectively.

overall underestimations were 1.7% in the basal area and 5.1% in the number of stems when using Model 6 or 7, respectively. The stand specific biases with respect to the quadratic mean diameter are shown in Fig. 4. Overestimations above 10% were not found, but underestimations exceeded 10% value in about 8% and 30% of cases using Model 6 (error in G) or Model 7 (error in N), respectively. The goodness of fit of the predicted distributions was acceptable since only four predicted dbh distributions out of 37 did not pass the K-S test at the 10% risk level. Three of the estimated distribution did not pass the K-S test when they were examined as dbh-frequency distributions. However, only one basal area-dbh distribution failed to pass the K-S test when the fitted distributions were compared to the observed basal area-dbh distributions.

4 Discussion

Due to flexibility in shapes, the theoretic S_B distribution proved to be useful in describing the differences in dbh distributions between stands with varying cutting history. The initial, iterative maximum likelihood estimators failed to converge in quite many cases, as found also by Kamziah et al. (1999). At the final estimation, the endpoints were predetermined and a closed-form solution of the maximum likelihood estimates for the shape parameters of the S_B distribution were calculated. Predetermined finite values have been quite widely used with the S_B distribution (e.g. Hafley and Buford 1985, Gadow 1987, Knoebel and Burkhart 1991, Zhou and McTague 1996 and Tewari and Gadow 1999). In this study the dbh-frequency and basal area-dbh distributions had common endpoints defined as a function of the quadratic mean diameter of living spruce trees. The remaining variation in shape parameters is assumed to be more closely related to stand characteristics due to fixed endpoints (Knoebel and Burkhart 1991). Furthermore, the goodness-of-fit is not necessarily strongly dependent on the finite values of the distribution as far as they are logical (Hahn and Shapiro 1967).

The model for predicting the shape of the distribution utilized knowledge of various distribution characteristics, namely median diameter, basal area and stem number. Using the both sum characteristics (G and N) together has been found to be efficient in predicting the parameters of S_B distribution (Siipilehto 1999). When the degree of previous cutting was incorporated into the model, again both the number and basal area of cut stumps were used. Consequently, the size of cut trees was indirectly included in the model.

The reverse J-shape dbh distribution was not as common in the seminatural or slightly managed stands in our material as could be expected e.g. according to the early National Forest Inventory (NFI) results (Norokorpi et al. 1994). Most probably this is due to the fact that the increase in stocking volume decreases the number of smallest trees. This phenomenon could be seen in later NFI data (Laiho et al. 1994), as well as in a study of mature and old-growth unmanaged forests in eastern Finland and Russian Karelia (Uotila et al. 2002). Linder (1998) and Linder and Östlund (1998) reported similar development in old-growth forests in Sweden, where the same stands were remeasured after a long period of time. Even in drained peatland the dbh distribution of spruce turned from the initial reverse J-shaped distribution to left-skewed distribution after 40–60 years from drainage, regardless of thinning treatments (Sarkkola et al. 2003).

One of the aims of selective cutting is to maintain the uneven-aged structure of stands (e.g. Lähde et al. 2002, Øyen and Nilsen 2002). According to the present models, the diameter distributions in the natural stands and the slightly managed, selectively cut stands were surprisingly similar. This is probably due to recovery from past cutting disturbance, i.e. regeneration in the gaps. Uotila et al. (2002) suppose that less than 5 cut stumps per ha indicates that natural stand structure is maintained. On the other hand, more intensive management using thinnings from below resulted in a clearly more peaked distribution and decreased the proportion of smaller trees as compared with the diameter distribution in a natural stand. Siipilehto (2001) found similar differences between managed and natural stands.

The increasing degree of previous cutting resulted in more peaked dbh-frequency and basal area-dbh distributions. In the examples of model behavior, the dbh-frequency model gave less biased distributions than the basal area-dbh model, which overreact the thinning effect by shifting the dbh distribution too much to the right. Thus, increasing the intensity of thinning resulted in a considerable underestimate in the number of stems by the basal area-dbh distribution model. A slightly less evident trend in bias could be seen with the dbh-frequency model. Furthermore, the basal area obtained by the dbh-frequency model was less biased on the average than the stem number obtained by the basal area-dbh distribution model, even though the dbh-frequency model did not explain the variation in shape parameter as well.

The decay class of cut stumps could also be utilized as a predictor variable in the models. The more decomposed the stumps are the longer time the stand had for recovering from the disturbance. However, the variation in decay class was not suitable for modelling purposes in our data. Stumps in the seminatural stands were all far decomposed while hard stumps could only be found in the intensively managed stands. Thus, the models are not necessarily able to describe dbh distributions well in recently selectively cut stands. The weak trend in parameter δ from natural stands ($N_s = 0$) to slightly managed stands ($N_s < 250$ ha^{-1}) may be partly due to recovery from past felling disturbances. To complete the models, data including stands that have been treated with old and recent selective fellings should be available.

The study showed that variables describing the intensity of past cutting, i.e. the number and basal area of cut stumps, were useful in describing the dbh distributions of mature Norway spruce stands which had been managed with varying intensity. Thus, the number and basal area of cut stumps also proved to be simple and useful measures of stand naturalness. They have potential applications in modelling stand structure, nature conservation inventories and biodiversity-oriented forestry planning.

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