Natural Development of Stand Structure in Peatland Scots Pine Following Drainage: Results Based on Long-Term Monitoring of Permanent Sample Plots

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We studied the dynamics of stand structure on drained peatland sites in Scots pine dominated stands untreated with thinnings. The data consisted of consecutive stand measurements in 10 permanent sample plots where the monitoring periods varied from 29 to 66 years. We assumed that the stand's structural development was driven by the natural processes of regeneration, growth, and mortality, all related to inter-tree competition within the stand. The DBH distributions of live and dead trees at different times of post-drainage stand development – smoothed by Weibull function – were analysed to characterise the change in stand structure. The initial uneven-sized structure of the natural, widely-spaced stands became more uneven during the first decades following drainage due to enhanced regeneration. Later, as stand density and mean tree size continuously increased, the DBH distributions approached bell-shaped distributions. Accordingly, the suppressed trees showed their highest mortality rate during the first decades, but the peak of the mortality distribution shifted to larger trees along stand succession. The change in structure was faster in southern Finland than in northern Finland. We assumed the changes in stand dynamics reflected increased inter-tree competition, initiated by enhanced site productivity and increased stand stocking resulting from the ditching operation.

Keywords stand structure, DBH distribution, *Pinus sylvestris*, peatland, drainage, tree mortality
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1 Introduction

In Finland, 3.3 million hectares of meso-oligotrophic or poorer peatland sites supporting Scots pine (*Pinus sylvestris* L.) as the main tree species have been drained for forestry (Hökkä et al. 2002). In undrained pristine pine peatlands, the stands are characteristically uneven-structured; they contain uneven-aged and -sized trees (Heikurainen 1971, Gustavsen and Päivänen 1986) and are also spatially clumped. Especially in composite peatland sites (having features of both treeless and forested peatlands), the high water level controls tree growth and seedling survival. Consequently, the pine stands on pristine peatlands are typically low-stocked and show low productivity.

Drainage of a peatland that naturally supports a Scots pine stand results in a considerable release in growth (Seppälä 1969), and better survival of saplings, resulting in enhanced regeneration and larger numbers of trees (Hånell 1988, Hökkä and Laine 1988, Roy et al. 2000). Thus, improved site productivity initiates a specific secondary succession, which involves a distinct change in stand structure: stand density, in terms of number of trees per hectare, increases for some decades after drainage and further enhances the structural unevenness (Hökkä and Laine 1988).

Our understanding of the structural development of pine stands on drained peatland is based on more or less managed stands (Hånell 1988, Hökkä et al. 1991, Hökkä et al. 1997, Gustavsen et al. 1998, Jutras et al. 2003). In Scots pine dominated drained peatlands, the processes of regeneration, growth, and mortality drive the natural stand dynamics. The inherent stand dynamics, however, are poorly documented, but would be specifically important for evaluating the necessity and feasibility of thinnings, which may become a common management procedure on drained peatland sites (Nuutinen et al. 2000). The better documentation of the development of peatland stands would also offer a different view on the dynamics of uneven-aged stands of Scots pine, which has been regarded as a typical species proper for even-aged management (e.g. Assman 1970).

The aim of this study is to describe the structural dynamics of peatland pine stands with no silvicultural management following drainage. The study is based on the monitoring of successively collected stand data. In the analysis, we used tree diameter (measured at breast height, DBH 1.3 m) distributions to characterise the stand structure.

2 Material and Methods

The data consisted of 10 repeatedly measured permanent sample plots (1000–2000 m^2 in size) established and maintained by the Finnish Forest Research Institute (Metla). These sample plots belong to a wide and geographically representative network of permanent sample plots established on drained peatlands in the 1920–1930s in Metla's research forests throughout Finland. Originally, the aim of the sample plots was to monitor the effects of drainage and compare the growth and yield of thinned and unmanaged stands (Lukkala 1929). For this study, we selected those sample plots which had been unmanaged for a period of at least 30 years; the data from at least four successive stand measurements were available, and besides the live trees, also the dead trees had been measured at every re-measurement.

The study sites chosen were located in southern (5 plots) and in northern Finland (5 plots) within a region delimited by 60°01'–67°10'N and 23°07'–26°40'E. The mean annual temperature sum (threshold value 5°C) in this area varies between 1400 and 850 dd. (Table 1).

The stands were naturally established before drainage. They were dominated by Scots pine and included some pubescent birch (*Betula pubescens* Ehrh.) as admixtures. The stands were left to develop without silvicultural measures, but the drainage was maintained in good condition during the entire monitoring period. In the data, meso-oligotrophic (*Vaccinium myrtillus* type, MT II) and oligotrophic (*Vaccinium vitis-idaea* type, VT II) composite peatland site types represented good and medium quality sites for pine, and ombrotrophic peatland sites (Dwarf-shrub type, DsT I) represented poor sites (Table 1). These site types have been common targets of operational forestry drainage. For more information on the classification of drained peatland sites in Finland, see Laine (1989).

Table 1. General attributes of the study sites. Site location: SF = southern Finland; NF= northern Finland. Site types: MT = Vaccinium myrtillus type; VT = Vaccinium vitis-idaea type; DsT = dwarf-schrub type; and a Roman numeral as the suffix: I = genuine forested peatland; II= composite forested peatland (see Laine 1989).

Sample plot	Location	Site type	Drainage year	First meas. year	Monitoring period, years	Number of meas.
Solböle 9	SF (60°01’, 23°07’)	DsT I	1930	1930	29	4
Vilppula 7b	SF (62°04’, 24°30’)	VT II	1909	1928	66	10
Vilppula 8b	SF (62°04’, 24°30’)	VT II	1909	1928	66	10
Vilppula 10b	SF (62°04’, 24°30’)	VT II	1909	1928	66	10
Karstula 7a	SF (62°56’, 24°24’)	DsT I	1932	1932	46	4
Kolari 14a	NF (67°10’, 23°45’)	MT II	1932	1932	34	4
Kolari 15e	NF (67°10’, 23°45’)	MT II	1932	1932	34	5
Kolari 16b	NF (67°10’, 23°45’)	MT II	1932	1932	34	5
Kolari 30b	NF (67°10’, 23°45’)	MT II	1933	1933	33	5
Kivalo 8f	NF (66°25’, 26°40’)	MT II	1933	1934	50	6

The trees on the plots were measured for diameter at breast height (1.3 m, DBH), separating dead (DBH ≥ 4 cm) and live (DBH ≥ 1 cm) trees, with 3- to 25-year intervals, from 4 to10 times. The duration of the monitoring period varied between 29 and 66 years (Table 1). For both regions, the plot-wise DBH data for both live and dead trees at each measurement occasion were smoothed with the two-parameter Weibull-function, which has proved to be feasible and flexible in smoothing distributions of different shapes and has been widely used to describe the DBH or basal area distribution of tree stands (e.g. Bailey and Dell 1973, Rennolls et al. 1985, Maltamo et al. 1995, Sarkkola et al. 2003).

The probability distribution function of the two-parameter Weibull distribution for a random variable *x* takes the form:

$$F(x) = 1 - \exp\left[-\left(\frac{x}{b}\right)^c\right], \quad \text{when } x \geq 0 \qquad (1)$$
$$= 0, \quad \text{when } x < 0$$

where $F(x)$ is the number of trees in DBH class x, and b and c are the parameters to be estimated. Parameter c describes the shape of the DBH distribution, and the scale parameter b indicates the diameter where 63% of the cumulative DBH distribution is represented.

Eq. 1 was fitted to both live and dead DBH distribution at every re-measurement with the MODEL procedure included in SAS statistical software, which applies the maximum likelihood (ML) method (SAS 1996). The performance of the fitting was checked by comparing the smoothed DBH distributions to the empirical ones.

The birches (47% of the total stand basal area at the maximum) and the few Norway spruces (*Picea abies* Karst. (L.)) in the dominant tree layer were combined with pine. In some plots, natural regeneration of spruce and birch occurred, which commonly appears at later successional stages forming a separate tree layer under the dominant tree layer. This advanced undergrowth was not included in the results because our aim was to study the post-drainage succession of tree stands established mainly before or immediately after drainage, and which formed the basic growing stock in these plots. The analyses of stand dynamics was based on the visual examination of the smoothed live and mortality DBH distributions, the development of stand density (stem number and basal area) and the average size of dead trees.

3 Results

The initial DBH distributions of the live trees were strongly positively skewed indicating uneven-sized structures. This skewness further increased during the first two decades after drainage (Fig. 1), but later decreased constantly, and in southern Finland the distributions became bell-shaped by 50–70 years after drainage. The stem number first increased about threefold (from 1400 to 4500 stems ha^{-1}), but began to decrease from a peak 20 years after drainage (Fig 2A). In northern Finland, the post-drainage flush of new trees culminated about 10 years later, but otherwise the trend was very similar to that in southern Finland (Fig. 2A). The stand basal area increased rapidly in southern Finland, and with a delay in northern Finland (Fig 2B). Although stem number peaked quite early, stand densities continuously increased over the whole monitoring period in terms of stand basal area.

The shapes of the DBH distributions of the dead trees closely resembled those of live trees in all drainage age classes (Fig 1). The peaks of the dead tree distributions, however, remained more persistently in smaller DBH classes than in those of the live tree distributions. The absolute annual mortality rate in number of trees increased steadily during the first 50 years following drainage, but then decreased towards the oldest drainage ages (Fig. 2C). In terms of basal area, the absolute annual mortality rate did, however, increase steadily (Fig. 2C). In the beginning, the mean diameter of the dead trees was equal to that of live trees, but later the mortality rate increased in trees with a diameter smaller than the mean of the live trees (Fig 2D). The proportion of dead trees was highest in DBH classes below 10 cm, and mortality increased as time elapsed since drainage (Fig. 3).

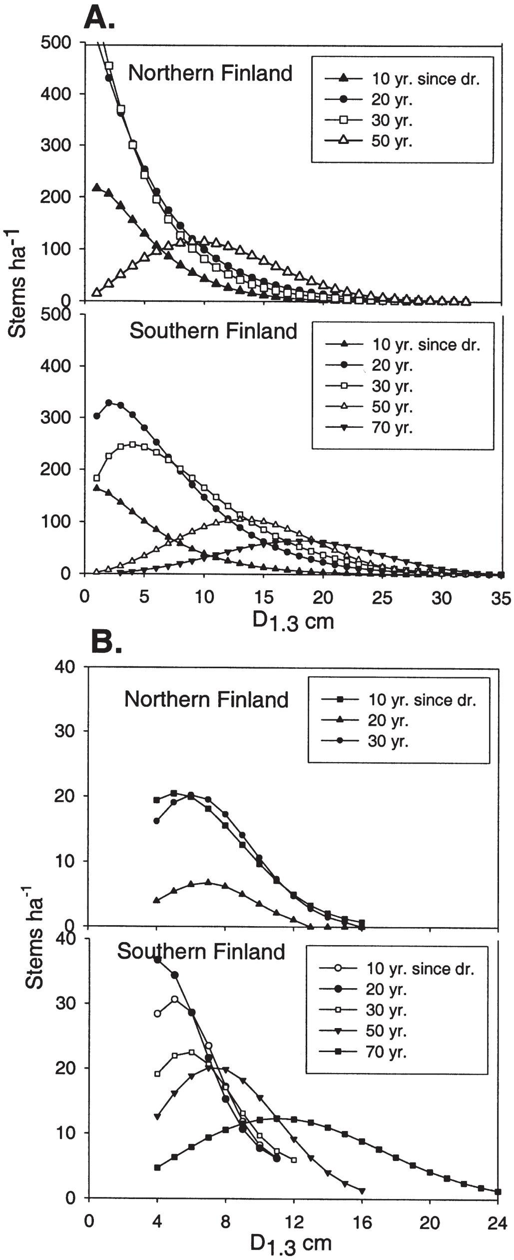

Fig. 1. The average post-drainage Weibull-distributions of diameter at breast height (DBH) for (A) live trees and (B) dead trees, by drainage age class (Class 10; 1–15 years elapsed since drainage; class 20; 16–25 years, etc.).

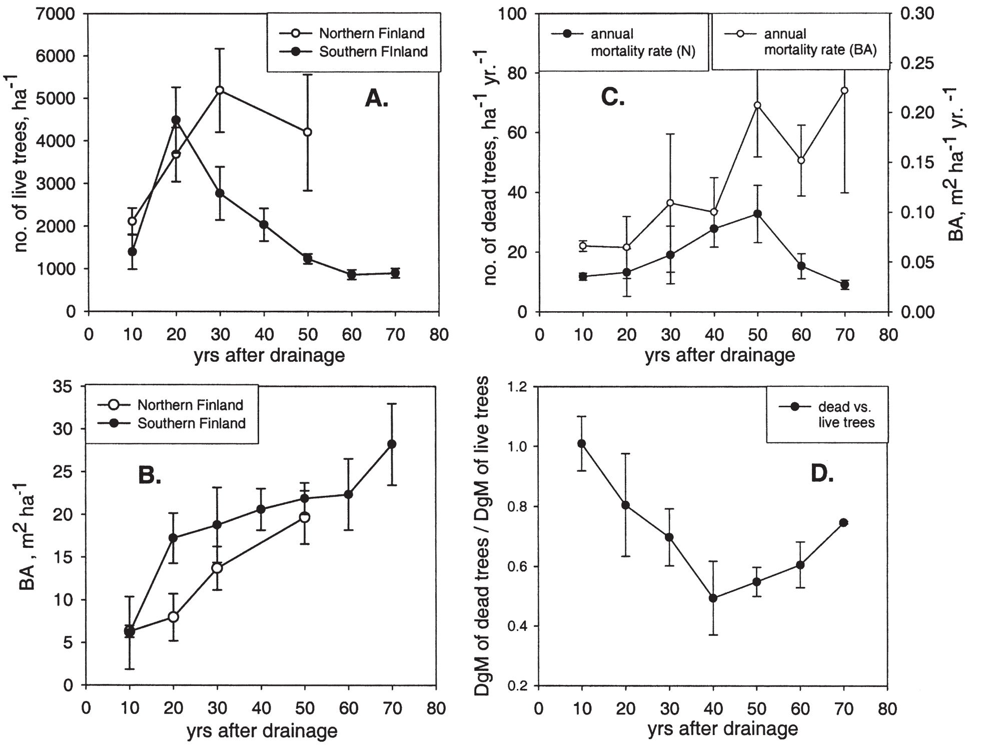

Fig 2. The average (A) number of live trees, and (B) live stand basal area for southern and northern Finland separately, the average (C) annual tree mortality rate of stand stem number (No.) and stand basal area (BA), and (D) the relationship between the median diameter of stand basal area (DgM) of dead and live trees for the data combined, respectively, by drainage age class. Error bars depict standard error of mean.

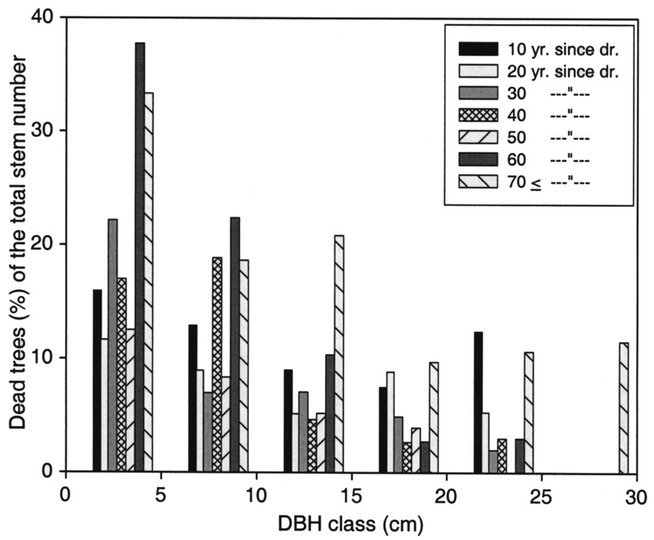

Fig 3. The average proportion (%) of dead trees of the total stand stem number by tree diameter (DBH) classes and drainage age classes. The DBH class 5: 4–5 cm; 10: 6–10 cm; 15: 11–15 cm, etc.

4 Discussion

The study was based on permanent sample plots that were small in number, but had been monitored for a relatively long period of time. Accordingly, the study sought to describe correctly the trends of natural temporal dynamics of uneven-aged Scots pine stands on peatlands following drainage, which is needed as a reference for the numerous earlier studies carried out in managed stands. For this purpose, the data was the best available, although insufficiently representative to characterise stand-wise differences in the dynamics. Furthermore, with regard to operational forestry drainage in Finland, the sites included in this study have been the most common targets of drainage, and the plots well represent the range of climatic variation.

Our results on the long-term natural development towards more even-structured stands, indicated by the change from positively skewed to bell-shaped DBH distributions and increased mortality of smaller trees over time, deviated from those of some other studies (e.g. Hökkä and Laine 1988, Norokorpi et al. 1997). In the other studies, the temporal trends were obtained from cross-sectional data by constructing age categories from different stands of similar ages (or time elapsed since drainage) growing in similar site types, but possibly having different developmental stages, stand structures, and management histories. Building DBH distribution chronosequences in this manner generally leads to over-estimation of small trees in the DBH distributions of more advanced stands, as demonstrated by Päivänen (1999). Thus, we suggest that the main reason for the contradictory results originates from the different methodological approaches, and that our results, based on truly longitudinal data, better reflect the general trends in temporal dynamics that take place in these stands after drainage.

After drainage, the number of small trees increased for two to three decades, probably as a result of enhanced conditions for regeneration and sapling survival and growth. Later, the mortality rate increased, the number of live trees decreased, and the initially skewed DBH distributions evolved gradually towards bell-shaped distributions. A similar development has also been reported in a bog pine (*Pinus uncinata*) stand following drainage of a cut-over peat extraction area (Freléchoux et al. 2000). Macdonald and Yin (1999) have reported a decrease in the size variability of trees in mixed black spruce (*Picea mariana*) and tamarack (*Larix laricina*) stands following drainage.

Average stand basal area by drainage age class was interpreted as a measure reflecting the accumulated effect of the processes of regeneration, growth, and mortality. As a result of increased stem numbers and the evidently enhanced tree growth and low relative mortality, stand basal area increased rapidly in the beginning, while in older drainage age classes, the increase was markedly smaller, probably due to higher tree mortality and reduced growth rates of individual trees (Ryan et al. 1997). In managed peatland pine stands, it has been shown that the probability for tree mortality increases (Jutras et al. 2003) and individual tree growth decreases (Hökkä et al. 1997) by increased stand basal area, and that the decreased growth is related to intensified inter-tree competition (Penner et al. 1995, Hökkä et al. 1997). Also, this study suggests that in the later part of post-drainage development, increased stocking restricted the growth of small-dimension trees, increased their mortality, and thus strongly influenced stand structural development. However, the gradual increase of the mean size of dying trees after 40 years or more from drainage may be due partly to the age-related mortality of the largest trees, since they were old already at the time of drainage.

The uneven-sized stand structure, typical for stands in pristine peatlands, was not retained in stands that were left to develop without silvicultural measures after drainage, except for the first decades when a lot of growing space was available for new trees. The smallest trees generally respond most vigorously to drainage (Heikurainen and Kuusela 1962, Seppälä 1969) and are evidently able to fill the initial openings in the stand. Most of the largest trees did, however, maintain their initially more competitive positions until the end of the monitoring period. The results are consistent with those of Ruha et al. (1997), who observed that in naturally regenerated Scots pine sapling stands, the height positions are established during the first 5–10 years of stand development and are virtually invariant up to 6 meters in height.

Our results suggest that improved drainage of initially water-logged peatland sites results in a dramatic change of otherwise unmanaged Scots pine-dominated stands from a clearly uneven-sized structure to a bell-shaped diameter distribution. This is consistent with what is generally considered the natural tendency of unmanaged stand development with light-demanding tree species such as Scots pine (Assmann 1970, Kramer 1988). In contrast, maintaining the uneven-sized structure would presume low site productivity resulting from low soil fertility or harsh climate conditions, or in productive sites, considerably low stand densities that prevent suppressed trees from dying from competition.

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