Korhonen K.T., Ahola A., Heikkinen J., Henttonen H.M., Hotanen J.-P., Ihalainen A., Melin M., Pitkänen J., Räty M., Sirviö M., Strandström M. (2021). Forests of Finland 2014–2018 and their development 1921–2018. Silva Fennica vol. 55 no. 5 article id 10662. https://doi.org/10.14214/sf.10662

Supplementary file S1: Estimation methods

Estimation of areas

We estimated the area for a domain of interest using the same methods as in NFI9, NFI10 and NFI11 (Tomppo et al. 2011, Korhonen et al. 2013, Korhonen et al. 2017). The area estimates are based on the land area statistics by municipalities, the number of the NFI sample plot center points on land, and the number of sample plot center points in the domain of interest (Equation 1). As presented in Equation 1, the area represented by one sample plot center point is calculated by dividing the total land area of the municipalities in the sampling region by the number of plot centers on land in the sampling region.

$$\hat{A}_{i,s} = \frac{n_{i,s}}{n_s} A_s \qquad (1)$$

where

$n_{i,s}$= number of NFI plot centers in domain of interest i in a sampling region s

n_s= number of NFI plot centers on land in a sampling region s

A_s = land area of sampling region s.

Estimation of growing stock volumes and biomass

The estimation of volume of growing stock, or similarly biomass, consists of (i) estimating the volumes of sample and tally trees and (ii) estimating regional (domain level) values from the tree volumes.

Estimation of volume for a sample and tally tree

We estimated the volume of a sample and tally tree using the volume models by Laasasenaho (1982) and, for the common alder, European aspen, larch and small trees, the models published in Tomppo et al. (2011). The criteria for small trees is defined by species-specific height thresholds: Scots pine 4.5 m, Norway spruce 3.5 m, birch (silver birch and downy birch) 3.5 m, European aspen 5.0 m, and common alder 4.0 m.

The volume models predict the stem volume from the stump to the tree top. The breast height diameter (d), height (h) and, for trees at least 8.1 m in height, also the upper diameter at the height of 6 meters (d_6) are the independent variables in these models. Since d_6 and h of the tally trees are not measured, and on the contrary to NFI11, d_6 was not measured for the sample trees in NFI12, we first estimated models that predict these variables. For the d_6 models we used the sample tree data from NFI11 and for the height models that from NFI12.

We estimated separate d_6 models for the following tree species groups 1) Scots pine and other conifers than Norway spruce, 2) Norway spruce, 3) birch, 4) black alder, 5) broadleaf tree species other than birches and black alder. For Scots pine we estimated the model parameters independently for each sampling region, but for the other tree species groups we merged some sampling regions to increase the number of observations, bringing the total number of models to 20. We used the difference of measured d_6 and the d_6 estimated with taper curve models (Laasasenaho 1982) as the dependent variable in these models. As the independent variables we used following plot or stand level variables: altitude, effective temperature sum, distance from the coast, site type and site class, and following tree level variables: d, h, canopy layer, and origin. We added a dummy variable for downy birch in the model for birches. Correspondingly, we added a dummy variable for European aspen in the model for the other broadleaf tree species. We estimated the models as mixed models with the R software package nlme (Pinheiro et al. 2018) so that the models had random factors of clusters and stands for the constant parameter. We also estimated a smoothing model for the residual using the loess function of R (R Core Team 2018), in which the coordinates of the sample plot were the independent variables.

For estimating heights for the tally trees we used a model based on an earlier linear mixed model predicting the height and canopy ratio (Eerikäinen 2009), which was updated with the NFI12 data (Myllymäki 2016). Of the new models, only the height model was used (Myllymäki 2016, model 18), in which the independent variables of the fixed part have been partially changed as compared to the original models of Eerikäinen (2009). The height model has random factors of clusters and stands for the constant and for the diameter parameters.

Estimation of volumes by timber assortments for a sample and tally tree

For the sample trees we estimated the stem volumes by the timber assortment classes (saw log, pulp wood and waste wood) by bucking the trunks in such a way that the value of the trunk was maximized (Korhonen 1994, Tomppo et al 2011). We used the taper curve models (Laasasenaho 1982) for the bucking of stems, with tree species, d, estimated d_6, and h as the independent variables. Each quality part has minimum length and diameter requirements as specified in the field manual. We used relative values of 3 for the branchless saw logs, 2.5 for the sawlogs with dry or fresh branches, and 1 for the pulpwood logs.

For the tally trees we estimated the volumes by the timber assortment classes through proportions of stem volume using the k-nearest neighbor (knn) method. For the knn search, we first predicted these proportions by tree species groups using smoothing models estimated with live sample tree data and the loess function of R. For the tree class “saw log stems” we estimated models predicting the proportions of saw log and waste wood volumes to the stem volume. Fort the tree class “pulp wood” we estimated a model predicting the proportion of waste wood. We applied the following tree species groups in the modeling and in the knn search: 1) Scots pine and conifers other than Norway spruce and larch, 2) Norway spruce and larch, 3) birches and European aspen, and 4) other broadleaf trees. The independent variables in the knn search were the sample plot coordinates, d, h, tree species group and the predicted proportions of saw log and waste wood volumes. We searched five nearest neighbors and weighted them inversely to the distance when estimating the target variable values (see e.g. Tuominen et al. 2014). We used the same knn search for predicting tree age at breast height and lower limit of the crown as well for the use in biomass models.

Estimation of biomass by tree components for a tally tree

We estimated the biomass of the following components for each tally and sample tree: stem, needles, living and dead branches, stumps, and roots larger than one cm in diameter. The possible set of independent variables for different models included tree species, diameter and either measured or predicted tree height, age at breast height and crown height. We used the wood density models of

Repola et al. (2007) to predict the stem biomass. For the other biomass components, we used models of Repola (2009) for conifers and models of Repola (2008) for broadleaf trees.

Estimation of domain level mean and total volumes and biomasses

In NFI12, trees with diameter at least 45 mm are measured on concentric sample plots with radius 9 meters for trees more the 95 mm in diameter and 5.64 meters for trees at maximum 95 mm in diameter. Trees less than 45 mm in diameter are selected with Bitterlich sampling, where the plot radius depends on the tree diameter and selected basal area factor. Equation 2 presents the sample plot radius applied in NFI12 as a function of tree diameter.

$$r_{k=}\begin{cases} 9, if\ d_k > 9.5 \\ 5.64, if\ 4.5 \leq d_k \leq 9.5 \\ \frac{50 d_k}{100\sqrt{q}}, otherwise \end{cases} \quad (2)$$

where

d_k=diameter at breast height for a tree k, in centimeters
q=basal area factor=1.5.

We estimated the mean volume or biomass of growing stock in a domain with a ratio estimator presented in Equation 3 (see also Tomppo et al. 2011 p. 73).

$$\hat{y}_{i,s} = \frac{10\ 000}{n_{i,s}} \sum_{k \epsilon S} \frac{y_k}{\pi r_k^2} \quad (3)$$

where

$n_{i,s}$=number of plot centers in the domain of interest in sampling region s,
y_k= volume (or biomass) of tally tree k, in m3 (or ton),
$k \in S$ indicates that tally tree k belongs to the domain of interest and is in the sample NFI12, and
10 000 is a scaling factor to covert the values to m3 per hectare (or ton per hectare).

We estimated the mean volume over sampling regions by the ratio of the estimates of total volume (or biomass) and area (see paragraph below). In this way, we weight each sample plot and each tally tree by the area represented by the plot center in question (see Tomppo et al. 2011, p. 72).

We estimated the total volumes (or biomasses) for a domain of interest by the product of the mean volume (per area unit) estimate and area estimate. When the domain of interest includes several sampling regions, the total is the sum of totals by sampling regions.

Estimation of volume increment

Volume increment in the Finnish NFI is defined as the increase in tree stem volume over bark. It includes trees alive at the inventory time and the increment of drain (i.e. trees that have been harvested or died naturally during the increment measurement period. In NFI12 the increment estimates are based on permanent plots. Thus, the length of the increment measurement period is appr. 5 years for each sample plot. The increment results are calculated as the annual average over the measurement period.

We calculated the mean increments for productive forest and poorly productive forest land. Therefore, we did not include in the increment calculation those sample plots whose land use category had changed from productive forest or poorly productive forest land in NFI11 to some other land use category in NFI12. We estimated the total increment (million m^3) of a domain (e.g., forest land) by multiplying the average increment ($m^3ha^{-1}a^{-1}$) calculated from the permanent plots by the area estimate of the domain, which we estimated using the entire plot data.

Increment of trees alive at the inventory time

(i) Tree height > 1.3 m at the beginning of the increment measurement period

On remeasured permanent plots, trees are divided into categories according to the inclusion into the sample in the initial inventory (NFI11) or in the subsequent inventory (NFI12) and the threshold tree size. Especially, the remeasured NFI12 plots have trees that were not included into the NFI11 sample. The use of these trees in the increment estimation depends on, whether tree height at the time of NFI11 was over 1.3 m, which is the threshold tree size in NFI. Trees included only into the NFI12 sample and exceeding the threshold size (height more than 1.3 meters) were not included (i.e., had zero weights) in the increment estimation. Methods have been developed to include these trees in the calculation (e.g. Roesch et al. 1989) and to improve the sample plot level estimates of increment (Heikkinen and Henttonen 2001). However, these methods require prediction of tree size in the initial inventory (NFI11). It is problematic to develop unbiased methods for this purpose because between NFI11 and NFI12 the plot type was changed from a Bitterlich relascope sample plot to a fixed radius sample plot. Therefore, we estimated the increment of survivor trees using the method of Grosenbaugh (1958), in which tree weights are calculated from the sampling probabilities of the initial inventory (NFI11) (Gregoire 1993). The maximum plot radius used for including the trees was the 9 meters, which was the maximum plot radius in NFI12.

It would be possible to use directly the volumes generalized to the tally trees in NFI11 and NFI12 for the calculation of volume increment. However, the volume generalization method has changed between NFI11 and NFI12 and the generalization method does not take into account the fact that the same trees have been measured repeatedly in permanent plots. Therefore, we used the original tally and sample tree measurements in the increment estimation. Two-level information on volume increment is available from tree measurements on permanent sample plots. Firstly, for all trees (tally trees and sample trees) the volume increment (x) can be estimated using the difference of stem volumes predicted as a function of dbh (Laasasenaho 1982). Secondly, more accurate volume increment (y) can be estimated for the sample trees using the difference of stem volumes predicted as a function of dbh, height and d6. This is possible because NFI11 sample trees were remeasured in NFI12.

Finally, we applied regression estimation (e.g., Cochran 1977) to combine the increment estimates from the sample trees and tally trees:

$$\bar{y}_{reg} = \bar{y}_{n2} + b\left(\bar{x}_{n1} - \bar{x}_{n2}\right), \quad (4)$$

where
$\bar{y}_{reg}$ = regression estimate for increment, $m^3ha^{-1}a^{-1}$,
$\bar{y}_{n2}$ = increment estimate from the sample trees using dbh, d6 and h as predictors of stem volume, $m^3ha^{-1}a^{-1}$,

$\overline{x}_{n1}$ = increment estimate from all the tally and sample trees, $m^3ha^{-1}a^{-1}$,

$\overline{x}_{n2}$ = increment estimate from the sample trees when using dbh as a predictor for stem volume, $m^3ha^{-1}a^{-1}$,

b = parameter β for the model $y_i = \alpha + \beta x_i + e_i$, estimated using the sample tree data

We estimated the coefficient β for sampling regions, land use classes (productive forest land, poorly productive forest land) and tree species groups (Scots pine, Norway spruce, birch, other broadleaf species) using the SAS SURVEYREG procedure. For Scots pine on productive forest land in the whole country as well as for Norway spruce and birch in South Finland the coefficient was estimated for the following size classes: dbh ≤ 95 mm, 95 <dbh ≤ 175 mm, 175 <dbh ≤ 245, dbh> 245mm. For Norway spruce and birch in North Finland the number of size classes in the estimation was three and the highest class was dbh > 175 mm. For the tree species group 'other broadleafs' only two size classes (over/up to 95 mm) were used in estimating the coefficient β.

Measurements in permanent plots are made during the growing season and re-measurement of the plot does not always occur at the same stage of the growing season as the previous measurement. We used the functions of Henttonen et al. (2009) to estimate the length of increment period in terms of growing seasons (years). Those functions are presented for Scots pine and Norway spruce, for broadleaf species we applied the function of Scots pine. The volume increment between NFI11 and NFI12 was converted to average annual volume increment by dividing it by the calculated length of the growth period. The number of growing seasons between NFI11 and NFI12 measurements ranged from four to six and averaged to 4.93.

(ii) Tree height ≤ 1.3 m at the beginning of the increment measurement period. For trees with height up to 1.3 m at the time of NFI11 (according to the NFI12 field assessment), we estimated the increment percentage using the sample trees measured on the temporary plots. Tree weights were calculated from the sampling probabilities of NFI12. These threshold trees accounted to 1% of the increment of survivor trees.

(iii) Trees with missing data

NFI11 measurement data were not available for a small number of permanent plots classified as productive forest or poorly productive forest in NFI12. This group includes plots where land use class in the NFI11 measurement was not forest land or poorly productive forest land as well as plots which were re-established in NFI12 because the plot center of NFI11 was not found. For these plots we estimated the increment using the sample trees measured on temporary plots. We used the land use change class as a classifying variable, in addition to those variables mentioned for estimation of increment on temporary plots. Tree weights were calculated from the sampling probabilities of NFI12. This component accounted to 0.5% of the increment of survivor trees.

Increment of drain

Drain includes removals and natural losses, i.e. trees that were harvested or died naturally between NFI11 and NFI12. For these trees the dbh measured in NFI11 was available and the year of removal or dying was assessed in the field in NFI12. We estimated the volume increment for these trees with models where the dependent variable was the annual increment of the tree divided by its basal area ($m^3m^{-2}a^{-1}$) and the fixed predictors were stem volume divided by the basal area (m^3m^{-2}), dbh, canopy layer, tree species group, soil type, drainage situation, origin (natural / cultivated), site class, effective temperature sum, stand age and tree quality class. The values of the explanatory variables were from the initial measurement. In addition, we included a random sample plot factor in the model. We estimated the model parameters in paired sample tree data from NFI9-NFI10, NFI10-NFI11, and NFI11-NFI12 using the SAS MIXED procedure.

Removed and natural losses trees grow less than the survivor trees with the same set of explanatory variables. Therefore, we derived correction factors in domains defined by the sampling region, tree species group, and tree type (harvested stump, stump of trunk left in the forest, naturally fallen tree, standing dead tree). We estimated these correction factors using the ratio (predicted increment / measured increment) of the NFI9 to NFI10 and NFI10 to NFI11 sample trees that we removed (or died) before the following measurement occasion (NFI11 or NFI12). The annual increment prediction was multiplied by the number of growth seasons between the NFI11 measurement and the time of removal or dying estimated in the field. The average number of growing seasons was 2.4.

Estimation of growth indices

The annual variation of volume increment is usually described by growth indices. Growth indices describe the annual variation in increment caused by the variation of environmental factors outside the forest stand. Such factors include e.g. climatic variations and epidemic insect damages over large areas. Years of abundant flowering and seed production, which especially reduce the volume increment of Norway spruce, are discernible in growth indices, also. We estimated the growth indices by tree species, site classes and sampling regions for the years 1975 – 2018 employing mixed linear models (Henttonen 1990, 2000). The comprehensive tree-ring data collected on the temporary plots of NFI8 – NFI12 were used in the estimation.

Estimation of forest balance

The forest balance calculation employed in NFI (Kuusela 1978) examines the compatibility of volume, increment and drain estimates between two consecutive inventories. We calculated the forest balance between NFI11 and NFI12 by tree species groups (Scots pine, Norway spruce, broadleaf) and separately for the South and North Finland as follows:

Initial growing stock (GS11)	NFI11 volume estimate
Final growing stock (GS12)	NFI12 volume estimate
Calculated final GS	Initial GS + Volume increment estimate – drain
Measured change	Final GS – Initial GS
Calculated change	Volume increment estimate – drain
Volume increment	NFI12 annual volume increment estimate multiplied by 5 years
Drain	The average of total drain in 2009–2013,…,2014–2018 from drain statistics (Official Statistics of Finland: Total roundwood removals and drain 2020).

Estimation of mortality and natural losses

Both annual mortality and annual natural losses are estimated using the measurements on the permanent plots. Mortality is defined as the volume of trees that die during the mortality assessment period. Natural losses are defined as mortality minus harvested mortality, i.e. volume of the mortality trees that remain in the forest. Both mortality and natural losses are expressed as annual values. Mortality includes:

- Trees that were alive at the time of NFI11 but dead at the time of NFI12 measurement. These trees include the new dead trees that were above the minimum size (h>1.3 m) at the time of NFI11 but were not in the NFI11 sample and were included in the NFI12 sample.
- Trees that were in the NFI11 sample but were no longer found in NFI12. These trees were included in the mortality trees only for those permanent plots where the plot center point was found and there were no recent cuttings registered.

Natural losses include those trees that were classified as usable dead wood in the NFI11 data and as removed trees in the NFI12 data.

Estimation of sampling variance

We estimated the sampling variances for the area estimates by land use classes and for mean and total volume estimates. The basis for estimating the sampling variance for the proportions of land use classes (or any other domain of interest) and for mean volumes is the variance in the cluster-level residuals:

$$z = x - My \qquad (5)$$

where, in the case of estimating proportion of land use classes from the land area
x is the number of sample plot center points in the land use class of interest in a cluster
M is the proportion of the land use class of interest in the whole sampling region, and
y is the number of plot center points on land;

and in the case of estimating mean volumes
x is the sum of mean volumes (per hectare) represented by tally trees in the cluster and domain of interest
M is the mean volume estimate in the domain of interest in the sampling region
y is the number of plot center points in the domain of interest in the sampling region.

The sampling variance of M depends on the variation of the z values and on the sum of number of plot center points (n) over the sampling region. If the clusters were located at random, an approximately unbiased estimator of the standard error (=square root of sampling variance) would be:

$$\hat{s} = \frac{1}{n}\sqrt{\sum_{k=1}^{K} z_k^2} \qquad (6)$$

where z_k=the residual associated to cluster k,
K=number of clusters.

In NFI12 the field plot clusters were located using systematic and balanced sampling. Both of these methods are more efficient than random sampling, which means that the sampling variance in NFI is lower than in random (cluster) sampling with the same number of clusters. Since the first NFI in 1920s the systematic design has been considered in the variance estimators by replacing the sum of squared residuals in Equation 6 by a sum of appropriately scaled indicators of local variation (see e.g. Heikkinen 1999).

When the clusters are on a regular square grid, local variation is measured by

$$T_g = (z_{k1(g)} - z_{k2(g)} - z_{k3(g)} + z_{k4(g)})^2/4 \tag{7}$$

where g refers to a square group of four adjacent clusters, $k1(g)$ is the cluster in the North-West, $k2(g)$ in the North-East, $k3(g)$ in the South-East, and $k4(g)$ in the South-West corner of the group (see Tomppo et al. 2011, Figure 3.1). When the groups are formed so that each cluster is a member of four groups the scaling factor ¼ is needed to ensure that the squared sum in the variance estimator

$$\sum_g T_g = \sum_g \left(\sum_k a_{g,k} z_k\right)^2 \tag{8}$$

fulfills condition $\sum_g a_{g,k}^2$=1 for all clusters k, so that the sum of all squared weights $a_{g,k}^2$ in $\sum_g T_g$ equals the total number of clusters, K, which is a necessary condition to ensure an unbiased estimator for variance in the case of uncorrelated clusters (Matérn 1969).

Since NFI10 the clusters have not been located in a regular square grid and the variance estimator has been modified to be applicable with the current design. In those NFI12 sampling regions, where systematic sampling is applied (Southmost Finland, Central Finland, Northern Ostrobothnia and Kainuu, Lapland and Kuusamo), we formed groups of four or five clusters (Fig. 1).

In the case of groups with five clusters, where there is a permanent cluster surrounded by four temporary clusters,

$$T_g = \left(z_{k0(g)} - \frac{1}{4}\sum_{j=1}^{4} z_{kj(g)}\right)^2 \tag{9}$$

where $k0(g)$ is the permanent cluster in the center of the group and clusters $kj(g)$, $j = 1,..,4$, as above (see Grafström and Schelin 2014, Equation 6).

In the case of groups with four clusters (temporary clusters with no permanent cluster in the center of the square formed by their locations)

$$T_g = 5(z_{k1(g)} - z_{k2(g)} - z_{k3(g)} + z_{k4(g)})^2/16 \tag{10}$$

which is similar to the case of square grid of clusters, but the weights are adjusted. These adjusted weights fulfill the above-mentioned condition for unbiasedness since each permanent cluster is a member of only one group (i.e. is only in one term in the sum $\sum_g T_g$ and there with a weight 1) and each temporary cluster k is a member of one group of five clusters and member of three groups with four clusters, thus,

$$\sum_g a_{g,k}^2 = \left(\frac{1}{4}\right)^2 + 3\frac{5}{16} = 1 \tag{11}$$

In the region Åland the clusters were located irregularly due to the balanced sampling method. There we used a quadratic sum

$$\sum_{k=1}^{K} \frac{n_k}{n_k+1} \left(z_k - \frac{1}{n_k} \sum_{j=1}^{n_k} z_{kj} \right)^2 \qquad (12)$$

where the clusters $kj, j = 1, \ldots, n_k$ are the natural neighbors of cluster k in the Voronoi tessallation generated by the cluster reference points (see e.g. Okabe et al. 2000). Scaling by the factor $n_k/(n_k + 1)$ ensures that the squared sum of the weights = 1 in each term of Equation (12).

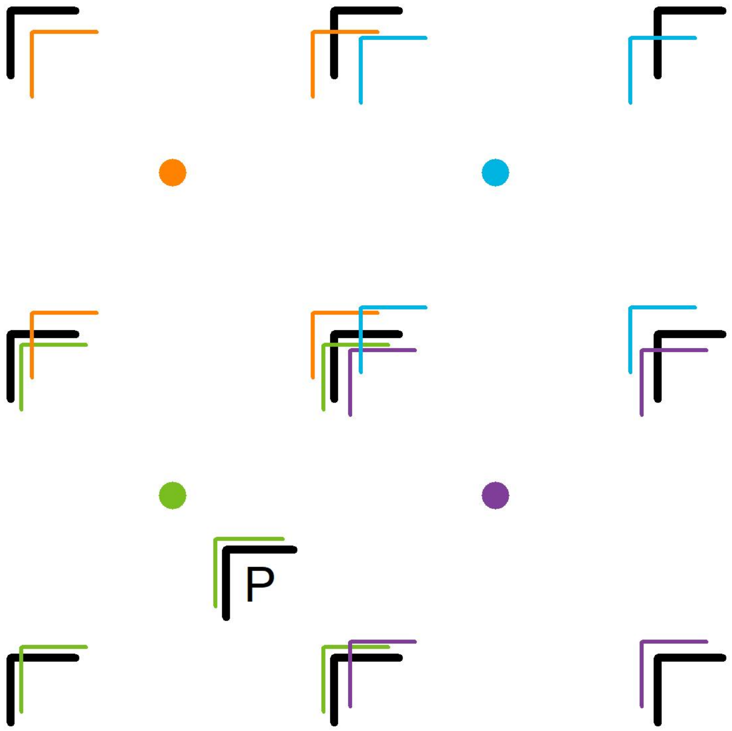

Fig. 1. NFI12 cluster design in the Southern Finland (black lines) and the grouping of clusters in 4 or 5 cluster groups (colors indicate the different groups). The clusters in this scheme form four whole groups around the points marked in the scheme. For example, the cluster in the middle of the scheme is a member of all the four groups (indicated with different colors) and the permanent cluster (P) is a member of one group only (green). Each temporary cluster (=clusters not marked with P) is a member of four groups but not all the groups are shown for the clusters at the edges of this scheme. This design is repeated in the other sampling regions but the location of the permanent cluster (P) inside the cluster group varies by sampling region.

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