Silva Fennica vol. 58 no. 5 article id 24045
Category: research article
https://doi.org/10.14214/sf.24045

SILVA FENNICA

http://www.silvafennica.fi
ISSN-L 0037-5330 | ISSN 2242-4075 (Online)
The Finnish Society of Forest Science

Kari T. Korhonen [1], Minna Räty [2], Helena Haakana [2], Juha Heikkinen [2], Juha-Pekka Hotanen [1], Mikko Kuronen [2] and Juho Pitkänen [1]

Forests of Finland 2019–2023 and their development 1921–2023

Korhonen K.T., Räty M., Haakana H., Heikkinen J., Hotanen J.-P., Kuronen M., Pitkänen J. (2024). Forests of Finland 2019–2023 and their development 1921–2023. Silva Fennica vol. 58 no. 5 article id 24045. 47 p. https://doi.org/10.14214/sf.24045

Highlights

- The latest Finnish National Forest Inventory is presented.
- Volume of growing stock has almost doubled since the 1920s and has continued to increase since the previous inventory.
- Volume increment is more than double the increment 100 years ago but has declined recently.
- Mortality is increasing at alarming rate; Amount of dead wood has now increased also in North Finland.

Abstract

In 2019–2023 the 13th Finnish National Forest Inventory (NFI) was implemented by measuring a total of 62 266 sample plots across the country. The methodology of the sampling and measurements was similar as in the previous inventory, but the proportion and number of remeasured permanent plots was increased to improve the monitoring of annual increment and other changes in the forests. Only 6.2 M ha (14%) of Finland's total land area (30.4 M ha) is other land than forestry land. Productive and poorly productive forests cover 22.9 M ha (75%) of the total land area. The forest area has remained stable in recent decades but the forest area available for wood supply (FAWS) has decreased due to increased forest protection – 23% of the forestry land and 10% of the productive forest are not available for wood supply. Compared to the previous inventory, forest resources have continued to increase but the average annual increment has declined from 107.8 M m^3 to 103.0 M m^3. The quality of forests from the timber production point of view has remained relatively good or improved slightly. The area of observed forest damage on FAWS is 8.4 M ha (46% of FAWS area), half of these minor damages with no impact on stand quality. Although the area of forest damage has not increased, the amount of mortality has continued to increase, and is now 8.8 M m^3 $year^{-1}$. The amount of dead wood has continued to increase in South Finland, while in North Finland the declining trend has turned into a slight increase. Since the 1920s, the area of forestry land has remained stable, but the area of productive forest has increased due to the drainage of poorly productive or treeless peatlands. The total volume of growing stock has increased by 84% and annual increment has more than doubled.

Keywords forest damage; forest management; forest resources; growing stock; increment; monitoring indicators of biodiversity; National Forest Inventory
Addresses [1]Natural Resources Institute Finland (Luke), P.O.Box 68, FI-80100 Joensuu, Finland; [2]Natural Resources Institute Finland (Luke), P.O.Box 2, FI-00790, Helsinki, Finland
E-mail kari.t.korhonen@luke.fi
Received 23 July 2024 **Revised** 23 October 2024 **Accepted** 24 October 2024

1 Introduction

Systematic forest assessments, National Forest Inventories (NFI) based on statistical sampling were started in the Nordic countries in the early 20th century (Tomppo et al. 2010). The first NFI of Finland, implemented in 1921–1924, was mainly motivated by the concern that destructive land use (shift and burn agriculture), human induced wildfires, and increasing industrial use of timber were leading to the scarcity of forest resources (Ilvessalo 1927). Forests were seen as important national capital and it was necessary to assess the value and condition of this resource. Since the very beginning of inventories, NFI's have played an important role in formulating forest policies. Knowing the state of forests and vision on their potential development are essential for making informed forest policies. This is the fundamental task of NFI. Equally important task is the monitoring of forests and land use. Monitoring is necessary to observe and understand the changes taking place in the environment, forest resources, structure and condition of forests. Monitoring results can be used, for example, to evaluate the success or impact of forest policies. An important role of NFI is to provide data for future scenarios, modelling and other scientific research.

Since the 1920s, the needs on forest information have evolved in Finland and globally (Vidal et al. 2016; Korhonen et al. 2020; Ferretti et al. 2023). This relates to increased understanding of the different ecosystem services that forests provide. Over decades and centuries, forests have been important for hunting, gathering berries and mushrooms, reindeer husbandry etc., but these kinds of forest functions have not always been well recognised in forest policies. As society's values and policies change over time, so do the information needs about forests. While the first NFIs in Finland were mainly oriented in assessing the condition of forests from a timber production point of view, the third NFI3 (1951–1953) included a much broader assessment of forests. Observations made in the NFI3 field plots included the abundance of various vascular plants, mosses and lichens and even the registration of wildlife and occurrence of anthills. The subsequent NFIs, from NFI4 (1961–1964) to NFI7 (1977–1984), were again very much oriented towards assessing the economic sustainability of forest resource usage.

In the 1980s, forest damage raised concern and this was reflected in the NFI8 (1986–1994) information content. A methodology was developed to register forest damage at forest stand level and this assessment is still part of the current NFI. In the 1990s, conservation of biodiversity became part of forest management (Korhonen et al. 2021b) and biodiversity indicator measurements were added in NFI9 (1996–2003) (Tomppo et al 2011). Climate change and the reporting of greenhouse gas emissions and sequestration led to a fundamental change in the design of the 10th NFI (2004–2008): NFI was changed from the regional inventory to a continuous panel system with a 5-year cycle. While planning the NFI12 (measured 2014–2018), it became evident that the assessment of changes in forests is increasingly important. One driver was the increasing evidence on climate change. Another, more concrete driver was the substantial changes in Finnish forest legislation in early 2013, which allowed continuous cover management of forests.

The aim of this publication is 1) to describe the state of Finland's forests, 2) to analyse the development of the forests during the past 100 years, and 3) to document the methods applied in the NFI13. This publication continues the series of final reports from the previous NFI's: NFI1 1921–1924 (Ilvessalo 1924, 1927), NFI2 1936–1938 (Ilvessalo 1940, 1942, 1948), NFI3 1951–1953 (Ilvessalo 1956), NFI4 1960–1963 (Tiihonen 1968), NFI5 1964–1970 (Kuusela 1972), NFI6 1971–1976 (Kuusela 1978), NFI7 1977–1984 (Kuusela and Salminen 1991), NFI8 1986–1994 (Tomppo et al. 2001), NFI9 1996–2003 (Tomppo et al. 2011), NFI10 2004–2008 (Korhonen et al. 2013), NFI11 2009–2013 (Korhonen et al. 2017), and NFI12 2014–2018 (Korhonen et al. 2021a). The result tables are shown for South Finland, North Finland, and the whole country (Fig. 1). The South Finland consists of the 16 southmost administrative regions of Finland and the North Finland of the 3 northmost administrative regions.

2 Material and methods

2.1 Sampling design

The general design of NFI13 was similar to the most recent previous inventories (Tomppo et al. 2011; Korhonen et al. 2021a). The details of the design varied between the six sampling regions (Fig. 1). The basic sampling unit is a cluster of systematically located points that serve as the centre points of the field plots. The number of plots per cluster varies from 8 to 11 and the distance between the nearest neighbouring plot centres from 250 m to 450 m (Supplementary file S3: Fig. 1, available at https://doi.org/10.14214/sf.24045).

Apart from the Northernmost Lapland (sampling region 6), clusters cover each sampling region according to a region-specific systematic layout. The "skeleton" of the layout is a square grid of permanent clusters, established in NFI9 (Tomppo et al. 2011) and measured for the fifth

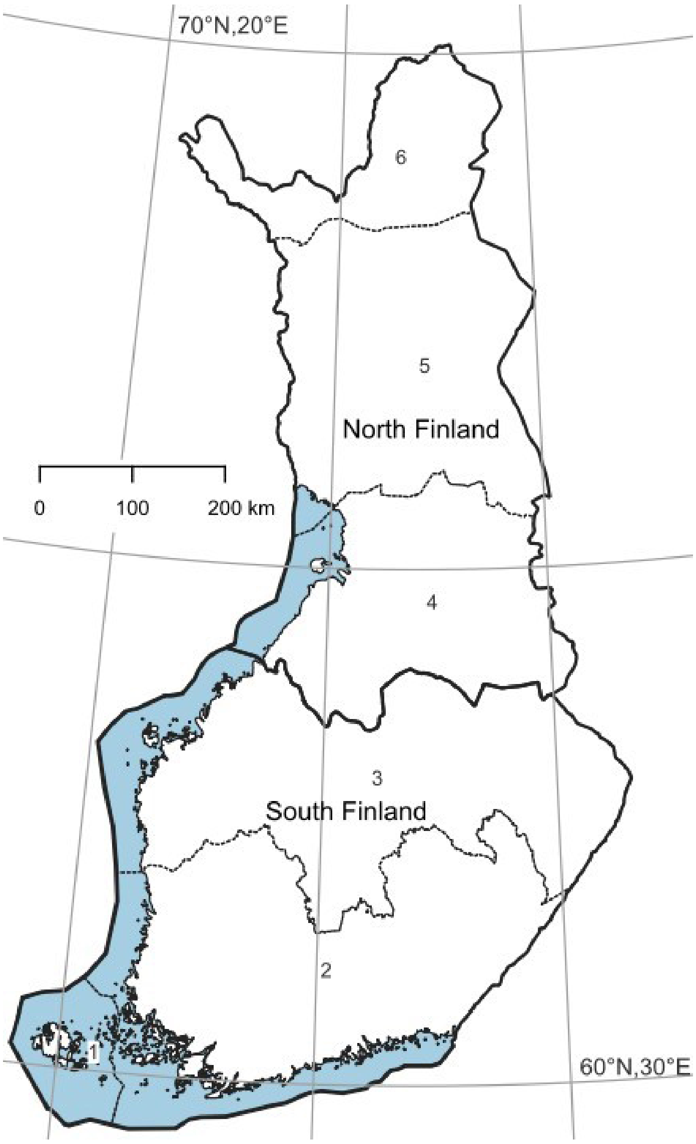


Fig. 1. Sampling regions 1–6 used in the 13th National Forest Inventory (NFI13) of Finland. Regions 1–3 form the reporting domain South Finland and regions 4–6 form the reporting domain North Finland.

Table 1. Stratification of first-phase clusters in Northernmost Lapland in the 13th National Forest Inventory of Finland. The proportions were computed from MS-NFI-2019 (multi-source NFI 2019; Mäkisara et al. 2022) land pixels in 4 × 4 pixel windows containing the plot centres. If the mean canopy height (CHM, https://www.metsakeskus.fi/fi/avoin-metsa-ja-luontotieto/metsatietoaineistot/metsavaratiedot) of the pixels around a sample plot location was less than 5 m, then all pixels of that window originally classified as 'poorly productive forest' were re-classified into 'unproductive land'.

At least one pixel classified into other land use than forestry in MS-NFI-2019		**Stratum 0**			
No other land use pixels		Proportion of productive forest			
		≤1%	>1%, ≤25%	>25%, ≤85%	>85%
Proportion of unproductive land	<10%	**Stratum 3**	**Stratum 3**	**Stratum 2**	**Stratum 1**
	≥10%, <40%	**Stratum 3**	**Stratum 3**	**Stratum 2**	**Stratum 2**
	≥40%, ≤85%	**Stratum 3**	**Stratum 3**	**Stratum 3**	**Stratum 3**
	>85%	**Stratum 4**	**Stratum 3**	**Stratum 3**	**Stratum 3**

time in NFI13. The spacing in that grid varies from 8 km (Åland, sampling region 1) 20 to 20 km (Lapland and Kuusamo, sampling region 5; for details, see Suppl. file S3). Around each of these "old-permanent" clusters, four other clusters were located so that (apart from Åland) two of them were those established as permanent in NFI12 (Korhonen et al. 2021a) and the two new ones did not overlap with the clusters measured in the previous campaigns. One of the two new clusters was established as permanent (to be re-measured; trees not bored). In Åland, all four clusters around an old-permanent cluster were new and established as temporary.

Two-phase sampling for stratification (Cochran 1977, sec. 12.2) was applied in Northernmost Lapland. The first-phase sample was a dense square grid of potential field plot clusters with 250 m spacing between neighbouring corner points. Each first-phase cluster was assigned to one of the five strata (Table 1) based on the 2019 thematic maps of the multi-source NFI (MS-NFI-2019; Mäkisara et al. 2022) and the canopy height model of Finland (CHM, https://www.metsakeskus.fi/fi/avoin-metsa-ja-luontotieto/metsatietoaineistot/metsavaratiedot; in Finnish). The second-phase sample of new clusters for field assessment was selected as a stratified, spatially systematic subsample of the first-phase sample. Apart from special stratum 0, sampling density was greater in strata with a greater expected proportion of productive forest and a smaller proportion of unproductive land (Table 2). A relatively large sample was selected from stratum 0 with the aim to ensure inclusion of other land-use plots in the sample. This was considered necessary, since forestry land covers over 99% of the land area of Northernmost Lapland, but monitoring of other land use is important for the greenhouse gas inventory, which uses NFI for that purpose. The 37 permanent clusters established in NFI9 were included in the second-phase sample. A more comprehensive description of the two-phase approach can be found in Tomppo et al. (2011, sec. 2.1.4) in the context of NFI9 and Heikkinen et al. (2024, manuscript).

Table 2. Land areas represented by strata, number of second-phase clusters and field sample plots on land, as well as land areas represented by one plot in Northernmost Lapland of Finland in NFI13.

Stratum	Area, km^2	Number of clusters	Number of land plots	area/plot, km^2
0	2552	29	188	13.574
1	1975	27	168	11.756
2	6193	67	457	13.551
3	8834	62	442	19.986
4	8603	11	80	107.54
Northernmost Lapland total	28 158	196	1335	

Table 3. Number of plot centres in the NFI13 of Finland for the old permanent, new permanent and temporary clusters by land use class.

Land use class	Temporary clusters	Old permanent clusters	NFI12 established permanent clusters	New NFI13 permanent clusters	Total
Productive forest	8641	9693	16654	8756	43744
Poorly productive forest	768	927	1169	846	3710
Unproductive land	714	786	1193	904	3597
Other forestry land	98	106	180	111	495
Forestry land total	**10221**	**11512**	**19196**	**10617**	**51546**
Agriculture land	1440	1610	2423	1302	6775
Built-up land	561	630	1073	515	2779
Roads	191	200	322	174	887
Power lines	48	56	115	60	279
Land total	**12461**	**14008**	**23129**	**12668**	**62266**

The field sample plots in Northernmost Lapland were measured in year 2022 and those in Åland in 2023. Elsewhere, one fifth of the clusters were measured annually during the five-year period (2019–2023). The total number of plots on land was 62266 (Table 3).

2.2 Field measurements

The field measurements on the sampled locations include 1) stand level assessments, 2) measurement of trees on concentric circular plots, and 3) measurements of dead wood on a fixed radius plot. In addition, a 30 m radius plot is used for recording signs and infrastructure related to recreational use of forest. However, results related to recreational use are not included in this report.

2.2.1 Stand level assessments

The stand level assessments include description of a) land use/land cover class b) administrative status, c) site and soil, d) composition of growing stock, e) damage, f) accomplished forest management operations for the 10-year period before the field assessment, g) recommended operations for the future 10-year period, and h) naturalness of the stand. Forest stand is defined as a unit that is homogenous in respect to the administrative status, site, growing stock, accomplished and recommended forest management. Recommended minimum size for a forest stand is 0.5 hectares but if the stand is clearly different from its surroundings, smaller units can be used. The stand level variables are assessed at the closest 0.25 hectares to the plot centre. If the sample plot is divided into two or more stands, each stand is described separately.

The description of land use/land cover class includes classification according to both national classification system and according to FAO Global Forest Resource Assessment (FRA) classification, including possible changes since 1990 and time of the change. The administrative status related variables – e.g. ownership, restrictions for forestry operations – are prefilled before the field work using available map data and checked in the field. The description of the composition of growing stock includes mean diameter, mean height, age and basal area or number of stems for each tree stratum. Each tree species and tree layer form an individual tree stratum. The accomplished and recommended forest management operations include possible cuttings, soil preparation, planting or direct seeding, restoration operations (only for accomplished operations) and their timing. The assessment of naturalness includes separate assessment for the naturalness of the growing stock, dead wood composition and signs of human interventions.

For further details on the stand level assessments see the Suppl. file S3: NFI13 Field Manual.

2.2.2 Tree measurements

The sample plot consists of a Bitterlich relascope sample plot with a basal area factor of 1.5 for trees with a breast height diameter (d) below 4.5 cm, a 4 m radius plot for trees with d larger than 4.4 cm but less than 9.5 cm, and a 9 m radius plot for trees with d at least 9.5 cm. Thus, all trees above 1.3 m in height have a known, non-zero sampling probability. Note that the Bitterlich relascope principle is employed for the selection of trees below 4.5 cm in diameter, not the relascope (angle cauge) instrument itself. Inclusion of the small trees in the sample plot is always decided by measuring the diameter and distance from the plot centre. For the plot measurements, a tree is defined as a single stem multi perennial woody plant with a height exceeding 1.3 meters. Tree measurements include both living trees and those dead trees that are still hard enough to be utilised at least as firewood.

Trees are measured in two categories: all trees in the sample plot described above are tally trees and a sub-sample of the tally trees are sample trees. The measurements for a tally tree include tree species, diameter, tree status, timber quality class and crown layer. Trees are measured with an electronic calliber, which automatically registers the tree location in relation to the plot centre. When a potential tally tree is close to the plot border (for the respective d), the distance from the plot centre is always checked with a tape because the distance measured with the electronic calliber may be erroneous by a few centimetres.

In NFI13, the sample trees were selected from the tally trees with probability proportionate to size (PPS) sampling. The selection was made by summing the basal areas (m^2 ha^{-1}) represented by each tally tree. In South Finland, the sample trees were selected with an interval of 15 m^2 ha^{-1} and in North Finland with an interval of 10 m^2 ha^{-1}. Tally trees below 4.5 cm in diameter are sampled as sample trees separately from the larger trees. On permanent plots, sample trees measured as sample trees in the previous inventory are always measured as sample trees. Additional variables recorded for the sample trees include, among others, tree height, height to the base of living crown, possible damages, and the lengths of timber assortment classes. On temporary plots, the sample trees are bored for measuring the tree age and diameter increment in a laboratory. On permanent plots, the age of a sample tree is estimated in the field without boring.

2.2.3 Dead wood measurements

Dead trees (including both recently died hard dead trees and decaying dead wood, as well as both lying and standing dead trees) are measured on those permanent plots that were established in NFI9 and have been remeasured in all NFI's after that. A circular plot with a radius of 7 m is employed for the dead wood measurements. Only pieces longer than 1.3 m and a diameter more than 10 cm are included in the dead wood measurements. On divided plots, dead wood is measured only within the stand of the plot centre point.

2.3 Estimation methods

2.3.1 Estimation of areas

Within each region *R*, an intersection of sampling region and reporting domain, (or within each stratum *h* in Northernmost Lapland), the area of target domain *d* (land use class, ownership category, etc.) was estimated using ratio estimator (Cochran 1977, ch. 6):

$$\hat{A}_{Rd} = A_R \frac{n_{Rd}}{n_R}, \tag{1}$$

where A_R is the land area of region R, based on the National Land Survey of Finland (Suomen pinta-ala kunnittain... 2024), n_R is the number of sample plot centre points located on land within region R, and n_{Rd} the number of those among them that belong to domain d. In Northernmost Lapland, where stratified sampling was applied (Sec. 2.1), stratum weights (area represented by clusters in a stratum) were similarly estimated by:

$$\widehat{W}_h = A_R \frac{N_{Rh}}{N_R},$$

where A_R is now the land area of Northernmost Lapland, N_R the number of first-phase sample plots located within that area (at least one of the four MS-NFI-2019 pixels surrounding the theoretical location of the sample plot centre was classified as land and located within the boundaries of the region), and N_{Rh} the same number from those first-phase clusters that were assigned to stratum h. The stratified area estimators for Northernmost Lapland were then obtained as weighted sums of the stratum-specific estimators of area proportions (proportions of the domain among second-phase plots):

$$\hat{A}_{Rd} = \sum_h \hat{W}_h \frac{n_{hd}}{n_h}.$$

2.3.2 Estimation of growing stock volumes and biomass

Mean volume of growing stock (m^3 ha^{-1}), within domain d of region R (or stratum h) was estimated as:

$$\hat{v}_{Rd} = \frac{10\,000}{n_{Rd}} \sum_{k \in S_{Rd}} \frac{v_k}{\pi r_k^2}, \tag{2}$$

where S_{Rd} is the set of all tally trees in the target domain × region, v_k is the predicted volume of tree k (m^3) and r_k is its sample plot radius (m), depending on breast height diameter d_k (cm):

$$r_k = \begin{cases} 9, \text{ if } d_k \geq 9.5 \\ 4, \text{ if } 4.5 \leq d_k \leq 9.4 \\ \frac{d_k}{2\sqrt{q}}, \text{ otherwise, } q = 1.5 \text{ being the relascope factor.} \end{cases}$$

Mean biomass (t ha^{-1}) was estimated similarly; prediction of tree-level stem volume and biomass is explained in Suppl. file S1, available at https://doi.org/10.14214/sf.24045. Mean volumes by species and diameter classes were obtained by including in S_{Rd} only those tally trees that belonged to the target class. Similarly, mean volumes by timber assortment were obtained by letting v_k be that portion of the stem volume of tree k that belonged to the target assortment. The applied bucking is also explained in Suppl. file S1.

Region/stratum-specific total volumes (1000 m^3) and biomasses (1000 t) were estimated as appropriately scaled products of area estimates and mean value estimates, e.g.,

$$\hat{V}_{Rd} = 10\hat{A}_{Rd}\hat{v}_{Rd}\,, \qquad (3)$$

when $\hat{A}_{Rd}$ is expressed in km^2. This publication presents results for reporting domains North Finland, South Finland, and whole country (Fig. 1), which are unions of several sampling regions and/or strata with different sampling intensities. Therefore, the estimates of totals and areas are sums of the region/stratum-specific totals and areas over the included regions and strata and the mean volumes and biomasses for these aggregate regions were estimated as ratios of the aggregated totals and areas: For $R = \bigcup_{j=1}^{J} R_j$,

$$\hat{A}_{Rd} = \sum_{j=1}^{J} \hat{A}_{Rjd}\left(km^2\right),$$
$$\hat{V}_{Rd} = \sum_{j=1}^{J} \hat{V}_{Rjd}\left(1000\,m^3\right),$$
$$\hat{v}_{Rd} = \frac{\hat{V}_{Rd}}{10\hat{A}_{Rd}}\left(m^3\,ha^{-1}\right).$$

2.3.3 Estimation of sampling variance

Uncertainty of area and volume estimates due to NFI sampling was assessed based on between-cluster variability and on the number of sample plots contributing to the estimate. Both area and mean volume estimators, Eqs. 1 and 2, are ratios, $\hat{R} = Y/X$, of two random variables, both of which can be expressed as a sum of cluster-level variables, $Y = \sum_c y_c$, $X = \sum_c x_c$. For area estimators (Eq. 1), $x_c = A_R n_{Rdc}$, where n_{Rdc} is the number of those sample plot centres in cluster *c* that are located within region *R* and belong to domain *d*. Similarly, $y_c = n_{Rc}$ in Eq. 1, and $x_c = 10000\sum_{k\in S_{Rdc}} \frac{v_k}{\pi r_k^2}$ and $y_c = n_{Rdc}$ in Eq. 2. In case of simple random sampling (SRS), variance of such ratio estimators could be estimated by (Cochran 1977, sec. 2.9)

$$\widehat{\text{var}}_{SRS}\left(\hat{R}\right) = \frac{n}{n-1}\frac{\sum_c\left(y_c - \hat{R}x_c\right)^2}{\left(\sum_c x_c\right)^2},$$

where *n* is the number of clusters contributing to $\hat{R}$.

However, for the spatially balanced design of NFI cluster locations, $\widehat{\text{var}}_{SRS}$ is likely to yield substantial overestimation of sampling variance (e.g., Tomppo et al. 2011, p. 88; Räty et al. 2020). As a more realistic alternative, we applied the approximate variance estimator proposed by Grafström and Schelin (2014), modified to account for ratio estimation:

$$\widehat{\text{var}}\left(\hat{R}\right) = \frac{n}{(n-1)\left(\sum_c x_c\right)^2}\sum_c \frac{n_c^*}{n_c^*-1}\left(z_c - \frac{1}{n_c^*}\sum_{c'\in s_c^*} z_{c'}\right)^2,$$

where $z_c = y_c - \hat{R}x_c$ and set s_c^* consists of cluster *c* and its n_c^* Voronoi-neighbours (Fig. 2).

The motivation behind $\widehat{\text{var}}$ is similar to that behind general pairwise difference estimators of variance in systematic sampling (Wolter 2007, Ch. 7): Elimination of the impact of locally linear spatial trends. In earlier NFIs, where all clusters within a sampling region were on a square grid (cf. Sec. 2.1), a spatial pairwise difference estimator introduced by Matérn (1947) was used and was found to yield up to 20% smaller standard errors than $\widehat{\text{var}}_{SRS}$ (Tomppo et al. 2011, p. 88).

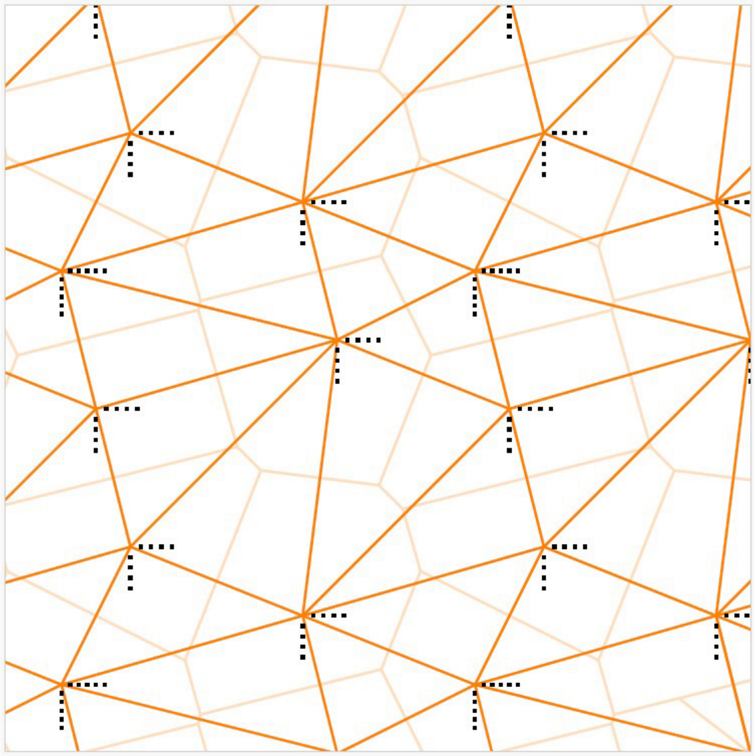


Fig. 2. An illustration of Voronoi-neigbourhoods of some field plot clusters (black dots) of NFI13 in Finland. Light orange lines show the boundaries of Voronoi-tiles associated to each cluster and dark orange lines connect neighouring clusters, i.e., those with a common boundary segment.

The estimator of Grafström and Schelin (2014) is essentially an extension of Matérn's variance estimator, which is applicable to the current cluster layout (spatially balanced and well-spread but not a rectangular grid).

For total volumes $\hat{V} = \hat{A}\hat{v}$ (c.f. Eq. 3), we applied the delta method:

$$\widehat{\text{var}}\left(\hat{V}\right) = \hat{A}^2\,\widehat{\text{var}}\left(\hat{v}\right) + \hat{v}^2\,\widehat{\text{var}}\left(\hat{A}\right). \tag{4}$$

Sampling variances $\widehat{\text{var}}(\hat{A}_R)$ and $\widehat{\text{var}}(\hat{V}_R)$ of the estimates of areas and total volumes over unions R of several sampling regions and/or strata (cf. Sec. 2.3.2) were estimated as sums of the region/statum-specific variances. Estimators $\widehat{\text{var}}(\hat{v}_R)$ of the sampling variances of mean volumes over such aggregate regions were obtained by using these $\widehat{\text{var}}(\hat{A}_R)$ and $\widehat{\text{var}}(\hat{V}_R)$ and "solving" $\widehat{\text{var}}(\hat{v}_R)$ from Eq. 4: if $R = \cup_{j=1}^{J} R_j$ then:

$$\widehat{\text{var}}\left(\hat{v}_R\right) = \frac{\widehat{\text{var}}\left(\hat{V}_R\right) - \hat{v}_R^2\,\widehat{\text{var}}\left(\hat{A}_R\right)}{\hat{A}_R^2} = \frac{\sum_{j=1}^{J}\widehat{\text{var}}\left(\hat{V}_{Rj}\right) - \hat{v}_R^2\sum_{j=1}^{J}\widehat{\text{var}}\left(\hat{A}_{Rj}\right)}{\left(\sum_{j=1}^{J}\hat{A}_{Rj}\right)^2}.$$

Standard errors reported in this publication are square roots of the estimates of sampling variance.

2.3.4 Estimation of volume increment

In principle, the mean annual volume increment of growing stock (m^3 ha^{-1} a^{-1}) within domain *d* of region *R* (or stratum *h*) was estimated analogously to the mean volume, i.e., the predicted volume v_k in Eq. 2 was replaced by the mean annual increase in volume over bark, i_k. In practice, however, increment estimation is a much more complex task than the estimation of current volume. First, the estimation of increment was based on the re-measured plots, i.e., those 60% that were also measured in NFI12 (Note: NFI11 in Northernmost Lapland. This note is valid for other occasions in this Section where NFI12 is mentioned). Thus, n_{Rd} is now the number of such plots in the target domain × region and S_{Rd} is a set of tally trees included in the increment estimation from those plots. Secondly, the estimate needs to include the increment of drain, i.e., trees that were harvested or died between NFI12 and NFI13, as well as that of the ingrowth, i.e., NFI13 tally trees with height less than the threshold of 1.3 meters at the time of NFI12 measurement.

The estimation of the increment of drain and ingrowth is explained in Suppl. file S1. Here, we focus on the estimation of survivor growth, i.e., the increment due to the growth of trees that were alive and over 1.3 m high at the time of both the NFI12 and NFI13 measurements. The target population of increment estimation, the trees growing on stands that were classified as productive or poorly productive forest in NFI13, includes a small number of stands where trees were not measured in NFI12. The stands were then classified differently or the plot centre of NFI12 was not found in NFI13. The estimation of their contribution to the survivor growth is also explained in Suppl. file S1.

From stands where trees were measured in both NFI12 and NFI13, those trees *k* were included in the estimator of survivor growth that were tallied already in NFI12. Accordingly, the radius of the sample plot r_k was determined according to the NFI12 diameter d_k. The mean annual increase in volume, i_k, was determined as the difference between the NFI13 and NFI12 volume predictions divided by the number of growing seasons between the two measurements of that particular plot. Finally, for reasons explained in Korhonen et al. (2021; Suppl. file S1), regression estimation was applied to this primary component of survivor growth, based on stands where trees were measured in both NFI12 and NFI13:

$$\hat{I}_{Rd} = \hat{I}_{Rd,s} + b_{Rd}\left(x_{Rd,t} - x_{Rd,s}\right),$$

where $\hat{I}_{Rd,s}$ is the increment estimate (m^3 ha^{-1} a^{-1}) based on (more accurate) stem volume predictions of sample trees, $x_{Rd,t}$ is the increment estimate based on (less accurate) stem volume predictions available for all tally trees (including the sample trees) as a function of breast height diameter and $x_{Rd,s}$ is the increment estimate based on these simpler stem volume predictions for the sample trees. The regression parameters b_{Rd} were estimated in the same way as in Korhonen et al. (2021; Suppl. file S1).

The total annual volume increment of growing stock (1000 m^3 a^{-1}) within domain *d* of region *R* (or stratum *h*) was estimated by multiplying the corresponding mean increment with the appropriate area estimate (Section 2.3.1). Note that in area estimation all NFI13 plots were utilized.

2.3.5 Estimation of mortality, natural losses, and forest balance

Mortality includes the volume of growing stock for all trees which have been living trees with a height over 1.3 m in the first field survey but died during the survey period before the subsequent field inventory. Therefore, it can be assessed only on permanent sample plots, which comprise approx. 60% of all sample plots in the NFI13. In other words, it was based on the same sample used for the estimation of volume increment (Chapter 2.3.4).

Natural losses were derived from the mortality by subtracting the volume of dead trees harvested during the same inventory period. The harvested volume was estimated from the tree population which was classified to be usable dead wood in the first inventory survey but harvested before the proceeding survey – either the stump was found or there is a certainty of harvest operation.

Both variables – mortality and natural losses – were estimated as an average annual volume over a five-year observation period from NFI12 to NFI13 except for Northernmost Lapland, where the observation period length is 10 years.

The forest balance calculation employed in NFI (Kuusela 1978) examines the compatibility of growing stock volume, increment, and drain estimates between two consecutive inventories. We calculate the forest balance between NFI12 (Initial) and NFI13 (Final) by tree species groups (Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* [L.] H. Karst.), broadleaves) and separately for the South, North and whole Finland. With these values the change in growing stock volume (GS) can be estimated either using the estimated increment and drain or directly using measured Initial and Final growing stock as follows:

Measured change = Final GS – Initial GS
Calculated change = Volume increment – Drain
Calculated final GS = Initial GS + Volume increment estimate – Drain

2.3.6 Estimation of growth indices

The growth indices were estimated by tree species (Scots pine, Norway spruce, and birch [*Betula pubescens* Ehrh. and *Betula pendula* Roth]), site classes and sampling regions (Fig. 1) for 1990–2023 employing mixed linear models (Henttonen 1990; Henttonen 2000). The data set included field measurements from NFI9 (1996–2003) to NFI13 (2019–2023). Diameter increments, measured from the tree-ring cores of sample trees on temporary sample plots, were used in the estimation. Severely damaged sample trees were removed from the data set to avoid including the damage-related effects in the index. Site classes separated mineral soils and peatlands, and were further classified by the site fertility type. The estimation of growth indices aims to present the annual variation in tree increment that is caused by environmental conditions, rather than by the growing stock. Therefore, ditched peatlands and paludified mineral soils were excluded from the estimation because the effects of other environmental factors are difficult to separate from the effect of ditching. In the estimation, the average annual increment of tree diameter in 1990–2023 was set at 100 (by tree species, sampling regions and site classes), and the annual indices present the growth level compared to the average.

The indices for South Finland and North Finland were combined from the indices estimated by site classes and sampling regions, weighted by the annual volume increment of the class and region. Although the number of bored sample trees in the whole NFI9–NFI13 data is high, the number of observations for the latest years in some classes was less than ten.

Growth indices for Scots pine in Northernmost Lapland were estimated separately. In Northernmost Lapland all the sample plots were permanent and, therefore, increment cores were bored from trees outside the plots. A representative tree of the main tree stratum of the plot stand was selected for boring.

3 Results

3.1 Land use/Land cover classes

26.2 M ha (86%) of the total land area (30.4 M ha) is forestry land. Thus, only 6.2 M ha (14%) of the land area of Finland is agriculture land or built-up land. Forestry land includes classes productive forest (20.3 M ha), poorly productive forest (2.6 M ha), unproductive land (3.1 M ha), and other forestry land (0.2 M ha). In North Finland the proportion of forestry land (95%) is clearly higher than in South Finland (78%). The term forestry land can be misleading because it includes forests that are not available for wood supply for economic or legislative reasons (see Chapter 3.2). Productive forest is defined as forests where the site productivity is more than 1 $m^3 ha^{-1} a^{-1}$. Poorly productive forest has site productivity between 0.1 and 1 $m^3 ha^{-1} a^{-1}$ and unproductive land less than 0.1 $m^3 ha^{-1} a^{-1}$. (Suppl. file S2: Table 1, available at https://doi.org/10.14214/sf.24045)

The standard error of the forestry land area estimate for the whole country is 62 000 ha, which is 0.2% of the estimate.

The area of forest according to the FAO definition is 22.6 M ha. The FAO forest includes classes productive forest, other forestry land and most of the poorly productive forest in the national land use classification. The area of other wooded land is 0.750 M ha. Within the category of other land (7.1 M ha) there is 0.270 M ha of other land with tree cover.

For each NFI plot stand it is assessed if there has been any land use changes since the year 1990. The results of these for the latest 10 years before the NFI field work are presented in Suppl. file S2: Table 4.

The area of forestry land in the current territory of Finland has slightly decreased in the past 100 years: from the 26.8 M ha in 1921 to the current 26.2 M ha. Reasons for the slight decrease has been the increasing area of agricultural land and building of infrastructure such as roads, power lines, and in the late1960s also hydropower with reservois. The concept of productive forest land

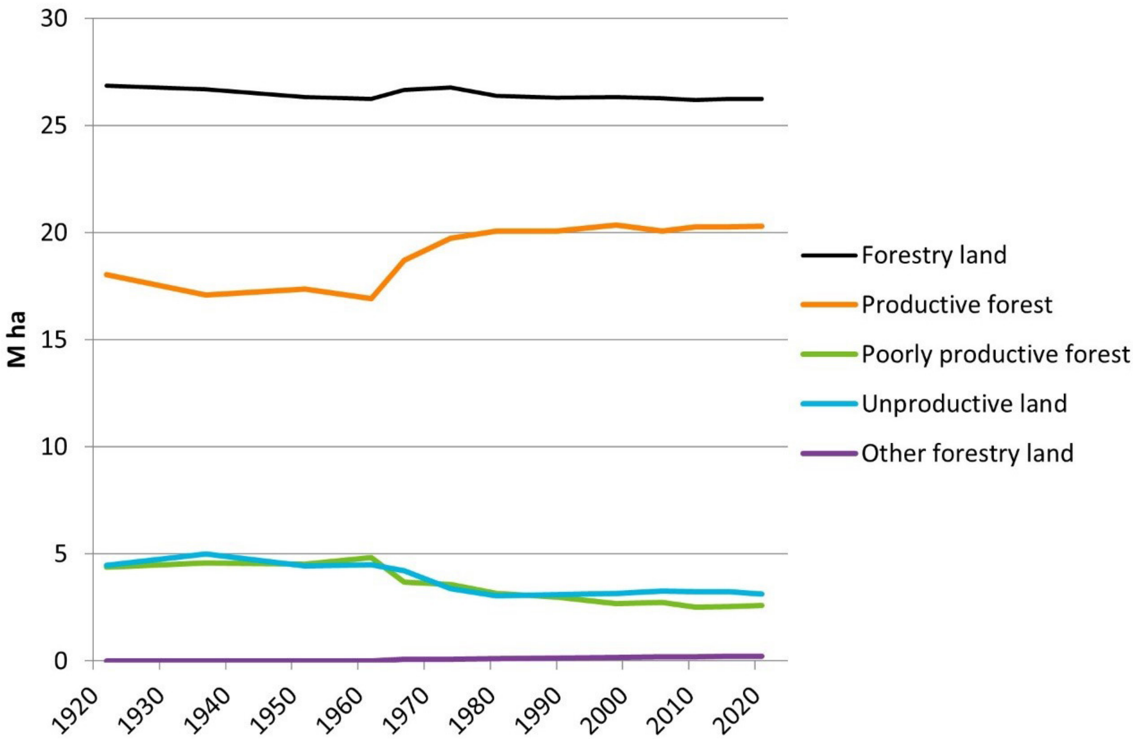


Fig. 3. Area by land use class in 1921–2023 in Finland according to NFI1–NFI13.

has been consistent in NFI since the mid-1960s (NFI5). Thus, the area of current productive forest land cannot be directly compared to the area estimates of NFI1–NFI4. Since the mid 1960s the area of productive forest has increased by 1.6 million hectares due to drainage of treeless or poorly productive peatlands. Most of this change was before the 1980s. Since the year 1990, which is the baseline for greenhouse gas reporting, the area of productive forest has remained stable: the slight decrease of 30 000 hectares is statistically insignificant. The change in the area of productive and poorly productive forest since the year 1990 is even less, 11 000 hectares (Fig. 3).

3.2 Forest ownership and restrictions on timber production

3.2.1 Ownership categories

Private individuals own 51% of the forestry land, communities 6%, companies 8% and government 35%. In the productive forests the proportions are 59%, 6%, 9%, and 26%, respectively. The proportion of private ownership is larger in the productive forests than in the poorly productive forests or unproductive land. The role of private ownership is further emphasized when we exclude the protected forests – among the productive forests available for wood supply the proportion of forests owned by private individuals is 64%, and the proportion of government owned forests is 19%. The government-owned forests are concentrated in the North Finland. (Suppl. file S2: Table 5)

3.2.2 Restrictions on timber production

23% (6.1 M ha) of the forestry land is not available for wood supply, 10% (2.7 M ha) partly available for wood supply and 67% (27.5 M ha) is production forest. In North Finland the proportions of forest not available or partly available for wood supply are larger than in South Finland – up to 50 % of the forestry land area in North Finland is not available or partly available for wood supply. (Suppl. S2: Table 6)

In the productive forest, the proportion of production forests is larger than in the forestry land in total: 85% (17.2 M ha) of the productive forest is production forest, 5% (1.1 M ha) partly available and 10% (2.0 M ha) not available for wood supply.

In terms of hectares, the Nature Protection Act is the most important restriction for excluding productive forest from timber production – 925 000 ha of productive forest is protected by the Nature Protection Act. The owner’s decision, mainly in government owned lands, is the second most important restriction (550 000 ha), followed by legislation other than the Nature Protection Act (471 000 ha).

Since NFI12 (2014–2018) (Korhonen et al. 2021a), the area of forestry land not available for wood supply has increased by 800 000 ha. The area of forestry land partly available for wood supply has decreased by the same amount. The change has happened in the category where the reason for restriction is the forest owner’s own decision. Almost all these restrictions are in the government owned forests. In the productive forest, the area of forest not available for wood supply due to owner’s decision has increased by 140 000 ha between NFI12 and NFI13.

In the past 25 years, the area of productive forest not available for wood supply or with restrictions on management activities has increased from 2.1 M ha to the current 3.2 M ha (Tomppo et al. 2011) (Suppl. S2: Table 6).

In the following chapters, the notation ‘FAWS’ (forest available for wood supply) is used for forests where there are no restrictions (other than those set out in the Forets Act) for forestry or where the restrictions allow harvesting. The notation ‘FNAWS’ (forest not available for wood supply) is used for forests where the restrictions do not allow timber harvesting.

3.3 Site fertility classes

3.3.1 Mineral soils

The classifications for mineral and peatland soil sites used in NFI13 are described in detail in the Field Manual (Suppl. file S3), with further descriptions in Hotanen et al. (2018) and Laine et al. (2018). Mineral soil sites comprise 64% of the total 26.2 M ha of forestry land and 74% of the total 20.3 M ha of productive forests (Suppl. file S2: Tables 1 and 10).

The mesic heath forest is the most typical site type (fertility class) both in South and North Finland (Fig. 4). The proportion of this class is 47% of the productive forests on mineral soils in South Finland, and 58% in North Finland. In South Finland, the proportion of herb-rich forests is 4% (371 000 ha, standard error 14 000 ha) and the proportion of herb-rich heath forests is 23%. In North Finland, the proportions of these classes are below 1% (26 000 ha, standard error 5000 ha) and 3%, respectively (Suppl. file S2: Table 10).

Since the 1950s, the proportion of the most fertile site types (herb-rich, herb-rich heath) has increased by about 10%-units and the proportion of mesic sites by about 6%-units in South Finland (Fig. 5). There has been no major change in the proportion of the most fertile site types in North Finland, but the proportion of the mesic heath forests has risen by 30%-units, i.e., doubled. The proportion of sub-xeric heaths decreased in South Finland from the 1950s to the 1980s but has remained almost the same since then. In North Finland, the decrease of sub-xeric and xeric sites stopped in the 1990s.

There are 1.22 M ha of drained mineral soil sites, i.e., 8% of the productive forests on mineral soils (Suppl. file S2: Tables 8 and 10) (Fig. 6). A large part of these drained mineral soil sites, about 660 000 ha, have originally been thin-peated spruce and pine mires, and the peat layer has decomposed because of the drainage (Tomppo 1999).

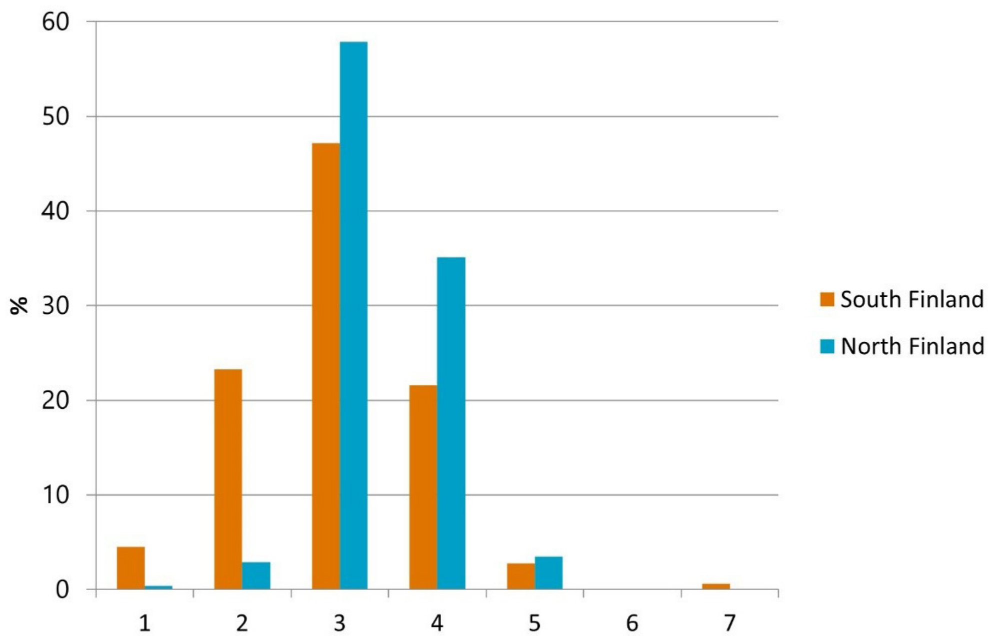


Fig. 4. The proportions of site types (fertility classes) (Hotanen et al. 2018b) on mineral soils of the productive forest a) in South and b) in North Finland according to NFI13: 1 = herb-rich forests, 2 = herb-rich heath forests, 3 = mesic heath forests, 4 = sub-xeric heath forests, 5 = xeric heath forests, 6 = barren heath forests, 7 = rocky and sandy soils and alluvial lands.

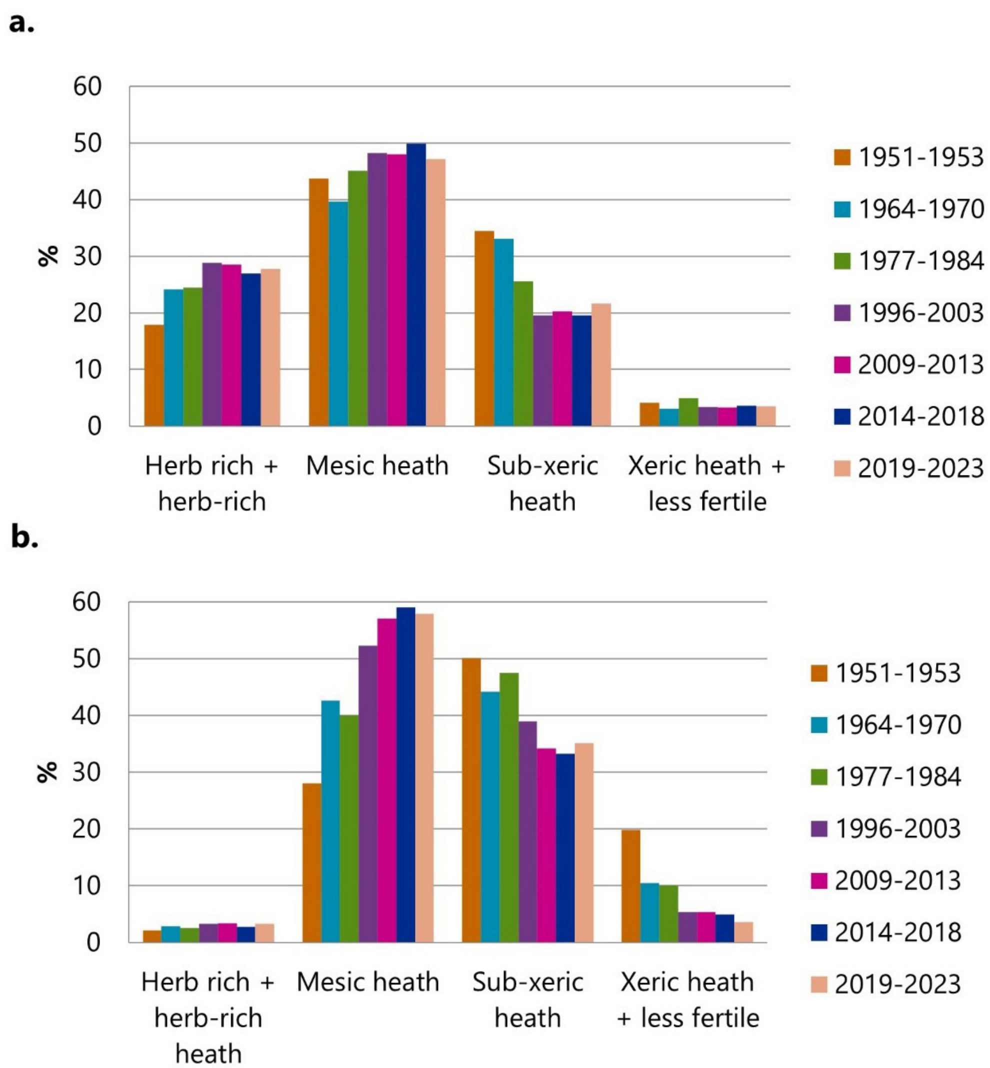


Fig. 5. The proportions of grouped site types (fertility classes) (Hotanen et al. 2018) on mineral soils in 1951–2023 a) in South Finland and b) in North Finland according to NFI3–NFI13.

The proportion of moraine soils in productive mineral soil forests is 73%. The proportion is the highest in mesic (79%) and sub-xeric (74%) site types (Suppl. file S2: Table 15). Moraine and sorted soils account for a total of 96% of the productive mineral soil forests, and 77% of them are medium grained with a predominant grain size of 0.06–0.2 mm or 0.2–0.6 mm. The soil type of sorted soils is often fine-grained in the most fertile sites and quite often in mesic types. Also in the moraine soils, the proportion of fine-grained particles is higher in fertile site types than in dryer ones.

The soil layer thickness above the bedrock is almost always more than 30 cm in mineral soil productive forests. The proportion of the 10–30 cm class is 8% and the proportion of less than 10 cm is only 3% (Suppl. file S2: Table 16).

3.3.2 Peatlands

The total area of peatlands (undrained and drained summed) is 9.13 M ha, which is 35% of forestry land (Suppl. file S2: Tables 1 and 7). There are 3.33 M ha of peatlands in South Finland and 5.80 M ha in North Finland.

Undrained peatlands

The total area of undrained peatlands is 4.22 M ha, comprising 18% spruce mires, 51% pine mires and 31% open mires (Suppl. file S2: Table 7). In South Finland (829 500 ha of undrained peatlands), the proportions are: spruce mires 33%, pine mires 45% and open mires 23%. In North Finland (3.39 M ha), the corresponding proportions are 15%, 54% and 33%, respectively.

Of the undrained peatlands, 21% are productive forest, 30% poorly productive forest and 49% unproductive land. The corresponding proportions for spruce mires are 63%, 29% and 8%, for pine mires 19%, 48% and 33% (Suppl. file S2: Table 7). All the open mires are unproductive land.

Of the undrained spruce mires, 49% are thin-peated (peat thickness less than 30 cm) (Suppl. file S2: Table 12). For the undrained pine mires and undrained open mires, the values are 21% and 4%, respectively. The most common peat layer thickness class for the spruce mires is 0–29 cm, with 63% in South Finland and 42% in North Finland. For the pine mires the most common class is 200+ cm (34%) in South Finland and 30–99 cm (41%) in North Finland. In open mires, the most common class in South Finland is 200+ cm (61%). In North Finland, the thickness classes 30–99, 100–199 and 200+ cm are almost equally common with proportions 27%, 36% and 33%, respectively.

Of the undrained spruce mires, the most common type both in the whole country (168 000 ha) and in North Finland (121 000 ha) is herb-rich spruce mire (RhK). In South Finland this is thin-peated *Myrtillus* spruce mire (KgK, 85 000 ha) (Suppl. file S2: Table 13). Regarding the whole Finland, *Rubus chamaemorus* spruce mire (MrK, 3000 ha, standard error 2000 ha), Cotton grass spruce mire (TK, 5000 ha, standard error 2000 ha) and *Equisetum sylvaticum* spruce mire (MkK, 6000 ha, standard error 2000 ha) get the lowest values. Standard errors for these scanty types are proportionally the highest.

In South Finland, the most common pine mire type is dwarf-shrub pine bog (IR, 94 000 ha). The rarest are *Betula nana* pine mire (VkR) and eutrophic pine mires (VLR, RaLR) (Suppl. file S2: Table 13). In North Finland, thin-peated pine mire (KgR, 283 000 ha), tall sedge pine fen (VSR, 254 000 ha) and low sedge *Papillosum* pine fen (LkKaR, 204 000 ha) are the most common pine mire types. IR (193 000 ha) and cottongrass pine bog (TR, 183 000 ha) also are abundant. Eutrophic pine mires (VLR and RaLR) constitute 62 000 ha together. VkR (36 000) and *Fuscum* hollow bog (KeR, 38 000) are the scantiest.

Of the open mires, the most common types in South Finland are ombrotrophic low sedge bog (LkN, 59 000 ha) and *Fuscum* bog (RaN, 31 000 ha), as well as minerotrophic tall sedge pine fen (VSN, 35 000 ha) and herb-rich pine fen (RhSN, 33 000 ha) (Suppl. file S2: Table 13). In North Finland these are VSN (347 000 ha), LkN (220 000 ha) and flark fen (VRiN, 201 000 ha). Compared to the types above, Eutrophic fen (VL, 8000 ha, standard error 3000 ha) and eutrophic flark fen (RiL, 16 000 ha, standard error 4000 ha) are quite scanty. These two eutrophic types are clearly scantier in South Finland.

Drained peatlands

The area of drained peatland, 4.91 M ha, is 54% of the total peatland area (Suppl. file S2: Table 7). This same percentage is 75% in South Finland and 42% in North Finland. 88% of the drained mires are productive forest; 96% in South Finland and 81% in North Finland. 10% of the drainage area is poorly productive forest; 3% in South Finland and 17% in North Finland.

Transformed mires, in which the undergrowth resembles mineral soil forest type, already totals 3.78 M ha, which is 77% of the current drained peatland area (Suppl. file S2: Tables 7 and 8) (The assessment of drainage status is described in the Suppl. file S3). In South Finland, there are

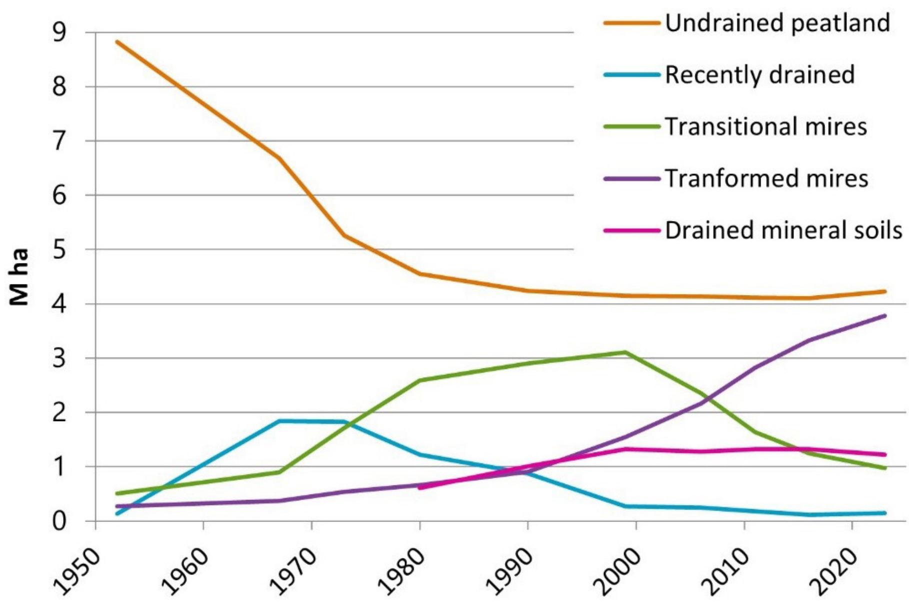


Fig. 6. Area of the drained mires by drainage stages and area of drained mineral soil sites in 1951–2023 in Finland according to NFI3–NFI13.

2.27 M ha of transformed mires, which is 91% of the drained peatland area. For North Finland, the values are 1.50 M ha and 62%, respectively.

The area of transformed mires has grown continuously (Fig. 6). In the 1980s only 19% of the drained peatlands were transformed mires. According to NFI11 (2009–2013), 61% of the drained peatlands were transformed mires (South Finland 78%, North Finland 45%) (Korhonen et al. 2017).

The area of transforming mires is 982 000 ha, and it has continuously decreased since the late 1990s (Fig. 6). The area of recently (non-changed) drained mires is 153 000 ha. The draining of undrained peatlands has decreased close to zero in the late 1990s and most of the earlier drained peatlands have developed to more advanced drainage phases. 66% of the recently drained peatlands locate in North Finland (Suppl. file S2: Table 8).

There are 561 000 ha of misditchings, i.e., the drained sites have remained unsuitable for wood production because of nutrient or technical problems. This corresponds 11% of the current drained peatland area in the whole country, 4% in South Finland and 19% in North Finland (Suppl. file S2: Tables 7, 8 and 9).

Since NFI10 (2004–2008) all the drained mires are also classified directly to the different drained peatland forest types despite drainage status. The traditional *V. myrtillus* and *V. vitis-idaea* types have each been divided into two types; type1 develops from genuine, forested mire types and type2 from treeless and sparsely forested composite types (Laine et al. 2018). The area of drained peatland *Vaccinium vitis-idaea* type (Ptkg1 + Ptkg2) is the widest, 1.76 M ha, which is 36% of the total drained peatland area (Suppl. file S2: Table 11). The area of *V. myrtillus* type (Mtkg1 + Mtkg2) is 1.44 M ha, respectively. The area of the dwarf shrub type (Vatkg) is 1.06 M ha, herb-rich type (Rhtkg) 568 000 ha and the poorest, *Cladonia* type, 81 000 ha (standard error 7000 ha).

Of the drained mires, the proportion of thin-peated sites (peat thickness less than 30 cm) is the highest in the Mtkg1 type, 45%; for the Mtkg2 type the value is half of that, 22% (Suppl. file S2: Table 12). For the Ptkg1 and Ptkg2 types the proportions are 38% and 14%, respectively. The proportions for Rhtkg, Vatkg and Jätkg are 37%, 9% and below 0.01%, respectively.

3.4 Stand structure, tree species and age structure of forests

3.4.1 Stand structure and origin

Only 44 000 hectares (0.2%) of the productive forest area is classified as uneven-aged forest. This includes both forests that are naturally uneven aged structured and forests where uneven-aged type of forest management has been started. 29 000 hectares of uneven-aged forests are in South Finland and 15 000 hectares in North Finland. In productive forest available for wood supply, the area of uneven-aged forests is 35 000 hectares. (Suppl. file S2: Table 20)

Most of the even-aged forests are single-storey forests. The proportion of forests with two or three tree storeys is 13% of the productive forest area. (Suppl. file S2: Table 20)

Stand origin (regeneration method) is assessed in the field only for stands on seedling or thinning stage. It is not assessed on mature forests because in most cases it is impossible to estimate the stand origin for older forests due to natural regeneration in planted forests and thinnings that change the structure of forests. Out of the 15.8 million hectares of seedling and thinning forests in the productive forest available for wood supply, 8.3 million hectares are naturally regenerated, and 7.5 million hectares are originated from artificial regeneration, mostly from planting. (Suppl. file S2: Table 26)

3.4.2 Dominant tree species and mixed forests

63% of the productive forests in Finland are pine dominated, 25% spruce dominated, 9% birch dominated and 1% are dominated by other broadleaf species. Among the group of other broadleaf species, the European aspen (*Populus tremula* L.), common alder (*Alnus incana* [L.] Moench) and black alder (*Alnus glutinosa* (L.) Gaertn.) forests are the most frequent. The proportion of treeless (clear cut) area is 1.4% of the productive forest. Forests in the North Finland are more pine dominated than the forests in South Finland. The proportion of spruce or broadleaf dominated forests is less than 25% in North Finland. (Suppl. file S2: Table 17)

64% of the pine dominated productive forests are almost pure coniferous forests where the proportion of conifers is more than 95% of the growing stock. In spruce dominated forests the proportion of almost pure coniferous forests is 44%. In forests dominated by broadleaved species, the proportion of almost pure broadleaf stands is 31%. All in all, 55% of the productive forests are almost pure conifer stands or almost pure broadleaf stands, and 14% of the productive forests are mixed conifer-broadleaf stands where the proportion of conifers in a conifer dominated stand or the proportion of broadleaves in a broadleaf dominated stand is not more than 75%. (Suppl. file S2: Table 18)

Especially in South Finland, the proportion of different tree species varies by age class. Young forests, younger than 20 years, are very often spruce dominated stands – more than 50% of these are spruce dominated. Forests older than 60 years are most frequently pine dominated in South Finland. (Suppl. file S2: Table 50) (Fig. 7)

3.4.3 Age and development classes

One third (35%) of the productive forest area is younger than 40 years, 39% is in the age class 41–80 years, and remaining 16% is older than 80 years. The proportion of forests older than 160 years is 4%. Most of the oldest forests are pine dominated. In the youngest age class, 1–20 years, the proportion of spruce forests is the highest in South Finland, but in North Finland the pine forests dominate also in the youngest age classes. (Suppl. file S2: Table 50) (Fig. 7)

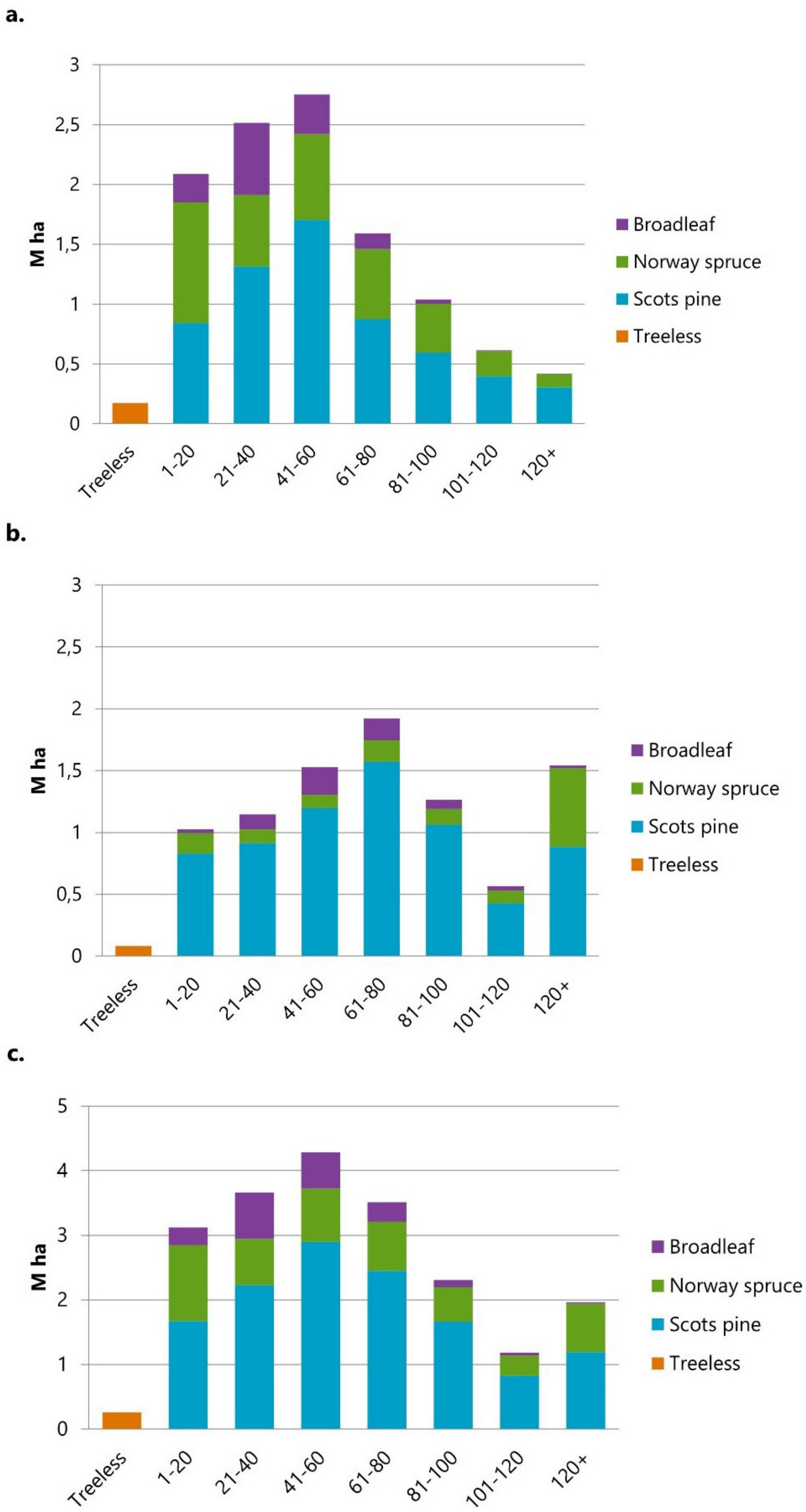


Fig. 7. Area of productive forest by age class and dominant tree species in a) South Finland, b) North Finland, and c) whole Finland according to NFI13.

The proportion of young seedling stands (the mean height of crop seedlings less than 1.3 m) is 6%, advanced seedling stands 11%, young thinning stands 32%, advanced thinning stands 37%, mature forests 12% from the area of productive FAWS. The proportion of regeneration sites (treeless clear-cut sites that have not yet been planted, shelter and seed tree stands) is 2%. The area of uneven-aged forests in productive FAWS is 26 000 hectares (0.1%). In this context, uneven-aged forests include only such forests where the uneven stand structure is purposively created through continuous cover forest management. (Suppl. file S2: Table 52)

3.4.4 Changes in forest structure

During the past 100 years there have been clear changes in proportions of the tree species both in South and North Finland. In South Finland, the proportion of pine dominated forests decreased from 50% in the 1920s to 45% in the 1950s. From the 1950s to 2000 the proportion increased close to 60%, but has then declined during the latest 20 years. The increase from the 1950s to 2000 was caused partly by the drainage of peatlands. Another reason is that in the 1970s and 1980s pine was used very often in planting, even in rich sites that were better for spruce or birch. In South Finland, the trend in the proportion of spruce dominated forests have been opposite to the trend of pine forests. The proportion of birch forests has dropped from the 15 to 20% of the 1920s and 1930s to 7% in early 1970. Since then, the proportion of birch dominated forests has gradually increased to the current 11%. (Fig. 8)

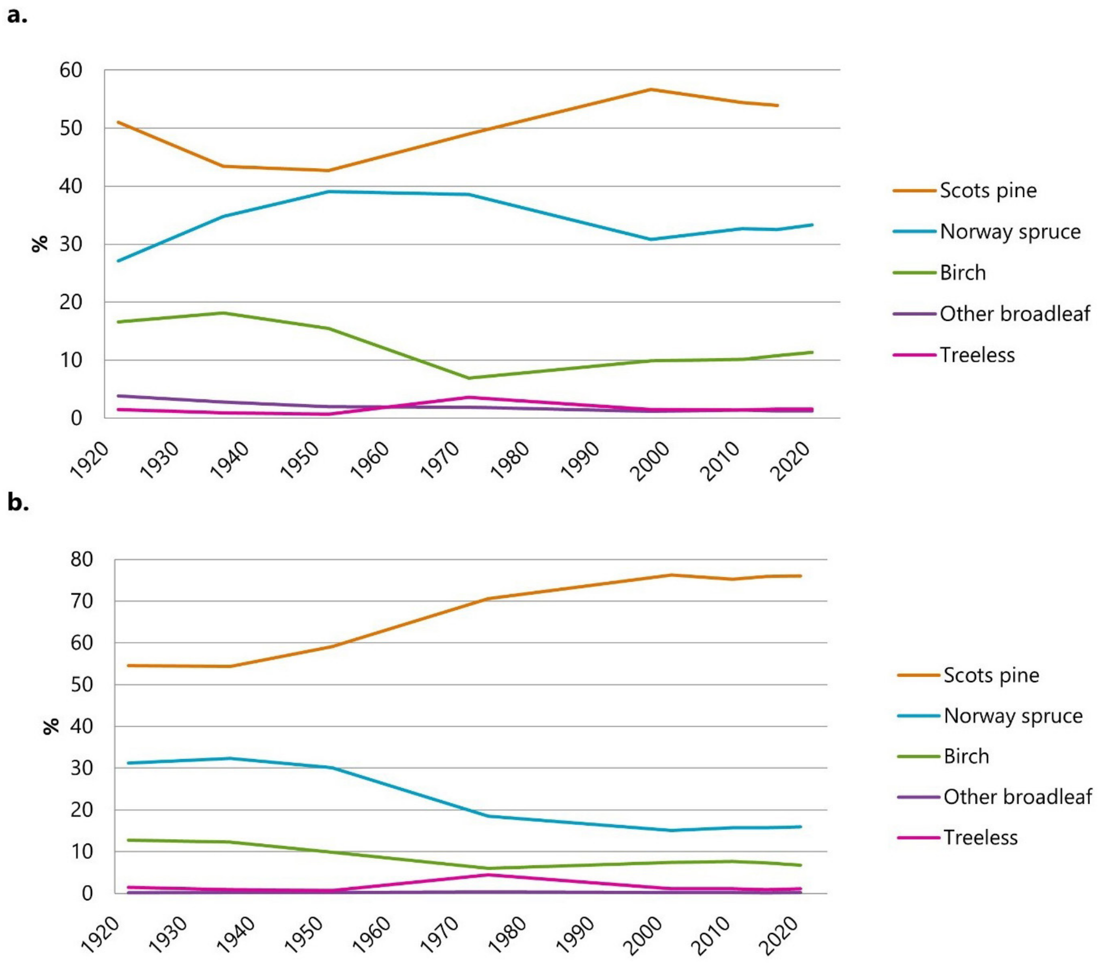


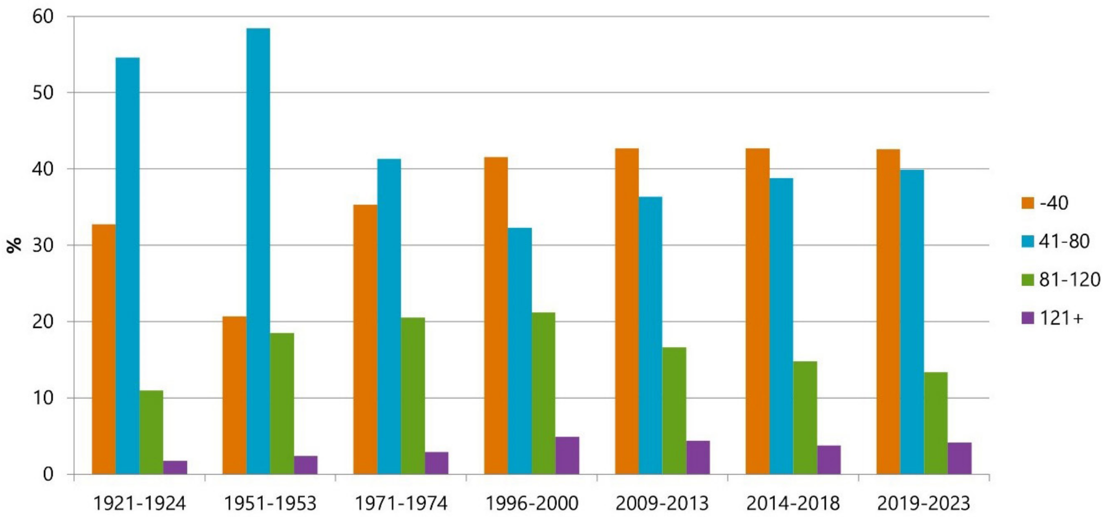
Fig. 8. Proportion of dominant tree species in productive forests 1921–2021 in a) South Finland, and b) North Finland according to NFI13.

In North Finland, the proportion of pine dominated forests increased from the 1930s to 2000. The regeneration of the old spruce dominated forests have caused this change. During the last two decades, the proportion of the pine forest has remained in 76% in North Finland.

The stand age structure has in South Finland changed in 100 years so that now the proportions of young (less than 40 years) and old forests (more than 120 years) have increased and the proportion of mid-aged forests decreased. The proportion of old forests increased from the 1.6% in the 1920s to the 5 % in 2000 and decreased since then to the current 4%. Since the end of the 1990s, the proportion of the age class 81–120 years has dropped from 21% to the current 13%. (Fig. 9)

In North Finland, the proportion of old forests (older than 120 years) decreased from the 52% in the 1920s to the 18% in 2009–2013. Since then, the proportion of old forests has remained stable. Due to the regeneration of the old forests, the area of the youngest forests (1–40 years) increased markedly from the 1920s (5%) to 2001–2003 (29%). Since then, the proportion of the youngest forests has slightly decreased and the proportion of the forests in age class 41 to 80 years has slightly increased.

a.



b.

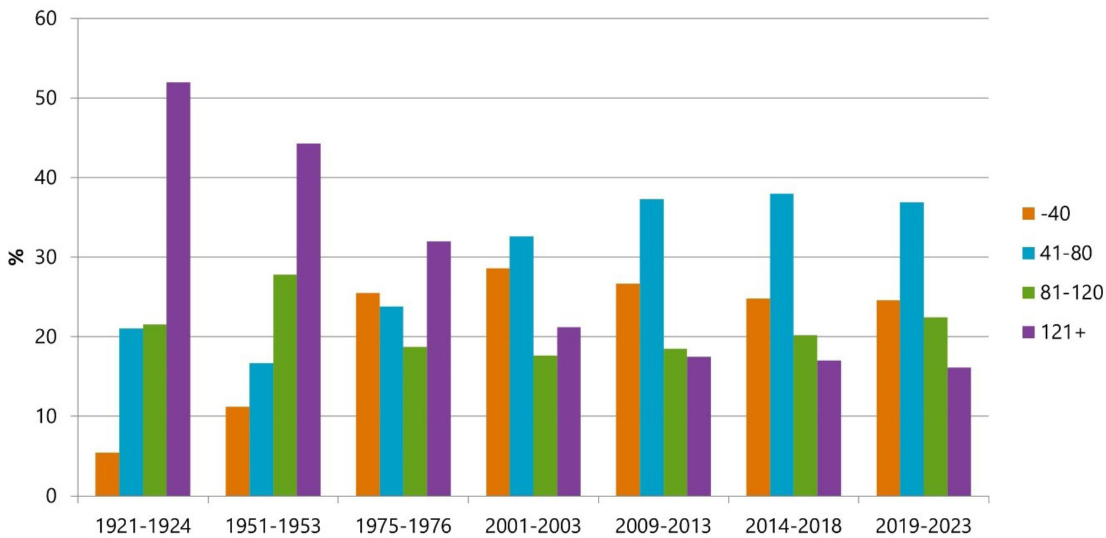


Fig. 9. Proportion of age classes in productive forests 1921–2023 in a) South Finland and b) North Finland according to NFI1-NFI13.

Compared to the previous inventory (NFI12, 2014–2028), the area of mature forests in FAWS has decreased from 2.168 M ha to 2.119 M ha, i.e. by 49 000 hectares. The change is not statistically significant, but it is in line with the increased forest protection – the area of FAWS has decreased from the 18.444 M ha in NFI12 to the 18.301 M ha in NFI13. Most of the forest protection aims at protecting old forests. During the same time period, the area of advanced thinning stands in FAWS has increased from 6.373 M ha to 6.852 M ha, i.e. by almost 0.5 M ha.

3.5 Volume and biomass of growing stock and their changes

3.5.1 Volume and biomass

The total volume of growing stock in productive and poorly productive forest is 2552 M m^3. The standard error of the total volume estimate is 13 M m^3 (0.53%). Half of the total volume consists of pine, 30% of spruce and remaining 20% of broadleaves. The standard error of the volumes by tree species groups varies from 0.7% (pine) to 2.3% (other broadleaves). The total volume of growing stock in South Finland is 1655 M m^3 and in North Finland 897 M m^3. The total volume of growing stock in peatland forests is 0.658 M m^3 (26% of the total volume). (Suppl. file 2: Table 55)

The total volume of growing stock in FAWS is 2.252 M m^3 which is 88% of the total volume. The mean volume in productive FAWS is 121.6 m^3 ha$^{–1}$, which is almost the same as in all productive forest. (Suppl. file 2: Table 55)

The mean volume of growing stock is 111.5 m^3 ha$^{–1}$ in the combined productive and poorly productive forest. In productive forest, the mean volume is 122.2 m^3 ha$^{–1}$. The relative standard error of the mean volume estimate is 0.4%. The mean volume in the productive peatland forests (117.3 m^3 ha$^{–1}$) is only slightly less than in the productive forests on mineral soils (123.9 m^3 ha$^{–1}$). (Suppl. file 2: Table 55)

In the forests available for wood supply, the mean volume is 234.9 m^3 ha$^{–1}$ in mature forests, 163.8 m^3 ha$^{–1}$ in advanced thinning stands and 91.5 m^3 ha$^{–1}$ in young thinning stands. In treeless clear-cut sites, the mean volume is 9.3 m^3 ha$^{–1}$, indicating that almost 10 m^3 ha$^{–1}$ retention trees have been left unharvested in clearcuttings. (Suppl. file 2: Table 53)

0.744 M m^3 (33%) of the total volume in the productive forest available for wood supply is of saw timber size and quality, 1.313 M m^3 (59%) of pulp wood quality, and 0.167 M m^3 (7%) of waste wood quality/size. The saw timber proportion is the highest for spruce (45%) and the lowest for other broadleaves (14%). (Suppl. file 2: Table 58)

63% of the growing stock on productive forest is owned by private individuals, 7% by communities (including jointly owned forests, parishes, municipalities and other communities), 9% by companies, and 21% by the state (Suppl. file 2: Table 58).

The average number of stems in the productive and poorly productive forest is 3092 stems/ha totalling to 142 000 M stems. More than 50% of the stems are in the first two-centimetre classes. Downy birch is the most common tree species when measured with the stem number – 42% of the trees are downy birch. In the larger diameter classes, conifers are clearly more common than broadleaves. (Suppl. file 2: Table 56)

The mean volume of dead trees that are still hard enough to be used at least as firewood is 4.0 m^3 ha$^{–1}$ (Suppl. file 2: Table 61).

The total biomass of growing stock (living trees) is 1786 M t. Out of this 1039 M t (58%) consist of stem, 97 M t (5%) of leaves, 210 M t (12%) of living branches, 93 M t (5%) of stump, 309 M t (17%) of coarse roots and 37 M t (2%) of dead branches. (Suppl. file 2: Table 60).

3.5.2 Development of growing stock volume

During the past 100 years, the total volume of growing stock has increased from 1.4 G m^3 to the current 2.6 G m^3, i.e. by 84% (Fig. 10). The volume estimate for NFI1 has been recalculated using the same volume functions as in the latest NFIs. However, trees below 2 cm in diameter at breast height were not measured in the first NFIs. The proportion of trees below 2 cm from the total volume in NFI13 is 0.7%. Most of the increase in total volume has taken place after the end of the 1960s. In recent years, the increase has slightly slowed down in South Finland and remained high

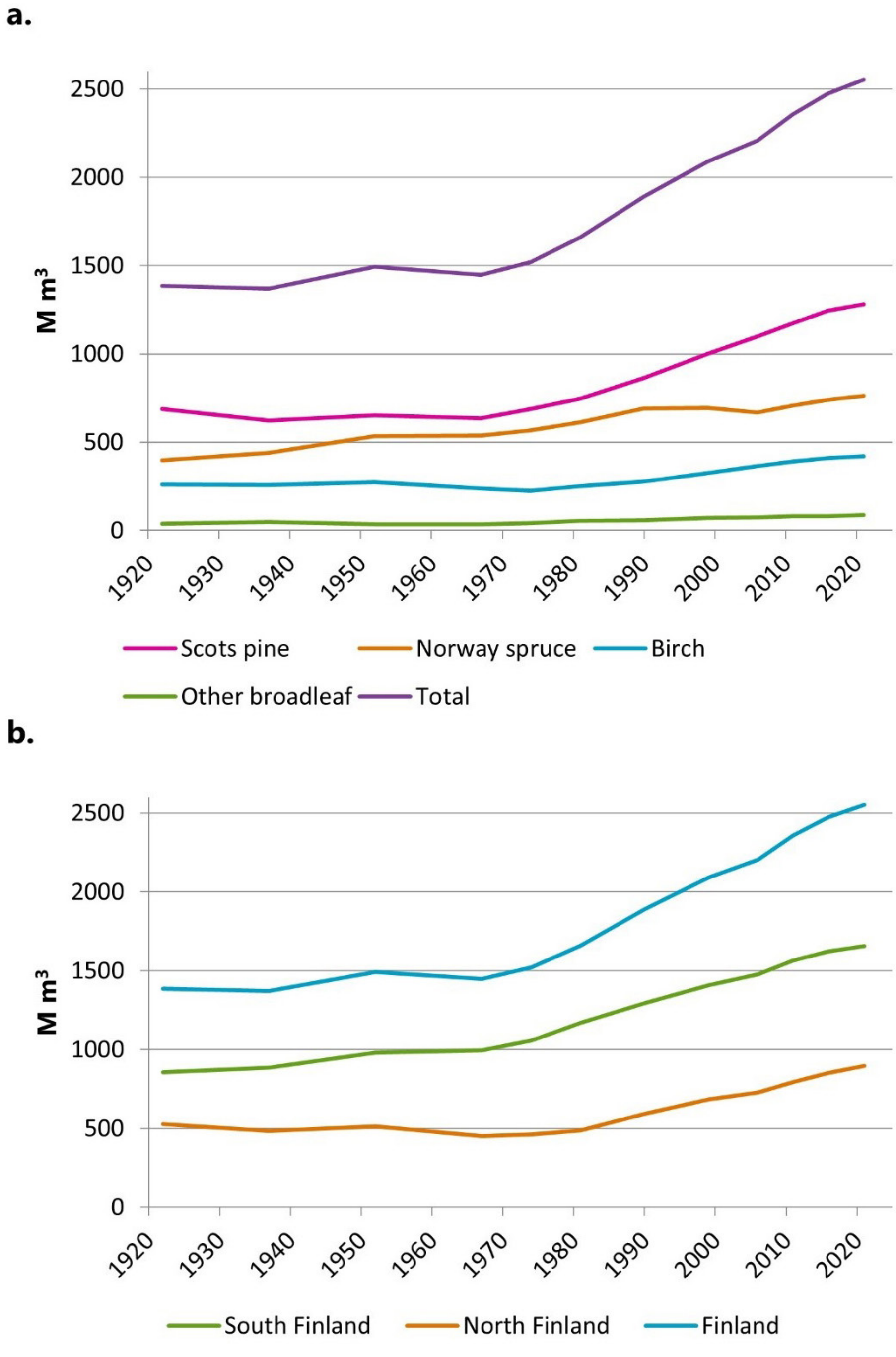


Fig. 10. Total volume of growing stock in a) whole Finland by tree species group and b) South and North Finland according to NFI1–NFI13. Scots pine group in a) includes other conifers than Norway spruce.

in North Finland. Between NFI12 and NFI13, the total volume has increased by 77 M m^3. The increase is statistically significant as the standard error of the total volume estimate is 13.5 M m^3 in NFI13 and 13 M m^3 in NFI12.

The total volume of pine has increased the most but also the total volumes of spruce, birches and other broadleaves have increased markedly. In relative terms, the increase has been highest for the other broadleaves, 118%.

The mean volume on productive forest land available for wood supply has increased from 118.8 $m^3 ha^{-1}$ to 121.6 $m^3 ha^{-1}$ between NFI12 and NFI13. The mean volume has increased both in South and North Finland. Between NFI12 and NFI13, the mean volume has somewhat decreased in advanced thinning stands and increased in young thinning stands and mature forests. Also, in treeless clear-cut sites the mean volume of retention trees has increased from 7 to 9 $m^3 ha^{-1}$ (Suppl. file 2: Table 53) (Korhonen et al. 2021a).

3.6 Volume increment and forest balance

3.6.1 Volume increment

The volume increment was estimated based on the permanent sample plots where the previous measurement was in NFI12 (2014–2018), except in the Northernmost Lapland where the previous measurement was in NFI11 (2012). The total annual volume increment in productive and poorly productive forests is 103.0 M m^3. The estimate is an average over the period between NFI12 (Northernmost Lapland NFI11) and NFI13 measurement. The increment divides into tree species groups as follows: 43% Scots pine, 34% Norway spruce, 18% birches, and 4% other broadleaves (Supp. file S2: Table 62). Further, 98.6% of the total annual volume increment is in productive forests. 6% of the increment is in the productive or poorly productive FNAWS (Supp. file S2: Table 63).

Forests in South Finland have higher increment than in North Finland. The mean annual increment in the productive forests in South Finland is over double (6.5 $m^3 ha^{-1}$) that of North Finland (3.1 $m^3 ha^{-1}$) (Fig. 11). Further, the mean annual increment is 5.0 $m^3 ha^{-1} year^{-1}$ in FAWS,

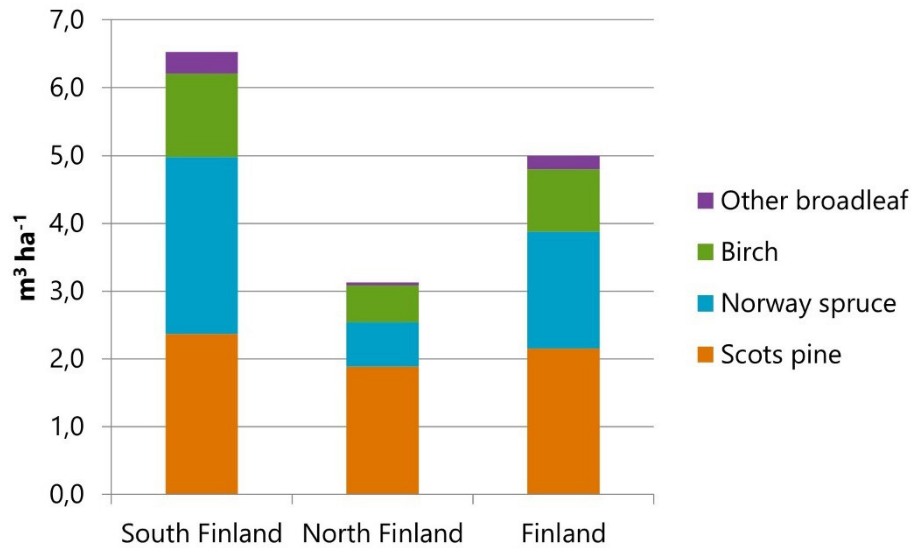


Fig. 11. The mean annual volume increment in productive forests by tree species groups according to NFI13 in South Finland, North Finland, and whole country.

compared to the 1.6 m³ ha⁻¹ in FNAWS. The mean annual increment in all productive and poorly productive forests is 4.5 m³ ha⁻¹ (Supp. file S2: Tables 62–64).

About ¾ of the total annual volume increment is on mineral soils in the productive and poorly productive forests, with a mean annual volume increment of 4.9 m³ ha⁻¹. The mean annual volume increment on peatland is lower than on mineral soils (3.6 m³ ha⁻¹), but the difference in the increment between undrained (1.8 m³ ha⁻¹) and drained (4.4 m³ ha⁻¹) peatland is remarkable (Supp. file S2: Table 65). 75% of the annual volume increment in productive and poorly productive forest is in privately owned forests (Supp. file S2: Table 66).

The time series of annual volume increment shows how the volume increment increased for decades until this inventory (Fig. 12). Since the first NFI the annual increment has more than doubled. The current total annual volume increment is 4.8 M m³ lower than the previous esti-

a.

b.

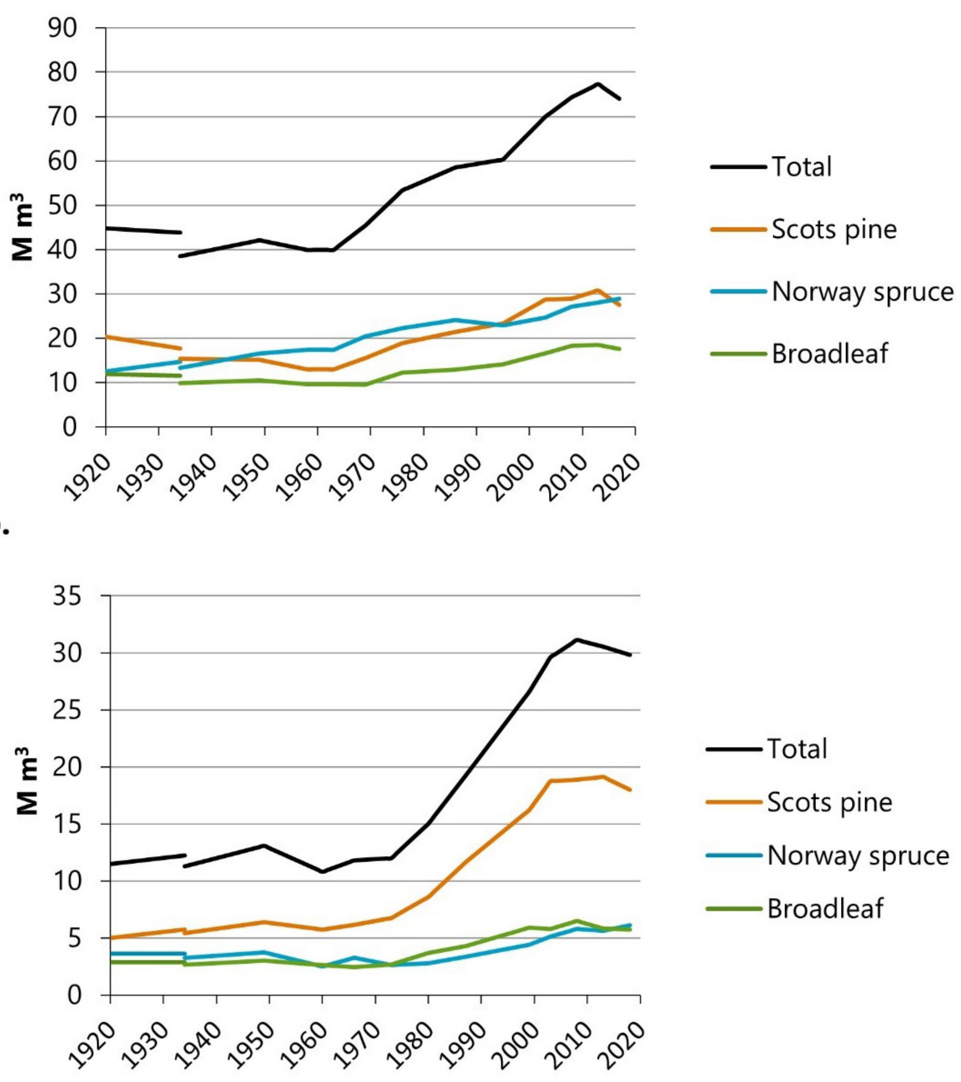


Fig. 12. The annual volume increment (M m³) by tree species in a) South Finland, b) North Finland, and c) the whole country 1921–2023 according to NFI1–NFI13. NFI1 estimate is for the territory of Finland of those times, NFI2 estimate for both the current and historical territory of Finland.

Table 4. Average growth indices for the increment measurement periods of NFI13 and NFI12 in South Finland and in North Finland (100 = average level of 1990–2023).

	Scots pine		Norway spruce		Birch	
NFI	South Finland	North Finland	South Finland	North Finland	South Finland	North Finland
NFI12	104	101	113	101	97	89
NFI13	93	89	110	103	90	90

mate (Korhonen et al. 2021a). Most of the change is in the increment of Scots pine, which has declined both in South and North Finland. Also, in the increment of broadleaves we observe a slight decline. In contrast, the increment of Norway spruce has continued to increase, particularly in South Finland.

3.6.2 Annual variation in increment

Growth indices are important when comparing growth estimates based on tree measurements carried out in different time periods. Growth indices describe the annual variation in tree increment that is not explained by factors such as tree size or density of the growing stock but caused by environmental factors such as weather conditions or abundant flowering that uses tree reserves, especially in the case of Norway spruce. An index value illustrates the relation of an annual increment of tree diameter to the average annual increment in the period of 1990 to 2023, which was set to 100 (see Sub-Chapter 2.3.6).

For Scots pine, the measurement period of NFI13 was unfavorable. The growing conditions were less favorable in NFI13 than in NFI12 both in South and North Finland (Table 4; Fig. 13). For Norway spruce, the increment measurement period of NFI13 was positive, above the average level of 1990–2023 in the whole country. The growing conditions were good for spruce especially in South Finland, similarly as in NFI12. For birch, the growing conditions were less favorable in NFI13 than in NFI12 in South Finland.

3.6.3 Mortality and natural losses

The current estimate of mortality in productive and poorly productive forests equals to 8.8 M m^3 (Supp. file S2: Table 67). This estimate describes the annual mortality between the measurements in NFI13 (2019–2023) and NFI12 (2014–2018), except in the Northernmost Lapland where the previous measurement is from NFI11 (2012). Most of the increase from previous estimate of 7.0 M m^3 (between NFI12 and NFI11) has occurred in North Finland (Korhonen et al. 2021a). There the volume of annual mortality is now 3.6 M m^3 while the previous estimate was 2.4 M m^3.

Volume of annual natural losses in productive and poorly productive forests equals to 7.9 M m^3, which means that only a small proportion of annual mortality is harvested. Most of the annual mortality (69%) and natural losses (68%) occur on mineral soils, but the proportion of mortality and natural losses from the total volume is higher in peatland forests than in forests on mineral soils.

The estimate of annual natural losses has increased continuously since the early 1970s (Fig. 14). Similarly, its proportion of annual volume increment has increased.

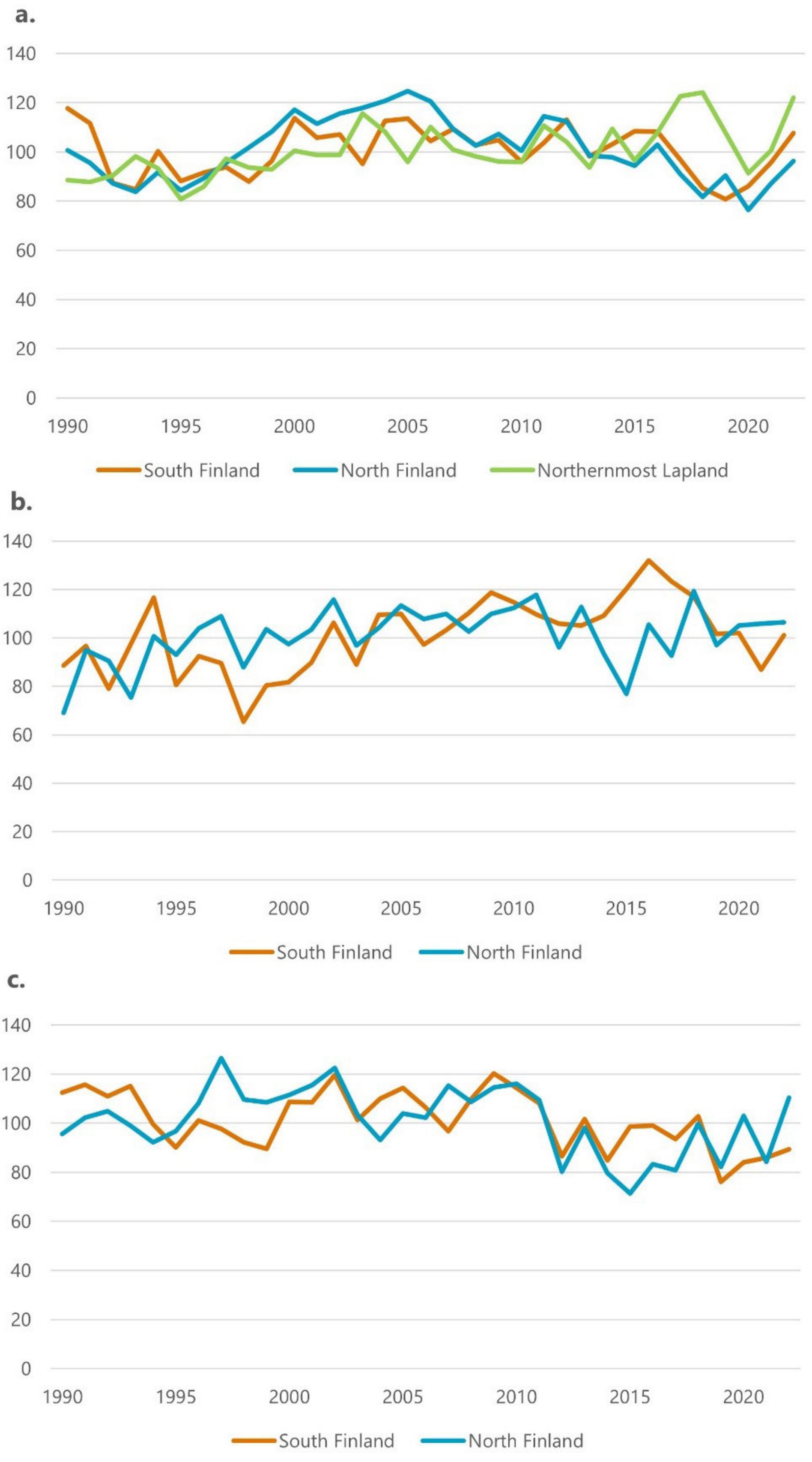


Fig. 13. Annual diameter increment indices in South and North Finland for a) Scots pine b) Norway spruce, and c) birch. Index value 100 is the average in 1990–2023.

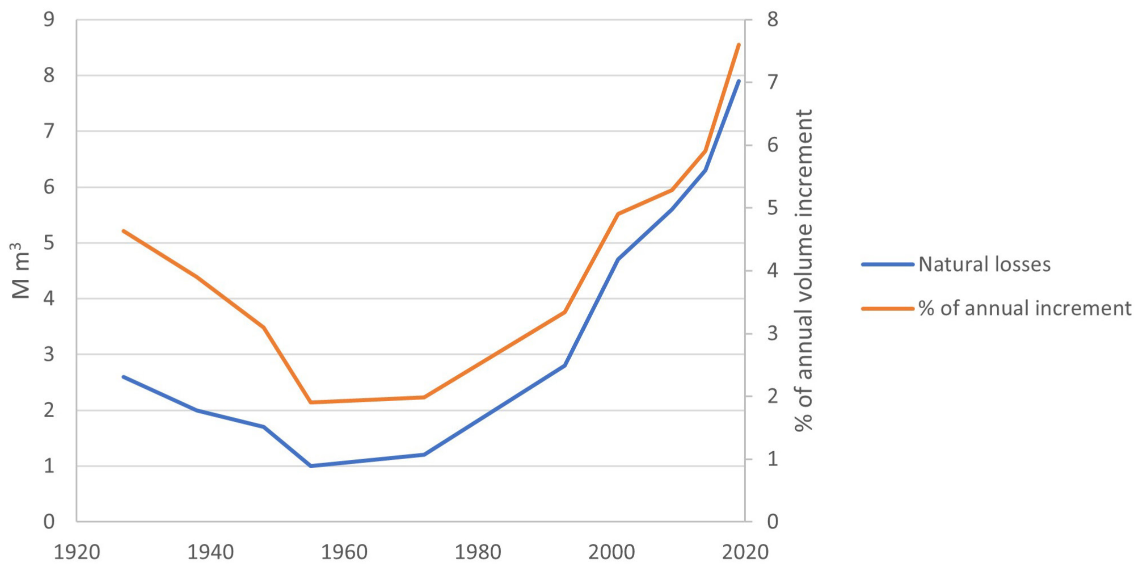


Fig. 14. Estimates of annual natural losses (M m^3) and its proportion of annual volume increment (%) 1920–2016 according to National Forest Inventories (NFIs) of Finland. Until the 1970s the estimates of annual natural losses are excluding bark.

3.6.4 Forest balance

Forest balance calculation is based on the following estimates: initial growing stock (GS12, the NFI12 volume estimate) (Korhonen et al. 2021a), final growing stock (GS13, the NFI13 volume estimate) (Supp. file S2: Table 55), and volume increment (Inc13, the NFI13 estimate) (Supp. file S2: Table 62). The drain is an average of the removal statistics over period (2014–2023) (OSF 2024). Both the increment and drain are turned from annual into periodical values by multiplying by 5 years (Inc13, Drain) (Table 5).

The difference Increment minus Drain is 3 M m^3 larger than the actual measured change in growing stock (GS13 – GS12) (Table 5). This difference is smaller than the difference was between NFI11 and NFI12 estimates (26 M m^3, Korhonen et al. 2021a).

In South Finland the measured change in growing stock (GS13 – GS12) estimate is 5 M m^3 larger than the difference Increment minus Drain. In North Finland the situation is opposite – the measured change being 8 M m^3 smaller than the difference Increment minus Drain. The largest difference is for broadleaved species where the measured change is 13 M m^3 larger than the difference Increment minus Drain. This whole difference originates entirely from the estimates for South Finland.

The standard error of the growing stock change estimate is 18.8 M m^3 which is larger than any of the differences between the estimates. Our uncertainty estimate is most probably an overestimate since we assume that the volume estimates of NFI12 and NFI13 are independent even though appr. 60% of the sample plots are permanent.

The forest balance calculation has several sources of uncertainty which are linked either to inventory data or removal statistics (OSF 2024). On one hand, the volume and volume increment estimates have sampling error, data collection spans over several years and inventories are therefore missing exact datum, and land-use changes may have an impact on estimates. On the other hand, the drain estimate may be incomplete, may include wood harvested from non-forestry land and contain other errors.

Table 5. Forest balance between NFI12 and NFI13 mid years (2016–2021) for South Finland, North Finland, and the whole country. Notation: GS12 = Volume for growing stock in NFI12, GS13 = Volume for growing stock in NFI13, Difference = Increment – Drain – (GS13 – GS12). All values are in M m^3.

	GS12 A	Increment B	Drain C	GS12 + Increment – Drain D = A + B – C	GS13 E	Increment – Drain F = D – A = B – C	GS13 – GS12 G = E – A	Difference F – G	Standard error of change
South Finland									
Scots pine	713	133	121	726	719	13	6	7	9.2
Norway spruce	572	146	130	588	586	16	14	2	9.9
Broadleaves	339	87	89	337	350	–2	11	–13	5.2
Total	1624	366	339	1651	1655	27	31	–5	15.2
North Finland									
Scots pine	530	90	56	564	564	34	34	0	9.0
Norway spruce	168	31	15	183	177	15	9	7	5.2
Broadleaves	153	29	25	157	156	4	3	1	3.6
Total	852	149	96	905	897	53	45	8	11.0
Whole country									
Scots pine	1244	223	177	1292	1283	48	39	8	12.9
Norway spruce	740	176	145	772	763	32	23	8	11.2
Broadleaves	492	115	113	495	507	3	17	–13	6.3
Total	2475	515	436	2558	2552	83	77	3	18.8

3.7 Forest damage

In forest available for wood supply (FAWS), forest damage is observed on 8.4 M ha, corresponding to 46% of the total area of FAWS in the whole country (Suppl. file S2: Table 40). About half of the damage (52% of the damage area) is classified as mild, meaning that symptoms of damage are observed but the damage has no impact on the silvicultural quality of the stand (for definition of stand quality see Sub-Chapter 3.8). The area of significant damages affecting stand quality is 4.1 M ha, which is 22% of the area of FAWS. Most of these are notable (21%), whereas severe damage occurs on 1.5%, and complete damage, requiring immediate regeneration of a stand, only on 0.1% of the area of FAWS.

Damage is more frequent, and it is more often classified as significant in North Finland than in South Finland. Damage was observed on 54% of the area of FAWS in North Finland and on 41% in South Finland. The proportions of significant, quality degrading damage in FAWS are 31% and 16%, respectively (Suppl. file S2: Table 40 and Table 42).

The most significant groups of causal agent as regards to the affected area in FAWS are abiotic (1.7 M ha), ungulate (0.52 M ha) and fungal pests (0.42 M ha) (Suppl. file S2: Table 40). In North Finland, majority of the abiotic damages are snow damages (1.0 M ha), corresponding to 13% of FAWS in North Finland. In South Finland, abiotic damages, including mainly snow and wind damages, occur on 0.45 M ha that is 4% of FAWS (Fig. 15). The largest group (in terms of area affected) of causal agents in South Finland is however "Unidentified" (5%). In the case of mild damage, it is even more common that the causal agent remains unidentified. In North Finland, ungulate browsing damage is mainly caused by moose (*Alces alces* L.), whereas in South Finland also by deer, namely roe deer (*Capreolus capreolus* L.) and white-tailed deer (*Odocoileus virginianus* Zimmermann). Among the group of fungi, the most common pests in

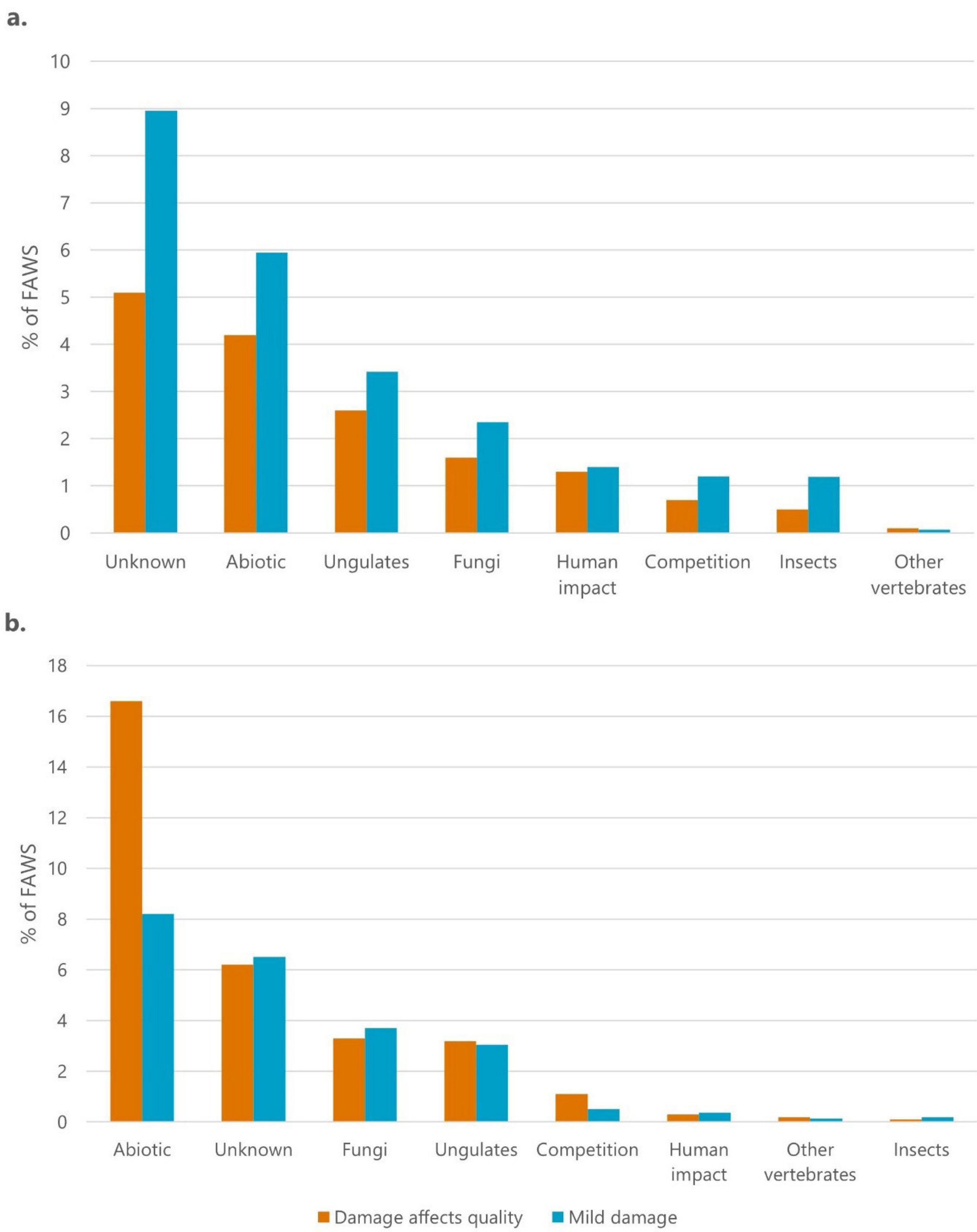


Fig. 15. Proportion of damaged area by causing agent group in productive forest available for wood supply in a) South Finland, and b) North Finland according to NFI13.

South Finland are *Heterobasidion annosum* causing root and butt rot in conifers and other rot fungi (on 54% of the damage area caused by fungi), when quality affecting damage is considered. In North Finland, 41% of the area of significant fungi damage is caused by decaying fungi (other than *Heterobasidion annosum*) and 24% by *Cronartium flaccidum* and *Peridemium pini* causing resin top disease on pine.

In the case of unidentified causal agent (on total of 14% of FAWS), the most frequent symptoms of both significant and mild damage are malformed stem, dead trees and forked tree tops (Suppl. file S2: Table 40). Malformed stem and forked tree tops are also clearly the most common symptoms of all damage (Suppl. file S2: Table 44). Stem malformation cover all kind of stem curves and clumps caused by, for example, earlier top damages related to ungulate browsing or heavy snow load. Ungulates browse on young tree shoots and twigs, but browsing damage remain as stem malformation even when the risk of browsing is over. Consequently, as symptoms of many causal agents are similar, it is difficult to distinguish the causal agent, especially in the case of earlier damage, of which symptoms are observed although the damage itself is not continuing.

Most of the quality affecting damage in FAWS are observed in pine dominated forests (2.8 M ha) (Suppl. file S2: Table 41), relating to the species dominancy in Finland: 62% of FAWS is pine-dominated. The area of significant damage in spruce dominated forest is 0.77 M ha and in forest dominated by broadleaved trees 0.49 M ha. However, the relatively largest area of significant damage, 26%, is observed in the forest dominated by broadleaved trees compared to 24% in the pine dominated and 17% in spruce dominated forests. In all cases, the proportion of significant damage is greater in North Finland than in South Finland. For example, in pine dominated forests significant damage is observed on 31% of the area in North Finland and on 17% in South Finland.

The most common of the identified causal agents both in pine and spruce dominated forests are abiotic factors, namely snow and wind, and ungulates (Fig. 16). Significant snow damages occur especially in North Finland, for example, on 15% of the pine dominated forest (Suppl. file S2: Table 41). In the case of broadleaved trees, decaying fungi (other than *Heterobasidion annosum*) is the most common of the identified causal agents (Fig. 16). It should be noted that on 8% of the forests dominated by broadleaved trees, causal agent of significant damage is unidentified. Regarding the affected area, Fig. 16 also shows the most common species-specific fungi such as resin top disease caused by by *Cronartium flaccidum* and *Peridemium pini* and Scleroderris canker caused by (*Gremmeniella abietina*) on pine, and the most common species-specific insects, pine sawfly (*Neodiprion sertifer*) and spruce bark beetle (*Ips typographus*).

Ungulate browsing damage is observed on 27% of the area of pine dominated seedling stands in FAWS in the whole country (Suppl. file S2: Table 43). More than half of the damage area are classified as significant, decreasing stand quality (on 15%). Relatively more significant browsing damage occur in North Finland (17%) than in South Finland (13%). Compared to the results of the previous NFIs, the area of ungulate damage in pine seedling stands is at the same level. In NFI12 (2014–2018), ungulate damage was observed on 27%, and significant damage on 15% of the pine seedling stands (Korhonen et al. 2021a). According to NFI11 (2009–2013) the percentages were 27% and 16%, respectively (Korhonen et al. 2017).

In NFI13 in general, the area of forest damage in FAWS is at the same level as, but somewhat smaller than in the two previous NFIs. Quality affecting damage is observed on 24% of the area, whereas it was observed on 25% in NFI12 and on 26% in NFI11 (Korhonen et al. 2017, 2021). The total damage area including also mild damage has decreased from 51% in NFI11 to 48% in NFI13 (Korhonen et al. 2017).

In forest not available for wood supply (FNAWS), damage was observed on 1.5 M ha (74%) of the area of FNAWS in the whole county (Suppl. file S2: Table 40). When classified with the same criteria as in FAWS, most of the damage (1.0 M ha, 52%) are significant and degrading silvicultural quality. Causing agent was identified on 73% of the damage area with significant damage, and the most frequent causing agents are abiotic (0.54 M ha, 27%) and fungal pests (0.18 M ha, 9%). Among these groups, snow damage accounts for 83.0% of the area of abiotic damage and resin top disease 56% of the damage area caused by fungi.

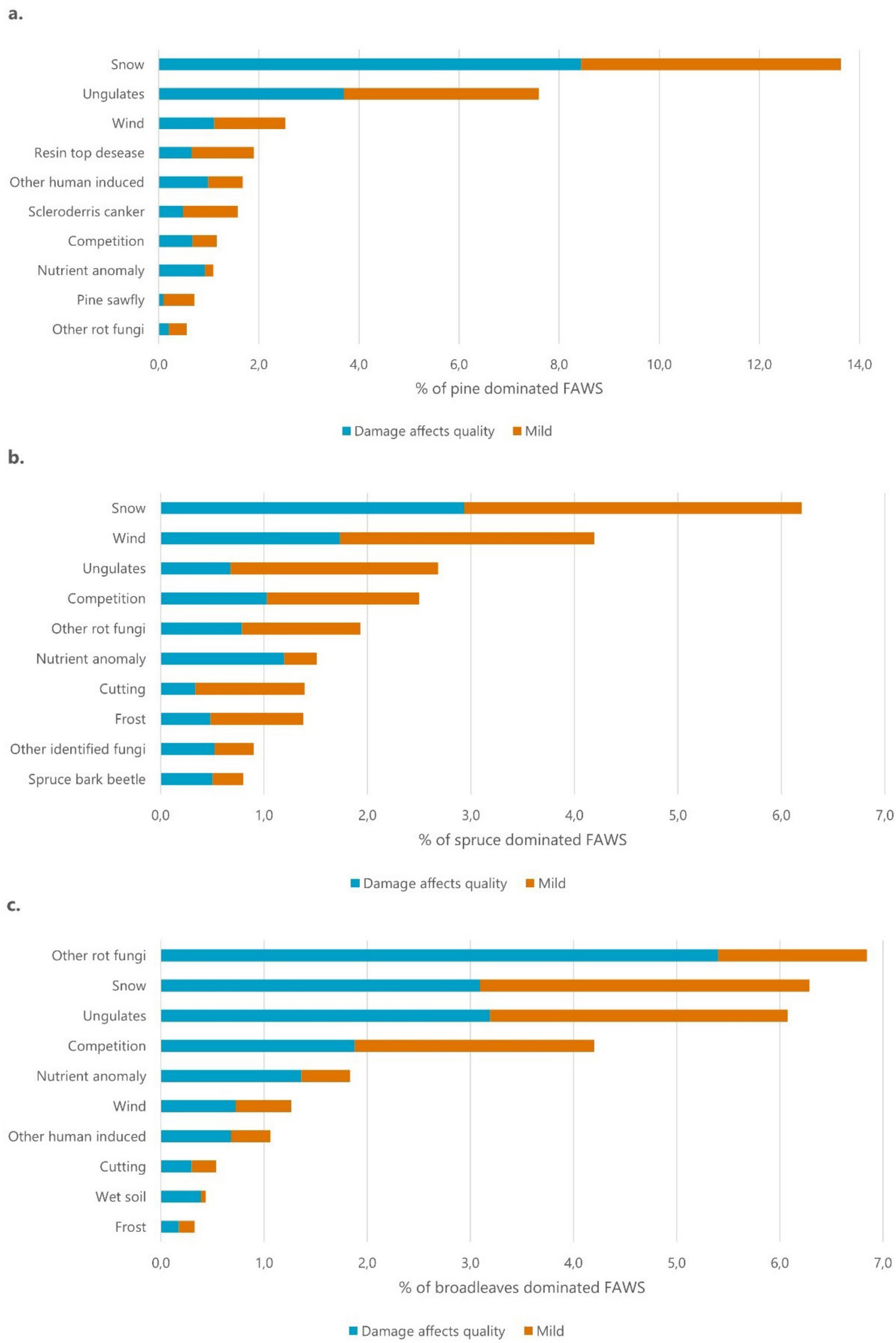


Fig. 16. Proportion of the most significant causing agents in terms of damaged area in a) pine dominated, b) spruce dominated, and c) broadleaf dominated productive forest available for wood supply in Finland according to NFI13. Proportions are calculated from the forest area dominated by the tree species group in question.

3.8 Forest quality and forest management

3.8.1 Forest quality

Forest quality is assessed for each plot stand from timber production point of view, following the criteria of NFI Field Manual (Suppl. file S3). The quality criteria are based on current forest management guidelines (Äijälä et al. 2019).

32% of the FAWS area is in quality class good, 46% satisfactory, 16% passable, and 6% is under-productive. Class under-productive means that from timber production point of view it recommended to regenerate the stand immediately even if growing stock is not yet mature. In North Finland, the proportion of quality class good is markedly lower and proportion of quality class satisfactory higher than in South Finland. The proportions of quality classes passable and under-productive are very similar in South and North Finland.

The proportion of good quality class from the total FAWS area has slightly (by 4.7%-units) increased from the previous inventory (Fig. 17). The proportion of under-productive forests have continued to slightly decrease as compared to the previous inventory. Since NFI5 (mid 1960s) the proportion of under-productive forests have decreased from 19% to 6%.

The most common reason for degraded quality of forest is damage – there is 3.2 M ha of FAWS where damage has decreased the quality of stand. The second-most common reason for degraded quality is uneven structure of growing stock (on 2.9 M ha). Uneven structure may refer to uneven size distribution (in a forest stand managed with even-aged management system) or too uneven spatial distribution. Damage is the reason for degraded quality most often in advanced thinning stands while uneven structure occurs mostly in young thinning stands. Poor management, typically delayed or neglected pre-commercial or first thinning is observed on 880 000 ha of FAWS. There are 58 000 ha of treeless areas where poor management has degraded the quality – these are typically forests where the soil preparation and other regeneration measures are delayed. (Suppl. file S2: Table 25).

By development class in FAWS, the proportion of good quality class is the highest in treeless clear cut sites (78%) and the lowest in shelter tree stands (20%). The proportion of under-productive stands is the highest in clear cut sites (11%) and the lowest in uneven aged forests (1.5%).

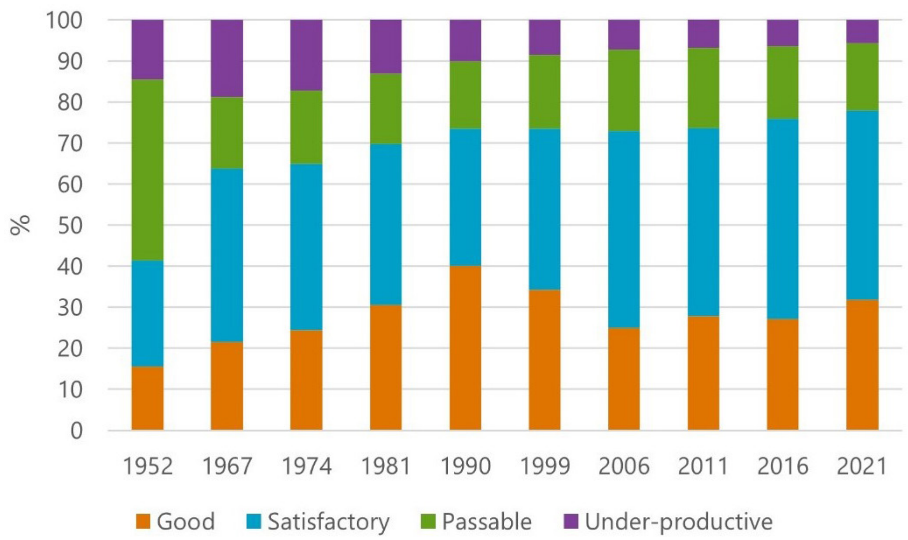


Fig. 17. Proportion of stand quality classes on productive forest available for wood supply in Finland according to NFI3–NFI13.

3.8.2 Regeneration methods and succes of regeneration

28% of the young and advanced seedling stands are naturally regenerated, appr. 50% planted and appr. 20% established with direct sowing. For young seedling stands the proportion of planted stands is slightly higher and the proportion of direct sown stands slightly lower than for advanced seedling stands. For young thinning stands the proportion of naturally regenerated stands is 58% and for advanced thinning stands 66%. For mature forests the stand establishment method is not assessed in the field. The proportion of naturally regenerated stands includes those stands where it has not been possible to assess the regeneration method. This explains partly the increase of naturally regenerated forests when the stand grows older. (Suppl. file 2: Table 26)

The area planted during the 10-year period before the field inventory is 890 000 ha and the area regenerated with direct sowing is 230 000 ha. 10% of both planting and sowing is classified as failed. In addition to the first-time planting, 30 000 ha of supplementary planting were observed. (Suppl. file S2: Table 33 and Table 34)

2% of the pine dominated, 3% of the spruce dominated and 21% of the broadleaf dominated planted young seedling stands have very low density of crop seedlings, less than 950 seedlings per hectare. In advanced seedling stands, the proportions are 5%, 3%, and 16% for pine, spruce and broadleaf dominated stands, respectively. These results do not indicate poor success of planting with broadleaved species because for the dominant species is not necessary the same as the planted species. For example, a seedling stand planted with pine may shift to the category of birch dominated forest if the planted seedlings die to large extent.

46% of the pine dominated, 40% of the spruce dominated and 21% of the broadleaf dominated planted young seedling stands have high or very high density of crop seedlings, more than 1950 seedlings per hectare. In advanced seedling stands, the proportions are 50%, 45%, and 25% for pine, spruce and broadleaf dominated stands, respectively. These results indicate that natural regeneration occurs to significant extent in planted stands. (Suppl. file S2: Table 27)

Planting or seeding is proposed on 290 000 ha for the coming 10-year period in forests where the regeneration cutting has already been done. In addition, planting or seeding after the proposed regeneration cutting is proposed on 2.5 M ha for the coming 10-year period. (Suppl. file S2: Table 35)

3.8.3 Accomplished and proposed cuttings

During the 10-year period before the field work there has been cuttings on 7.8 M ha (43%) of productive forest land available for wood supply. This area includes accomplished pre-commercial thinnings (2.1 M ha). Final felling was observed on 1.4 M ha, 15% of these were final felling for natural regeneration and 85% for artificial regeneration. Thinnings (other than pre-commercial thinning) were observed on 3.9 M ha, which is 21% of the productive forest available for wood supply. Continuous cover forest management (selective cutting or cutting with small openings for uneven-aged forests) were observed only on 28 000 ha. The area of special cuttings is 323 000 ha, this category includes sanitation cuttings, openings for forestry roads or ditches. The area of accomplished clear cuttings (1.2 M ha) is larger than the observed area of planting and direct sowing (1.1 M ha). (Suppl. file S2: Table 29).

Since NFI8 (1986–1994), the area of accomplished cuttings has increased from 530 000 hectares to the 650 000 hectares observed in NFI13. The estimates have been calculated from the area of accomplished cuttings in the 5-year period of each field measurement year, and by dividing this area by 5. The estimates do not include the pre-commercial thinnings or tending of seedling stands. The increase has been only in thinnings which have increased from 280 000 hectares to

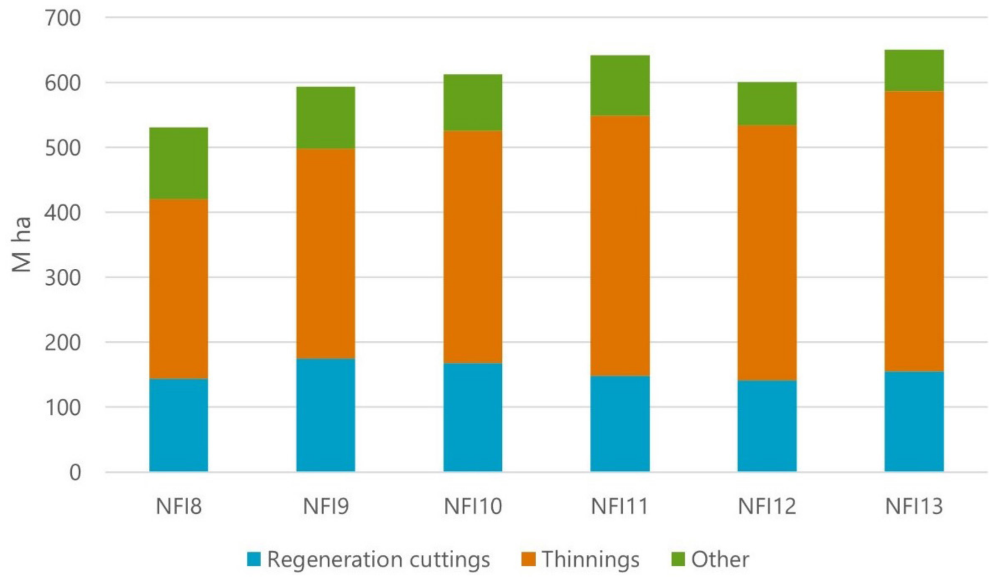


Fig. 18. Observed area (M ha) of annual thinnings and regeneration cuttings in Finland according to NFI9–NFI13.

430 000 hectares. The area of regeneration cuttingns have remained relatively stable, between 140 000 and 180 000 hectares. (Fig. 18)

21% of all the cuttings have been in peatland forests. The proportion of accomplished cuttings from the productive forest area available for wood supply is markedly lower in peatland forests than on mineral soils, 34% and 47%, respectively. (Suppl. file S2: Table 29)

From forest management point of view, cutting (including pre-commercial thinning) is proposed for 11.3 M ha for the 10-year period following the field measurement of each plot. This includes 2.2 M ha pre-commercial thinnings, 5.6 M ha commercial thinnings, 3.2 M ha regeneration cuttings and removing of seed trees on 340 000 ha. The ratio accomplished operations in the past 10-year period to the recommended operations for the coming 10-year period is 1.1 for pre-commercial thinnings, 1.5 for commercial thinnings, and 2.2 for final fellings. The proposals for the coming 10-year period are done at stand level, following the forest management guidelines (Äijälä et al. 2014) and without any consideration of sustained yield at regional or forest holding level. The recommended area for pre-commercial thinnings does not include those mature forests that would be regenerated immediately after the field assessment. Therefore, for pre-commercial thinning it is more relevant to compare the ratio at 5-year period. This ratio is 1.7, indicating that the area of pre-commercial thinnings should in coming years be 70% larger than it has been in past years. (Suppl. file S2: Tables 29 and 30)

The urgent need for pre-commercial thinnings is 590 000 ha and for first thinnings 800 000 ha. In NFI12, these estimates were 770 000 ha and 920 000 ha, respectively. Since the 1980s the area for urgent need for both prec-commercial thinnings and first thinnings has continuously increased but now markedly decreased. (Suppl. file S2: Table 30; Korhonen et al. 2021a)

25% (4.7 M ha) of productive forest available for wood supply has not been managed in the past 30 years (Suppl. file S2: Table 32).

3.8.4 Other accomplished and proposed forest management measures

The list of other accomplished forest management measures includes pruning, clearing for cutting operation, harvesting of cutting residues or stumps and restoration. The area of observed pruning

(10-year period) is 26 000 ha and area of clearing for cutting operation 210 000 ha. The area of harvesting of cutting residues or stumps totals to 190 000 ha, from this 15 000 ha includes stump harvesting. The observed area of restoration measures on productive land is only 3000 ha, this does not include restoration of drained peatlands. (Suppl. file S2: Table 34)

3.8.5 Accomplished and proposed soil preparation

The total area of accomplished soil preparation in the 10-year period before the field measurement is 1.2 M ha. The most common soil preparation method is mounding (710 000 ha, including mounding with ditches for draining), followed by disc trenching (250 000 ha), patch scarification (220 000 ha). Ploughing was observed on 18 000 ha, only. The area of prescribed burnings is even less, 3000 ha. (Suppl. file S2: Table 36)

The total area of proposed soil scarification in connection with regeneration cutting is 3.0 M ha for the 10-period following the field measurement. This is almost the same as the area of proposed regeneration cuttings, 3.2 M ha. In addition, 380 000 ha of soil scarification is proposed without regeneration cutting involved. These are clear cut sites or seed tree stands where the soil preparation has not yet been done or has been neglected. Mounding and patch scarification are the most typically proposed soil preparation methods. Patch scarification and disc trenching are not separated in the proposals. (Suppl. file S2: Table 37)

3.8.6 Accomplished and proposed drainage operations

New ditching on previously undrained land was observed in 38 000 hectares of forestry land when including ditching operations accomplished at maximum 10 years before the NFI13 field measurement. Almost all (32 000 ha) of this was on (paludified) mineral soils and only 6000 ha in peatland. (Suppl. file S2: Table 38)

Clearing of old ditches was observed for 460 000 ha and complementary ditching (which may include clearing of old ditches) was observed for 110 000 ha, when including ditching operations accomplished at maximum 10 years before the NFI13 field measurement (Suppl. file S2: Table 38).

3.9 Indicators of forest biodiversity

3.9.1 Amount and quality of dead wood

Based on the specific measurements for the hard and decaying dead wood having diameter at least 10 cm (see Chapter 2.2.3), the total volume of dead wood in productive and poorly productive forest is 150 M m^3, of which 139 M m^3 is in productive forest (Supp. file S2: Table 68). In both domains, half of the total volume consists of Scots pine, 28% of Norway spruce, 14% of birches and 8% of other identified or unidentified species. About 70% of the total volume is in dead wood lying on ground and the rest is in standing trees. In productive and poorly productive forest the mean volume of dead wood is 5.5 m^3 ha^{-1} in South Finland, 7.7 m^3 ha^{-1} in North Finland and 6.6 m^3 ha^{-1} in the whole country (Supp. file S2: Tables 68 and 69). About 58% of the total volume of 150 M m^3 is in North Finland. In poorly productive forest alone, the total volume is 10.8 M m^3, being 4.2 m^3 ha^{-1} (Supp. file S2: Table 73).

In productive forest the mean volume of dead wood is 6.9 m^3 ha^{-1} (Supp. file S2: Tables 73 and 75). This figure was 5.8 m^3 ha^{-1} in NFI12 (Korhonen et al. 2021a) and it has been under 6 m^3 ha^{-1} also in NFIs 9–11 (Fig. 19). The mean volume in South Finland is 5.5 m^3 ha^{-1} and it has risen in all inventory cycles since NFI9. In North Finland, the trend has been the opposite but

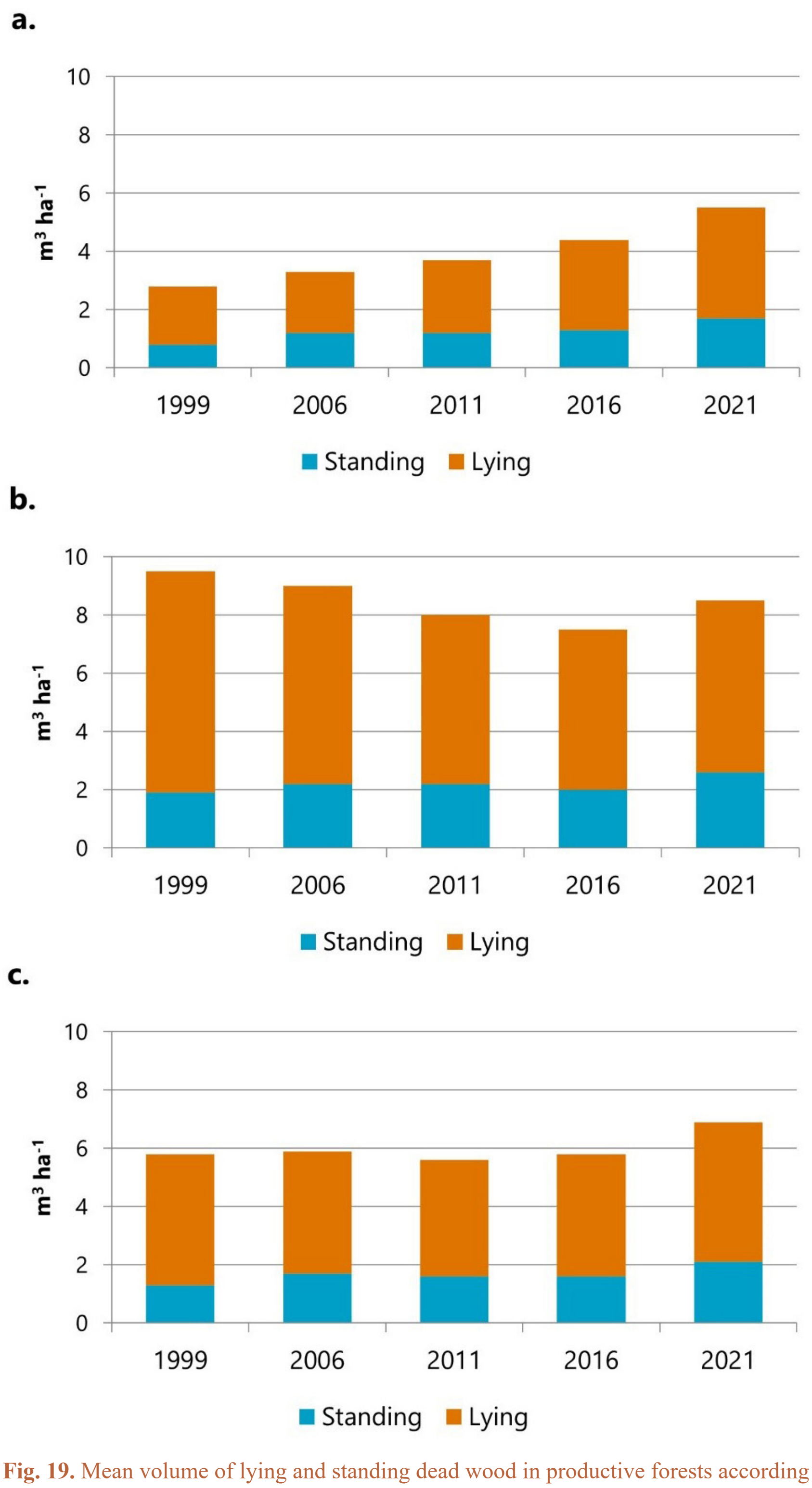


Fig. 19. Mean volume of lying and standing dead wood in productive forests according to NFI9–NFI13 in a) South Finland, b) North Finland and c) whole Finland.

now the mean volume increased to 8.5 m^3 ha^{-1} from 7.5 m^3 ha^{-1} in NFI12. The mean volumes of standing and lying dead wood in South Finland are 1.7 and 3.8 m^3 ha^{-1} and in North Finland 2.6 and 5.9 m^3 ha^{-1}, respectively.

Also, both in productive forest available (FAWS) (Fig. 20) and not available for wood supply (FNAWS) (Fig. 21), the mean volume of dead wood has risen since NFI9 in South Finland while the decreasing trend turned now in North Finland. In productive FAWS the mean volume of dead wood is 5.0 m^3 ha^{-1}, being 4.8 m^3 ha^{-1} in South and 5.2 m^3 ha^{-1} in North Finland (Supp. file S2: Table 75). Compared with NFI12, the mean volumes of standing and lying classes of dead wood have increased both in South and in North Finland (Fig. 20), at most by 0.6 m^3 ha^{-1} for lying dead wood in South Finland.

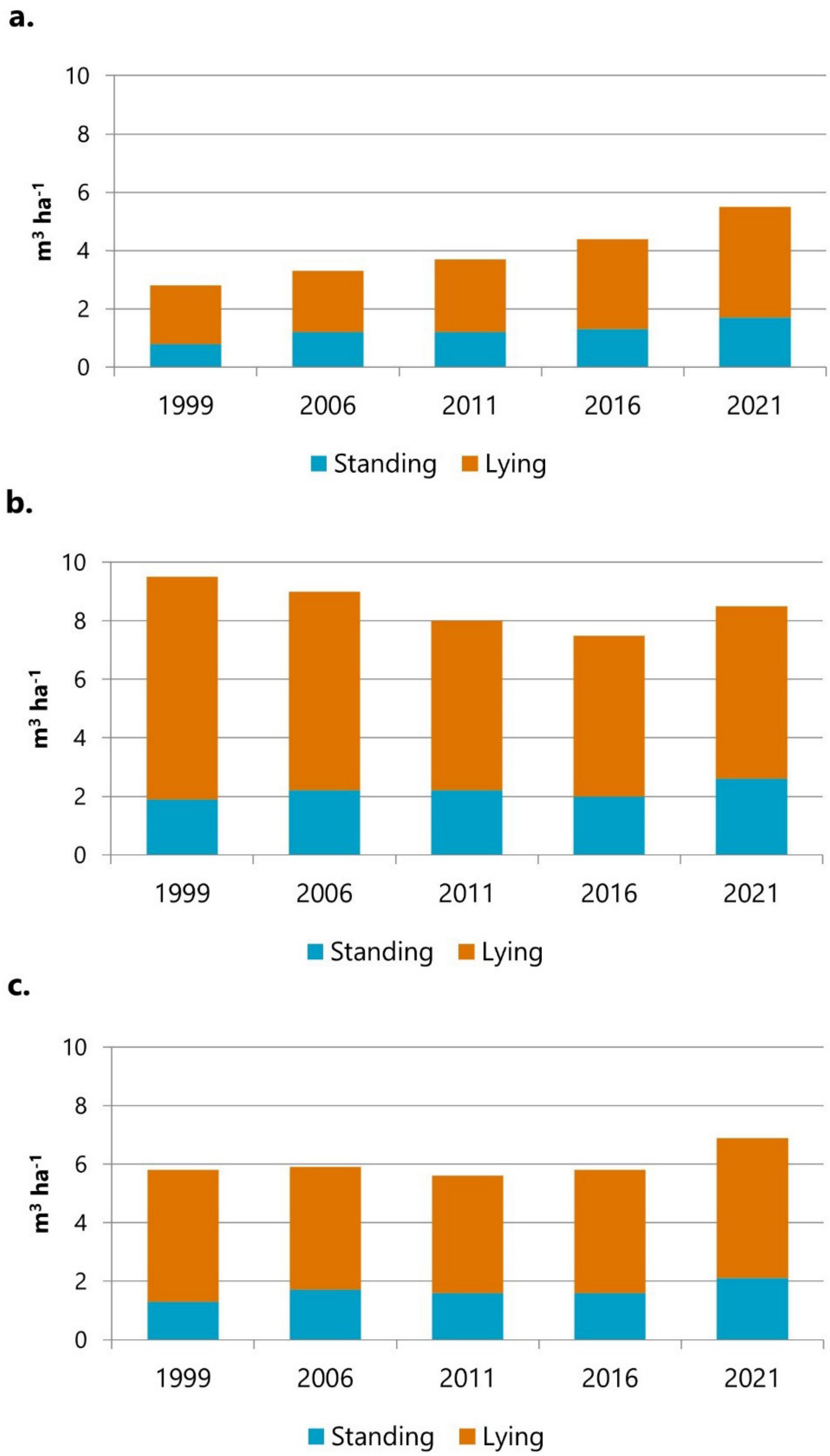


Fig. 20. Mean volume of lying and standing dead wood in productive forests available for wood supply (FAWS) according to NFI9–NFI13 in a) South Finland, b) North Finland and c) whole Finland.

In productive FNAWS the mean volume of dead wood is 23.9 $m^3 ha^{-1}$, being 23.0 $m^3 ha^{-1}$ in South and 24.1 $m^3 ha^{-1}$ in North Finland (Supp. file S2: Table 75). Compared with the previous inventory, the mean volumes of standing and lying classes of dead wood have increased both in South and in North Finland (Fig. 21), at most by 3.4 $m^3 ha^{-1}$ for standing dead wood in South Finland.

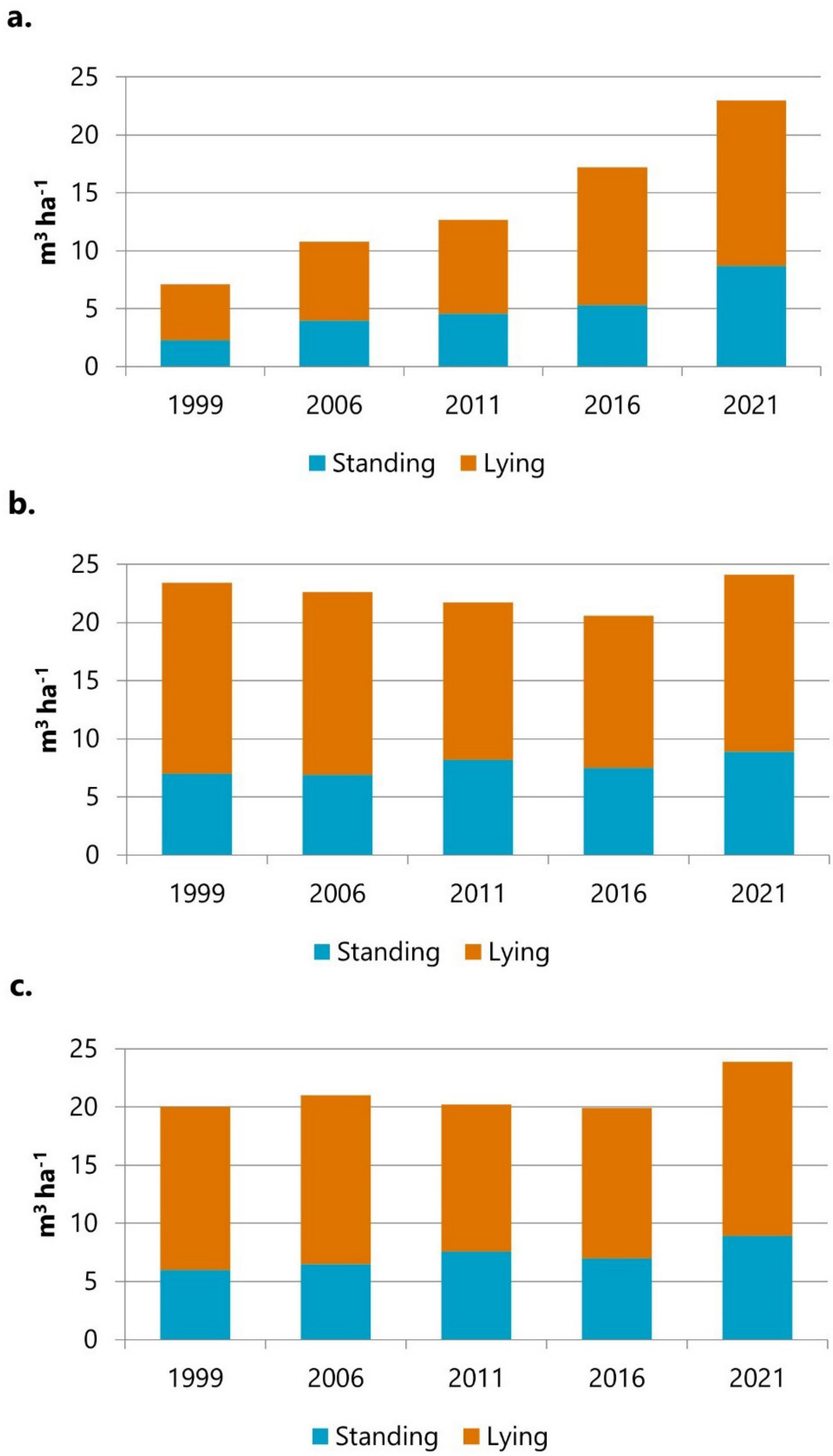


Fig. 21. Mean volume of lying and standing dead wood in productive forests not available for wood supply (FNAWS) according to NFI9–NFI13 in a) South Finland, b) North Finland and c) whole Finland.

The mean volume of dead wood is larger on mineral soils compared with that on peatland (Supp. file S2: Table 70). In productive forest the amount is 7.6 m^3 ha^{-1} on mineral soils and 4.7 m^3 ha^{-1} on peatland. The difference in these figures relates mostly to North Finland where especially the mean volume of lying dead wood (7.1 m^3 ha^{-1}) on mineral soils is larger than on peatland (2.7 m^3 ha^{-1}). In poorly productive forest in the whole country, the mean volume of dead wood is 6.0 m^3 ha^{-1} on mineral soils and 3.3 m^3 ha^{-1} on peatland.

In productive forest, the mean volume of large dead wood, having diameter at least 30 cm, is 0.79 m^3 ha^{-1} in South Finland and 1.78 m^3 ha^{-1} in North Finland (Supp. file S2: Table 71). In the whole county, the same figure is 1.24 m^3 ha^{-1}, a slight increase as compared to 1.09 m^3 ha^{-1} in NFI12. About 65% of the large dead wood is in lying wood. Dead wood is classified as standing or lying and also by the appearance type, e.g. severely rotten, fallen with roots or abandoned timber (Supp. file S3: p. 109). The total volumes in these classes are presented in Suppl. S2: Table 72. Lying dead wood originates most often from the trees fallen with roots, and its share of the total 97 M m^3 of lying dead wood is 44% while the share of broken trees is 36% and the combined share of abandoned timber and cutting residues is 15%. The largest share of trees fallen with roots comes from Scots pine and Norway Spruce in South Finland while broadleaf species and Norway Spruce in North Finland have the largest share from the broken trees.

The total volume of hard dead wood in productive forest is 51.3 M m^3 while the amount in decay class “very soft”, defined only for lying dead wood, is 15.7 M m^3 (Supp. file S2: Table 73). The amounts in three intermediate classes are between 26.6 and 21.9 M m^3. In the hard dead wood class, standing dead wood covers 30.4 M m^3, or 59%, of the total volume. This relates to the larger share of standing dead wood in productive FNAWS (Supp. file S2: Table 75) where the mean volumes of lying and standing dead wood are 2.3 and 6.5 m^3 ha^{-1}, respectively. In productive FAWS, the mean volumes of both classes are 0.9 m^3 ha^{-1}.

In the development classes of productive FAWS, the highest mean volume of dead wood is 11.0 m^3 ha^{-1} in mature stands and the lowest is 4.0 in thinning stands (Supp. file S2: Table 74). In the whole country, all mean volumes in dead wood classes lying, standing and total, except one, have increased by 0.1–1.3 m^3 ha^{-1} from NFI12 (Korhonen et al. 2021a). The only exception is the decrease of lying dead wood in regeneration areas by 0.2 m^3 ha^{-1}.

3.9.2 Tree species abundance

According to the stand level data by tree strata, recorded by tree storeys and species, 25% of productive forest are single species stands (Suppl. file S2: Table 19). In South Finland, the same share is 21% and in North Finland 30%. In the whole country, 89% of forests contains three tree species or less. These numbers are affected by the data collection method: two species can be combined in one stratum, if the proportion of a species is minor (e.g., basal area less than 1 m^2 ha^{-1} and proportion less than 5%) or if a tree storey contains over four tree species.

The most common case is a stand with two tree species, which cover 34% of the productive forests. Two tree species is the most common number in the Scots pine dominated forests and in North Finland, if the dominant species is Norway spruce, downy birch or common alder. The stands with three tree species cover 28% of productive forest. Three tree species is the most common number in silver birch dominated forests and in South Finland, if the dominant species is Norway spruce, downy birch or common alder. Among the six most common dominant species, European aspen is the only one having the largest area in the stands of four tree species.

Chapter 3.4.2 presents the results where sample plot stands are classified according to the dominant tree species proportion of growing stock basal area.

3.9.3 Naturalness

Naturalness of forest stands is evaluated in respect to three variables: structure of growing stock, occurrence of dead wood and signs of human intervention. Each of these is assessed to be in one of the classes natural or almost natural, modified or clearly modified.

In all productive forests, the area of forest having natural or almost natural structure of the growing stock is 1.2 M ha (6% out of total 20.3 M ha) and the area of the modified class is 1.4 M ha or 7% (Suppl. file S2: Table 46). In NFI12 (Korhonen et al. 2021a), these figures were 870 000 ha and 1.4 M ha, respectively. Only 7.5% of the natural or almost natural stands are in South Finland while 48% of the modified class is in this region. In the productive FAWS, 225 000 ha (1.2% out of 18.3 M ha) is in the natural or almost natural class. The area of this class in all productive forests in South Finland is 94 000 ha, of which 48% is in FAWS. The area of the class in all productive forests in North Finland is 1.2 M ha, of which 16% is in FAWS.

In all productive forests, the area of forest having natural or almost natural occurrence of dead wood is 494 000 ha (2.4% out of total 20.3 M ha) and the area of the modified class is 1.3 M ha or 6% (Suppl. file S2: Table 47). In NFI12, the same figures were 485 000 ha and 1.4 M ha. Ten per cent of the natural or almost natural stands are in South Finland while 42% of the modified class is in this region. In the productive FAWS, 119 000 ha (0.6% out of 18.3 M ha) is in the natural or almost natural class. In South Finland, the area of this class is 29 000 ha, and it covers 59% of the class total in all productive forests in South Finland while 90 000 ha in North Finland covers 20% of the class total in the region.

In all productive forests, the area of forest that is in natural or almost natural state in respect to the signs of human intervention is 1.26 M ha (6% out of total 20.3 M ha) and the area of the modified class is 920 000 ha or 5% (Suppl. file S2: Table 48). In NFI12, the same figures were 970 000 ha and 890 000 ha. About 10% of the natural or almost natural stands are in South Finland while 43% of the modified class is in this region. In the productive FAWS, 214 000 ha (1.2% out of 18.3 M ha) is in the natural or almost natural class. In South Finland, the area of this class is 62 000 ha, and it covers 51% of the class total in all productive forests in South Finland while 152 000 ha in North Finland covers 13% of the class total in the region.

If a stand is classified as natural or almost natural in all cases with respect to the structure of growing stock, occurrence of the dead wood and signs of human intervention, we can say that it is in a close-to-natural state. The area of close-to-natural class in combined productive and poorly productive forest is 886 000 ha, of which only 3% (26 000 ha) is in South Finland (Suppl. file S2: Table 49). The area of the same naturalness class in combined productive and poorly productive FAWS is 113 000 ha, of which 8% (9000 ha) is in South Finland.

4 Discussion

The NFI results show that the forest area has remained stable over the recent decades. When comparing the area estimate of productive and poorly productive forest to the estimate of the previous NFI (NFI12) there is no statistically significant change. However, according to the land use change recordings to the NFI13 sample plots the area moving out of classes productive and poorly productive forest is 100 000 ha larger than the area moving in the same classes, indicating a loss of forest area of 10 000 hectares per year in the recent 10-year period. The area of forest available for wood supply has continued to decrease due to increasing forest protection. 15% of productive forest area is either not available for wood supply or has restrictions on management activities.

The total area of peatland in forestry land is 9.13 M ha. At the beginning of the 1950s, there were still 9.74 M ha of peatland (Hökkä et al. 2002). The area of peatland has decreased due to clearing for agriculture land, peat production, the construction of water regulation basins and other construction, and the turning of thin-peated drained peatland to the mineral soils category after their peat layer has disappeared (Tomppo 1999; cf. Hökkä et al. 2002). There has been some fluctuations in the area estimates of peatland and mineral soil sites between the recent inventories, maybe due to classification issues (Korhonen et al. 2013, 2017, 2021). For example, in the NFI12 there were 1.32 M ha drained mineral soil sites, and now in the NFI13 the area estimate is 1.22 M ha. At the same time, the area estimate of drained peatland has slightly increased. It is probable that some of the area previously classified as drained mineral soil has now been classified as drained peatland.

Ditching of previously undrained peatland has almost stopped. The estimated area of peatland drained less than 10 years before the field work is now 6000 hectares, only.

There are 561 000 ha (11% of drained peatlands) of misditchings, i.e ditched peatlands where the draining did not turn the site to productive forest due to nutrient or technical problems. In fact, the proportion of misdrained peatlands (in the sense of wood production) is less than 11% because in course of time some of the thin-peated peatlands have transformed to mineral soil sites due to decomposed peat layer. Based on different studies and calculation principles, the misdrained area varies between 500 000 ha – 1.0 M ha (Laiho et al. 2016; Hotanen et al. 2018a).

On mineral soils, the proportion of the most fertile site classes has increased and the proportion of poorer sites has decreased since the 1950s. The most probable reasons for the change are fertilization, recovery of nitrogen storages in humus layer after the slash-and-burn agriculture period, accelerated nutrient cycling due to forest management, and changes in climatic conditions (Reinikainen et al. 2000; Salemaa et al. 2010; Henttonen et al. 2017). In northern Finland, the coverage of lichens (*Cladina*) has decreased due to reindeer overgrazing. Lichens are indicators of poor sites, therefore the reduced coverage of lichens causes overestimation of the site productivity on these sites (Reinikainen et al. 2000). However, regarding the field layer, there might be slight opposite trends in some places: since reindeer browse over 200 plant species during their summer grazing, also the cover of many other plants has been affected, e.g., *Deschampsia flexuosa* and *Vaccinium myrtillus* (Reinikainen et al. 2000).

The area of mature forests in FAWS is 2.119 M ha, which is 49 000 ha less than according to the previous inventory. The change is not statistically significant, but it is in line with the increased forest protection – the area of FAWS has decreased from the 18.444 M ha in NFI12 to the 18.301 M ha in NFI13.

The current total volume of growing stock 2.552 G m^3 is 1.7 times the total volume according to the first NFI implemented in the 1920s. Since the previous inventory, the estimate of total growing stock has increased by 77 M m^3. This difference between NFI13 and NFI12 growing stock volume estimate matches well with the change estimate calculated as the diffence between annual increment and annual drain summed over the years between the two inventories.

The estimate of annual increment of growing stock, 103 M m^3, is for the first time since the late 1960s less the estimate of previous inventory. The increment estimation method was changed in NFI12 so that tree measurements on the permanent plots are the basis for the estimation, instead of the diameter increment measuremets on temporary plots, that was applied in the previous inventories before NFI12. Change in the methodology decreased the increment estimate in NFI12 by appr. 2 M m^3, but between NFI12 and NFI13 the methodology has not changed. The number of remeasured permanent plots in NFI13 is markedly higher than the number of remeasured permanent plots in NFI12. Thus, the sampling variance of increment (and mortality) estimates is lower than in the previous inventory. Henttonen et al. (2024) showed that environment related factors (such as weather conditions) have mainly caused the reduction of annual increment. Mäkinen et al. (2022)

and Haakana et al. (2023) have identified draught and cone production/flowering as those environment related factors that explain the reduced growth of pine. Decline in annual increment has been observed also in Sweden, where draught is regarded as main driver for the decline (Laudon et al. 2024). According to Hynynen et al. (2023) the age structure of Finland's forests is such that it is expected that annual increment will remain at the level of 100–105 M m^3 in the next decades. Eventhough the increment has slown down and mortality has increased the net increment is still higher than harvests and the total volume of growing stock has continued to increase.

The forest balance analyses show that at the whole country level the NFI12 and NFI13 growing stock volume estimates, NFI13 increment estimate, and drain statistics sum up in a consistent way. Changing the increment estimation on permanent plot data in NFI12 reduced the increment estimate and this has improved the consistency of the forest balance components.

The quality of forests, from timber production perspective, has remained at relatively good level or slightly improved. Area of forests where pre-commercial thinning or first commercial thinning is delayed has decreased since NFI12. Continuous cover forest management was accepted in the Forest Act in 2013. However, only 0.2% of the productive forest area is classified as uneven-aged forest.

Annual mortality, current estimate 8.8 M m^3, is increasing at alarming rate even though the total area of observed damage has not increased in recent inventories. This discrepancy is probably explained by the fact that dying of only few, single trees should not be registered as damage in NFI. Estimates of both mortality and harvesting of dead trees are most likely underestimates because estimation of mortality does not include those trees which have both died and been harvested during the 5-year inventory interval. Assessment of tree status – dead or alive – at the time of harvest based on a stump is difficult. The number of permanent sample plots in NFI has increased markedly and therefore the sampling error for both mortality and natural losses estimates has reduced compared to the previous inventories.

The amount of dead wood has continuously increased in South Finland since the starting of dead wood measurements in NFI9 (1996–2003). In North Finland the trend has been the opposite but now the amount has increased in North Finland, also.

Acknowledgements

The authors wish to thank the NFI field teams for extensive field work to collect the data; Mr. Arto Ahola for supervising the field work; Mr. Kai Mäkisara for developing the data entry and preprocessing systems; Mr. Ville Pietilä for organizing the training of field workers, preparation of field manual, organising quality control and pre-processing of the data; Mr. Timo Pitkänen for processing the GNSS data; Ms. Kati Tammela for maintenance of field gear and for increment core measurements; Mr. Mikael Strandström for developing the data entry and transfer systems, support of field work training and participation in data processing; and Luke's IT department for support in renewal of field computers and data transfer system. The authors wish to thank Mr. Hannu Hökkä, Mr. Heikki Nuorteva, and Mr. Markku Saarinen for supporting the training of field teams and the two anonymous reviewers who gave valuable comments to improve the manuscript.

Declaration of openness of research materials and data

As described in the article meta data from the research materials and data are available for scientific research on request from the authors, excluding exact location of the plots. Access to the plot location data is limited to protect the monitoring system based on revisited permanent plots.

Authors contribution

Planning of the manuscript (all), data analyses (JP, MR, JH), estimation of standard errors (MR, JH, MK), writing (all), project administration and finalizing the manuscript (KTK).

Supplementary files

S1.pdf; Details of volume and increment estimation methods,
S2.xlsx; 75 result tables calculated from the data,
S3.pdf; NFI13 Field Manual,
Metadata of research data.pdf,
available at https://doi.org/10.14214/sf.24045.

References

Äijälä O, Koistinen A, Sved J, Vanhatalo K, Väisänen P (eds) (2014) Metsänhoidon suositukset. [Forest Management Guidelines]. Metsätalouden kehittämiskeskus Tapion julkaisuja.

Cochran WG (1977) Sampling techniques, 3rd edition. John Wiley & Sons.

Finnish Statistical Yearbook of Forestry (2004) Metsäntutkimuslaitos, Vantaa http://urn.fi/URN:ISBN:951-40-1946-6.

Grafström A, Schelin L (2014) How to select representative samples. Scand J Stat 41: 277–290. https://doi.org/10.1111/sjos.12016.

Haakana M, Haikarainen S, Henttonen HM, Hirvelä H, Hynynen J, Korhonen KT, Launiainen S, Mehtätalo L, Miettinen A, Mutanen A, Mäkinen H, Ollila P, Pitkänen J, Räty M, Salminen H, Tikkasalo O-P, Tuomainen T, Viitanen J, Vikfors S (2023) Suomen LULUCF-sektorin 2021–2025 velvoitteen toteutuminen. [Will Finland reach its LULUCF reference level 2021–2025?]. Natural Resources Institute Finland, Helsinki. http://urn.fi/URN:NBN:fi-fe2022123074123.

Henttonen H (1990) Kuusen rinnankorkeusläpimitan kasvun vaihtelu Etelä-Suomessa. [Variation in the diameter growth of Norway spruce in southern Finland]. Helsingin yliopiston metsänarvioimistieteen laitoksen tiedonantoja 25.

Henttonen H (2000) Growth variation. In: Mälkönen E (ed) Forest condition in a changing environment – the Finnish case. Forestry Sciences 65. Springer, Dordrecht, pp 25–32. https://doi.org/10.1007/978-94-015-9373-1_3.

Henttonen HM, Nöjd P, Mäkinen H (2017) Environment-induced growth changes in the Finnish forests during 1971–2010 – an analysis based on National Forest Inventory. Forest Ecol Manag 386: 22–36. https://doi.org/10.1016/j.foreco.2016.11.044.

Henttonen HM, Nöjd P, Mäkinen H (2024) Environment-induced growth changes in forests of Finland revisited – a follow-up using an extended data set from the 1960s to the 2020s. Forest Ecol Manag 551, article id 121515. https://doi.org/10.1016/j.foreco.2023.121515.

Hökkä H, Kaunisto S, Korhonen KT, Päivänen J, Reinikainen A, Tomppo E (2002) Suomen suometsät 1951–1994. [The peatland forests of Finland 1951–2004]. Metsätieteen aikakauskirja 2A/2002: 201–357. https://doi.org/10.14214/ma.6242.

Hotanen J-P, Kokko A, Mäkelä K (2018a) Metsäojitetut suot. [Drained peatlands]. In: Kontula T, Raunio A (eds) Suomen luontotyyppien uhanalaisuus 2018. Luontotyyppien punainen kirja. Osa 1 – tulokset ja arvioinnin perusteet. Suomen ympäristö 5/2018: 156–161. http://urn.fi/URN:ISBN:978-952-11-4816-3.

Hotanen J-P, Nousiainen H, Mäkipää R, Reinikainen A, Tonteri T (2018b) Metsätyypit – kasvupaikkaopas. [Forest types – guide for site classification]. Metsäkustannus.

Hynynen J, Korhonen KT, Kärkkäinen L, Mehtätalo L, Mutanen A, Rautio P, Viitala E-J (eds) (2023) Metsälain ilmastovaikutusten arviointi. [Assessment of the climate impacts of the new Forest Act]. Natural resources and bioeconomy studies 49/2023. http://urn.fi/URN:ISBN:978-952-380-696-2.

Ihalainen A (2013) Metsähukkapuu ja luonnonpoistuma poistumatilastoissa. [Statistics on cutting residues and natural losses]. Metsätieteen aikakauskirja 3/2013: 609–623. https://doi.org/10.14214/ma.6026.

Ihalainen A, Mäkelä H (2009) Kuolleen puuston määrä ja laatu Etelä- ja Pohjois-Suomessa 2004–2007. [Volume and quality of dead wood in South and North Finland 2004–2007]. Metsätieteen aikakauskirja 1/2009: 35–56. https://doi.org/10.14214/ma.5834.

Ilvessalo Y (1924) Suomen metsät. Metsävarat ja metsien tila. [The forest resources and the condition of the forests]. Comm Inst For Fenn 9. http://urn.fi/URN:NBN:fi-metla-201207171042.

Ilvessalo Y (1927) Suomen metsät. Tulokset vuosina 1921–1924 suoritetusta valtakunnan metsien arvioimisesta. [The Forests of Suomi (Finland). Results of the general survey of the forests of the country carried out during the years1921–1924]. Comm Inst For Fenn 11. http://urn.fi/URN:NBN:fi-metla-201207171044.

Ilvessalo Y (1940) Suomen metsävarat vv. 1936–1938. [Finland's forest resources 1936–1938]. Comm Inst For Fenn 28.6. http://urn.fi/URN:NBN:fi-metla-201207171060.

Ilvessalo Y (1942) Suomen metsävarat ja metsien tila. II valtakunnan metsien arviointi. [The forest resources and the condition of the forests of Finland]. Comm Inst For Fen 30. http://urn.fi/URN:NBN:fi-metla-201207171062.

Ilvessalo Y (1947) Pystypuiden kuutioimistaulukot. [Volume tables for standing trees]. Comm Inst For Fen 34.4. http://urn.fi/URN:NBN:fi-metla-201207171066.

Ilvessalo Y (1948) The forests of present-day Finland. Commun Inst For Fenn 35.6. http://urn.fi/URN:NBN:fi-metla-201207171067.

Ilvessalo Y (1956) Suomen metsät vuosista 1921–24 vuosiin 1951–53. Kolmeen valtakunnan metsien inventointiin perustuva tutkimus. [The forests of Finland from 1921–24 to 1951–53]. Commun Inst For Fenn 47.1. http://urn.fi/URN:NBN:fi-metla-201207171079.

Kniivilä M, Hantula J, Hotanen J-P, Hynynen J, Hänninen H, Korhonen KT, Leppänen J, Melin M, Mutanen A, Määttä K, Siitonen J, Viiri H, Viitala E-J, Viitanen J (2020) Metsälain ja metsätuholain muutosten arviointi. [Effects of the changes in the Forest Act and Forest Damage Act]. Natural resources and bioeconomy studies 3/2020. http://urn.fi/URN:ISBN:978-952-326-897-5.

Korhonen KT, Ihalainen A, Viiri H, Heikkinen J, Hotanen J-P, Mäkelä H, Nevalainen S, Pitkänen J (2013) Suomen metsät 2004–2008 ja niiden kehitys 1921–2008. [Forests of Finland 2004–2008 and their development in 1921–2008]. Metsätieteen aikakauskirja 3/2013: 269–608. https://doi.org/10.14214/ma.6025.

Korhonen KT, Ihalainen A, Ahola A, Heikkinen J, Henttonen HM, Hotanen J-P, Nevalainen S, Pitkänen J, Strandström M, Viiri H (2017) Suomen metsät 2009–2013 ja niiden kehitys 1921–2013. [Forests of Finland 2008–2013 and their development in 1921–2013]. Natural resources and bioeconomy studies 59/2017. http://urn.fi/URN:ISBN:978-952-326-467-0.

Korhonen KT, Ihalainen A, Kuusela S, Punttila P, Salminen O, Syrjänen K (2020) Metsien monimuotoisuudelle merkittävien rakennepiirteiden muutokset Suomessa vuosina 1980–2015. [Development of forest biodiversity indicators in Finland 1980–2015]. Metsätieteen aikakauskirja, article id 10198. https://doi.org/10.14214/ma.10198.

Korhonen KT, Ahola A, Heikkinen J, Henttonen H, Hotanen J-P, Ihalainen A, Melin M, Pitkänen J, Räty M, Sirviö M, Strandström M (2021a) Forests of Finland 2014–2018 and their development

1921–2018. Silva Fenn 55, article id 10662. https://doi.org/10.14214/sf.10662.
Korhonen KT, Huuskonen S, Kolström T, Kurttila M, Punttila P, Siitonen J, Syrjänen K (2021b) Closer-to-nature forest management approaches in Finland. Natural resources and bioeconomy studies 83/2021. http://urn.fi/URN:ISBN:978-952-380-314-5.
Kuusela K (1972) Suomen metsävarat ja niiden omistus 1964–70 sekä niiden kehittyminen 1920–70. [Forest resources and ownership in Finland 1964–70 and their development 1920–70]. Comm Inst For Fenn 76.5. http://urn.fi/URN:NBN:fi-metla-201207171108.
Kuusela K (1978) Suomen metsävarat ja metsien omistus 1971–1976. [Forest resources and ownership in Finland 1971–1976]. Comm Inst For Fenn 93.6. http://urn.fi/URN:ISBN:951-40-0396-9.
Kuusela K, Salminen S (1991) Suomen metsävarat 1977–1984 ja niiden kehittyminen 1952–1980. [Forest resources of Finland 1977–1984 and their development in 1952–1980]. Acta For Fenn 220. https://doi.org/10.14214/aff.7666.
Laasasenaho J (1982) Taper curve and volume functions for pine, spruce and birch. Comm Inst For Fenn 108. http://urn.fi/URN:ISBN:951-40-0589-9.
Laiho R, Tuominen S, Kojola S, Penttilä T, Saarinen M, Ihalainen A (2016) Heikkotuottoiset ojitetut suometsät – missä ja paljonko niitä on? [Poorly productive drained peatland forests – where and how large area]. Metsätieteen aikakauskirja 2/2016: 73–93. https://doi.org/10.14214/ma.5957.
Laine J, Vasander H, Hotanen J-P, Nousiainen H, Saarinen M, Penttilä T (2018) Suotyypit ja turvekankaat – kasvupaikkaopas. [Peatland types and transformed mires – guide for classification]. Metsäkustannus. ISBN 978-952-338-036-3.
Laudon H, Mensah AA, Fridman J, Näsholm T, Jämtgård S (2024) Swedish forest growth decline: a consequence of climate warming? Forest Ecol Manag 565, article id 122052. https://doi.org/10.1016/j.foreco.2024.122052.
Mäkisara K, Katila M, Peräsaari J (2022) The multi-source national forest inventory of Finland – methods and results 2017 and 2019. Natural resources and bioeconomy studies 90/2022. http://urn.fi/URN:ISBN:978-952-380-538-5.
Matérn B (1947) Methods of estimating the accuracy of line and sample plot surveys. Meddelanden från Statens Skogsforskningsinstitut 36.
Official Statistics of Finland (OSF) (2024) Total roundwood removals and drain. Natural Resources Institute Finland, Helsinki. https://www.luke.fi/en/statistics/total-roundwood-removals-and-drain. Accessed 6 June 2024.
Räty M, Kuronen M, Myllymäki M, Kangas A, Mäkisara K, Heikkinen J (2020) Comparison of the local pivotal method and systematic sampling for national forest inventories. For Ecosyst 7, article id 54. https://doi.org/10.1186/s40663-020-00266-9.
Reinikainen A, Mäkipää R, Vanha-Majamaa I, Hotanen J-P (eds) (2000) Kasvit muuttuvassa metsäluonnossa. Tammi, Helsinki. ISBN 951-31-1963-7.
Repola J (2008) Biomass equations for birch in Finland. Silva Fenn 42: 605–624. https://doi.org/https://doi.org/10.14214/sf.236.
Repola J (2009) Biomass equations for Scots pine and Norway spruce in Finland. Silva Fenn 43: 625–647. http://urn.fi/URN:NBN:fi-fe2016101225066.
Repola J, Ojansuu R, Kukkola M (2007) Biomass functions for Scots pine, Norway spruce and birch in Finland. Working Papers of the Finnish Forest Research Institute 53. http://urn.fi/URN:ISBN:978-951-40-2046-9.
Salemaa M, Tonteri T, Korpela L, Rautio P, Tamminen M, Ilvesniemi H (2010) Changes in forest vegetation in Finland during 1985–2006. In: Ukonmaanaho L, Derome K, Rautio P, Merilä P (eds) John Derome – Ambassador for forest monitoring in Europe Memorial seminar, November 30th 2010, Rovaniemi, Finland. Working Papers of the Finnish Forest Research Institute 180. http://urn.fi/URN:ISBN:978-951-40-2270-8.

Sarasto J (1961) Über die Klassifizierung der für Walderziehung entwässerten Moore. [On classification of peatlands drained for forestry purposes]. Acta For Fenn 74. https://doi.org/10.14214/aff.7132.

Suomen pinta-ala kunnittain 1.1.2024. (2024) [Land area of Finland by municipalities 1.1.2024]. National Land Survey of Finland. https://www.maanmittauslaitos.fi/sites/maanmittauslaitos.fi/files/attachments/2024/01/Vuoden_2024_pinta-alatilasto_kunnat_maakunnat.pdf. Accessed 14 June 2024.

Tiihonen P (1968) IV valtakunnan metsien inventointi. 4. Suomen metsävarat vuosina 1960–63 [Fourth National Forest Inventory. Forest resources of Finland 1960–63]. Commun Inst For Fenn 66.3. http://urn.fi/URN:NBN:fi-metla-201207171098.

Tomppo E (1999) Forest resources of Finnish peatlands in 1951–1994. Int Peat J 9: 38–44.

Tomppo E (2000) Kasvupaikat ja puusto. [Site types and growing stock]. In: Reinikainen A, Mäkipää R, Vanha-Majamaa I, Hotanen J-P (eds) Vegetation in changing forest ecosystems. Tammi, Helsinki, pp 60–83. ISBN 951-31-1963-7.

Tomppo E (2005) Suomen suometsät 1951–2003. [Peatland forests in Finland]. Metsäntutkimuslaitoksen tiedonantoja 947: 26–38. http://urn.fi/URN:ISBN:951-40-1987-3.

Tomppo E, Henttonen H, Tuomainen T (2001) Valtakunnan metsien 8. inventoinnin menetelmä ja tulokset metsäkeskuksittain Pohjois-Suomessa 1992–94 sekä tulokset Etelä-Suomessa 1986–92 ja koko maassa 1986–94. [The method and results in the 8th national forest inventory of Finland by regions in North Finland 1992–94 and the results for South Finland 1986–92 and for the whole country 1986–94]. Metsätieteen aikakauskirja 1B/2001: 99–248. https://doi.org/10.14214/ma.6434.

Tomppo E, Heikkinen J, Henttonen HM, Ihalainen A, Katila M, Mäkelä H, Tuomainen T, Vainikainen N (2011) Designing and conducting a forest inventory – case: 9th National Forest Inventory of Finland. Managing Forest Ecosystems 22, Springer Dordrecht. https://doi.org/10.1007/978-94-007-1652-0.

Valtakunnan metsien 12. inventointi (NFI12) (2018) Maastotyön ohjeet 2018. Koko Suomi ml. Ahvenanmaa. [12th National Forest Inventory of Finland. Field manual 2018, including the Åland region]. Natural Resources Institute Finland, Helsinki.

Wolter KM (2007) Introduction to variance estimation, 2nd edition. Springer Verlag Inc, New York.

Total of 54 references