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Damaged and Dead Trees in Swedish Forests

Assessment and prediction based on data from the National Forest Inventory

Jonas Fridman

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Abstract

Trees in the forest die, and this fact has implications for both forest production and biological diversity.

This thesis deals with different aspects of damaged and dead trees in Swedish forests using data provided by the Swedish National Forest Inventory (NFI).

A model system for risk assessment of snow and wind damage to trees on a site, i.e., windthrow and stem breakage, was developed with logistic regression. The models use characteristics of the largest sample tree, together with site and stand characteristics on a plot, to predict the risk. Estimated probabilities of the risk can be used to adapt silvicutural treatments to limit damage caused by snow and wind.

The method used by the NFI for acquisition of data on dead wood (DW) is described together with estimates based on data collected in 1994-1996. Estimates show that the volume of DW decreases from almost 10 $m^3 ha^{-1}$ in northern Sweden to about 4 $m^3 ha^{-1}$ in the south, giving an average on productive forestland of 6 $m^3 ha^{-1}$ for the whole country. Results showing the lack of large dimensions of DW, and the decrease in the volume of DW after logging are also presented.

In 1994 and 1996 the NFI included plots within reserves, i.e., national parks, nature reserves, and Forest Service reserves, in the inventory. That data, together with data from 1983 to 1987 for plots on land that were later established as reserves, were used for analyses of the Swedish reserve network in terms of proportion of forest, stand age, site quality, tree species composition, and tree volumes. The results show that the proportion of productive forest within reserves is 20% compared to 60% of the land area of non-reserves, and that the volume of dead trees is higher within reserves. In general the distribution of forests within Swedish reserves is skewed towards old low-productivity Norway spruce (*Picea abies* L. Karst) forests in Northwest Sweden. This allocation might not meet the demands for protection of the habitats of endangered species.

Tree mortality functions were developed using logistic and linear regression. The 3-step approach consisted of: (I) estimating the probability of mortality on a sample plot, (II) quantifying the mortality in terms of the proportion of basal area on a sample plot, and (III) distributing the mortality among individual trees on the plot. Independent variables used for steps I and II were specific to site, stand, and plot size. Step III models were specific to tree species, and in addition to site and stand variables tree variables such as diameter and competition indices were included.

In summary, this thesis provides tools for inclusion in long-term management planning that would improve the possibilities for analyses of silvicultural treatments and their impact on risk of snow and wind damage, and also for their impact on the conditions for species depending on dead trees. The thesis also presents background data on the state of the forest within reserves, and the volume, structure and dynamics of dead wood on productive forestland in Sweden.

Key words: snow and wind damage, risk assessment, dead trees, dead wood, forest reserves, tree mortality, National Forest Inventory

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Contents

Appendix

Papers I-V

The present thesis is based on the following Papers, which will be referred to by their Roman numerals.

I. Valinger, E., and Fridman, J., 1997. Modelling probability of snow and wind damage in Scots pine stands using tree characteristics. *Forest Ecology and Management 97(3)*, 215-222.

II. Valinger, E., and Fridman, J., 1999. Models to assess the risk of snow and wind damage in pine, spruce, and birch forests in Sweden. *Environmental Management 24(2)*: 209-217.

III. Fridman, J., and Walheim, M., 2000. Amount, structure and dynamics of dead wood on managed forestland in Sweden. *Forest Ecology and Management 132(1-3)*: In press.

IV. Fridman, J., 2000. Conservation of forest in Sweden, -A strategic ecological analysis. Accepted for publication in *Biological Conservation.*

V. Fridman, J., and Ståhl, G., 2000. A 3-step approach for modelling tree mortality in Swedish forests. Manuscript.

Papers I, II, III, and IV are reproduced with the kind permission of the publishers.

Introduction

Trees in the forest die, and this fact has implications for both forest production and biological diversity. Ecologists consider the lack of snags (standing dead trees) and logs (lying dead trees) as a major threat to sustainable biodiversity in both temperate and boreal forests (e.g., Stubbs, 1972; Harmon et al., 1986; Esséen et al., 1992; Nilsson, 1997; Ohlson et al., 1997). Dead trees are vital for the existence of numerous species (e.g., Samuelsson et al., 1994) and it has been shown that 39% of the 1487 red-listed forest species in Sweden require dead trees for their survival (Samuelsson and Ingelög, 1996). Results by Ohlson et al. (1997) show that the amount of dead trees is highly correlated with species richness in Swedish boreal old-growth swamp forests. Several studies have also showed that the amount of dead trees is higher in unmanaged forests, e.g., reserves, compared to managed forests (Andersson and Hytteborn, 1991; Tyrrell and Crow, 1994; Lämås and Fries, 1995a; Reid et al., 1996; Linder et al., 1997; Green and Peterken, 1997). The Swedish Environmental Protection Agency has established Swedish Environmental Quality Criteria concerning the amount of dead trees that should exist in the forest landscape (SEPA, 1999). These criteria will aim at influencing forest managers to increase the amount of dead trees in their forests.

Contradictory to the benefits of dead trees in promoting biodiversity, trees that get severely damaged and/or die cause economic losses to forest owners. On average during the late 1980s and the beginning of the 1990s, snow and wind annually damaged approximately 4 million m^3, worth about SEK 1200 million, in Sweden (Valinger and Fridman, 1995). In order to limit the consequences from severe insect-outbreaks and attacks on the remaining stands (Schroeder and Eidmann, 1993) the Swedish forest legislation (SKSFS, 1993) prescribes limitations of newly dead conifers to 5 m^3 ha^{-1}, forcing forest owners to remove larger quantities of dead trees from the forest.

Adaptation of silvicultural treatments could limit damage caused by snow and wind on high risk sites (Valinger and Lundqvist, 1992). Therefore, it would be desirable to include risk assessments within management planning. Since the form of a tree is strongly correlated to its susceptibility to those forces (e.g., Peltola and Kellomäki, 1993) the development of a risk assessment model for snow and wind damage could use individual observations of tree form together with snow and wind damage registrations.

Altogether, there are many aspects of dead trees that should be included in forest management planning. Thus, there is a need to assess the amounts present both in managed forests and in reserves. Lämås and Fries (1995a) described a concept for an inventory as a basis for forest management planning combining biodiversity goals and timber production goals. In that inventory the volume of dead trees was assessed in strips between sample plots, on which all trees were tallied. Ståhl et al. (2000) reviews inventory methods of dead trees.

Before 1994, tree data recorded by the Swedish National Forest Inventory (NFI) only included dead trees that could be used as fuel wood, i.e., consisting of wood that was only slightly decomposed (Anon., 1993). Estimates on all dead wood could not thus be performed. The NFI neither included plots within reserves, i.e., national parks, nature reserves, and Forest Service reserves, nor has any other objective nation-wide field inventory within reserves been conducted so far. Kardell and Ekstrand (1990) compiled information on the state of the forest within reserves. However, the estimates might be biased due to the data acquisition method used. The lack of objective background data on the state of the forests within reserves is a general problem, especially in conservation management planning of the future reserve network (Usher, 1986; Rebelo and Siegfried, 1992).

In long-term forest management planning the essential components for reliable forecasts are; (i) ingrowth, (ii) growth, (iii) harvest, and (iv) natural mortality of trees (e.g., Söderberg, 1986; Monserud and Sterba, 1999). At present, the HUGIN-system (Lundström and Söderberg, 1996) and the Forest Management Planning Package (Jonsson et al., 1993) are the two major long-term forest management planning systems in Sweden. In both systems, predictions of the amount of natural mortality are performed using models by Bengtsson (unpublished) and Söderberg (1986). These models are based on data recorded before 1975 and do not distribute the mortality on individual trees, which would be desirable. Neither of the systems provides risk assessments of snow and wind damage.

Objectives

The main objectives of this thesis were to develop methods and predictive instruments for acquiring information on damaged and dead trees in Swedish forests, and also to present background results. Data from the NFI have been used for all purposes.

The specific objectives of the Papers included were:

- To establish the possibilities for development of predictive models for assessments of the risk of snow and wind damage on a specific site (Paper I)

- To develop a nation-wide model system for risk of snow and wind damage of pine-, spruce-, and birch-dominated sites (Paper II)

- To describe the method used by the NFI for acquiring data on dead wood and to present estimates based on that data to provide background information (Paper III)

- To describe the method used by the NFI for acquiring data on forest within reserves, and also to present estimates based on that data in comparison with estimates of forest outside reserves (Paper IV)

- To develop new tree mortality functions to be used in Swedish long-term forest management planning systems (Paper V)

NFI data

Background

The state of the forest resources in Sweden has been of great concern since the 16th century, when the fear of local over-utilisation grew (Anon., 1914). In 1735 the Swedish county governors were ordered for the first time to report to the Government on the state of the forests in their counties (Anon., 1914). In 1849 the first national estimates ever in Sweden on growth and consumption of timber volumes were reported by Israel af Ström (Anon., 1914). Internationally, it is likely that the first discussions on the global forest resource situation took place in Paris during the World Fair in 1910 (von Segebaden, 1998). The growing concern for the forest state in Sweden, i.e., standing volume, forest growth, and annual cut, eventually lead to the initiation of the NFI in 1923 (Thorell and Östlin, 1931; SOU, 1932). Since 1923 the NFI has been modified on several occasions (von Segebaden, 1998). The present general design, an annual stratified sample plot design with plots clustered into tracts (Figure 1) using sampling with partial replacement (SPR), was implemented for the first time in 1983 (Ranneby et al. 1987). The SPR design combines temporary tracts (measured only once) and permanent tracts (repeated measurement) to increase the accuracy in estimates of changes (Schreuder et al., 1993).

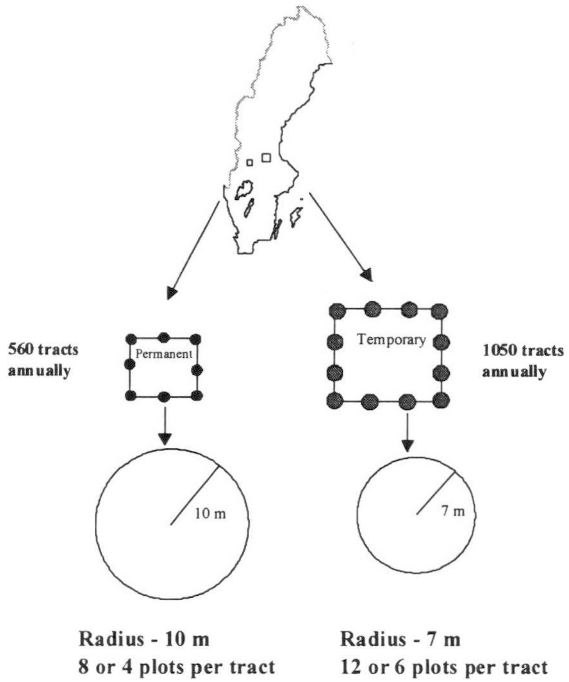

Figure 1. The general design of the Swedish National Forest Inventory as of 1998.

The desired output from the NFI has varied. Initially, basic data for strategic planning consisted of assessments of land and forest class distribution, growing stock, and annual growth (SOU, 1932). In 1938 a stump inventory was introduced for estimating the annual cut (von Segebaden, 1998). When the Swedish forestry legislation in 1994 gave equal weight to the objectives of sustainable forest production and sustainable biological diversity (SKSFS, 1993; Lämås and Fries, 1995b), the NFI obviously had to adapt to this. Two major improvements of the NFI in this regard have been the inclusion of measurement of all dead trees of at least 10 cm (Anon., 1994, cf. Paper III) and the completion of a special inventory within reserves by the NFI in 1994 and 1996 (cf. Paper IV).

Advantages and disadvantages of using NFI data in research

Generally it is very cost-efficient to use NFI data in research and modelling since the data are available without any costs for fieldwork. NFI data are acquired using an objective design, and methods that lead to unbiased estimates. In modelling, representative data covering wide conditions is a major advantage, which is generally achieved by using NFI data. Permanent sample plots with repeated measurements on the same trees in 5 to 10 year intervals were introduced in 1983 (Ranneby et al., 1987), providing unique possibilities to follow the development of forest characteristics. Examples of this can be seen in Papers I, II, and IV, where initial characters of an individual tree are linked to events on the same tree during the period between inventories, e.g., if the tree has died or been damaged. Since the co-ordinates of sample plots are registered (since 1995 using GPS) estimates can be elaborated for arbitrary areas, e.g., reserves as in Paper IV or vegetation zones as in Papers III and IV. In Paper IV data from sample plots situated in areas that later became reserves were identified using a GIS, showing the advantage of a well-defined, easily available sample such as the NFI.

Although the use of NFI data is cost efficient and provides objective data, there are drawbacks as well. Primarily, survey data are, in contrast to experimental data, difficult to use for establishing cause-effect relationships. Furthermore, the forest management history is difficult to have a good grasp of since stand based silvicultural treatments are to be determined for a small sample plot. Accordingly some events may be impossible to detect, even though permanent sample plots are used. In Papers I, II, III, and IV, the amount of damaged or dead trees is most probably underestimated, producing biased predictions for the models developed. One reason for the bias is that trees get damaged or die during the period between inventories, but are removed before re-measurement and are therefore not registered. Another obvious reason, as in any inventory, is that damaged or dead trees are simply overlooked. In addition, the design of the NFI is based on optimising estimates of volume (Ranneby et al., 1987), which results in a decreasing sampling intensity from north Sweden to south Sweden. For studies of other characteristics the design may be non-optimal. Finally, the overall sampling intensity in the NFI is not adapted for estimates of infrequent populations, e.g., red-listed species.

However, to be able to use the NFI data in a flexible way one must stress the importance of detailed knowledge about the actual fieldwork and design used. Today, NFI data from 1983 onwards are easily available for researchers. However, since 1983 several changes in definitions, fieldwork, and design have been made, causing problems in interpreting the data. The reasons for the changes are mainly budget restrictions, adaptation to new demands, and the need to continuously improve the inventory. In conclusion, easy access to NFI data is provided, but differences in design and definitions in the data limit the usability for occasional users. The general design of the NFI can also cause difficulties for researchers not used to the data. Estimations, including estimations of standard errors, can be quite complex as shown in Paper III.

Methods

Estimates based on NFI data

Below follows a brief description on how estimates based on NFI data, used in Papers III and IV, are elaborated. A more thorough description is contained in the Appendix to Paper III.

Area estimates

Estimates of the total area ($\hat{A}$) within a certain domain of study (I_i=1, 0 otherwise) derived from NFI sample plot attributes, e.g., vegetation zone, forest type, and stand age, are determined by:

$$\hat{A} = \sum_{i=1}^{n} AFAC_i I_i \qquad [1]$$

where

n is the number of sample plots

$AFAC_i$ = area of plot $i \times \frac{\text{known total land area}}{\text{total area of sample plots}}$ (ha), and

I_i is an indicator variable for plot i

Per hectare estimates

Per hectare estimates, e.g., volume per hectare, ($\hat{\bar{Y}}$) within a certain domain of study (J_{ij}=1, 0 otherwise) derived from both plot attributes and individual tree attributes, e.g., species and diameter class, are determined by:

$$\hat{\bar{Y}} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m_i} y_{ij} J_{ij}}{\sum_{i=1}^{n} a_i I_i} \qquad [2]$$

where

n is the number of sample plots

m_i is the number of trees on plot i

y_{ij} is the volume (or some other attribute) of tree j on plot i

I_i is an indicator variable for plot i

J_{ij} is an indicator variable for tree j on plot i, and

a_i is the area of sample plot i (ha)

Estimates of the total volume ($\hat{Y}$) are made using [2] multiplied with the estimate of the total area [1];

$$\hat{Y} = \hat{\bar{Y}} \hat{A} \qquad [3]$$

Composite estimates

Results generated using NFI data are generally derived from two independent samples, i.e., plots from permanent and temporary tracts. Hence, composite estimates ($\hat{Y}$) are derived using a standard minimum-variance weighting procedure (e.g., Ranneby et al., 1987);

$$\hat{Y} = w_T \hat{Y}_T + w_P \hat{Y}_P \qquad [4]$$

where

$\hat{Y}_T$ is the estimate for temporary tracts

$\hat{Y}_P$ is the estimate for permanent tracts

w_T is the weight for temporary plots

w_P is the weight for permanent plots, and

$w_T + w_P = 1$

The estimators described above do not consider a stratified sample, which the NFI is. Estimators regarding a stratified sample is contained in the Appendix to Paper III.

Precision of estimates

Although systematic sampling is used in the NFI, the variance in this thesis is estimated assuming simple random sampling of tracts. This will generally give an overestimation of the variance (the variance estimator is described in the Appendix of Paper III).

Logistic and linear regression

In Papers I, and II, the dependant variables used are coded as 1 if damage caused by wind or snow are observed, or as 0 otherwise. In the same way the dependant variables in Paper V are coded as 1 if 5-year mortality is observed on a plot, or a tree, 0 otherwise.

In modelling where the dependant variable is dichotomous, i.e., the dependant variable (*Y*) takes a value of 0 or 1, linear regression is not appropriate. Instead logistic regression can be applied. The form of the logistic regression model (cf. Hosmer and Lemeshow, 1989) which can be used to model the probability of the dependant variable taking the value 1, i.e., *P(Y*=1) is;

$$P(Y = 1) = \frac{e^{a+\mathbf{b'X}}}{1 + e^{a+\mathbf{b'X}}} \qquad [5]$$

where *a* is the intercept, **b'X** a linear combination of parameters (**b**) and independent variables (**X**), and *e* is the base of the natural logarithm.

Estimation of the parameters *a* and **b** are then made using the maximum likelihood method.

Applying the logistic distribution is convenient since it is a flexible and easily used function that also provides biologically meaningful interpretations (Hosmer and Lemeshow, 1989).

Linear regression is also used in Paper V (cf. Wonnacott and Wonnacott, 1990) when estimating the mortality in terms of proportion of basal area (Y). We use the general model here:

$$Y = a + \mathbf{b}'\mathbf{X} \quad [6]$$

where a is the intercept, and $\mathbf{b}'\mathbf{X}$ a linear combination of parameters (**b**) and independent variables (**X**).

We then use ordinary linear regression to estimate a and **b** minimising the squared deviation between observed (Y) and predicted ($\hat{Y}$) values.

Results and discussion

A predictive model for assessment of the risk of snow and wind damage (Paper I)

Paper I focuses on exploring the use of the stem form of a single tree to assess the probability, or risk, of snow and wind damage at a specific site. Growth of trees is influenced by all climatic factors acting on stems after establishment (e.g., Jacobs, 1954; Mattheck, 1991; Telewski, 1995). Mechanical perturbations that act on trees while they are dormant, i.e., during winter at northern latitudes, have also been shown to influence the growth pattern within the stem (Valinger et al., 1994, 1995; Lundqvist and Valinger, 1996). This means that trees are able to register influences of mechanical forces, such as snow and wind, throughout the year and respond to them during growth. We used characteristics of the form of the largest sample tree of Scots pine (*Pinus sylvestris* L.) on permanent NFI sample plots, together with data on snow and/or wind damage to all sample trees on the plot, to develop logistic risk assessment models for Västerbotten County. Results showed that decreasing upper diameter (diameter at 3 or 5 m height) and decreasing height to diameter ratio on the largest sample tree indicated an increased risk for damage on the plot.

This study uses tree characteristic measurements taken from the largest sample tree on each plot. This tree is probably the one that has been at the site for the longest period of time, and therefore its stem is most adapted to the environment. The largest tree is also least influenced by competition and protection by neighbours. Therefore, information about the stem form of the largest tree can be used as an indicator of whether the site needs special considerations when silvicultural strategies are planned. This could mean that late thinning and fertilisation should be avoided (Valinger and Lundqvist, 1992), while early thinning could be used to minimise future damage (Roe and Stoeckler, 1950). Our results show that single tree characteristics can be used as a measure of the susceptibility of snow and wind damage to a site.

A nation-wide model system for snow and wind damage risk prediction (Paper II)

The findings in Paper I were used to develop a nation-wide model system for the risk assessment of Swedish forests using NFI data. Two levels of models were developed; level T where the independent variables consist of single tree characteristics only, and level TSS where the independent variables consist of single tree, site, and stand characteristics. T and TSS models were developed for sites dominated by Scots pine, Norway spruce (*Picea abies* L. Karst.) and Birch (*Betula pendula* Roth., *B. pubescens* Ehrh.). Scots pine and Norway spruce models were developed for three different regions (Figure 2), while models for Birch were developed for all Sweden. Maps were compiled to show the predicted risk levels for the whole country (Figure 3).

Figure 2. Map of Sweden showing the three regions used for development of Scots pine and Norway spruce models.

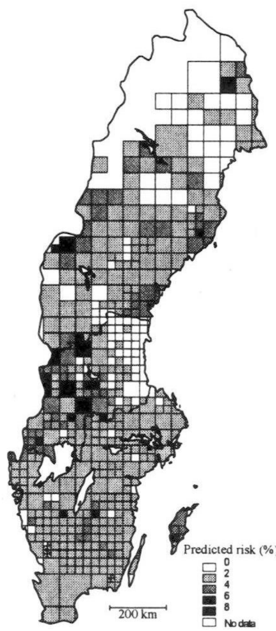

Figure 3. Mean value of estimated risk of damage (%) from snow and wind calculated for NFI-plots for all species, using TSS-models. Squares include at lest five sample plots.

The variables included in the functions confirm that the form of a tree is a good predictor of the susceptibility of a site to damage. The result from the evaluation showed that the developed models over-predicted the risk of damage. This was an effect of the threshold values used, i.e., the method to re-code the estimated probability to a dichotomous output (cf. Monserud, 1976).

Mapping of risks is one way to detect areas prone to damage. The developed models can be used by decision-makers as a step in the selection of silvicultural methods for a specific site. High probability values indicate that forestry operations must avoid treatments known to increase the risk of damage. For example, this means that the combination of heavy thinning and fertilisation, repeated fertilisation, and retention of seed trees for natural regeneration should be avoided at high-risk sites (e.g., Laiho, 1987; Hirvela and Hynynen, 1990). At low risk sites more intensive forest management can be allowed. This study shows that it is possible to classify overall susceptibility of sites to damage from snow and wind using a logistic analysis technique. To broaden the use of the models, a similar methodology can be used to develop single-tree models to integrate risk assessments in existing single-tree based growth models, i.e., the probability of damage can be estimated for individual trees.

Estimates of dead wood based on NFI data (Paper III)

In this study the method, which have been used since 1994 by the NFI for acquiring data on dead wood, i.e., standing and lying dead trees (snags and logs, respectively), is described (cf. Anon, 1994). Using the data recorded during three field-seasons (1994-1996) estimates were presented for five vegetation zones, and for the whole country, by forest types. The results showed a north-south gradient with decreasing volumes of dead wood (DW), from almost 10 m^3 ha^{-1} northern Sweden to about 4 m^3 ha^{-1} in southern Sweden (Figure 4), giving an average on productive forestland of 6 m^3 ha^{-1} for the whole country.

The north-south gradient could be entirely explained by a higher volume of logs in northern Sweden, while the volume of snags was on the same level for all vegetation zones. A more pronounced accumulation of DW due to lower decomposition rate (e.g., Alban and Pastor, 1993), but also less intensive utilisation of DW as fuel wood, can most probably explain the higher volume of logs in the north. The general results of the study confirm the results from other studies (e.g., Reid et al., 1996), i.e., the almost complete lack of large dimensions of DW (Figure 5). Our results of the impact on the amount of DW from clear-cut and thinning show the great potential to increase the total amount of DW in Swedish forestry. Since clear-cut reduces the DW volume with almost 50%, more caution during logging operations would save logs and snags from being destroyed. The effect of reduced volume of DW after logging has also been showed by Zarnowitz and Manuwal (1985) in the USA, and by Eckerberg (1988) in Sweden. This study clearly shows that the method described is well suited for assessing the DW volume on a national and regional level. Since DW is considered as one of the most important indicators of biodiversity this method can also be a substantial tool for assessments of biodiversity.

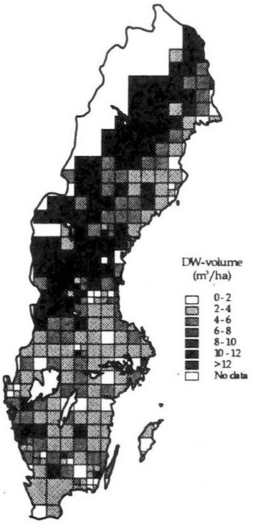

Figure 4. DW volume calculated for squares using NFI plots on productive forestland. Squares include at least 25 plots.

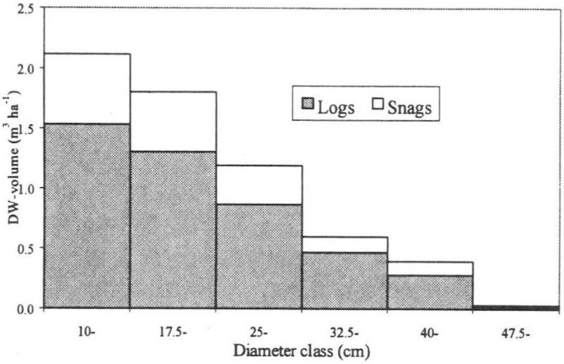

Figure 5. DW volume of logs and snags, by diameter class, for all of Sweden.

Estimates within and outside reserves based on NFI data (Paper IV)

The method used by the Swedish NFI for inventory of land within reserves (Figure 6) is described in this Paper.

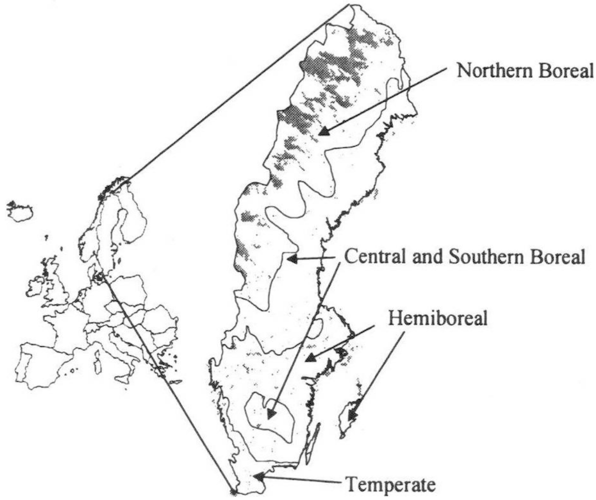

Figure 6. Sweden with vegetation zones according to Ahti et al. (1968). Reserves, i.e., existing national parks, nature reserves and Forest Service reserves as of February 1994, are shaded grey.

Results based on that data are also presented, e.g., area estimates regarding land classes, forest types, and productivity classes, and also volume estimates of dead trees. In contrast to Paper III, only dead trees that could be used as fuel wood (Anon., 1993) was included. Estimates within reserves are compared with estimates for land outside reserves.

Results show an under-representation of productive forest within reserves compared to outside. Forest within reserves is dominated by old-growth low productive spruce forest in Northwest Sweden (Figure 6). Results also show that the volume of dead trees is higher within reserves (Table 1).

Table 1. Proportion of the total volume (Total $m^3\ ha^{-1}$) on all productive forest by tree species. Total volume of dead trees ($m^3\ ha^{-1}$), SE within parenthesis, * indicates significant difference compared to outside reserves ($p<0.05$). Distribution within and outside reserves and by vegetation zones. Northern boreal (NB), Central and Southern boreal (CSB), Hemiboreal (HB) and Temperate (T)

Veg. zone		Pine %	Spruce %	Dead trees %	Dead trees $m^3\ ha^{-1}$	Total $m^3\ ha^{-1}$
NB	Within	19	59	8	7.8 (*0.71*)*	93
	Outside	46	39	3	2.3 (*0.11*)	84
CSB	Within	45	39	2	3.4 (*0.92*)	153
	Outside	40	46	2	2.2 (*0.07*)	123
HB	Within	40	32	2	3.3 (*0.85*)	146
	Outside	33	49	1	1.9 (*0.08*)	159
T	Within	14	29	3	5.6 (*3.40*)	171
	Outside	17	45	1	2.1 (*0.16*)	173
All	Within	23	52	7	7.1 (*0.60*)*	103
Sweden	Outside	38	45	2	2.2 (*0.05*)	121

From a national perspective the allocation of the Swedish reserve network could be described as a cost-effective strategy for maximising the total reserve area because forest in the north is less valuable economically. However, results from Norway show that over-representation of low productivity sites does not meet the requirements of biodiversity conservation (Stokland, 1997).

The conclusion by Ohlson et al. (1997), who studied biodiversity within natural old-growth swamp forests in Sweden, was that the amount of dead wood present was the most important variable explaining biodiversity, i.e., the higher the amount of dead wood the greater the biodiversity. If that conclusion is valid for all kinds of forests, and if the results presented in Paper IV are valid in all vegetation zones, then forests within reserves actually do contain a higher biodiversity than managed forests. A general conclusion from the results was that the allocation and magnitude of the Swedish reserve network might not meet the demands for protection of the habitats of endangered species.

Tree mortality functions for Swedish forests (Paper V)

This paper presents new mortality functions for application within Swedish long-term forest planning systems. The study used a 3-step approach, which consisted of (I) estimating the probability of mortality on a sample plot, (II) quantifying the mortality in terms of proportion of basal area on a sample plot, and (III) distributing the mortality among individual trees on the plot. Data from re-measured permanent sample plots of the NFI were used. Independent variables used for steps I and II were site-, stand-, and plot specific, and for step III functions tree variables such as diameter and competition indices were included. Logistic regression was used for steps I and III, while linear regression was used for step II.

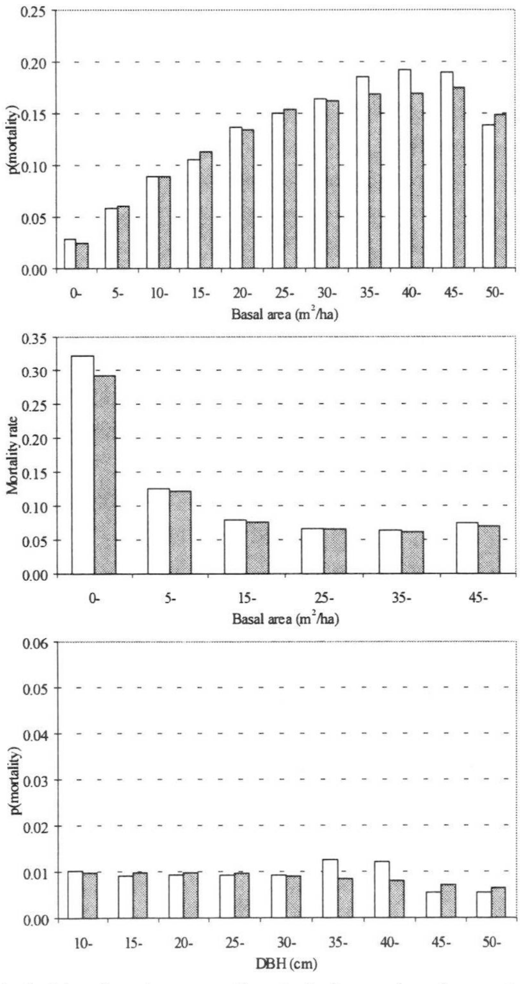

Figure 7. Observed (white bars) vs. estimated (grey bars) mortality for step I (top; probability of mortality on a plot by stand basal area), step II (centre; proportion of basal area by stand basal area), and step III function for spruce (bottom; probability of mortality for a spruce single tree by DBH).

Validations of the functions were made by studies of figures showing observed mean values versus mean estimated probabilities (Figure 7). In long-term forest planning systems, components for forecasts of natural mortality of trees are important (e.g., Lee, 1971; Teck and Hilt, 1990; Monserud and Sterba, 1999), but natural mortality is considered extremely difficult to predict (Lee, 1971; Dobbertin and Biging, 1998). However, without a reliable mortality component, long-term forecasts of forest yield will generally be severely biased, although the accuracy of the other model components may be high. This affects not only the planning of timber utilisation, but also the forecasts of future conditions for species dependant on dead wood (e.g., Harmon et al., 1986; Ohlson et al., 1997).

The significant advantage of the functions presented in this study, compared to the mortality functions by Bengtsson (unpublished) and Söderberg (1986), used in Sweden so far, is the better differentiation of mortality among trees. Applying the step I function generates plots where no mortality will occur during the next 5-year period, while models used so far generate mortality for all plots. Mortality is also predicted separately for five groups of tree species, and most important, individual tree mortality is dependent on the tree size (step III models). Although the predictability of the functions seems fair, using NFI-plots will probably cause bias in estimating mortality. One major source of bias is logging of dead trees between measurements of plots. The effect of such logging must be modelled separately in long-term forecasting systems.

Conclusions and recommendations

The results presented in this thesis could be used in strategic long-term forest management planning. Inclusion of the functions developed in Papers II and V in planning packages would provide possibilities to study the impact of different silviculture regimes on the assessed risk of damage together with the outcome of natural mortality and its effect on volume production. Results in Paper III can be used as background data when comparing results from regional or local inventories where data on dead wood are included. Results in Paper III can also be used as a baseline when assessing the outcome of environmental objectives in terms of the volume of dead wood in the forest landscape. Results in Paper IV can be used in strategic planning of the future reserve network in Sweden.

Altogether this thesis shows the high value of a National Forest Inventory, from which data can be used in a wide range of applications, including traditional forest applications like long-term management planning and assessments of biodiversity. This thesis also points out some of the drawbacks connected with using NFI data. However, for a high usability of NFI data, it is important that the data collected are not restricted to the topics of interest at the time for designing the inventory. It is crucial to keep the focus of the inventory wide, both with regard to what areas are included and what parameters are recorded on the plots.

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