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Danish National Forest Inventory

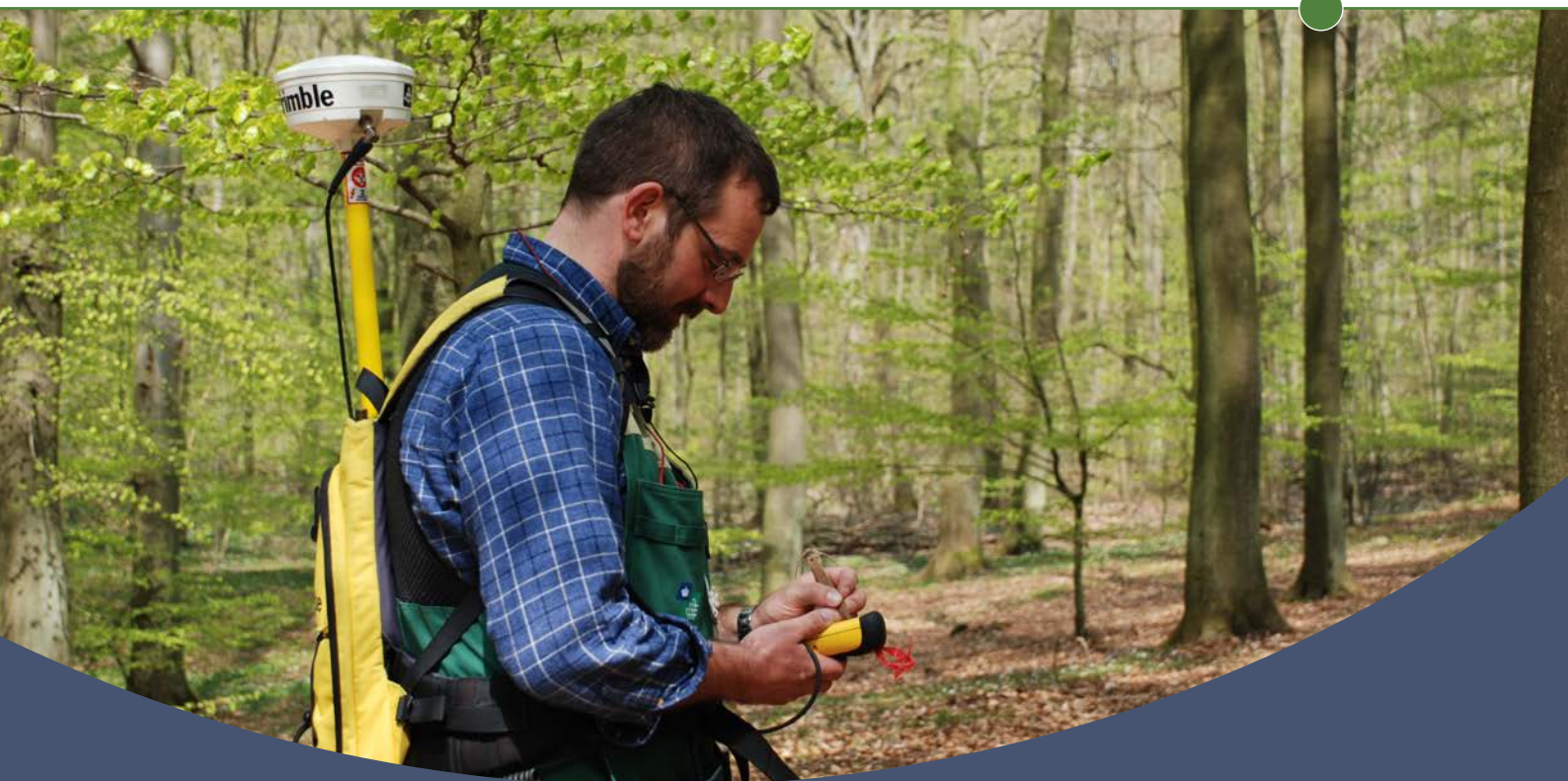
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Danish National Forest Inventory

Design and calculations

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Preface

The following report is a reference document for the Danish National Forest Inventory (NFI), which was initiated in 2002. The report presents the general design of the NFI and provides insight to the basic calculations of forest statistics made with the data collected in the NFI.

The report is thought to provide a general overview and thus does not claim to provide full insight into the field procedures or the calculations. The field manual for the Danish NFI (in Danish) provides a detailed description of field procedures.

Frederiksberg

May 9th 2016

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National Forest Census

From 1881 to 2000, a National Forest Census was carried out roughly every 10 years based on questionnaires sent to forest owners (Larsen and Johannsen, 2002). Since the data was based on questionnaires and not field observations, the actual forest definition may have varied. The basic definition was that the tree covered area should be minimum 0.5 ha to be classified as a forest. There were no specific guidelines as to crown cover or the height of the trees. Open woodlands and open areas within the forest were generally not included. All values for growing stock, biomass or carbon pools, based on data from the National Forest Census, were estimated from the reported data on forest area and its distribution to main species, age class and site productivity classes. The two last censuses were carried out in 1990 and 2000.

The 1990 National Forest Census was based on reported forest statistics from 22,300 respondents, resulting in information on area, main species, age class distribution and productive indicators. The estimated forest area was 445 000 ha or 10.3 % of the land. Of the total forest area, 64 % was coniferous forest and 34 % was deciduous forest (the remainder was temporarily unstocked). The total volume was estimated at 55.2 million cubic metres, of which 57 % was coniferous.

The number of respondents in the 2000 National Forest Census was 32,300, which is considerably higher than in the 1990 survey. The change in the number of respondents probably contributed to the observed increase in forest area and growing stock between the 1990 and 2000 census. The estimated forest area was 486 000 ha or 11.3 % of the land. Of the total forest area 60 % was coniferous forest and 36 % was deciduous forest (the remainder was temporarily unstocked). The total volume was estimated at 77.9 million cubic metres, of which 63 % was coniferous.

National forest inventory

The Danish National Forest Inventory (NFI) is a continuous, sample-based inventory, with partial replacement of sample plots based on a 2 x 2-km grid

covering the Danish land surface (Figure 1). Approximately one-third of the plots are permanent and are re-measured in every cycle of the NFI, whereas two-thirds are temporary and are moved randomly within the particular 2 x 2-km grid cells in subsequent cycles.

The sample of permanent and temporary field plots has been systematically divided into five non-overlapping, interpenetrating panels that are each measured in a single year and constitute a systematic sample of the entire country. Hence all the plots are measured in a 5-year cycle.

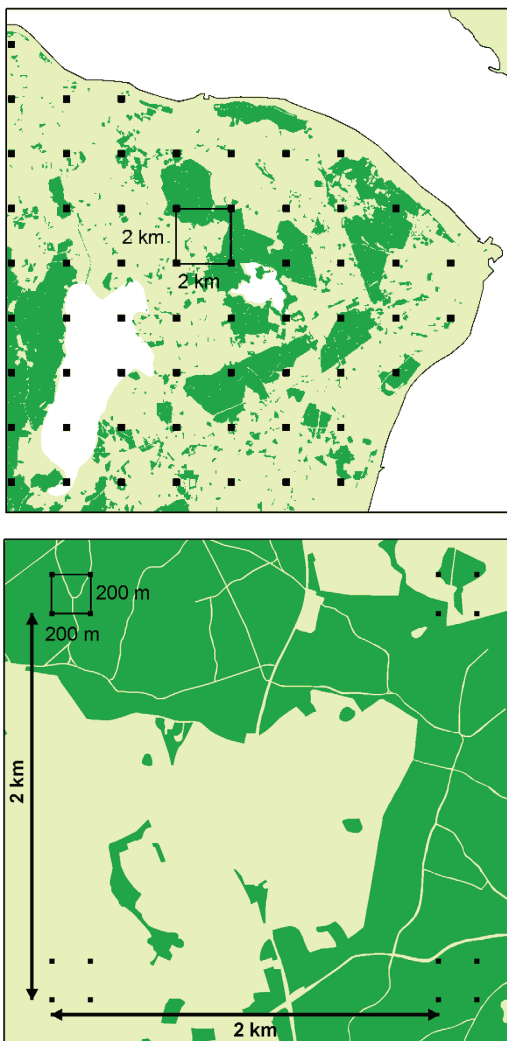


Figure 1. Design of the Danish National Forest Inventory. Clusters of sample plots are placed in a 2x2 km grid. Each cluster contains four sample plots placed in the corners of a 200x200 m square.

In each square grid cell, a cluster of four circular plots (primary sampling unit, PSU) is placed at the corners of a square with 200-m side length (Figure 2).

Each circular plot (secondary sampling unit, SSU) has a radius of 15 meters. When plots include different land-use classes or different forest stands, the individual plot is divided into tertiary sampling units (TSU). Based on an analysis of aerial photos, each sample plot (SSU) is assigned one of three categories, reflecting the likelihood of plot-level forest or other wooded land (OWL): (0) unlikely to contain forest or other wooded land cover, (1) likely to contain forest, and (2) likely to contain other wooded land. All plots in the last two categories are inventoried in the field.

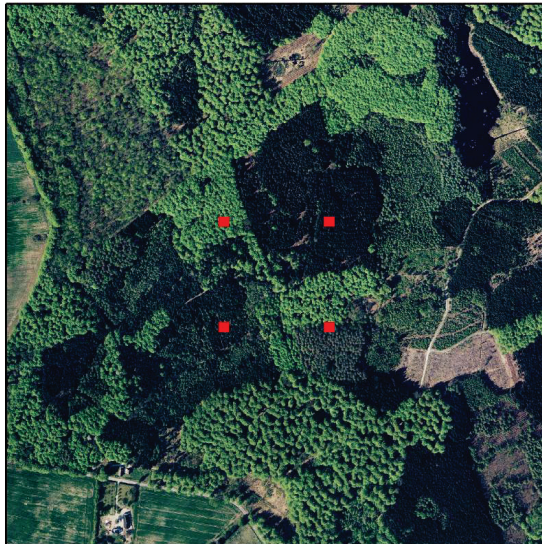
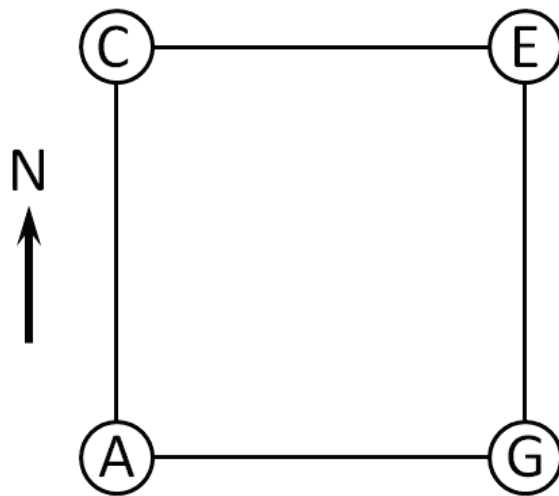


Figure 2. Left: cluster (PSU) of four sample plots (SSU's) in a square with side length of 200 m. Right: aerial photographs are used for identifying sample plots with forest cover.

Each plot is composed of three concentric circles with radii of 3.5, 10 and 15 m. A single calliper measurement of diameter is made at breast height for all trees in the 3.5 m circle. Trees with diameters larger than 10 cm are measured in the 10 m circle, and only trees with diameters larger than 40 cm are measured in the 15 m circle. For a random sample of 2-6 trees, further measurements of total height, crown height, age and diameter at stump height are made, and the presence of defoliation, discoloration, mast, mosses and lichens is recorded. The presence of regeneration on the plots is registered as well as the species, age and height of the young trees.

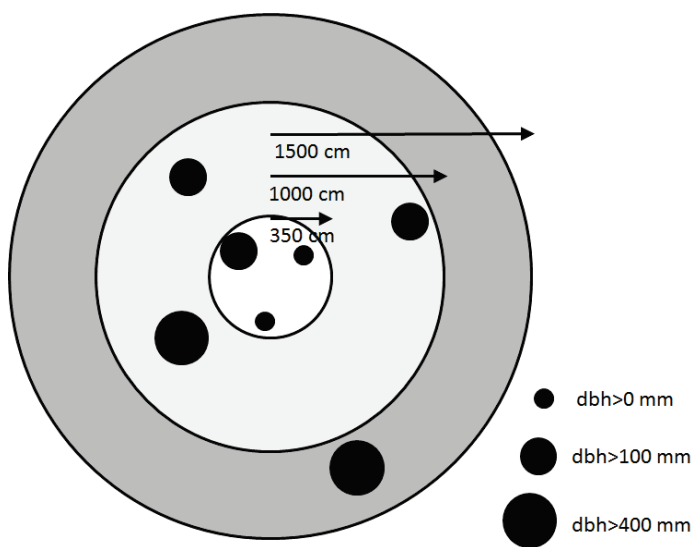


Figure 3. Division of the sample plots into three concentric circles with radius 15, 10 and 3.5 m. Black circles illustrate trees measured on the sample plot.

Standing deadwood and lying deadwood where the growing point of the stem was within the 15 m radius of the sample plot with a diameter at breast height larger than 10 cm is measured for breast height diameter (Figure 4). When the tree is broken the height of the breakage is further recorded.

Lying deadwood with a diameter of more than 10 cm where the growing point of the stem was outside the 15 m sample plot radius is measured for diameter and length. Length of the lying deadwood is measured as the length of the tree that exceeds 10 cm in diameter and is within the sample plot. The diameter is measured at the middle of the lying deadwood measured for length.

Stumps within the 15 m radius of the sample plot are measured for diameter and stump height.

In addition to the size measurements of deadwood, the degree of decay is recorded on an ordinal scale.

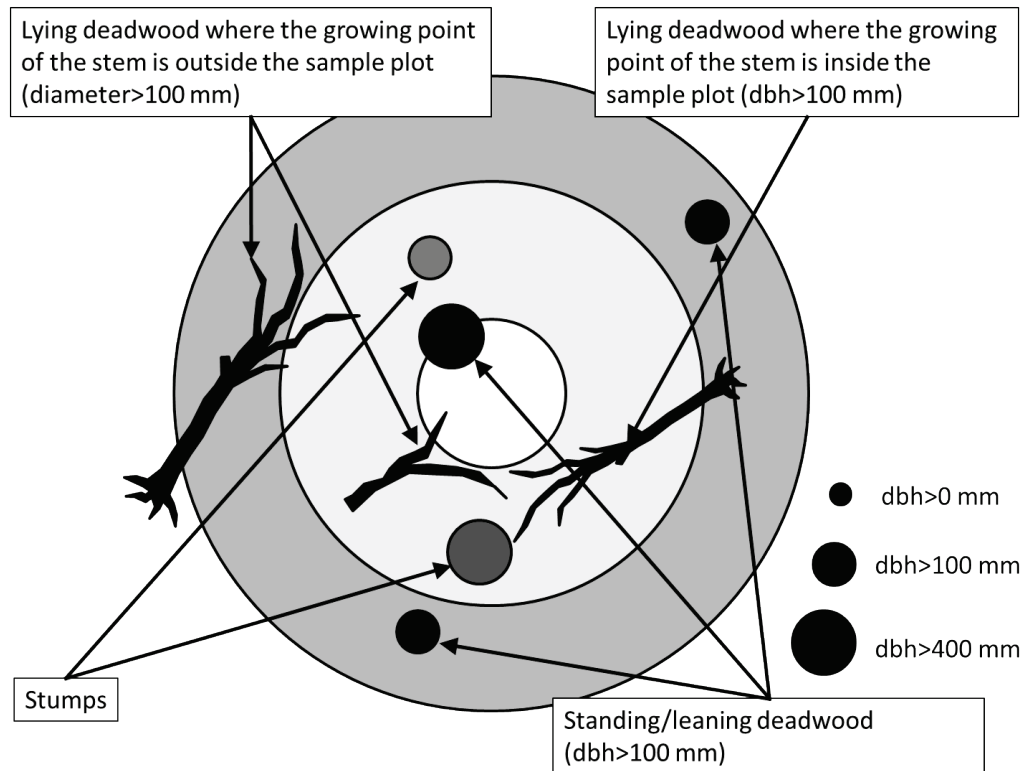


Figure 4. Measurements of dead wood on the NFI sample plots.

On each plot the presence and state of ditches and drainage conditions are recorded. Further, the presence of peatland is recorded and the depth of the peat is measured. Finally, the depth of the humus layer is measured on all plots.

Calculation of forest statistics

1.1 Estimation of forest area

Based on analysis of aerial photos, each sample plot (SSU) is allocated to one of three forest status categories (Z), reflecting the likelihood of forest or other wooded land (OWL) in the plot: (0) Unlikely to be covered by forest or other wooded land, (1) Likely to be covered by forest, and (2) Likely to be covered by other wooded land.

On individual sample plots (j) the forest cover percentage (X) is calculated as the proportion of the forest area (A) to the total plot area of the 15 m radius circle (A_{15}). The average forest percentage on plots with forest status $Z=1$ (and 2) is calculated as the sum of the forest percentages times an indicator variable (R) that is 1 if Z equals 1 (or 2) and 0 otherwise, divided by the number of plots with forest status $Z=1$ (or 2). See also (Table 1).

The overall average forest percentage is calculated as the sum of: (1) observed forest cover percentages of the individual sample plots, (2) the number of unobserved sample plots with forest status $Z=1$ times the average forest cover percentage of sample plots with forest status 1, and (3) the number of unobserved sample plots with forest status 2 times the average forest cover percentage of observed sample plots with forest status $Z=2$ divided by the number of observed and unobserved sample plots. In this context sample plots with forest status 0 are regarded as observed and assumed to have a forest cover percentage of 0. Finally, the overall forest area is calculated as the overall average forest percentage times the total land area.

Table 1. Estimation of forest area.

Description	Function
Forest cover on the j th sample plot. A_j is the forest area on the sample plot and $A_{15,j}$ is the total area of the circular sample plot with radius 15 meter.	$X_j = \frac{A_j}{A_{15,j}}$
Average forest cover on measured sample plots. R_j is 1 when the sample plot has been measured and 0 otherwise. Z is 1 for plots with forest cover and 2 for plots with other wooded land cover based on interpretation of aerial photographs. n_z is the number of measured sample plots with forest or other wooded land cover based on aerial photo interpretation.	$\bar{X}_z = \frac{1}{n_z} \sum_z X_j R_j$
Average overall forest cover. n is the total number of measured and non-measured sample plots. N_{21} and N_{22} are the number of non-measured sample plots with forest cover and other wooded land cover, respectively.	$\bar{\bar{X}} = \frac{1}{n} \left(\sum_{j=1}^n X_j R_j + N_{21} \bar{X}_1 + N_{22} \bar{X}_2 \right)$
Total forest area. A_{Total} is the total land area, is the average overall forest cover and A_{Forest} is the total forest area.	$A_{Forest} = \bar{\bar{X}} \cdot A_{Total}$

When estimating the forest area with a specific characteristic (k), such as forest established before or after 1990, the proportion of the plot area with the particular characteristic is found by summing the forested plot areas times an indicator variable (R) that is 1 if the plot has the k th characteristic and 0

otherwise (see also Table 2). Subsequently the plot area with the k th characteristic is divided by the total forested plot area. The total forest area with a particular characteristic is found as the forest area percentage with the particular characteristic k times the total forest area.

Table 2. Estimation of the forest area distribution to different types for example different forest types, ownership or tree species.

Description	Function
<p>Forest cover with a specific characteristic, k. R_{jk} is an indicator variable that is 1 if the area on the j'th sample plot has the kth specific characteristic and is 0 otherwise. A_j is the forest area on the sample plot and n is the total number of sample plots.</p>	$X_k = \frac{\sum_{j=1}^n R_{jk} A_j}{\sum_{j=1}^n A_j}$
<p>Basal area (g) of the i'th tree on the j'th sample plot. Basal area is the cross sectional area of the stem 1.3 meter above ground.</p>	$g_{ij} = \frac{\pi}{4} d_{ij}^2$
<p>Tree species forest cover indicator. R_{ijk} is an indicator variable which is 1 if the i'th tree on the j'th sample plot is of the k'th tree species. $A_{c,ij}$ is the area of the c'th, concentric circle (3.5, 10 or 15 m radius) to which the i'th tree belong. g_{ij} is the basal area of the i'th tree and m is the number of trees on the j'th sample plot.</p>	$R_{jk} = \frac{\sum_{i=1}^m R_{ijk} \frac{1}{A_{c,ij}} g_{ij}}{\sum_{i=1}^m \frac{1}{A_{c,ij}} g_{ij}}$
<p>Total forest area with the k'th characteristic. A_{Forest} is the total forest area.</p>	$A_k = X_k \cdot A_{Forest}$

1.2 Estimation of growing stock, biomass and carbon pools

Growing stock is calculated based on the trees measured on the NFI sample plots. As most tree volume functions include both diameter and height, a first step is to calculate the height of trees not measured for height using a diameter-height regression estimated based on trees measured for height.

Based on the trees measured for both height and diameter, diameter-height regressions are developed for each species and growth region. The functions use the observed mean height and mean diameter on each sample plot for creating localized regressions using the regression form suggested by Sloboda et al. (1993). For plots where no height measurements are available, generalized regressions are developed based on the Näslund-equation modified by Johannsen (1992) (see also Table 3).

The next step is to estimate the quadratic mean diameter of the trees on the sample plot. As the trees are measured in different concentric circles depending on their diameter, the basal area on each sample plot is estimated by scaling the basal area of each tree (standing or felled) according to the circular area in which the tree has been measured (Table 3). A similar calculation has been made for the number of stems. Finally, mean squared diameter is calculated from the basal area and stem numbers.

Table 3. Calculation of tree heights and plot specific variables.

Description	Function
<p>Diameter-height regression for calculation of tree height where only diameter is recorded. h_{ij} and d_{ij} is the height (in dm) and diameter, respectively, of the i'th tree on the j'th sample plot. The constant 13 is the height above ground where the trees diameter is measured and \bar{h}_j and \bar{d}_j are the average height and diameter of trees measured fore height on the j'th sample plot.</p>	$h_{ij} = 13 + (\bar{h}_j - 13) \cdot \exp\left(\alpha_1 \cdot \left(1 - \frac{\bar{d}_j}{d_{ij}}\right) + \alpha_2 \cdot \left(\frac{1}{\bar{d}_j} - \frac{1}{d_{ij}}\right)\right)$
<p>General diameter-height regression for calculation of the height of trees on sample plots where no other trees have been measured for height on the sample plot.</p>	$h_{ij} = 13 + \beta_1 \cdot \exp\left(-\frac{\beta_2}{d_{ij}}\right)$
<p>Basal area per hectare on the j'th sample plot. $A_{c,ij}$ is the forest area on the c'th concentric circle ($c=3,5; 10; 15$ m) and g is the basal area of the i'th tree on the j'th sample plot.</p>	$G_j = \sum_{i=1}^m \frac{1}{A_{c,ij}} g_{ij}$
<p>Number trees per hectare on the j'th sample plot. $A_{c,ij}$ is the forest area on the c'th concentric circle ($c=3,5; 10; 15$ m) and g is the basal area of the i'th tree on the j'th sample plot.</p>	$N_j = \sum_{i=1}^m \frac{1}{A_{c,ij}}$
<p>Quadratic mean diameter. Corresponds to the diameter of the mean basal area tree.</p>	$D_{g,j} = \sqrt{\frac{4 G_j}{\pi N_j}}$

Volume of individual trees are estimated using volume functions developed for the most common Danish forest tree species (Madsen, 1985, Madsen 1987 and Madsen and Heusèrr 1993). The functions use individual tree diameter and height as well as quadratic mean diameter of the forest stand as independent variables. The volume functions have the general form:

$$V = \exp(a_0 + a_1 \cdot X_1 + a_2 \cdot X_2 + a_3 \cdot X_3 + a_4 \cdot X_4 + a_5 \cdot X_5 + a_6 \cdot X_6 + a_7 \cdot X_7 + a_{14} \cdot X_{14} + a_{15} \cdot X_{15} + a_{16} \cdot X_{16} + a_{17} \cdot X_{17} + a_{18} \cdot X_{18} + a_{19} \cdot X_{19} + a_{24} \cdot X_{24} + a_{25} \cdot X_{25} + c_1/W_1 + c_2/W_2 + c_3/W_3 + c_4/W_4 + SA/2 + SE/2),$$

where:

$$\begin{aligned} X_1 &= \ln(\text{dbh}) \\ X_2 &= \ln(h) \\ X_3 &= \ln(Dg) \\ X_4 &= \ln(h/(h-1.3)) \\ X_5 &= (\ln(Dg))^{**2} \\ X_6 &= \ln(Hg) \\ X_7 &= (\ln(Hg))^{**2} \\ X_{14} &= \ln(1 - ((\text{tdl}/\text{dbh})^{**2}) * ((h-1.3)/h)) \\ X_{15} &= \ln(1 + ((\text{tdl}/\text{dbh})^{**2}) * ((h-1.3)/h)) \\ X_{16} &= \ln(1 - ((\text{tdl}/\text{dbh}) * ((h-1.3)/h))^{** (3/2)}) \\ X_{17} &= \ln(1 + ((\text{tdl}/\text{dbh}) * ((h-1.3)/h))^{** (3/2)}) \\ X_{18} &= \ln(1 - ((\text{tdl}/\text{dbh})^{**4}) * ((h-1.3)/h)^{**2}) \\ X_{19} &= \ln(1 - ((\text{tdl}/\text{dbh})^{**3}) * ((h-1.3)/h)^{**3}) \\ X_{24} &= Dg; \\ X_{25} &= (Dg)^{**2} \\ \\ W_1 &= 1 \\ W_2 &= (1 - (\text{tdl}^{**2}/\text{dbh}^{**2})) * (1 - (\text{dbh})/2) \\ W_3 &= (1 - ((\text{tdl})^{**2}/(\text{dbh}^{**2}))) * (1 - ((\text{dbh})/2))^{**2} \\ W_4 &= 1 - (\text{tdl}^{**2}/(\text{dbh}^{**2})) \end{aligned}$$

and a_0 - a_{25} and c_1 - c_4 are parameter estimates (see Appendix 1, Table 11). In the equation tdl is the top diameter limit, Dg is the mean squared diameter and Hg is the tree height corresponding to the mean squared diameter.

Estimates of growing stock are obtained by calculation of average growing stocks within the three concentric circles (3.5, 10 and 15 m radius) and subsequent summation of those average growing stocks (Table 4).

Table 4. Estimation of growing stock.

Description	Function
Volume of the i 'th tree on the j 'th sample plot is calculated from volume functions (F) based on tree diameter and (estimated) tree height and the squared mean diameter.	$v_{ij} = F(d_{ij}, h_{ij}, D_{g,j})$
Growing stock per hectare on the j 'th sample plot and the c 'th sample plot circle. R_c is an indicator variable that is 1 if the tree is measured within the c 'th circle ($c=3,5; 10; 15$ m) and 0 otherwise.	$V_{cj} = \frac{1}{A_{cj}} \sum_{i=1}^m R_c v_{ij}$
Calculation of the area weighted average growing stock of trees measured within the c 'th circles.	$\bar{V}_c = \frac{\sum_{j=1}^n A_{cj} V_{cj}}{\sum_{j=1}^n A_{cj}}$
Calculation of overall average growing stock.	$\bar{\bar{V}} = \bar{V}_{3,5} + \bar{V}_{10} + \bar{V}_{15}$
Calculation of total growing stock. $\bar{\bar{V}}$ is the overall average growing stock and A_{Forest} is the forest area.	$V = \bar{\bar{V}} \cdot A_{Forest}$

The growing stock with a specific characteristic (for example tree species, tree size or ownership) is calculated from the average growing stock per hectare with the particular characteristic on the measured sample plots times the total forest area (Table 5).

Table 5. Estimation of growing stock distributed to different categories, for example tree species or ownership.

Description	Function
<p>Volume per hectare with the k'th characteristic on the c'th circle in the j'th sample plot. R_c is an indicator variable that is 1 if the tree is measured in the c'th circle ($c=3,5; 10; 15$ m) and 0 otherwise. R_k is an indicator variable that is 1 if the i'th has the k'th characteristic and 0 otherwise. A_c is the forest area within the c'th circle.</p>	$V_{cj,k} = \frac{1}{A_{cj}} \sum_{i=1}^m R_{c,ij} R_{k,ij} v_{ij}$
<p>The area weighted average growing stock per hectare with the k'th characteristic for the c'th circles.</p>	$\bar{V}_{c,k} = \frac{\sum_{j=1}^n A_{cj} V_{cj,k}}{\sum_{j=1}^n A_{cj}}$
<p>Calculation of the average growing stock with the k'th characteristic.</p>	$\bar{\bar{V}}_k = \bar{V}_{3,5,k} + \bar{V}_{10,k} + \bar{V}_{15,k}$
<p>Calculation of the total growing stock with the k'th characteristic.</p>	$V_k = \bar{\bar{V}}_k \cdot A_{Skov}$

For calculation of forest biomass and carbon pools, local individual tree biomass functions are available for Norway spruce (Skovsgaard et al. 2010), beech (Skovsgaard and Nord-Larsen 2011), silver fir, grand fir, Douglas fir, Sitka spruce and Japanese larch (Nord-Larsen and Nielsen 2015). Biomass functions for other species are currently under development.

For tree species where biomass functions are available, individual tree biomass is estimated from measured diameter and the measured or estimated tree height.

For tree species where biomass functions are not yet available, total above ground volume for broadleaves and total stem volume for conifers is estimated with species specific volume functions. For species where no volume function is available, a volume function is chosen from a similar looking tree species. Subsequently, total above ground biomass and total stem biomass is calculated applying a species specific basic density (Moltesen 1985). Finally, total above ground biomass for conifers is calculated using a stem to total above ground biomass expansion factor model. The model was derived from the data used for developing the biomass functions for conifers mentioned above. For coniferous species an expansion factor model developed for Norway spruce (Skovsgaard et al. 2011) is applied, whereas for deciduous species an expansion factor model developed for beech (Skovsgaard & Nord-Larsen, 2012) is used.

Total biomass and pools of carbon are estimated based on the estimates of individual tree biomass. First, biomass per hectare is estimated for each of the concentric circles ($c=3.5, 10$ or 15 m radius) on each plot as the plot area depends on the diameter of the tree. Using the estimates from individual plots, the area weighted mean volume, biomass or carbon per hectare for the three concentric circles is estimated. The overall mean volume, biomass or carbon is estimated as the sum of the average volumes for the three circles. Finally, the total or regional volume, biomass or carbon is estimated as the forest area times the overall mean volume. See also Table 6.

Table 6. Estimation of biomass and carbon in live trees.

Description	Function
Biomass of the i 'th tree on the j 'th sample plot using biomass functions.	$b_{tot,ij} = f(dbh_{ij}, h_{ij})$
Biomass of the i 'th tree on the j 'th sample plot for species with no available biomass function. $V_{tot,ij}$ is the tree volume D (Appendix 1, Table 12) is the species specific wood basic density and e is a species specific expansion factor.	$B_{ij} = V_{tot,ij} \cdot D_i \cdot e_i$
Calculation of carbon (C) in the i 'th tree on the j 'th sample plot. An overall carbon content of 0.47 kg per kg biomass is assumed.	$C_{ij} = B_{ij} \cdot 0.47$
Carbon pool in the c 'th circle of the j 'th sample plot. R_c is an indicator variable that is 1 if the tree is measured in the c 'th circle and 0 otherwise. A is the area of the c 'th circle.	$C_{cj} = \frac{1}{A_{cj}} \sum_{i=1}^m R_c K_{ij}$
Area weighted average carbon pool per hectare of the c 'th circle.	$\bar{C}_c = \frac{\sum_{j=1}^n A_{cj} C_{cj}}{\sum_{j=1}^n A_{cj}}$
The average per hectare carbon pools	$\bar{\bar{C}} = \bar{C}_{3,5} + \bar{C}_{10} + \bar{C}_{15}$
Calculation of total carbon pools	$C = \bar{\bar{C}} \cdot A_{Forest}$

Biomass and carbon pools with a given characteristic are estimated in a similar way as for the forest growing stock (see Table 5). First, biomass or carbon per hectare with the given characteristic is estimated for each of the concentric circles ($c=3.5, 10$ or 15 m radius) on each plot. Using the estimates from individual plots, the area weighted mean biomass per hectare with the given characteristic for the three concentric circles is estimated. The overall mean biomass is estimated as the sum of the average volumes for the three circles. Finally, the total or regional biomass with the given characteristic is estimated as the forest area times the overall mean biomass or carbon.

1.3 Growth and removals

Forest growth is calculated as the difference in growing stock between two consecutive inventories (for example for the two five-year rotations 2007-2011 and 2012-2016) plus removals between the two inventories.

The growing stock in each of the inventories is calculated as described in Table 4.

Removals are calculated from permanent sample plots measured and remeasured in the two consecutive inventories. On permanent sample plots, individual trees are positioned and when remeasuring sample plots, field crews relate the new measurements to the previous. When trees are dead or removed during the five-year period since the last measurement, field crews record the reason for the removal (felled, dead, windthrown or unknown). Calculation of the removals follows the calculations of growing stock distribution to trees with specific characteristics (Table 7).

Table 7. Estimation of forest increment and removals.

Description	Function
Net periodic increment (NPI) is calculated as the difference in growing stock between two subsequent inventories.	$NPI = V_P - V_{P-1}$
Calculation of the area weighted average removals per hectare for the c 'th circle for plots inventoried in the subsequent inventories (belonging to I). $V_{cj,t}$ is the volume of trees dead or thinned between the inventories.	$\bar{V}_{c,t} = \frac{\sum_{j=1}^n A_{cj} V_{cj,t}}{\sum_{j=1}^n A_{cj}}, j \in I$
Calculation of the average removals per hectare.	$\bar{\bar{V}}_t = \bar{V}_{3,5,t} + \bar{V}_{10,t} + \bar{V}_{15,t}$
Calculation of the total removals.	$V_t = \bar{\bar{V}}_t \cdot A_{Forest}$
Calculation of gross periodic increment.	$GPI = NPI + V_t$
Calculation of gross annual increment (GAI) with a period length of five years between inventories.	$GAI = \frac{GPI}{5}$
Calculation of average mean periodic increment per hectare (MPI).	$MPI = \bar{\bar{V}}_P - \bar{\bar{V}}_{P-1} + \bar{\bar{V}}_t$
Calculation of mean annual increment per hectare (MAI) with a period length of five years between inventories.	$MAI = \frac{MPI}{5}$

1.4 Dead wood volume, biomass and carbon

The volume of standing dead trees is calculated similarly to the calculations for live trees. For standing dead trees, broken at some height, the volume is calculated using stem taper functions. The volume of lying dead trees within the sample plot is calculated as the length of the dead wood times the cross sectional area at the middle of the dead wood (Table 8). Biomass of the dead wood is calculated as the volume times the species specific basic density and a reduction factor according to the structural decay of the wood (Table 9). Finally, carbon content for each standing or lying dead tree is calculated by multiplying the dead wood biomass by 0.47.

Total or regional volume, biomass and carbon pools of deadwood are estimated based on the estimates of volumes, biomass and carbon for individual dead trees or pieces of dead wood. First, deadwood volume, biomass or carbon per hectare is estimated for each of the concentric circles ($c=3.5, 10$ or 15 m radius). Estimates for lying dead wood are made using the 15 m circle. Using the estimates from individual plots, the area weighted mean volume, biomass or carbon per hectare of deadwood for the three concentric circles is estimated. The overall mean deadwood volume, biomass or carbon is estimated as the sum of the average volumes for the three circles. Finally, the total or regional deadwood volume, biomass or carbon is estimated as the forest area times the overall mean volume.

Table 8. Estimation of dead wood volumes.

Description	Function
Volume of the i 'th standing dead tree on the j 'th sample plot is calculated from a volume function (F) based on the diameter and estimated height and squared mean diameter of trees on the plot.	$v_{s,ij} = F(d_{ij}, h_{ij}, D_{g,j})$
Volume of the i 'th lying piece of dead wood on the j 'th sample plot is calculated from the mid-diameter (d_i) and length of the piece.	$v_{l,ij} = \frac{\pi}{4} d_{l,ij}^2 \cdot l_{l,ij}$
Volume of dead wood per hectare of the c 'th circle on the j 'th samle plot. R_c is an indicator variable that is 1 if the tree is measured on the c 'th circle and 0 otherwise.	$V_{D,cj} = \frac{1}{A_{cj}} \sum_{i=1}^m R_c v_{s,ij} + R_c v_{l,ij}$
Calculation of the area weighted average dead wood volume per hectare for the c 'th circle.	$\bar{V}_{D,c} = \frac{\sum_{j=1}^n A_{cj} V_{D,cj}}{\sum_{j=1}^n A_{cj}}$
Calculation of the overall average volume of dead wood.	$\bar{\bar{V}}_D = \bar{V}_{D,3,5} + \bar{V}_{D,10} + \bar{V}_{D,15}$
Calculation of the total volume of dead wood.	$V_D = \bar{\bar{V}}_D \cdot A_{Skov}$

Similar to live trees, the biomass of dead trees is calculated by multiplying the volume with a species specific basic density. Further, the calculated biomass is reduced with a factor reflecting the structural decay of the dead wood.

Subsequent calculations of total volume, biomass and carbon pools and their distribution to different categories follow the calculations described for live trees (Table 4, Table 5).

Table 9. Estimation of biomass in dead wood.

Description	Function
Biomass in standing and lying dead trees (B_s and B_l). D is the species specific density (Appendix, Table 12) of the i 'th standing or lying dead tree and r is a reduction factor reflecting the structural decay (k) of the dead wood (Appendix, Table 13).	$B_{s,ij} = v_{s,ij} \cdot D_{ij} \cdot r_k$ $B_{l,ij} = v_{l,ij} \cdot D_{ij} \cdot r_k$
Carbon in standing ($C_{s,ij}$) and lying dead wood ($C_{l,ij}$).	$C_{s,ij} = B_{s,ij} \cdot 0.47$ $C_{l,ij} = B_{l,ij} \cdot 0.47$

1.5 Carbon in the litter layer

The amount of carbon in the organic litter layer depends on layer thickness and composition. Litter layer thickness is measured in the field with a soil auger.

The average litter layer carbon pools on the individual plots are calculated as the litter layer thickness times the average density of the litter layer and the average carbon content of the litter biomass (Table 10). The density of the litter layer depends on the main tree species (Table 14). The average carbon content of litter biomass is set at 40%.

Table 10. Estimation of biomass and carbon in the forest soils.

Description	Function
Average carbon in the litter layer (C_o) on the j 'th sample plot. T is the thickness of the litter layer and D is the density determined from the main tree species on the sample plot. The average carbon content of litter biomass is set at 40%.	$C_{o,j} = T_j \cdot D_j \cdot 0,4$
Calculation of the average carbon content of the litter layer.	$\bar{C}_o = \frac{\sum_{j=1}^n A_j C_{o,j}}{\sum_{j=1}^n A_j}$
Calculation of total litter layer carbon pools.	$C_o = \bar{C}_o \cdot A_{Forest}$

Appendix 1:

Table 11. Parameter estimates of the volume functions in the Danish NFI.

Function	TDL	a0	a1	a2	a3	a4	a5	a6	a7	a14	a15	a16	a17	a18	a19	a24	a25	c1	c2	c3	c4	SA	SE
<i>Picea abies</i>																							
0	0	-1,77222	1,769313	1,171489	0	0,470221	-0,02124	0	-0,0185	0	0	0	0	0	0	0	0	0	0	0,001453	0	0	0
1	0	-1,75358	1,775814	1,136852	0	0,524851	0	0	0	0	0	0	0	0	0	0,725722	-1,10822	0	0	0,001411	0	0	0
1	5	-1,96822	1,573607	1,157948	0	0	0	0	0	0	0,973479	0	-1,68529	0,906558	0	0,244828	0	0	0	0,001306	0	0	0
1	7	-2,11543	1,490901	1,197033	0	0	0	0	0	0	1,695886	0	-2,37616	1,056454	0	0,236993	0	0	0	0,001331	0	0	0
1	10	-2,38638	1,361796	1,285676	0	0	0	0	0	0	2,544124	0	-3,36683	1,064439	0	0,186363	0	0	0	0,001465	0	0	0
<i>Picea sitchensis</i>																							
0	0	-2,84583	1,735866	1,466364	0	1,69918	0	0	0	0	0	0	0	0	0	0,269563	-0,95195	0	0	0,001761	0	0	0
1	0	-2,71351	1,759844	1,44207	0	1,917824	0	0	0	0	0	0	0	0	0	0,252296	-0,81364	0	0	0,00175	0	0	0
1	5	-2,3845	1,513453	1,274685	0	0	0	0	0	0	0	0	-1,33971	0,323825	0	0,114545	0	0	0	0,001682	0	0	0
1	7	-2,59542	1,505677	1,348035	0	0	0	0	0	0	0	0	-0,77122	0,77781	0	0	0	0	0	0,001642	0	0	0
1	10	-2,76605	1,576879	1,403924	0	0	0	0	0	0	0	0	0	0,983722	0	0	0	0	0	0,001723	0	0	0
<i>Pseudotsuga menziesii</i>																							
0	0	-1,39991	1,817068	1,03796	0	0	0	0	0	0	0	0	0	0	0	0	0,180928	0	0,002287	0	0	0	0
1	0	-1,20251	1,832615	0,991312	0	0	0	0	0	0	0	0	0	0	0	0	0,259585	0	0,00216	0	0	0	0
1	5	-1,42327	1,800541	1,036478	0	0	0	0	0	0	0	0	0	1,022298	0	0	0,240247	0	0,002183	0	0	0	0
1	7	-1,42952	1,791862	1,033283	0	0	0	0	0	0	0	0	0	0,957605	0	0	0,275505	0	0,002252	0	0	0	0
1	10	-1,17197	1,800845	0,952246	0	0	0	0	0	0	0	0	0	1,016504	0	0	0,365047	0	0,002434	0	0	0	0
<i>Larix kaempferi</i>																							
0	0	-2,3087	1,760821	1,351809	0	0,646612	0	0	0	0	0	0	0	0	0	0	-0,60676	0	0,001373	0	0	0	0
1	0	-2,13198	1,774789	1,302453	0	0,764979	0	0	0	0	0	0	0	0	0	0	-0,28223	0	0,0013	0	0	0	0
1	5	-2,19419	1,69377	1,280707	0	0	0	0	0	0	0	0	0	1,087649	0	0	0	0	0,001343	0	0	0	0

Function	TDL	a0	a1	a2	a3	a4	a5	a6	a7	a14	a15	a16	a17	a18	a19	a24	a25	c1	c2	c3	c4	SA	SE	
1	7	-2,20908	1,682309	1,280128	0	0	0	0	0	0	0	0	0	0,986066	0	0	0	0	0,001364	0	0	0	0	
1	10	-2,34365	1,644613	1,309113	0	0	0	0	0	0	0	0	0	0,930808	0	0	0	0	0,001402	0	0	0	0	
<i>Abies alba</i>																								
0	0	-3,07564	1,76769	1,453828	0	3,735672	0	0	0	0	0	0	0	0	0	1,53803	-2,50233	0	0	0,001079	0	0	0	
1	0	-3,05886	1,789127	1,459622	0	4,226077	0	0	0	0	0	0	0	0	0	1,564662	-2,57388	0	0	0,001046	0	0	0	
1	5	-1,83617	1,786329	1,158275	0	0	0	0	0	0	0	0	0	0	0	1,036908	-1,64085	0	0	0,001053	0	0	0	
1	7	-1,86491	1,803636	1,168073	0	0	0	0	0	0	0	0	0	0	0	1,174249	-1,91471	0	0	0,001037	0	0	0	
1	10	-1,94156	1,755337	1,179995	0	0	0	0	0	0	0	0	0	0,808134	0	0,96566	-1,44801	0	0	0,00105	0	0	0	
<i>Abies grandis</i>																								
0	0	-2,07149	1,727505	1,171378	0	0	0	0	0	0	0	0	0	0	0	0,854869	-0,81197	0,00274	0	0	0	0	0	
1	0	-1,83606	1,750469	1,116252	0	0	0	0	0	0	0	0	0	0	0	0,81103	-0,59923	0,002599	0	0	0	0	0	
1	5	-2,1069	1,72694	1,176499	0	0	0	0	0	0	0	0	0	0,874295	0	0,974358	-0,96425	0	0,00235	0	0	0	0	
1	7	-2,13355	1,711983	1,165169	0	0	0	0	0	0	0	0	0	0,938564	0	1,147646	-1,08141	0	0,002298	0	0	0	0	
1	10	-2,21197	1,661504	1,148836	0	0	0	0	0	0	0	0	0	1,017624	0	1,398117	-1,17013	0	0,002495	0	0	0	0	
<i>Fagus sylvatica</i>																								
0	0	-1,80422	1,876008	1,182156	0	1,278466	0	0	0	0	0	0	0	0	0	0,155176	0	0	0	0	0,000293	0,004823	0	
1	0	0,467065	2,100761	0,715347	0,235416	0	0,064329	0	0	0	0	0	0	0	0	0	0	0,002777	0	0	0	0	0	0
1	5	-0,67449	2,137268	0,957545	0	0	0	0	0	0	0	0	0,668822	0,855764	0	0	0,175118	0	0,002036	0	0	0	0	
1	7	-0,82543	2,181697	0,994047	0	0	0	0	0	0	0	0	0,957453	1,008783	0	0	0,148965	0	0,001925	0	0	0	0	
1	10	-0,86566	2,158306	0,98676	0	0	0	0	0	0	0	0	0,608793	0,843249	0	0	0,157324	0	0,001848	0	0	0	0	
<i>Quercus robur</i>																								
0	0	-1,87629	1,876423	1,219715	0	1,306483	0	0	0	0	0	0	0	0	0	0,096859	0	0	0	0	0,000598	0,004919	0	
1	0	-0,17285	2,084477	0,801886	0	1,07969	0	0	0	0	0	0	0	0	0	0,280564	0	0,003174	0	0	0	0	0	
1	5	-0,7128	2,10968	0,919557	0	0	0	0	0	0	0	0	0,688118	0,816693	0	0,675413	-0,39078	0	0	0,001714	0	0	0	

Function	TDL	a0	a1	a2	a3	a4	a5	a6	a7	a14	a15	a16	a17	a18	a19	a24	a25	c1	c2	c3	c4	SA	SE
1	7	-0,85522	2,125952	0,94509	0	0	0	0	0	0	0	0	0,794239	0,991454	0	0,728208	-0,38867	0	0	0,00163	0	0	0
1	10	-1,07895	1,97802	0,988531	0	0	0	0	0	0	0	0	0	0,850331	0	0,482206	0	0	0	0,001546	0	0	0
<i>Fraxinus excelsior</i>																							
0	0	-2,38416	1,813248	1,296	0	1,917255	0	0	0	0	0	0	0	0	0	0,602923	-0,58401	0	0	0	0	0,00085	0,00358
1	0	-1,08869	2,002341	1,022051	0	2,174706	0	0	0	0	0	0	0	0	0	0,697865	-0,61407	0,002518	0	0	0	0	0
1	5	-1,34867	1,991887	1,098804	0	0	0	0	0	0	0	0	0,429361	0,955966	0	0,258224	0	0	0,001704	0	0	0	0
1	7	-1,51518	1,99115	1,125761	0	0	0	0	0	0	0	0	0,558633	1,070868	0	0,297575	0	0	0,001774	0	0	0	0
1	10	-1,75733	1,999106	1,18868	0	0	0	0	0	0	0	0	0,621417	1,088072	0	0,228857	0	0	0,001726	0	0	0	0

Table 12. Basic density for different tree species used in estimation of biomass and carbon (Moltesen, 1988). Basic density of beech and Norway spruce (marked with *) are estimated using basic density functions from Skovsgaard and Nord-Larsen (2012) and Skovsgaa

Broadleaves	Basic density Tons per m ³	Conifers	Basic density Tons per m ³
Beech	0.56*	Norway spruce	0.38*
Oak	0.57	Sitka spruce	0.37
Ash	0.56	Other fir sp.	0.38
Sycamore	0.49	Other pine sp.	0.43
Other	0.56	Mountain pine	0.48
		Contortafyr	0.37
		Scots pine	0.43
		Nordman fir	0.38
		Noble fir	0.38
		Other	0.38
		Douglasfir	0.41
		Larch sp.	0.45

Table 13. Basic density reduction factors for different degrees of structural decay of dead wood in broadleaves and conifers.

Observed structural decay class	Reduction factor	
	Broadleaves	Conifers
1	0.804	0.895
2	0.607	0.632
3	0.429	0.605
4	0.304	0.447

Table 14. Density of the litter layer in forest stands with different tree species, used in the estimation of soil carbon of the litter layer (Vesterdal and Raulund-Rasmussen, 1998).

Broadleaves	Basic density Tons per m ³	Conifers	Basic density Tons per m ³
Beech	0.55	Norway spruce	1.09
Oak	0.36	Sitka spruce	0.86
Ash	0.55	Other fir sp.	1.09
Sycamore	0.55	Pine sp.	0.79
Other	0.55	Nordmann fir	1.09
		Noble fir	1.09
		Other	0.94

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