Report for the 2023 Estonian national greenhouse gas inventory LULUCF (Land-use, land use change and forestry) sector forest land remaining forest land subcategory biomass pool.

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The purpose of this report is to serve as a quality assurance (QA) check performed by an external expert who is not directly involved in the preparation of the inventory and sectoral emissions estimates. As such, it can be included as part of the QA report of the LULUCF sector forest land remaining forest land subcategory biomass pool of the 2023 Estonian national inventory of greenhouse gases (GHG). The need for the QA check emerged from the fact that Estonian GHG inventory is changing the approach in subcategory in question from Stock-Difference Method to Gain-Loss Method (IPCC 2006, 2.2.1).

In an in person meeting in Tartu, Nov 29 to 30, 2023, a presentation of the whole Estonian NFI and LULUCF system and the relevant data sets were given, an overview of the new gain and loss calculations was provided, and new developments and changes to the models planned in the near future were explained. The difficulties with the previously applied stock change methods were also illustrated. This report is based on that presentation, ensuing discussions with sectoral experts in Tartu, and one further virtual meeting on Dec 11. Within the agreed time limits, it was not possible to assess the actual implementation of the computational methods. Hence this report is based on the assumption that they have been implemented as presented and discussed.

The report consists of two parts: Description of the new method (Part I) and review findings and expert judgement according to the provided template (Part II).

Part I: Gain and loss method to evaluate carbon (C) changes in forest land (FL) remaining FL

1. Overview

Relatively complex calculations and several models are required to implement the method in an appropriate manner. The details are explained in section 2, but the core of the method can be roughly summarised as follows:

- The current growing stock (stem volume) per unit area of FL is estimated based on the distribution of stand age and site quality index of the forest stands assessed by Estonian National Forest Inventory (NFI) during the last five years' field measurements. The estimate relies heavily on statistical model (4) that predicts plot-level growing stock (tree stem volume) given the average age of the dominating species and the site quality index.
- The stock is projected five years to the future from the measurement time using the same model (4) and assuming that the site quality index remains the same and age increases by five years.
- The annual gains (in stem volume) per area unit of FL are obtained as the difference of the projected and current stocks divided by five.
- Annual losses of stem volume are reported as an average over the last five harvest seasons. Mean volume lost per area unit of clear-felled FL is estimated by predicting the pre-harvest volumes of the clear-felled plots with the same model (4) that is used for gains and subtracing from this prediction the average share of volume remaining in clear-fellings (seed trees, retention trees etc.).
- The difference of stem volume gains and losses is converted to whole tree biomass with nationally developed stand-level biomass models and further to carbon applying the default carbon fractions.
- Biomass gains due to forest growth in converted FL are subtracted from the estimated change in total FL to obtain the C change in FL remaining FL.

The method relies on both tree-level measurements and stand-level assessments of NFI sample plots as detailed in Section 2. Model validations included in the presentation are reviewed in Section 3.

2. Computational details

Activity data

Areas of total FL and land coverted to FL are estimated based on current land use of all NFI plots (five years' average) as well as on land-use changes on those plots during the last five years before the measurement. Similar estimation of the areas of total FL and land coverted to FL is required regardless of the chosen approach (gain-loss or stock change). Hence the discussion that follows only concerns estimation of gains per area unit of target category. To estimate the losses, area of FL clear-felled in year t is estimated based on the proportion of plots that have been clear-felled during the last harvest season before the assessment among FL plots assessed by NFI during years $t-4, t-3, \ldots, t$.

Site quality index and dominant age

Both gains and losses of the growing stock are essentially estimated using the site quality index and the average age of the dominating species in tree stands assessed in NFI (pre-harvest age in case of clear-felled stands). The average age of dominant tree species, A_p, is assessed in the field for all NFI plots, as well as the average height of dominant tree species, H_p. In most cases, site quality indices for stand p are then computed as

$$H_{50,p} = \frac{H_p \left\{1 + \alpha\left[\left(50/A_p\right)^c - 1\right]\right\}}{\left\{1 - \beta H_p\left[\left(50/A_p\right)^c - 1\right]\right\}} \tag{1}$$

and

$$H_{100,p} = \frac{H_{50,p}}{\left[1 + \left(\alpha + \beta H_{50,p}\right)(0.5^c - 1)\right]}. \tag{2}$$

Species-specific parameters α, β, and c are based on forest management planning regulation. For the youngest stands, site quality index $H_{100,p}$ is determined, based on the same regulation, as

$$H_{100,p} = 33.5 - 4B_p, \tag{3}$$

where B_p is determined by the field-assessed bonity class as follows:

B	0	1	2	3	4	5	6
Bonity class	Ia	I	II	III	IV	V	VI

Model for plot-level volume prediction

Gains and losses per area unit are essentially estimated using the following general model to predict the volume of growing stock on all NFI plots p, when the averege age of dominant tree species is A_p:

$$V_p = V_p\left(A_p\right) = \left(a_1 + a_2 H_{100,p} + a_3 I_p\right)\left(\frac{A_p}{A_p + 5}\right)^{c_1 + c_2 H_{100,p}}. \tag{4}$$

Parameters a_1, a_2, a_3, c_1, and c_2 have been estimated separately for seven groups of dominant tree species using NFI data from so-called volume plots measured during years 1999-2018. Age limits are set to the species groups so that the volume predictions remain constant after limit age. Indicator variable I_p gets value 1, when plot p is located on seaside counties Saaremaa, Hiiumaa or Läänemaa, 0 otherwise.

To estimate the parameters of model (4), plot-level volumes for NFI volume plots are predicted by aggregating tree-level volume predictions. For trees i with height $h_i \geq 6\text{m}$, these are obtained from model

$$v_i = 0.0000785\, d_i^2 h_i \left(a + \frac{b}{d_i} + \frac{c}{h_i} + \frac{d}{d_i h_i}\right), \quad (5)$$

based on Estonian forest management planning regulation, which includes specific parameter values a, b, c, and d for five groups of species. When predicting tree-level volumes v_i with model (5), the breast-height diameters d_i, which are measured for all trees in NFI volume plots, are used. But since heights are measured only for 3-5 trees per NFI volume plot, height of tree i on plot p is predicted with model

$$h_i = 1.3 + \left(a_1 + a_2 H_{100,p} + a_3 I_p\right)\left(\frac{d_i}{d_i + b_1}\right)^{c_1 + c_2 H_{100,p}}, \quad (6)$$

where parameters a_1, a_2, a_3, b_1, c_1, and c_2 are estimated separately for eight groups of dominant species using the trees with measured h_i from NFI data from years 1999-2018. For trees i with height $h_i < 6\text{m}$, volume predictions are derived from a simpler model

$$v_i = 0.0000785\, d_i^2 h_i \left(a + \frac{b}{h_i^c}\right), \quad (7)$$

which, similarly to model (5), is based on Estonian forest management planning regulation giving separate parameter values a, b, and c to five groups of species.

Stem volume gains per unit area of FL

Gains of stem volume per hectare for years t=2004, 2005, ..., reporting year, are estimated with model (4) as an average over all NFI plots measured in years $t' = t-4, t-3, \ldots, t$ based on the field-assessed age of the dominant species $A_{p,t'}$ and the site quality index $H_{100,p}$. The gains per year contributed by plot p are estimated as

$$G_{t,p} = \frac{\left[V_p\left(A_{p,t'+5}\right) - V_p\left(A_{p,t'}\right)\right]}{5}. \quad (8)$$

It should be noted that this essentially estimates the average difference between the increment (tree growth) and stem volume reductions due to intermediate loggings (thinnings) and natural mortality – i.e. reductions, where the age of the dominant species is not altered – since the volumes used to fit model (4) include the impacts of these.

Stem volume losses per unit area of FL

In accordance with the previous subsection, losses are defined as reductions in stem volume of living trees caused by clear-fellings: average age of the dominant specis drops to 0. The losses per hectare of clear-felled FL are estimated for year t as an average over those NFI plots measured in years $t' = t-4, t-3, \ldots, t$ that have been clear-felled during the harvest season (May 1, year t'-1 – April 30, year t') preceding. The losses contributed by clear-felled plot p are estimated as

$$L_{t,p} = (1 - f)V_p(A_{p,t'-}), \tag{9}$$

where $V_p(A_{p,t'-})$ is obtained using model (4) with $A_{p,t'-}$ set to the averege age of dominant tree species before the harvest and f is the average share of trees that remain standing in clear-fellings (seed trees, retention trees, etc.) estimated from NFI permanent plots.

The age before harvest is not always available in the earliest NFI measurements. In such exceptional cases, pre-harvest volume is estimated from stump measurements using models (6) and (5) with breast-height diameters d_i predicted from stump-height diameters $d_{0,i}$ with model

$$d_i = a_1 + a_2\left(\frac{d_{0,i}}{10}\right) + a_3 I_p, \tag{10}$$

based on NFI model trees. The volume prediction is further corrected using the average share of missed stumps estimated from permanent NFI plots.

C change in total FL

The difference between stem volume gains and losses is converted to whole tree biomass with linear models

$$B = a_1 + a_2 V, \tag{11}$$

where separate values of parameters a_1 and a_2 for the seven tree species groups were deterimined in a study by V. Uri (2020). The IPCC default carbon fraction coefficients are applied to the resulting estimates of biomass change to convert them into C.

C change in FL remaining FL

Based on Estonian NFI data, the average annual increase of stem volume in young stands is estimated to be 3.04 m^3/ha. C gains in converted FL, based on this estimate, on the annual estimates of the area converted to FL, and on biomass expansion and C conversion explained in the previous subsection, are subtracted from C change in total FL to obtain C change in FL remaining FL for years 2004, 2005, ..., reporting year. The results for 1990 – 2003 are based on other sources, which were not discussed in detail.

3. Model validations

The following validations were presented in the Tartu meeting

- A comparison of felling volumes estimated with the presented method to an independent expert evaluation based on remote sensing, NFI and felling documentary for years 2007 – 2021. The latter shows more year-to-year variation, but the average levels are similar.

- A comparison of the estimated change in the volume of growing stock between the presented method and direct estimates based on NFI permanent plots for periods 1999 – 2004, ..., 2017 – 2022. The latter has been at a slightly higher level since 2011 – 2016, indicating that the presented method is rather under- than overestimating the C sink of living biomass.
- Comparison of growing stock volumes predicted with model (4) to corresponding plot-level volumes used in NFI (based on models (5) and (7). The latter has previously shown more year-to-year variation, but since 2016, the patterns are quite similar.

Part II: Review findings and expert judgement

Question	Assessment (including problems and recommendations)
Provide an expert judgment on the suitability/appropriateness of the Gain-Loss method with Estonian National Forest Inventory (NFI) system and available data (Forest land remaining Forest land subcategory biomass pool).	It is commonly accepted that National Forest Inventories (NFI) are the most reliable source of information on the average amount of living tree biomass per area of Forest land (FL) and on the area of FL at national and regional level. To my knowledge, NFI is used as the basis of FL category reporting in national GHG inventories whenever it is sufficiently developed for that purpose. The main benefit of a well-developed NFI, such as the current one in Estonia, is that it equally covers all land area and is based on accurate field measurements of trees. This implies that systematic errors due to omission of certain subpopulations (e.g., specific ownership), due to imperfect information (e.g., outdated maps), or due to interpretation of indirect measurements (e.g. remote sensing), are avoided. The main problems with NFIs are that they can only collect a sample of all forests and that the same locations can be visited relatively infrequently (e.g. five years' intervals). This implies that quick changes which are small compared to the stock size may not be detected with sufficient precision. In principle, the Gain-Loss Method can be appropriately implemented based on Estonian NFI data as explained in Part I of this report. However, it is not completely clear from the available documentation, how well the method captures the temporal dynamics of the C stocks. In particular, annual estimates of losses due to clear-fellings are computed as averages over five-year periods, which do not respond to

	changes quickly enough from the viewpoint of monitoring anthropogenic emissions. On the other hand, the Stock-Difference Method, as implemented this far, responds to changes even more slowly (see below for comparison) so that the switch to Gain-Loss Method is a definite improvement in that sense. The problem could be further mitigated by employing external sources of information, such as remote sensing or way bills, for more timely estimation of clear-felling areas and logging volumes.
Preliminary assessment of the Gain-Loss calculation approach.	As far as I can judge, the calculation approach is sound given that the applied models are valid. A potential weakness of the Gain-Loss Method is that it relies heavily on statistical models, as detailed in Part I of this report. According to the presented validations, the models appear to yield unbiased predictions of stock changes on average, which is to be expected, since they are based on large NFI data. The problem is that the models are static in time and may therefore not respond to all changes such as changes is damage frequency and/or severity. This issue is being investigated in an ongoing project led by Kalev Pärna at Tartu University.
Provide an expert judgment whether Gain-Loss or Stock-Difference method is more appropriate, considering activity data in accordance with Estonias NFI system, for Estonian LULUCF calculations.	According to the lastest National Inventory Report (Estonian Ministry of the Environment, 2023, 6.2.2.1), the calculation of carbon changes in living biomass by the previously applied Stock-Difference Method included the usage of 15-year trend. Thus the timeliness of the Gain-Loss Method is markedly better. Another problem with the Stock-Difference Method has been that majority of NFI plots are temporary (in different locations between subsequent field visits of the same tract). This adds substantially to the sampling variation of the estimates of stock changes, which is a commonly

	acknowledged problem, e.g. “where biomass change is very small compared to the total amount of biomass, the inventory error under the stock-difference method may be larger than the expected change” (IPCC 2006, 4.2.1.1). The principal idea of the Gain-Loss Method is to alleviate this sampling uncertainty problem by using collocated units when assessing changes (e.g., Equation (8), Part I of this report), The main problem with the presented Gain-Loss Method is its strong dependence on statistical models; the stocks in the Stock-Difference Method could be estimated more directly from the NFI measurement data. When weighting these pros and cons of the two methods, my judgement is that the Gain-Loss Method is more appropriate and better adaptable to further improvements as discussed below.
Provide expert judgement on potential risks of using Gain-Loss method based on Finnish experience	The Finnish version of the Gain-Loss Method is based on direct measurements of increment from permanent NFI plots (share of permanent plots is currently 80%) and on loss data that is primarily based on annual statistics of roundwood removals. Compared to the Estonian version, this provides • better timeliness of estimates of anthropogenic emissions due to harvests and • weaker dependence on model-based estimates. If the Estonian version is developed to the same direction, separate estimates of carbon losses due to thinnings and natural mortality would be required. Also the amount of permanent plots would likely have to be increased, if direct (model-free) estimates of increment are required. Furthermore, if additional data sources, such as remote sensing or way bills collected on transportation of logged wood, is required for better timeliness, then

	uncertainty assessments become much more complicated compared to estimates based on NFI data only. The problems related to annual recalculation of the entire time series are already familiar to the Estonian GHG inventory due to continuously evolving estimates of land-use transitions (Estonian Ministry of the Environment, 2023, 6.2.5.). Similarly, improvements in the assessment methods for gains and/or losses have required frequent recalculations of the Finnish time series. These are extremely difficult to communicate to the public although recalculation of the whole time series is a normal part of GHG inventory development and required by IPCC instructions. One source of problems in the Finnish case have been discrepancies between inventory results on one hand and scenario and/or reference level calculations on the other. Even if GHG inventory uses the Gain-Loss Method, scenarios may have to be based on the Stock-Change Method, which can cause such discrepancies.
Reccomendations for futher developments for calculations.	The following recommendations for further developments were already discussed in the Tartu meeting: • Losses (clear-fellings) could perhaps be estimated from a shorter time period, e.g., three years. Since they are the main anthropogenic driver in C stock changes, it would be justifiable to estimate them with smaller temporal smoothing than that used for the gains. • Additional sources of information for clear-felling areas should be considered. In particular, the potential of using way bills collected on transportation of logged wood to estimate logging volume is under investigation.

	• The gains could be more accurately targeted to the reporting year t by using $$\frac{V_p(A_{p,t+1}) - V_p(A_{p,t'})}{t+1-t'}$$ in (8). More generally, the method should be developed towards weaker model-dependence and more direct estimation of change components, if possible. Increasing the proportion of permanent plots could be one way. Several projects are already ongoing towards further development of the method. Since the developments are usually addressing specific components of change (e.g., harvests), they are usually easier to implement in the Gain-Loss context than in the Stock-Change context. The methods and models used should be subjected to peer-review. According to the discussions with the sectoral experts, a reasonable timing for aiming to publish the methods in a scientific journal would be after the ongoing development projects have been completed.

References

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