Data on soil carbon stock change, carbon stock and stock change in surface litter and in coarse dead wood prepared for the Swiss NIR 2024 (GHGI 1990–2022)

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Summary

Switzerland prepares annually a greenhouse gas inventory for reporting under the climate convention UNFCCC and the Paris Agreement (PA). The Land Use, Land-Use Change and Forestry (LULUCF) sector of the Swiss inventory includes, inter alia, data for the forest sector, encompassing amongst others C stocks and C stock changes (CSC) in above- and belowground dead biomass and in the soil. Starting with the National Inventory Report (NIR) 2013 covering the period 1990-2011, the C decomposition model Yasso07 was used for deriving estimates of C stock and CSC in dead wood, incl. stems, branches and roots, non-woody litter and in soils on productive forest lands.

In an effort to improve Switzerland's GHG accounting with regard to the criteria for transparency, consistency, comparability, completeness and accuracy (TCCCA; section 1.1), the method for estimating C stocks and CSC in above- and belowground dead biomass and in the soil is documented in section 2. Since the previous submission, several methodological changes were implemented, including the application of the improved model version Yasso20 (section 2.6.1) and application of new estimates from the 5th cycle of the National Forest Inventory.

In section 3, the results obtained for reporting in the NIR 2024 (1990-2022) are presented and discussed. The methodological changes had a statistically significant effect on estimated C stock changes compared to data reported in the NIR 2023. In the period 1990-2017 where NFI remained approximately the same, the application of the new Yasso20 model version was the main reason for the change compared to the NIR 2023. The new NFI data that represented the period since 2018, which was affected by increased natural mortality, provided a more accurate representation of the C fluxes as compared to the data reported in the NIR 2023. As reported in section 3.1, the total CSC in dead wood, litter, and mineral soil in Swiss forests from 2021 to 2022 was a gain of 0.189 ±0.015 (2SE) Mg C ha^{-1} a^{-1}. The pools dead wood (gain of 0.080 ±0.009 Mg C ha^{-1} a^{-1}) and litter (gain of 0.104 ±0.011 Mg C ha^{-1} a^{-1}) were the primary drivers of the overall C balance. Mineral forest soils were responsible for minor gains of 0.005 ±0.001 Mg C ha^{-1} a^{-1}.

Section 3.3 presents ongoing and planned projects to further improve the estimates of C stocks and CSC in dead wood, litter and soil on forest lands in Switzerland and which are expected to increase the quality of the Swiss GHGI.

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Glossary

Carbon pools: Terminology follows the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (Table 1.1, IPCC 2006b):

- Soil organic carbon (SOC)
- Litter
- Dead wood

Following the convention used by Switzerland in its National Inventory Reports and based on the National Forest Inventory definitions, the reported pools comprise

- **Soil**: organic C in mineral soil up to a depth of ca. 100 cm
- **Litter**: non-woody material including foliage, seeds and fruits, fine roots < ca. 5 mm diameter, and fine woody litter, including small branches and tree top < ca. 7 cm diameter and bark of the tree bole; corresponds to LFH (Litter - Fermenting - Humified) layer
- **Dead wood** : stemwood including stump and bole of trees ≥12 cm, large branches ≥ ca. 7 cm and coarse roots > ca. 5 mm;
- **All**: the sum of the above listed pools

***Dead organic matter* (DOM)**: Term is used as defined in IPCC (2006b), i.e. dead wood and litter.

National Forest Inventory of Switzerland (NFI; *Schweizerisches Landesforstinventar*, LFI; www.lfi.ch):

- State analyses (*Zustandsauswertungen*):

- NFI1: field data collected 1983-1985; assumed to be representative of the year 1985
- NFI2: field data collected 1993-1995; assumed to be representative of the year 1995
- NFI3: field data collected 2004-2006; assumed to be representative of the year 2005
- NFI4: field data collected 2009-2017;
    - starting with the NFI4, the methodology changed from a periodic to a continuous survey during which annually one-ninth of all NFI sample plots are visited; plots visited within each annual cycle provide a nationally representative sample
- NFI5: field data collected 2018-2026.

- Change analyses (*Veränderungsauswertungen*):

- NFI12: assumed to be representative of the period 1986 to 1995; the change is estimated based on all plots common to the inventories NFI1 and NFI2
- NFI23: assumed to be representative of the period 1996 to 2005; the change is estimated based on all plots common to the inventories NFI2 and NFI3
- NFI34: assumed to be representative of the period 2006 to 2017; the change is estimated based on all plots common to the inventories NFI3 and NFI4
- NFI45: assumed to be representative of the period 2018 to 2022; the change is estimated based on all plots common to the first five years of the inventories NFI4 and NFI5

Units of carbon measurements:

- Carbon stocks:

- Kilogram (Kg)
- Megagram (Mg) = 1 metric ton = 10^3 Kg

- Carbon stock changes:

- Kilogram per hectare and year (Kg ha^{-1} a^{-1}) = 0.1 g m^{-2} a^{-1}
- Megagram per hectare and year (Mg ha^{-1} a^{-1}) = 1000 Kg ha^{-1} a^{-1}
- Gigagram per hectare and year (Gg ha^{-1} a^{-1}) = 1000 Mg ha^{-1} a^{-1}

1 Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement are international treaties to reduce greenhouse gas (GHG) emissions. As a signature state to both, Switzerland is required to maintain a comprehensive GHG inventory, including emissions and removals of CO_2-eq. from Land Use, Land-Use Change and Forestry (LULUCF). Thus, C stocks and C stock changes (CSC) in above- and belowground living and dead biomass and in the soil have to be reported in Switzerland's annual National Inventory Reports (NIR). Starting with the NIR 2013 (FOEN 2013), the C decomposition model Yasso07 (Tuomi et al. 2011; Tuomi et al. 2009) was used for deriving estimates of C stocks and CSC in dead wood (incl. stems, branches and roots), non-woody litter and in soils on productive forest lands (Didion et al. 2012).

Together with the first publication of the results obtained with Yasso07 in the NIR 2013, Switzerland committed to further improve the model implementation and the accuracy of the estimates of temporal CSC in soil, litter, and dead wood. The estimates for these pools for the NIR submission 2024 (1990-2022) is based on the same methodology as the submission in 2023, but using a further developed model version Yasso20 that was shown to improve accuracy compared to Yasso07 (section 2.2). Further, new National Forest Inventory (NFI) data were available for the simulation (sections 2.4.1 and 2.4.2). The report describes input data for modelling and the methodology and presents and discusses the estimates of C stocks and CSC for publication in NIR submission 2024 (section 3).

1.1 TCCCA criteria and verification: specific information under UNFCCC and ETF under the Paris Agreement

Consistent with good practice outlined in Volumes 1 and 4 of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, the report addresses the criteria for transparency, consistency, comparability, completeness and accuracy (TCCCA):

Transparency is achieved by documenting data sources, assumptions and methodologies that were used, including relevant references. The methodology is described in detail to ensure that results can be reproduced. Consistent with the reporting guidelines on annual inventories for Parties included in Annex I to the Convention (decision 24/CP.19) and the modalities, procedures and guidelines for the transparency framework for action and support referred to in Article 13 of the Paris Agreement (decision 18/CMA.1), the methodology was ensured to be consistent with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006c) and the 2019

Refinement to the 2006 IPCC Guidelines (IPCC et al. 2019). Transparency is further ensured by applying the terminology of the IPCC 2006 guidelines.

Consistency is obtained by relying on data sources and methodologies of the Swiss National Forest Inventory that are maintained in a consistent manner and that will be available in the future. It was ensured that the methods were applied consistently for the base and all subsequent years and that results are reported correspondingly, including data per unit area which are independent of temporal changes in the underlying forest area.

Comparability is achieved by estimating removals by sinks and emissions by sources based on methodologies and formats agreed by the COP and CMA and following the inventory guidelines. The C cycling model Yasso20 was applied in a consistent manner with several other parties to the convention and the PA using the model, including Austria, Finland and Norway. See section 2 on Methods and section 3 for results and discussion.

Completeness is achieved by calculating annual estimates of removals by sinks and emissions by sources since 1989 for the litter, dead wood and soil pools. Full geographical coverage of the sources and sinks was ensured by relying on data from the Swiss National Forest Inventory. See section 2 on Methods and section 3 for results and discussion.

Accuracy is achieved by applying good practice inventory methodologies based on up to-date scientific knowledge, and on country-specific estimates where possible. Results were verified to ensure that emission and removal estimates are systematically neither over nor under true emissions or removals and that uncertainties are reduced as far as practicable (IPCC 2006a). See section 2 on Methods and section 3 for results and discussion.

2 Data and Methods

The Yasso07 model and its implementation for estimating C stock changes on lands with productive forests in Switzerland was first described in detail in Didion et al. (2012) as supporting documentation of the GHGI2013. In the following, the improved version Yasso20 is described (section 2.1) and supporting information on the validity of model for conditions in Switzerland is provided (section 2.2). Section 2.4 presents in detail the derivation of input data for the model and its implementation to estimate C stocks and changes in dead wood and litter (DOM) and in mineral forest soils in Switzerland. Methodological developments since 2013 are presented in section 2.5 demonstrating efforts of inventory improvement. The approach to analyze the estimates is described in section 2.7.

2.1 Yasso20

Yasso20 (Viskari et al. 2022) is a model of C cycling in mineral soil, litter and dead wood. The model was developed for general application with low parameter and input requirements. For estimating stocks of organic C in mineral soil up to a depth of ca. 100 cm and the temporal dynamics of the C stocks, Yasso20 requires information on C inputs from dead organic matter components (i.e. litter and dead wood) and climate (temperature and precipitation). Decomposition of the different components of C inputs is modeled based on their chemical composition, size of woody parts and climate (Tuomi et al. 2011; Tuomi et al. 2009; Viskari et al. 2022). Decomposition rates of C that is either insoluble (N), soluble in ethanol (E), in water (W) or in acid (A), and flow rates of C between these four compounds, to a more stable humus compartment (H) and out of the soil (Figure 1, Tuomi et al. 2011) were derived from a global data set (Tuomi et al. 2011; Tuomi et al. 2009; Viskari et al. 2022). Parameters defining C decomposition rates and C cycling between carbon compartments (Figure 1) are obtained probabilistically using Markov Chain Monte Carlo sampling and are fitted based on data from litterbag studies (Tuomi et al. 2009; Viskari et al. 2022) and woody litter decomposition experiments (Tuomi et al. 2011; Viskari et al. 2022). The approach allows calculating the maximum a posteriori point estimate and confidence sets for the model parameter vector which consists of a unique combination of 35 correlated parameters (Table 1 in Viskari et al. 2022). Compared to Yasso07, Yasso20 presents a further development, particularly regarding model calibration by considering all parameters simultaneously improving the general applicability of the model (Viskari et al. 2022). Furthermore, the temperature and precipitation effect on the decomposition rates of the C compounds was revised based on experimental data leading to a higher sensitivity particularly to temperature.

The latest Yasso20 release available from https://github.com/YASSOmodel/Yasso20 was used in this report. More information and also a R package 'Ryassofortran' is available from https://github.com/YASSOmodel/Ryassofortran. The statistical software R version 4.2.1 (R Core Team 2022) was used for administrating the Yasso20 simulations.

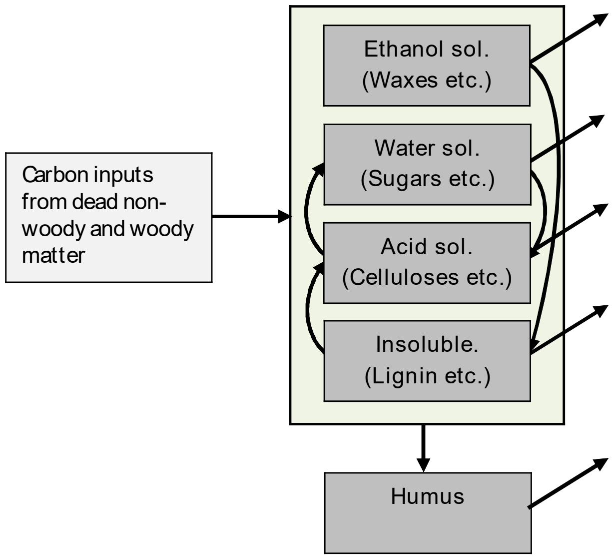

Figure 1. Flow chart of the C fluxes represented in the Yasso soil carbon model. The boxes represent soil carbon compartments, the arrows carbon flows; only those carbon flows are shown that deviate significantly from zero (adapted from Liski et al. 2009).

2.2 Deriving separate estimates for dead wood, litter, and mineral soil

Corresponding to empirical knowledge that dead wood and litter are transformed into humus that accumulates on the soil surface and is slowly transferred to the mineral soil (Prescott and Vesterdal 2021), in the Yasso model the fluxes between carbon inputs to and between C compartments represent a continuum. By default, the model does not provide separate estimates for dead wood, litter and mineral soil carbon pools. Switzerland decided to report these pools separately. In order to report estimates for each pool, the model structure of Yasso07 was examined to obtain separate estimates. Dead wood, litter and soil pools could be correlated with modelled data based on the category of carbon input, i.e., non-woody and woody material, and the five carbon compartments in Yasso07, i.e. four chemical compounds (insoluble, soluble in ethanol, soluble in water or in acid) and a more stable compartment. The approach was found plausible after comparison with independent, measured data (Didion et al. 2012). The basic model structure, i.e., five C compartment, is still the same in Yasso20 (Viskari et al. 2022). The separation of the model results into dead wood, litter, and mineral soil was examined and found to still be plausible although the fluxes between the three pools and within the mineral soil pool are more dynamic due to improved and more realistic model calibration affecting the fluxes between the Yasso carbon compartments (Viskari et al. 2022). The reporting of the dead wood, litter and mineral soil pools on forest land by Parties where the Yasso model is also applied follows different approaches. Switzerland and Norway (Norwegian Environment Agency 2023) report them separately, while Austria (Umweltbundesamt 2023) and Finland (Statistics Finland 2023) report the total.

2.3 Verifying the suitability of Yasso20 for application in Switzerland

Didion et al. (2014a) examined the validity of the Yasso07 model in Swiss forests based on data on observed decomposition of i) foliage and fine root litter from sites along a climatic and elevational gradient and ii) of dead trees from plots of the Swiss National Forest Inventory. The study analyzed, among other, the accuracy of Yasso07 for reproducing observed C decomposition in litter and dead wood in Swiss forests. Didion et al. (2014a) found that no statistically significant differences existed between simulated and observed remaining C in foliage and fine root litter after 10 years and in lying dead trees after 14 to 21 years. This evaluation was repeated using Yasso20. The results demonstrated a moderately higher accuracy of the new model version for foliage and fine roots by comparing the simulated mass loss with the measured mass loss at five Swiss forests sites (Figure 2 and Table 1), and of the observed decay over 14 to 20 years of dead wood obtained from NFI sample plots (considering the mean absolute errors, Figure 3); for a detailed description see Didion et al. (2014a). It was therefore decided to switch to the new Yasso20 version, also considering that particularly for dead wood the initial decomposition from NFI2 to NFI 3 where the C loss is highest (Hararuk et al. 2020) was reproduced better with Yasso20.

	Beatenberg	**Vordemwald**	**Bettlachstock**	**Schaenis**	**Novagio**	**Mean**
Y20 - foliage	5.30	3.22	13.73	6.96	4.12	5.49
Y07 - foliage	9.18	13.34	4.49	16.22	18.98	12.44
Y20 - fine roots	8.85	3.77	23.60	15.39	11.40	12.33
Y07 - fine roots	2.75	13.03	6.39	6.34	9.48	4.74

Table 1. Mean absolute errors for simulated remaining mass of C [%] in fine roots and foliage litter after 10 years of observed and simulated decomposition (cf. Figure 2) at five forest sites and the mean over all sites based on the model versions Yasso07 (Y07) and Yasso20 (Y20).

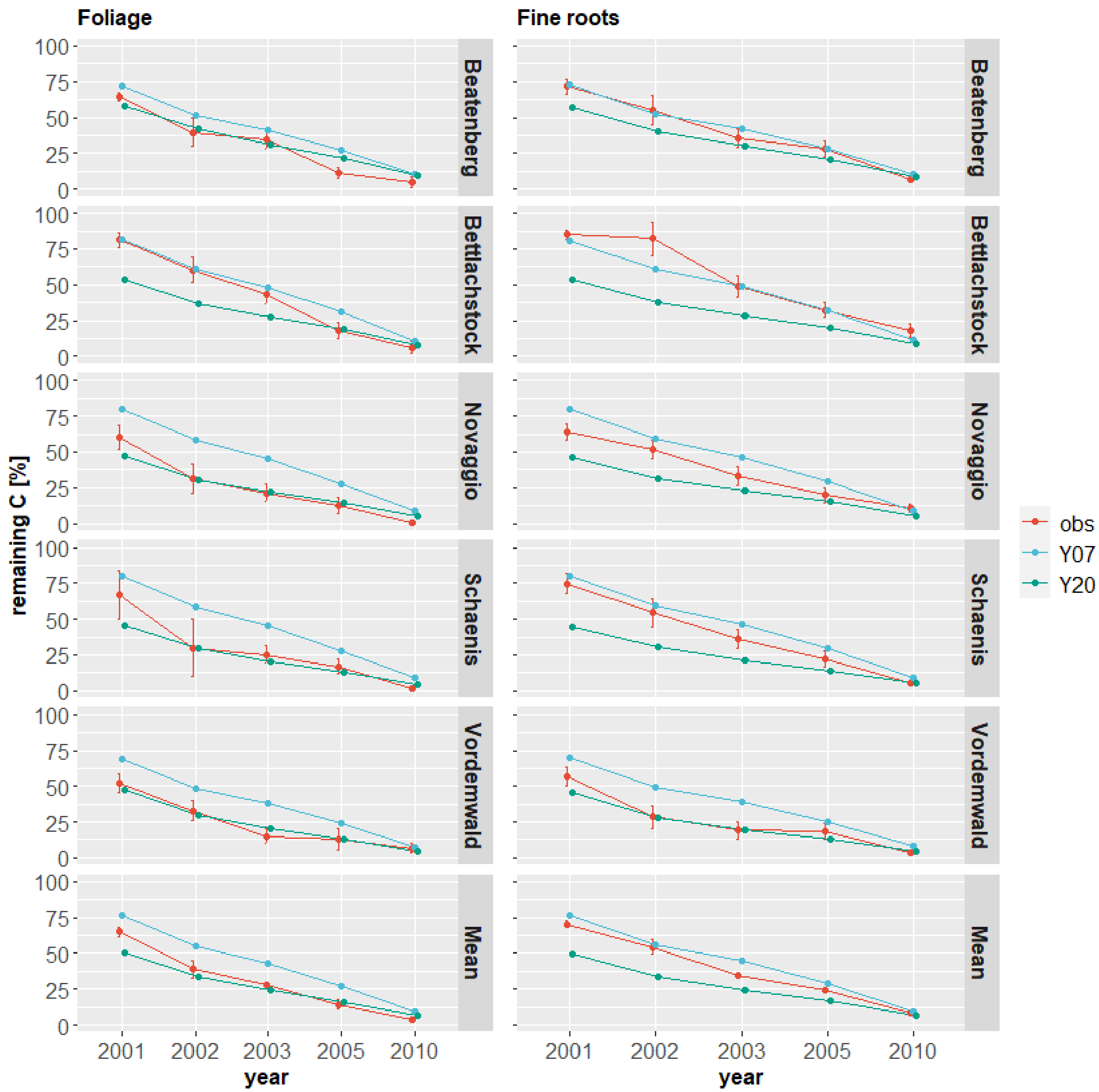

Figure 2. Mean and standard deviation for remaining mass of C [%] in foliage litter and fine roots at five forest sites and the mean over all sites. Measured data ('obs') were based on 20 replicate samples. Simulated data ('Y07' and 'Y20') were the result of 500 replicate simulations based on randomly selected parameter vectors.

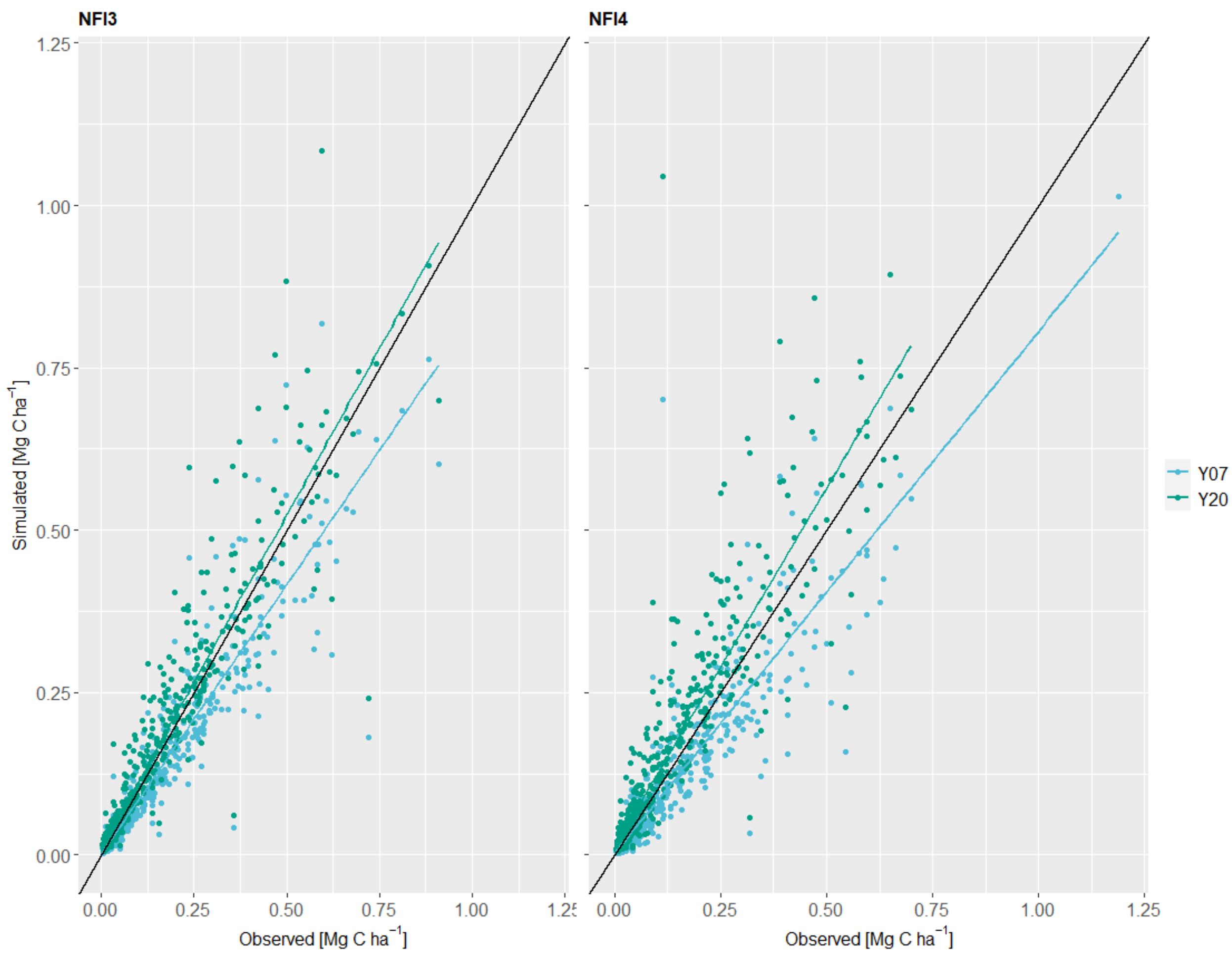

Figure 3. Observed and simulated C stored in individual pieces of dead wood at NFIs 3 (2004-2006) and 4 (2009-2013) in trees that were alive in the NFI1 and either standing (N=379) or lying (N=209) dead at the time of the NFI2 (1993-1995). The colored lines show the fit with observed data based on simulations with Yasso07 ('Y07') and with Yasso20 ('Y20'). The solid black line indicates a perfect fit. The values of the adjusted r^2 regressions (Y07 and Y20 for NFI3: 0.931 and 0.932, respectively, for NFI4: 0.894 and 0.895, respectively) are significant with p-values <0.01. The mean absolute errors at the NFI3 are 0.035 Mg C ha^{-1} for Yasso07 and 0.029 Mg C ha^{-1} for Yasso20, and at the NFI4 0.035 Mg C ha^{-1} for Yasso07 and 0.038 Mg C ha^{-1} for Yasso20.

2.4 Data and model implementation for estimating C stock changes in DOM and soil of productive forests in Switzerland

2.4.1 *National Forest Inventory*

The Swiss National Forest Inventory (NFI) is the primary source for estimating the C balance of Swiss forests. The inventory is based on permanent sample plots that are revisited in each sampling campaign (Table 2). On each plot living and dead standing and lying trees and certain shrubs according to a given species list with a diameter at breast height (dbh) > 12 cm (tally trees) are measured in detail (Lanz et al. 2019) providing representative data for further estimation of volume and biomass, among other attributes. The Swiss NFI is now in its 5th cycle. Results of the four completed NFIs are described in EAFV/BFL (1988; NFI1), Brassel and Brändli (1999; NFI2), Brändli (2010; NFI3), and Brändli et al. (2020; NFI4). Results of the first five years (2018-2022) of the NFI5 are available online (Abegg et al. 2023). The inventories NFI1, NFI2 and NFI3 were based on full surveys that were completed within 2 to 3 years and carried out in intervals of approximately 10 years. Since the fourth inventory, which started in 2009, a continuous survey over 9 years is conducted where annually a nationally representative subsample of approximately 12% of the Swiss forests is surveyed and evaluated (Brändli and Hägeli 2019). Otherwise, the methods to measure data in the field remained identical to the NFI3 (with the exception of new attributes), including the estimation of total tree biomass, which is based on tree species-specific

- volume estimates of stemwood and branches based on allometries to tree dbh and conversion to biomass using basic wood densities; and
- biomass estimates of foliage and coarse roots based on allometries to tree dbh.

Allometries and wood densities were developed using country-specific estimates where possible. Table 3 summarizes the methods to estimate tree volume and biomass. A detailed description of the current methods to estimate volume, biomass, and carbon based on the NFI data can be found in Herold et al. (2019) and Didion et al. (2019).

Table 2. Number of surveyed sample plots and tally trees in the National Forest Inventories NFI1, NFI2, NFI3, NFI4, and NFI5 (first five years 2018-2022) for accessible forest plots without brush forest based on the 1.4 x 1.4 km grid common to all NFIs (Brändli and Hägeli 2019); note the NFI5 is carried out in the years 2018 to 2026

	NFI1	**NFI2**	**NFI3**	**NFI4**	**NFI5**
Inventory cycle	1983-1985	1993-1995	2004-2006	2009-2017	2018-2022
Terrestrial sample plots	5517	5'679	5'920	6'042	3'435
Tally trees	64’414	67'297	70'061	71'962	40'537

Table 3. Applied allometric biomass functions, dependencies and references. DBH: tree diameter at breast height; D7: diameter at tree height 7 m.

Tree element	**Input parameter**	**Dataset (N trees)**	**References**
Stemwood over bark incl. stump	DBH, D7, Height, Wood density	ca. 38'000	ch. 12.2 in Herold et al. (2019) ch. 14.2 in Didion et al. (2019)
Branches: small (< 7 cm) and large (≥ 7 cm diameter)	DBH, Wood density	14'712	ch. 12.2 in Herold et al. (2019) ch. 14.2 in Didion et al. (2019)
Foliage	DBH	861	Didion et al. (in prep)
Coarse roots (≥ ca. 5 mm in diameter) **- broadleaved trees** **- coniferous trees**	DBH	 443 114	ch. 14.3 in Didion et al. (2019) Wutzler et al. (2008) Zell and Thürig (2013)

Based on sample plots that are common to two consecutive inventories and that are classified as accessible forest but not shrub forest (*gemeinsam zugänglicher Wald ohne Gebüschwald*) following the definition of “productive forest” in Switzerland’s GHGI (Combination Category 12, cf. Tab. 6-2 in FOEN 2023a), the annual forest litter and dead wood production is estimated. For this submission estimates for the period NFI45 are based on sample plots of the first five annual tranches, i.e. 2009 to 2013 of the NFI4 and 2018 to 2022 of the NFI5 (Table 4). An update of the 5-year window with the corresponding subset of sample plots every two years ensures the most current and accurate estimates are used for deriving litter and dead wood production data for modeling.

Table 4. Number of NFI sample plots in each NFI period where the total for a period represents the common plots of two consecutive NFIs based on which the annual forest litter and dead wood production is estimated. Note that NFI1, NFI2 and NFI3 were based on full surveys and that the NFI4 and later NFIs have been based on continuous survey over 9 years where annually a nationally representative subsample of approximately 12% of the Swiss forests is surveyed and evaluated. Regularly updated subsets of sample plots selected from the continuous survey are used to represent the most current forest dynamics.

GHGI time series	NFI period	NFI subset[1]	forest in previous period	Converted to forest since previous period	Total for period
			Number of sample plots		
1990–1995	**NFI12**	N/A[1]	N/A[2]	N/A[2]	5’456
1996–2005	**NFI23**	N/A[1]	5’370	211	5581
2006-2017	**NFI34**	N/A[1]	5’521	303	5824
2018-2022[3]	**NFI45**	2018 - 2022	3’242	95	3’337

[1]NFI1, NF2, and NFI3 were based on full surveys; NFI4 and NFI5 are continuous surveys and values are updated with new available data of the NFI5

[2]not applicable in this first NFI period

[3]for the period NFI45 sample plots common to the NFI4 and NFI5 visited in the years 2018 to 2022 were considered.

2.4.2 *C inputs*

Estimates of C inputs for the simulations with Yasso20 were obtained separately for all NFI sample plots classified as accessible forest but not shrub forest. Sample plots were distinguished into forest, i.e. plots with observed tree biomass, and non-forest, i.e. plots without observed tree biomass that were temporarily unstocked. Plot-specific C inputs on forest plots (Forest-C_{in}) were estimated for coniferous and broadleaved tree species for individual tree elements aggregated into three DOM pools:

- Coarse-woody pool comprising i) stemwood[1] of trees ≥12 cm (diameter at breast height; dbh), ii) large branches ≥ ca. 7 cm in diameter, and iii) dead coarse roots > ca. 5 mm in diameter;

[1] Stemwood includes stump, bole (merchantable part of the stem with diameter > 7 cm above the stump excluding bark), and top of a tree as defined in the Swiss NFI (Figure 14.1 in Didion et al. 2019).

- Fine-woody pool comprising i) small branches and twigs < ca. 7 cm in diameter, and ii) bark of the tree bole; and
- Non-woody pool comprising i) foliage incl. seeds and fruits, and ii) fine roots < ca. 5 mm.

The methodology to estimate stemwood, large and small branches, fine and coarse roots, and foliage is described in detail in Didion et al. (2019), for fruits in Didion and Zell (2019), and for bark in Rohner et al. (2019). The model for foliage was revised to account for additional data (Didion et al. in prep). In summary, individual tree elements are estimated using allometric relationships to tree dbh, wood densities, and C content. The tree state in two consecutive inventories determines the type and quantity of C inputs. It is assumed that trees that are alive in both inventories contribute to C inputs during the whole period, whereas trees that grow above the 12 cm dbh threshold (i.e. they were not measured in first inventory but were alive in the second) and those that died, including harvested trees, are assumed to contribute only for half the period. Turnover rates reflecting the longevity of leaves and needles, seeds and fruits, fine roots, and small branches are used to estimate biomass that is produced annually. Stemwood, large branches, and coarse roots are assumed to accrue only as the result of mortality. Depending on the cause of mortality, i.e. natural or timber harvesting, either the total mass of these tree elements including bark or only the non-merchantable fraction (coarse root, stump, top, and small branches including bark) is considered for C inputs, in addition to leaves and needles, seeds and fruits, fine roots, and small branches (Table 5). Etzold et al. (2011) verified the accuracy of the estimates with independent data from long-term forest ecosystem research sites.

Table 5. Tree elements considered for C inputs depending on the state of a tree at the end of the period between two consecutive National Forest Inventories.

Tree element	Contribution to C input (tree state)
foliage	alive, natural mortality, harvest
seeds and fruits	alive, natural mortality, harvest
small branches incl. bark	alive, natural mortality, harvest
large branches incl. bark	natural mortality
tree top incl. bark	natural mortality, harvest
tree bole incl. bark	natural mortality
tree stump incl. bark	natural mortality, harvest
coarse roots	natural mortality, harvest
fine roots	alive, natural mortality, harvest

Current measured data have been available since the NFI1 in 1985. For the spin-up, the development until 1940, and sample plots that were non-forest in 1940 but became forest after 1985 (i.e. classified as productive forest in a NFI period), C inputs of individual sample plots were obtained by using a spatial moving window including data from all forested plots within a 10x10km quadrat. Based on this procedure averaged C inputs were obtained for each plot included in an inventory period, i.e. Forest-C_{in}1-2 $_{avg}$, Forest-C_{in}2-3 $_{avg}$, Forest-C_{in}3-4 $_{avg}$, and Forest-C_{in4}-5 $_{avg}$. This was necessary to avoid artefacts resulting from simulating individual, temporarily unstocked sample plots without C inputs which were forested in the past. Since 1986 estimates of forest C inputs were obtained separately for each NFI plot to account for local conditions including the prevalent forest management type and natural mortality. Both can result in changes in the number and volume of trees on an inventory plot and, thus, to the production of coarse-woody and non-woody material. These effects are explicitly accounted for in the estimation of C inputs for the three DOM pools: Estimates of non-woody and fine-woody litter production vary with a change in tree number and volume. Estimates of coarse-woody production is directly related to the rate of tree mortality due to a disturbance and in the amount of residues that remain after a disturbance. If climatic disturbances such as storms cause the mortality of trees or tree elements such as branches and result in an increase in the amount of dead wood, NFI measurements show this increase. Since the input of C to the model is derived from NFI measurement, changes in the measured data affect the C inputs to the model accordingly. The result is a temporary (i.e. in the year of the disturbance and possibly also in subsequent years) increase in the amount of fresh C that enters the model and contributes to the annual C balance of the dead wood pool.

The uncertainty related to the estimation of C inputs was estimated to account for uncertainties in

- applying allometric functions to estimate tree stem volume from measured tree dbh (Berger et al. 2013);
- converting and expanding stem volume to whole tree biomass and estimating litter production (Wutzler and Mund 2007); and
- carbon concentration (Dobbertin and Jüngling 2009).

Based on the mean inputs at each NFI sample plot, the correlation between DOM components, and estimates of uncertainty (Table S. 1), a distribution of possible inputs was created.

Annual above-ground C inputs on temporarily unstocked sample plots (Non-Forest-C_{in}; Table 6) were estimated based on data by Didion (2020b) and the assumption that sample plots are covered by dense shrub- and herbaceous vegetation. Based on data by Freschet et al. (2013) for grasses (64%) and Gao et al. (2014) for herbs (50%), annual below-ground biomass was estimated as 50% of above-ground biomass. The estimated mean total Non-Forest-C_{in} which was used for each sample plot corresponded to between 3 and 100 % of the non-woody litter contribution to Forest-C_{in}. The mean contribution of 15 to 25% of the non-woody litter is consistent with de Wit et al. (2006) who reported that C inputs from litter produced by ground vegetation can account for almost all carbon inputs in recently harvested stands and between 10 to 50% in middle-aged and old stands. Etzold et al. (2014) found that understory vegetation contributed on average ca. 12% (0.1 to 36.8%) to the total observed annual C turnover at six sites of the Swiss Long-term Forest Ecosystem Research Programme LWF.

Table 6 shows the mean and standard deviation of annual C inputs calculated from all sample plots included in a particular NFI-period separately for DOM derived from conifers and broadleaves on forest sample plots as well as for non-woody litter on temporarily unstocked plots.

C inputs for each pool were portioned into the four chemical compartments (AWEN, cf. section 2.1) used by Yasso20 following experimentally derived fractions (Table 7) as discussed in Didion et al. (2014a).

Table 6. Mean and standard deviation of C inputs from trees >12cm dbh over all NFI sample plots simulated with Yasso20 for the GHGI2024. C inputs are based on averaged (Forest-C_{in}1-2$_{avg}$, Forest-C_{in}2-3$_{avg}$, Forest-C_{in}3-4$_{avg}$, Forest-C_{in}4-5$_{avg}$) and plot-specific (Forest-C_{in}1-2, Forest-C_{in}2-3, Forest-C_{in}3-4, Forest-C_{in}4-5) data from sample plots classified as forest in a particular NFI period. For sample plots with tree biomass, the mass of carbon in six dead organic matter (DOM) components was estimated for a) coniferous and b) broadleaved tree species. For temporarily unstocked sample plots, c) the mass of carbon was estimated based on non-woody litter produced by a dense herb and shrub cover. C inputs are shown for each NFI period.

a) conifers

NFI data	DOM component						Total
	Fine roots	Foliage	Fine woody	Coarse-woody (>7 cm diameter)			
				Roots	Branches	Stems	
	Kg C ha^{-1} a^{-1}						
Forest-C_{in}1-2$_{avg}$	656 ±237	754 ±264	310 ±129	257 ±153	54 ±35	48 ±31	2079 ±410
Forest-C_{in}1-2	721 ±644	832 ±745	339 ±323	279 ±664	61 ±181	54 ±160	2286 ±1254
Forest-C_{in}2-3$_{avg}$	699 ±250	779 ±270	330 ±141	307 ±237	79 ±59	70 ±52	2264 ±467
Forest-C_{in}2-3	754 ±685	843 ±757	353 ±346	323 ±802	84 ±236	74 ±208	2431 ±1380
Forest-C_{in}3-4$_{avg}$	693 ±249	765 ±273	322 ±129	291 ±221	79 ±49	70 ±44	2220 ±454
Forest-C_{in}3-4	720 ±695	796 ±753	334 ±351	303 ±935	82 ±315	73 ±279	2308 ±1491
Forest-C_{in}4-5$_{avg}$	705 ±259	874 ±340	333 ±133	281 ±210	111 ±78	98 ±69	2402 ±505
Forest-C_{in}4-5	724 ±699	898 ±883	341 ±359	285 ±849	112 ±383	99 ±337	2459 ±1542

b) broadleaves

NFI data	DOM component						Total
	Fine roots	Foliage	Fine woody	Coarse-woody (>7 cm diameter)			
				Roots	Branches	Stems	
	Kg C ha^{-1} a^{-1}						
Forest-C_{in}1-2$_{avg}$	252 ±164	524 ±332	121 ±86	87 ±83	29 ±24	10 ±9	1023 ±390
Forest-C_{in}1-2	271 ±430	562 ±767	128 ±178	93 ±317	32 ±163	11 ±53	1097 ±967
Forest-C_{in}2-3$_{avg}$	285 ±182	576 ±354	127 ±86	91 ±96	41 ±39	12 ±11	1132 ±420
Forest-C_{in}2-3	302 ±487	610 ±840	134 ±184	95 ±331	43 ±182	13 ±56	1197 ±1059
Forest-C_{in}3-4$_{avg}$	292 ±185	582 ±353	126 ±82	103 ±95	49 ±45	17 ±14	1169 ±420
Forest-C_{in}3-4	301 ±459	600 ±790	130 ±173	107 ±418	50 ±292	17 ±95	1205 ±1065
Forest-C_{in}4-5$_{avg}$	300 ±182	597 ±354	131 ±83	111 ±120	75 ±89	25 ±24	1239 ±434
Forest-C_{in}4-5	308 ±431	613 ±785	134 ±177	114 ±425	77 ±388	26 ±109	1272 ±1085

c) non-forest above-ground

	Kg C ha^{-1} a^{-1}
Non-Forest-C_{in}1-2	241
Non-Forest-C_{in}2-3	247
Non-Forest-C_{in}3-4	245
Non-Forest-C_{in}4-5	245

Table 7. Initial fractions for the simulation of foliage and fine root litter and of dead wood separated into the four chemical compartments in Yasso20, i.e. C that is either insoluble (N), soluble in ethanol (E), in water (W) or in acid (A); see Tab. 3 in Didion et al. (2014a).

Litter type	Tree species	A	W	E	N
Foliage	**Conifers**	0.4065	0.2935	0.065	0.235
	Broadleaves	0.4815	0.1315	0.055	0.33
Fine roots	**Conifers**	0.449	0.28	0.025	0.245
	Broadleaves	0.433	0.1595	0.015	0.39
Dead wood	**Conifers**	0.675	0.0175	0.0025	0.305
	Broadleaves	0.715	0.015	0	0.27

2.4.3 *Climate*

Data for observed climate were obtained from spatially gridded data prepared by the Federal Office of Meteorology and Climatology MeteoSwiss. Based on measured data from its network of weather stations, MeteoSwiss interpolates a country-wide data set of several climate variables with a spatial resolution of 1 km with monthly data since 1961 (MeteoSwiss 2020).

For the location of each NFI sample plot, data for mean monthly absolute temperature [°C] (TabsM) and for monthly precipitation sum [mm] (RhiresM) since 1961 to the current inventory year were extracted from the respective current versions of the gridded data, i.e. TabsM v1.4 (MeteoSwiss 2021a) and RhiresM v2.0 (MeteoSwiss 2021b).

Since plot-specific climate data from a national observation network are used, the effect of a climatic disturbance affecting temperature or precipitation is reflected in the respective measured data. Thus, changes in climatic conditions are explicitly accounted for in the simulations with Yasso20 because decomposition rates will be affected accordingly. Figure 4 shows the annual temperature and precipitation means for all sites defined as productive forest in any of the four NFI periods (N=6053) and, in comparison, the long-term annual means calculated for the norm periods 1961-1990 and 1981-2010 indicating the increase in temperature since the 1980ies and 90ies.

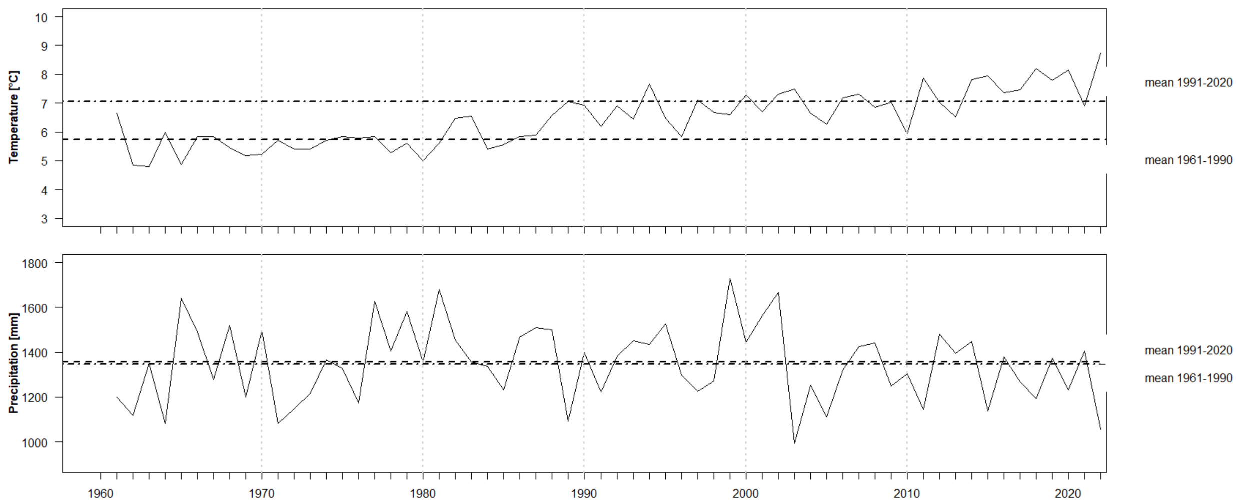

Figure 4. Annual means of temperature and precipitation sums since 1961 for all NFI sample plots classified as productive forest in any of the four NFI periods (N=6053). The long-term means of the norm periods 1961-1990 and 1981-2010 are indicated by the horizontal lines.

2.4.4 *Model implementation*

To estimate carbon stocks and carbon stock changes in DOM and mineral soil of productive forests in Switzerland, Yasso20 was run on each sample plot of the Swiss national forest inventory (NFI) that was classified as productive forest identified individually for each NFI period:

- NFI1-2 (from 1986 to 1995);
- NFI2-3 (from 1996 to 2005); and
- NFI3-4 (from 2006 to 2017); and
- NFI4-5 (from 2018 to 2022).

To drive the Yasso20 simulation and to obtain C stock estimates for dead wood, litter and mineral soil in Swiss forests, plot-specific annual inputs for a) for observed climate (section 2.4.3), and b) non-woody and woody C derived from measured data (sections 2.4.1 and 2.4.2) were used. Section 2.4.2 explains the derivation of C inputs including detail on the contribution of different non-woody and woody tree biomass pools.

The simulation of current C stocks based on the available climate and C inputs was implemented as follows:

a. **Historic C stocks assumed to represent the conditions in 1880**: Established based on the assumption that forest soils C stocks are the result of long-term processes. The year 1880 was used because it corresponds to the first year with a robust estimate of whether a NFI sample plot was forested (Ginzler et al. 2011).
    - Long-term equilibrium soil C stocks: Estimated in a spin-up procedure (cf. Liski et al. 2009) based on mean climate 1961 to 1990 and constant, averaged forest C inputs based on NFI1-2 data (Forest-C_{in}1-2_{avg}; section 2.4.2) assuming that C stocks in the soil have accumulated over centuries to millennia (Schlesinger 1990).
    - if a sample plot was not forested in 1880, the spin-up was continued with additional 250 years with constant mean non-forest C inputs representative of dense shrub- and herbaceous vegetation based data from Didion et al. (2018); (Non-Forest-C_{in}1-2; section 2.4.2).

b. **Forest development until 1985**: In order to cancel out the steady-state conditions after the spin-up phase (cf. Peltoniemi et al. 2007), the spin-up simulation is followed by simulating intermediated states before the start of the first period NFI1-2 in 1986.
    - State 1915 and 1940: In addition to 1880, Ginzler et al. (2011) provided robust estimates of whether a NFI sample plot was forested also in 1915 and 1940. Depending on the classification of a sample plot as forest or non-forest in 1880, 1915, and 1940, C stocks in 1915 and 1940 were estimated based on mean climate 1961 to 1990 and in case of
        - forest in 1880, 1915 and 1940: 60 years simulation with Forest-C_{in}1-2_{avg};
        - forest in 1880 and 1915 but non-forest in 1940: 47 years simulation with Forest-C_{in}1-2_{avg} (i.e. 35 years between 1880 and 1915 and 12 years between 1916 until halfway of the period 1916 to 1940) and 13 years simulation with Non-Forest-C_{in}1-2;
        - forest in 1880 but non-forest 1915 and in 1940: 17 years simulation with Forest-C_{in}1-2_{avg}, and 43 years simulation with Non-Forest-C_{in}1-2 (i.e. 18 years between from halfway between 1880 and 1915 and 25 years from 1916 to 1940);
        - forest in 1880 but non-forest 1915 and forest again in 1940: 17 years simulation with Forest-C_{in}1-2_{avg}, 30 years simulation with Non-Forest-C_{in}1-2 (i.e. 18 years from halfway between 1880 and 1915 and 12 years from halfway between 1916 and 1940), and 13 years simulation with Forest-C_{in}1-2_{avg};
        - non-forest in 1880 the procedure was the same as all above listed alternatives in the case of forest in 1880 but with reversed C inputs, i.e., Non-Forest-C_{in}1-2 instead of Forest-C_{in}1-2_{avg} and Forest-C_{in}1-2_{avg} instead of Non-Forest-C_{in}1-2 in the respective periods.

- State 1985: Depending on the classification in 1940 and the NFI period when a sample plot was first classified as forest, the simulation after 1940 was continued based in mean climate 1961 to 1990 until 1960 and annual climate from 1961 onward in case of
  - forest in 1940 and in NFI1-2: 45 years simulation with Forest-C_{in}1-2 $_{avg}$;
  - forest in 1940 and non-forest in NFI1-2: 22 years simulation with Non-Forest-C_{in}1-2 and 23 years simulation with Forest-C_{in}1-2 $_{avg}$, ie, halfway of the period 1940 and start of NFI1-2 in 1986;
  - non-forest in 1940 and in NFI1-2 but forest in NFI2-3: 27 years simulation with Non-Forest-C_{in}1-2 and 18 years simulation with constant, averaged forest C inputs based on NFI2-3 data (Forest-C_{in}2-3 $_{avg}$; section 2.3.3), ie, halfway of the period 1940 and start of NFI2-3 in 1996;
  - non-forest in 1940, in NFI1-2 and in NFI2-3 but forest in NFI34: 32 years simulation with Non-Forest-C_{in}1-2 and 13 years simulation with constant, averaged forest C inputs based on NFI34 data (Forest- C_{in}3- 4 $_{avg}$; section 2.4.2), i.e. halfway of the period 1940 and start of NFI3-4 in 2006;
  - non-forest in 1940, in NFI1-2, in NFI2-3, and in NFI34 but forest in NFI45: 44 years simulation with Non-Forest-C_{in}1-2 and 1 year simulation with constant, averaged forest C inputs based on NFI45 data (Forest- C_{in}4- 5 $_{avg}$; section 2.4.2), i.e. halfway of the period 1940 and start of NFI45 in 2018;

c. **Forest development after 1985**: Sample plot-specific climate data and, depending on whether a sample plot was forest or non-forest in a particular NFI period, C inputs corresponding to plot-specific forest C inputs for a period (i.e. Forest-C_{in}1-2, Forest-C_{in}2-3, Forest-C_{in}3-4, Forest-C_{in}4-5) or mean non-forest C inputs for a period (i.e. Non-Forest-C_{in}1-2, Non-Forest-C_{in}2-3, Non-Forest-C_{in}3-4, Non-Forest-C_{in}4-5).

This approach resulted in a total of 6053 NFI sample plots that were classified as forest in at least one inventory period and that were thus included in the derivation of C stocks and C stock changes in dead wood, litter, and mineral soil in Swiss forests.

To obtain an estimate of uncertainty related to model parameters and litter as well as dead wood inputs, a Monte-Carlo approach was used based on independent simulations of randomly sampled parameter vectors and dead wood and litter samples.

2.5 QA/QC

The preparation of the data on C stocks and C stock changes in dead wood, litter, and mineral soil in Swiss forests that are used for reporting gains and losses in the Swiss NIR applies procedures to ensure that the estimates meet the reporting requirements set out in the IPPC 2006 guidelines.

2.5.1 *Time series consistency*

The estimates of annual forest litter and dead wood production are based on data from the Swiss NFI. Data, data base and derivations of the Swiss NFI are continuously checked for plausibility, accuracy, and consistency, and identified issues are evaluated and, if required, corrected and all variables are recalculated. In particular, it is ensured that the same coefficients and methods for equivalent calculations at all points in the time series are used.

Climate data are obtained from the Federal Office of Meteorology and Climatology MeteoSwiss and it is ensured that after methodological improvements the entire time series is updated and recalculated.

To analyze time series consistency and accuracy, current estimates of DOM and mineral soil C stock changes are compared with data derived for use in previous NIR submissions.

2.5.2 *Completeness*

All potential sources of litter and dead wood production are considered, i.e. foliage, seeds and fruits, fine and coarse branch- and stemwood, as well as fine and coarse roots. The data are derived from the NFI, which ensured that the contribution also of trees that are removed from a plot by e.g. harvesting is accounted.

2.5.3 *Verification*

Simulated estimates of C stocks and C stock changes in dead wood, litter, and mineral soil are compared with independent measurements.

2.5.4 *Uncertainty*

Uncertainty in the simulated estimates of C stocks and C stock changes in dead wood, litter, and mineral soil is derived following a Monte-Carlo approach considering the following sources of uncertainty:

- NFI sampling
- carbon input estimates obtained from the NFI (measurement errors, allometries, etc.)
- decomposition parameters used in the Yasso20 model.

2.5.5 *Documentation*

The litter and dead wood production data are obtained from NFI estimates with a strict procedure to parametrize the database analyses to obtain reproducible estimates. Climate data are documented and archived at MeteoSwiss and at WSL. The simulation code executing the Yasso model has undergone an independent review and is archived at WSL with an anticipated switch to GitHub for more transparency and reproducibility.

2.6 Methodological improvements and updates of input data

2.6.1 *Improvements and updates compared to GHGI 2023*

Since the previous submission several changes to input data and methodology were implemented, including:

- New NFI data covering the periods NFI34 (now based on data from the NFI3 and the complete NFI4) and NFI45 (now based solely on data from the NFI4 (annual tranches 2009 to 2013) and NFI5 (annual tranches 2018 to 2022), see section 2.4.1;
- Revised foliage model following the planned improvement, see section 2.4.2;
- Implementation of the new model version Yasso20; see section 2.1.

2.6.2 *List of improvements and updates until GHGI 2023*

GHGI 2021 to 2023 (section 2.4.1 in Didion 2020a)

- *Minor updates to climate data by MeteoSwiss*

GHGI 2020 (section 2.4.1 in Didion 2019)

- No changes.

GHGI 2019 (section 2.4.1 in Didion and Thürig 2018)

- Revision of the selection of NFI sample plots to account also for temporary unstocked plots consistent with the approach for estimating C stock and C stock changes in living biomass.
- Incorporation of fine-woody litter in C inputs of forested plots and of non-forest vegetation in C inputs on temporarily unstocked plots.
- Consideration of forest development since 1880 in the spin-up procedure.

GHGI 2018 (section 2.4.1 in Didion and Thürig 2017)

- No changes.

GHGI 2017 (section 2.4.1 in Didion and Thürig 2016)

- Update of NFI sites to derive estimates of C inputs between NFIs 3 and 4.
- Improvements in the accuracy of the estimates of dead wood and litter production.

GHGI 2016 (section 2.3 in Didion and Thürig 2015)

- Corrections to the temperature data.
- Use of annual rather than averaged gains and losses estimates.

GHGI 2015 (section 2.3 in Didion et al. 2014b)

- Increased accuracy of the dead wood production estimates.
- Additional sites of the NFI4 become available.

GHGI 2014 (section 2.3 in Didion et al. 2013)

- Replacement of the model parameter set.

- Corrections to the precipitation data.
- Revision of the litter and dead wood pools used as input to the Yasso07 model.

2.7 Analysis

Yasso20 produces annual estimates of carbon available in the four chemical compartments (A, W, E and N) and in the humus compartment (H) separately for the six C input components (cf. Table 7). Using this information, the simulated annual C stocks were separated to obtain annual estimates of carbon stored in the soil (sum of C in the H compartment from all tree elements), in litter (i.e. sum C in the AWEN compartments of fine roots, foliage, fine-woody litter) and in dead wood (i.e. sum C in the AWEN compartments of stemwood (resp. stump and tree top), branches and coarse roots); cf. Appendix I in Didion et al. (2012) and Didion et al. (2014a).

Annual estimates of carbon stocks in the dead wood, litter, and mineral soil pools for each NFI plot were derived from Yasso20 simulations for the period 1989 to 2022. From the time series of C stocks, the annual change in carbon stock between consecutive years was calculated. Thus, for each pool two time series were obtained with annual means and standard errors (SE) derived from 100 replicate simulations (i.e. 10 parameter vectors and 10 dead wood and litter samples):

1) *annual carbon stock change*: mean and SE in the dead wood, litter, and mineral soil pools and their total; contained in result tables 1a to 1h (Table S. 2).
2) *annual carbon stocks*: mean and SE of dead wood and litter in result tables 2a to 2d (Table S. 2).

2.7.1 *Spatial stratification*

The LULUCF sector of the Swiss GHGI uses a primary spatial stratification based on three elevation strata and, additionally for Forest land, five NFI production regions (chapter 6.2 in FOEN 2023a):

- five NFI production regions: Jura, Central Plateau, Pre-Alps, Alps, Southern Alps
- three elevation classes: <601 m, 601–1200 m, >1200 m.

For Forest land, the resulting 15 spatial strata reflect the heterogeneity of forests in Switzerland and minimize the sampling error for growth, drain, and stocks (cf. Lanz et al. 2019). With the change to a continuous inventory in the NFI4, the number of sample plots within a spatial stratum that are visited in a particular year resulted in a limited accuracy and representativity of smaller spatial strata. Thus five annual tranches are used to derive estimates for the NIR. For this submission estimates for the period NFI45 are based on sample plots common to the first five annual tranches, i.e. 2009 to 2013 of the NFI4 and 2018 to 2022 of the NFI5 (Table 4). An update of the 5-year window with the corresponding subset of sample plots every two years ensures the most current and accurate estimates of biomass growth, drain, and stocks. This approach to combine annual tranches in a moving window also allows flexibility to account for unexpected events like large-scale disturbances that could significantly affect the C balance of the Swiss forest In addition, and consistent with the data on living biomass on forest land (section 2.1 in Didion et al. 2023; chapter 6.4.2.1.2 in FOEN 2023a) some smaller strata are aggregated to ensure that a sufficient number of sample plots is available to obtain statistically reliable estimates of means and sampling errors. The merged strata are

- NFI production region Central Plateau 601-1200 m and >1200 m
- NFI production region Pre-Alps ≤600 m and 601-1200 m
- NFI production region Alps ≤600 m and 601-1200 m
- NFI production region Southern Alps ≤600 m and 601-1200 m

3 Results and Discussion

3.1 Carbon stock change

Climate and the quality of the decomposing material are two of the main drivers of temporal dynamics of carbon stock changes (Bradford et al. 2016). These are represented in the Yasso model (section 2.1). Hence, the estimated C stock changes derived for reporting in the NIR are the result of the annual variation in temperature and precipitation overlaid with the periodic changes (i.e. between NFI periods) in dead wood and litter inputs and the resulting combination of older partially decomposed material and fresh material.

Figure 5 shows the time series of national estimates of C stock changes in dead wood, litter, and mineral soil, as well as their total since 1990 for reporting in the NIR 2024. For comparison, the corresponding estimates reported in the NIR 2023 are also shown. Changes between estimates for the two submissions are primarily the result of the application of the new model version Yasso20 (section 2.1) and of the accounting of the most current data on the first 5 years of the NFI5 (section 2.4.1 and 2.6.1). The effect of the revised foliage model was minor.

The switch to Yasso20 was the dominating reason for the differences in the estimates before 2018. The changes were due to the improved and more realistic calibration in the new model version Yasso20 resulting in a higher sensitivity of decomposition (section 2.1). Since 2018, the new NFI5 data were the dominating factor. The results for the total C stock change (i.e. the default Yasso results, section 2.2) in Figure 5 demonstrate this clearly. The overall temporal dynamics before 2018 are similar although the increased sensitivity of the new Yasso20 version affects primarily the results at the times of a change to a new NFI period (i.e. around 1996, 2006, and 2017, Table 6) and in years of particularly different weather as in the very moist years around 2000 and the drier and warmer years after 2015 (Figure 4; MeteoSwiss 2024).

Since the application of the new model version Yasso20 had a statistically significant effect on simulated CSC (Figure 5), the results were further evaluated for plausibility The CSC data prepared for the NIR 2023 (supplement 2 in Didion et al. 2020; FOEN 2023a) were reproduced with Yasso20 based on the same input data. The largest relative effect although at very low values <0.02 Mg C ha^{-1} a^{-1} were on the mineral soil pool (Figure S. 1). This was expected as the fluxes to, and the decomposition of the H compartment (see section 2.1), which is used to represent the soil pool, are more dynamic in Yasso20 than in Yasso07 (Viskari et al. 2022). The dead wood and litter pools were proportionally less affected although the increased sensitivity to temperature resulted in a higher temporal variability in the CSC in these pools (Figure S. 1).

The mean total CSC in the reporting year 2022 in dead wood, litter, and mineral soil in Swiss forests was estimated as a gain of ca. 0.189 ±0.015 (2SE) Mg C ha^{-1} a^{-1} (Total for Switzerland in Table 8, ALL_{csc} in Figure 6). Temporal dynamics of annual total CSC since 1990 were dominated by the dead wood and litter pools. Whether CSC corresponds to a gain (removal) or a loss (emission) depended on carbon pools and regions (Table 8 for data 2022). In the following, the results are presented for each of the three C pools, i.e. dead wood, litter, and mineral soil. The separation of default Yasso results into individual pools may introduce a general error in the pool estimates but does not affect the estimates of combined total C stocks and C stock changes (Didion et al. 2014a). The complete set of result tables of CSC and C stock that were prepared for the Swiss GHGI2024 (1990-2022) can be found in Table S. 2.

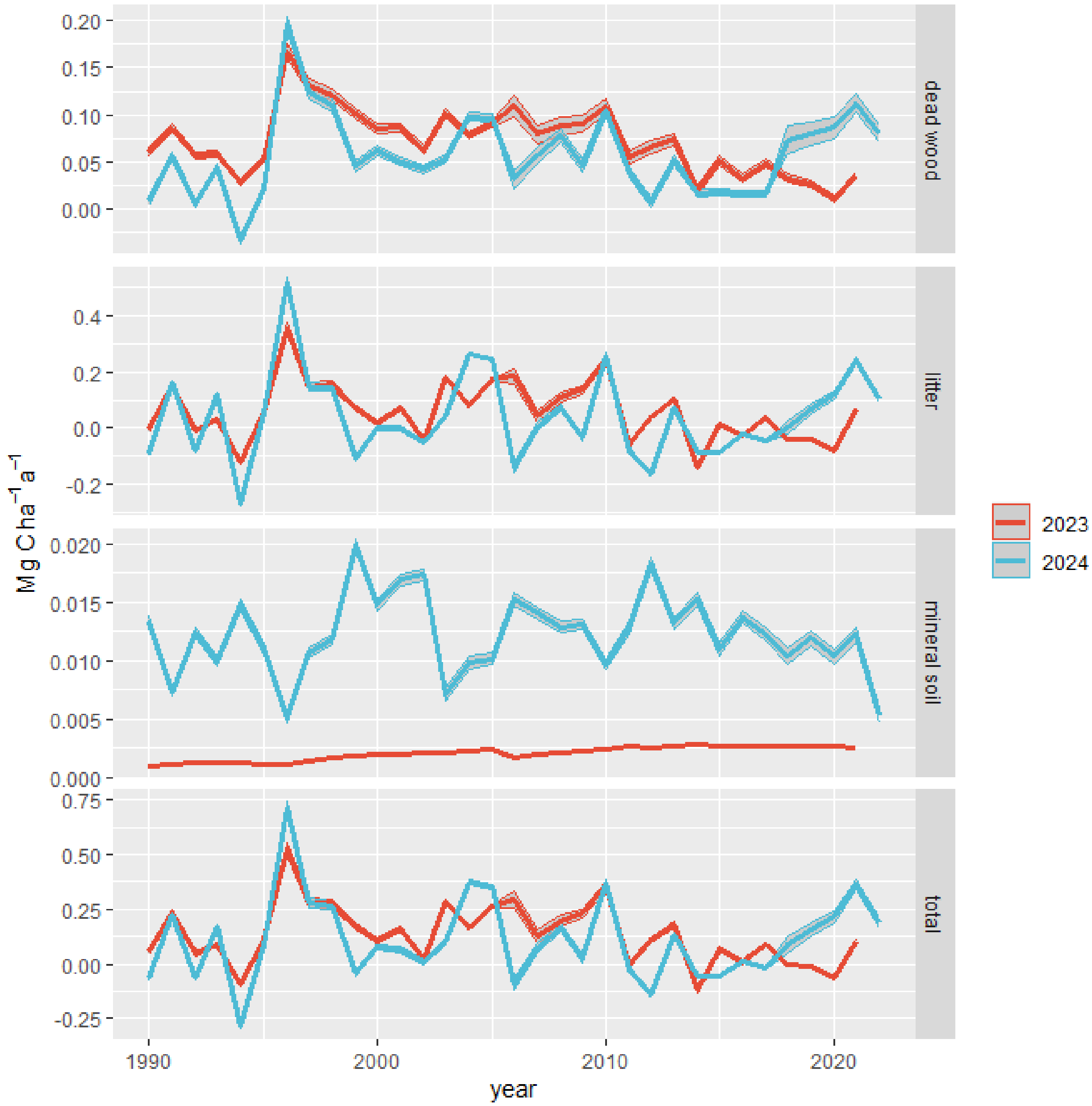

Figure 5. Time series of mean annual C stock change in the dead wood, litter and mineral soil pools as well as their total estimated for the GHGIs 2023 (supplement 2 in Didion 2020a) and 2024 from this report. Negative values indicate C losses, positive values C gains. Shaded areas indicate 2 SE of the mean.

3.1.1 *Dead wood*

Since 1990 the dead wood pool acted nationally as a sink with the exception of 1994 (Figure 6). The increased gain after 1996 was the result of the storm Lothar, which occurred in 1999 (i.e. in the period NFI23 thus affecting the years after 1996). The storm caused large scale mortality across Swiss forests and although the majority of the felled trees were removed, the dead wood volume increased significantly. As particularly the larger sized felled trees decay slowly (Didion et al. 2014a), the storm resulted in a sustained C sink in dead wood. The additional dead wood pool which resulted from the storm has been decreasing slowly releasing stored C as indicated by the decreasing trend of gains in this pool. The trend of decreasing harvesting rates for several years after NFI3 (starting 2007, Figure S. 3) further sustained the carbon sink of dead wood as mature trees, which could be harvested, remain in the forest to potentially contribute to the dead wood pool. With the period NFI45, i.e. after 2018 the gains increased again due to increased mortality as explained previously.

In the reporting year 2022, the dead wood pool gained C 0.080 ±0.009 (2 SE) Mg C ha^{-1} a^{-1} (Table 8, Figure 6). The decrease in the rate compared to the years since 2018 represented by the new NFI5 data was due to drier weather (Figure 4, MeteoSwiss 2023) which slowed the decomposition. This update of the NFI data, i.e. deriving estimates based on the NFI45 data instead of the NFI34/5 data (sections 2.4.1 and 2.4.2) indicated higher total coarse-woody inputs for the period NFI45 with a mean total of 713 Kg C ha^{-1} a^{-1} (Table 5) compared to a mean total of 618 Kg C ha^{-1} a^{-1} in the period NFI34/5 available for the previous GHGI (Table 5 in Didion 2020a). This increase in inputs is driven by increased mortality due to drought and heat stress observed in the previous years (FOEN 2023b).

3.1.2 *Litter*

The litter pool was the most dynamic pool since 1990 varying from a C source to a sink (Figure 6). This was expected as it is composed of fine and easily decomposable material where the decay is susceptible to variation in temperature and precipitation. Due to the faster decomposition of litter the effect of the variability of litter inputs between NFI periods, which was low (Table 6), was minor. The fast decomposition of litter was also reason that the effect of the revised foliage model was minor.

In the reporting year 2022, the litter pool gained 0.104 ±0.011 Mg C ha^{-1} a^{-1} (Table 8, Figure 6). This was lower than in previous years as a result of slowed decomposition due to drier weather, similarly to dead wood.

3.1.3 *Mineral soil*

Mineral forest soils continuously gained in C at a comparably moderate rate (Figure 6). As the soil C pool is fed by decomposing material on the surface, i.e. dead wood and litter, its dynamics reflect decomposition in these pools. This with delay as higher C fluxes from dead wood and litter can lead initially to an increase in the soil C pool, which in turn can result in higher C losses from the soil pool later. The more realistic model calibration in Yasso20 and the subsequent higher sensitivity (section 2.1) resulted in higher annual variability in the soil pool estimates prepared for the NIR 2024 compared to the NIR 2023, which was based on the older Yasso07. The comparatively small C stock changes are, however, below the detection limit of measurements (Keller et al. 2006; Schrumpf et al. 2011), which was estimated as ca. 0.18 t C ha^{-1} a^{-1} for mineral soils on forest land in Switzerland (chatper 6.4.4.5 in FOEN 2023a).

In the reporting year 2022 the mineral soil pool gained 0.005 ±0.001 Mg C ha^{-1} a^{-1} (Table 8).

Table 8. Mean carbon stock change ± 2 SE in 2022 in dead wood, litter and mineral soil by spatial stratum. Negative values C losses, positive values C gains.

Spatial stratum	Pool	Mg C ha^{-1} a^{-1}	2 SE
Jura <=600m	Dead wood	0.043	0.013
	Litter	0.182	0.031
	Mineral soil	-0.001	0.002
Jura >600m-1200m	Dead wood	0.037	0.009
	Litter	0.182	0.02
	Mineral soil	0.002	0.001
Jura >1200m	Dead wood	-0.037	0.018
	Litter	-0.062	0.039
	Mineral soil	-0.003	0.002
Plateau <=600m	Dead wood	0.061	0.012
	Litter	0.179	0.019
	Mineral soil	-0.003	0.001
Plateau >600m	Dead wood	0.038	0.014
	Litter	0.171	0.024
	Mineral soil	-0.002	0.001
Pre-Alps <=1200m	Dead wood	0.08	0.013
	Litter	0.186	0.022
	Mineral soil	0.008	0.001
Pre-Alps >1200m	Dead wood	0.008	0.017
	Litter	0.125	0.034
	Mineral soil	0.012	0.002
Alps <=1200m	Dead wood	0.07	0.015
	Litter	0.136	0.021
	Mineral soil	0.014	0.001
Alps >1200m	Dead wood	0.092	0.012
	Litter	0.196	0.019
	Mineral soil	0.012	0.001
Southern Alps <=1200m	Dead wood	0.046	0.01
	Litter	0.084	0.02
	Mineral soil	0.019	0.002
Southern Alps >1200m	Dead wood	0.015	0.01
	Litter	0.122	0.025
	Mineral soil	0.014	0.001
Switzerland	Dead wood	0.08	0.009
	Litter	0.104	0.011
	Mineral soil	0.005	0.001
	Total	**0.189**	**0.015**

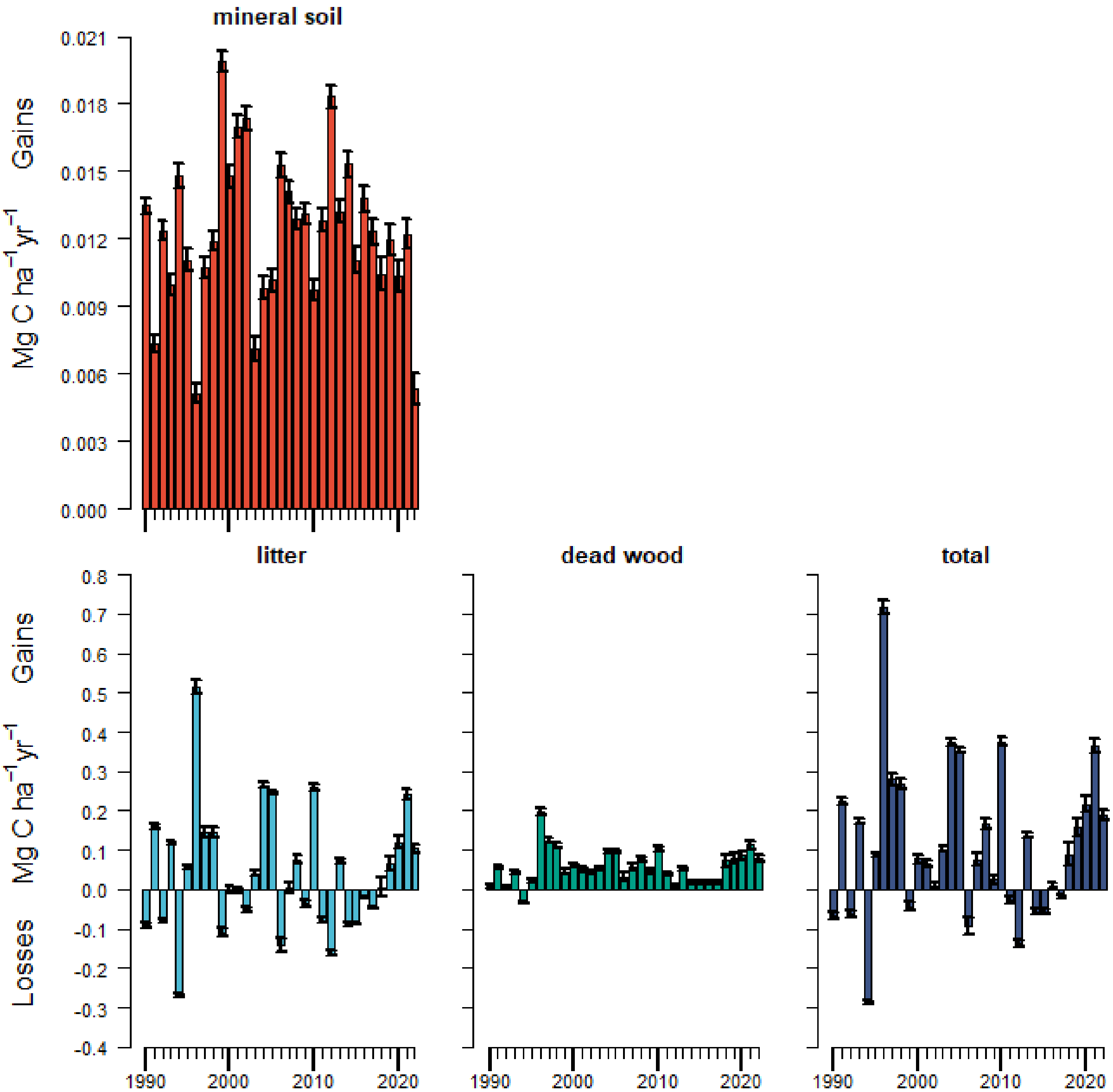

Figure 6. National mean carbon stock change since 1990 for three pools soil, litter, dead wood and their total in Mg C ha^{-1} yr^{-1}). Note the difference of the y-axis scale between mineral soil and litter, dead wood and total, respectively. Negative values indicate C losses, positive values C gains. The error bars indicate the standard error (2SE). Note the figure corresponds to Figure S. 2, which is prepared based on conventions in the NIR.

3.1.4 *Uncertainty*

Uncertainty of annual changes in C stock is primarily driven by the annual variability in litter and dead wood inputs (Lehtonen and Heikkinen 2015). This variability (section 2.4.2) as well as the uncertainty in the Yasso parameters (section 2.1) were addressed by applying a Monte-Carlo approach based on 100 replicate simulation (section 2.7). Following the change in the NFI4 from periodic to a continuous survey (sections 2.4.1 and 2.4.2), dead wood and litter inputs for the period NFI34 were derived based on shifting sample of sample plots common to NFI3 and multi-annual NFI4 and NFI 5 subsets, respectively.

This change in sample plots introduced additional variability, which was taken into account to obtain an uncertainty estimate over the period 2013 to 2020. The thus obtained double standard errors for the dead wood, litter and mineral soil C in the Swiss GHGI were 16.6%, 96.7, %, and 37.0%, respectively. The total uncertainty of the carbon stock change in DOM and mineral soil was estimated as 17.1%. This is in the range of uncertainty estimates in countries where the older version of the model Yasso07 was applied. For example, Norway reported an uncertainty of 15.5%, which applied to both the DOM and mineral soil pools (chapter 6.4.1.2 in Norwegian Environment Agency 2023), and Finland reports an uncertainty of 31.5% in the net CSC in DOM and mineral soil (Lehtonen and Heikkinen 2016; chapter 6.4.3.2 in Statistics Finland 2023).

3.2 Carbon stocks

Estimates of coarse dead wood C stocks based on measured tree volume are available since the NFI3. At the national level the simulated national mean dead wood C stock agrees well with the stock derived from the NFI (Table 9). Differences are expected because the dead wood pools are not fully comparable regarding their composition: C inputs to the model may not precisely correspond to dead wood falling from trees. Also, NFI data are associated with uncertainty (cf. Didion et al. 2014a), especially regarding the measurement of the decay class, which is important for applying the correct wood density. Further, the model cannot account for information that is available for the calculation of the C stocks of individual trees in the NFI, e.g., volume reduction due to damage, or diameter and length of a piece of dead wood. Generally, at the national level, the observed changes in coarse dead wood C stocks in Switzerland between NFIs 3 and was reproduced accurately by the model (Table 9) considering the uncertainty in the stocks. It has to be noted that the uncertainty of NFI stocks in Table 9 represents spatial uncertainty only. Considering further sources of uncertainty such as volume estimation and wood density an uncertainty of >50% is more realistic, i.e. larger than the total uncertainty of 43% estimated for living biomass (chatper 6.4.4.5 in FOEN 2023a).

Table 9. Mean and standard error of carbon stored in dead wood based on observations in NFI3 and NFI4 and simulated dead wood carbon stock with Yasso20; the simulated stock was calculated as the mean of the annual stocks in years 2004-2006 for NFI3 and 2009-2017 for NFI4. Percent change was calculated based on the respective means.

NFI3		NFI4		Change NFI3-NFI4	
Mg C ha^{-1}				%	
NFI	Yasso20	NFI	Yasso20	NFI	Yasso20
7.33 ±0.40	7.65 ±0.1	7.64 ±0.34	7.76 ±0.25	+4.2	+1.4

For verification of the litter C stocks, the simulated data were compared with observed data from Moeri (2007). These data rather than data from Nussbaum et al. (2012) are used since Nussbaum et al. (2012) placed little confidence in their method. At the national level Moeri (2007) and Nussbaum et al. (2012) report similar C stocks in the litter pool, i.e. 18.1 ±0.61 and 16.73 ±0.83 Mg C ha^{-1} a^{-1}, respectively.

The simulated national mean litter C stock was ca. 85% of the stock reported by Moeri (2007); cf. Table 10. This difference is not surprising since the simulated values do not include litter from herbs, shrubs and trees <12 cm dbh. The contribution of the herb- and shrub layer to annual litter inputs to the Yasso simulations on sample plots classified as forests is for consistency with the methodology used for the forest reference level (cf. FOEN 2020) however included.

Table 10. Mean and standard error of carbon stock in the litter pool based on observed (sum of L, F and H horizons from Tab. 5.3 in Moeri 2007) and simulated litter carbon stock with Yasso20; the simulated stock was calculated as the long-term mean over the period 1990-2022.

Moeri 2007	Yasso20
Mg C ha^{-1}	
18.1 ±0.6	15.36 ±0.2

On the basis of production regions (see section 2.7.1) , the spatial variability in litter C stocks is greater in the measured data from Moeri (2007) than in the simulated data (data not shown). (Note that Moeri (2007) did not stratify by elevation.) There are several explanations for this, including a) statistics (e.g., on harvest) that are used to derive inputs for the Yasso20 simulation are not available on the basis of NFI plots but are regional averages, and b) the measured data are based on a limited number of observations and thus the uncertainty of the means is higher as indicated by the standard error in Table 10.

Under the considerations explained previously, the estimates of dead wood and litter C stocks derived with Yasso20 agree with observations and are plausible, certainly at the national level. Since observed C decomposition was reproduced highly satisfactory with Yasso20 (section 2.2), confidence can be placed in the reported stocks and stock changes in the litter and dead wood pools.

Due to the incomplete knowledge of the origin of the high mineral soil carbon stocks in Swiss forests (Eckmeier et al. 2010; Guidi et al. in prep.; Nussbaum et al. 2012, 2014; Zanelli et al. 2006), they cannot be reproduced by models yet. Hence, only changes in soil C stocks derived from the Yasso20 are used for reporting purposes under the UNFCCC and the Paris Agreement. Although soil C stocks cannot be reproduced, it can be assumed that the changes obtained from the simulated stocks were realistic since a) the pyrogenic carbon which is found particularly in the soils of the Southern Alps is very stable (Eckmeier et al. 2010), and b) the simulated CSC including standard error is less than the minimum detection limit of repeated soil carbon stock measurements (e.g., Keller et al. 2006). Simulated soil C stocks were highly variable and did not show a clear correlation to environmental variables such as elevation. This is consistent with results from a study in the Bernese Alps by Hoffmann et al. (2014) who found a large unexplained variability in SOC stocks not correlated with environmental variables.

3.3 Further development

Research to improve Yasso20 is ongoing at WSL and elsewhere. Planned and anticipated improvements to the application in Switzerland for the coming years include:

- Improving the uncertainty estimates for litter production by revising allometries and by estimating tree compartments using a Monte-Carlo approach. This is expected to improve the accuracy of the estimates of C stocks and C stock changes.

Several opportunities for collaboration and further development of Yasso20 are arising from national and international projects, particularly in the context of the EU-Horizon project Pathfinder (https://pathfinder-heu.eu/) and the contribution by WSL to task 3.3 ‘Modelling carbon flux among pools’ (Task lead by M. Didion and research by C. Guidi).

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Supplemental data

Table S. 1. Uncertainty in litter inputs (%).

	Conifers	Broadleaves
Allometry[1]	11	11
Biomass Conversion and Turnover[2]	18	18
Carbon content[3]	0.35	0.25
Total[4]	21.1	21.1

[1] based on Berger, A., T. Gschwantner, R. E. McRoberts, and K. Schadauer. 2013. Effects of Measurement Errors on Individual Tree Stem Volume Estimates for the Austrian National Forest Inventory. Forest Science.

[2] based on Wutzler, T., and M. Mund. 2007. Modelling mean above and below ground litter production based on yield tables. Silva Fennica 41:559-574.

[3] Estimated based on data Table 1 in Dobbertin and Jüngling 2009. Totholzverwitterung und C-Gehalt. [Wood density and carbon content with changing degree of dead wood decay: First results]. Swiss Federal Research Institute for Forest, Snow and Landscape Research, Birmensdorf. avl. online at www.bafu.admin.ch/climatereporting.

[4] Calculated following equation 3.1 in chapter 3 'Uncertainty' in IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). IGES, Japan. (avl. at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/1_Volume1/V1_3_Ch3_Uncertainties.pdf).

Table S. 2. List of result tables on carbon stock change (CSC) and C stocks that were included in the data delivery from 16.08.2023.

Table	Content	Unit
1a	Mean dead wood pool CSC	Annual C stock change [Mg C ha^{-1} a^{-1}]
1b	Mean litter pool CSC	
1c	Mean mineral soil pool CSC	
1d	Mean stock change for the total CSC over all pools	
1e	Standard error dead wood pool CSC	
1f	Standard error litter pool CSC	
1g	Standard error mineral soil pool CSC	
1h	Standard error stock change for the total CSC over all pools	
2a	Mean dead wood pool C stock	Annual C stock [Mg C ha^{-1}]
2b	Mean litter pool C stock	
2c	Standard error dead wood pool C stock	
2d	Standard error litter pool C stock	

NOTE:
1) Table values were rounded to 6 decimal places.
2) Negative values for CSC indicate a C sink, positive values a C source.

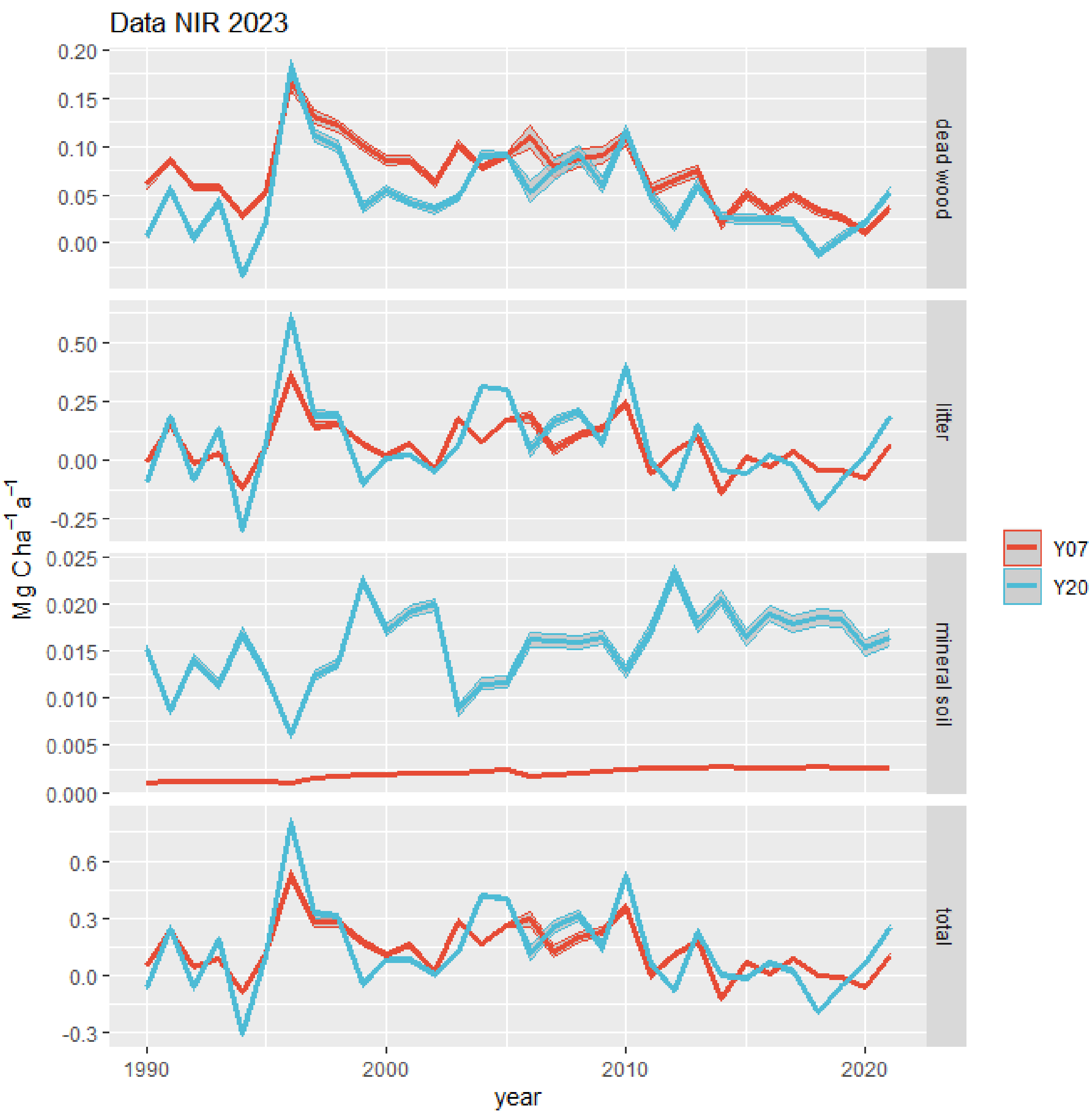

Figure S. 1 Time series of mean annual C stock change in the dead wood, litter and mineral soil pools as well as their total estimated for GHGI 2023 based on the previously used model version Yasso07 (Y07; supplement 2 in Didion 2020a) and the new Yasso20 (Y20). Negative values indicate C losses, positive values C gains. Shaded areas indicate 2 SE of the mean.

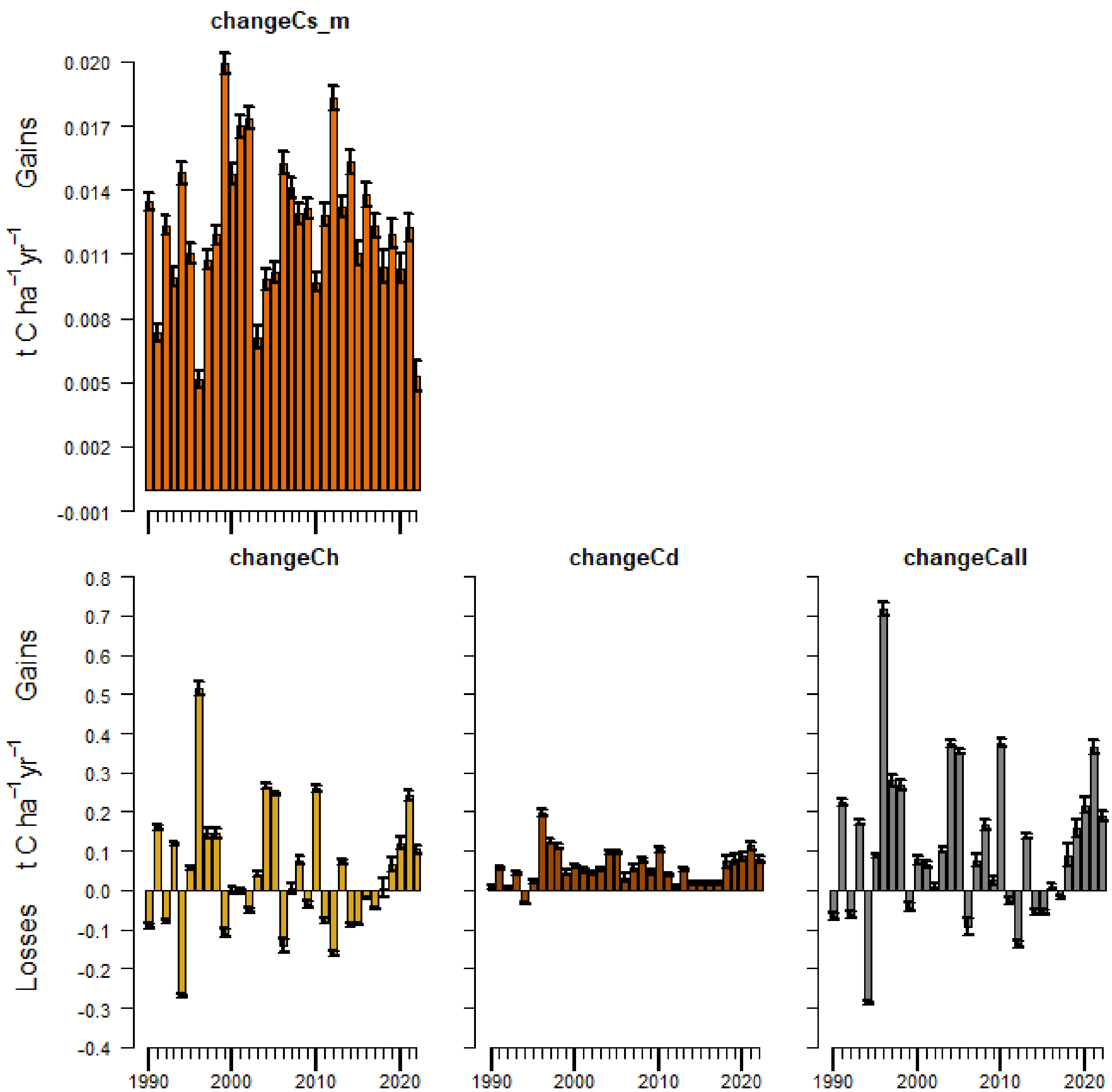

Figure S. 2. Mean carbon stock changes (changeC) over the inventory period for three pools mineral soil (s_m, 0–100 cm), litter (h), dead wood (d) and their sum (all) in t C ha-1 yr-1. Note the difference of the y-axis scale between changeCs_m and changeCh, changeCd and changeCall, respectively. Negative values indicate losses in carbon stock, positive values gains in carbon stock. The error bars indicate the double standard error.

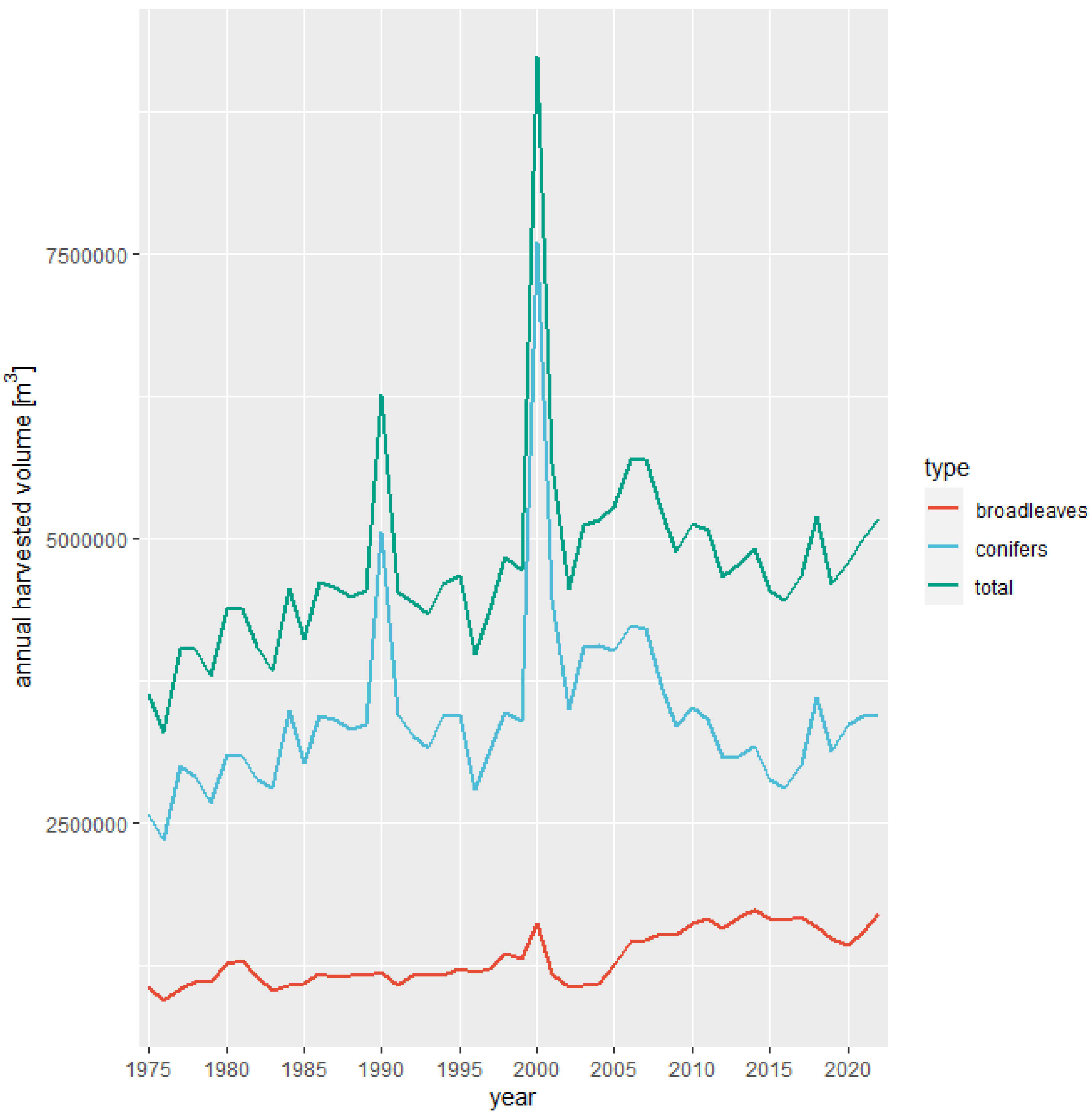

Figure S. 3. Annual harvesting amount in m³ merchantable wood separately for conifers and broadleaves and the total. Source: Federal Statistical Office (2023) Schweizerische Forststatistik 2022 [Swiss forest statistic 2022] Federal Statistical Office, Neuchâtel. https://www.bfs.admin.ch/bfs/de/home/statistiken/land-forstwirtschaft/forstwirtschaft.gnpdetail.2023-0417.html. Accessed 20.07.2023.