Data on C stocks and C stock changes in living tree biomass on forest land prepared for the Swiss NIR 2024 (GHGI 1990–2022)

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Markus Didion, Esther Thürig, and Erik Rösler

Forest Resources and Management, Swiss Federal Institute for Forest, Snow and Landscape Research WSL

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Swiss Federal Institute for Forest,
Snow and Landscape Research WSL

Summary

Switzerland prepares annually a greenhouse gas inventory for reporting under the climate convention UNFCCC and the Paris Agreement. 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 in above- and belowground biomass, dead organic matter, and soil. This reports presents data, methods and results relevant for reporting CO_2 emissions and removals in the Forest Land category in the LUUCF sector of Switzerland's NIR 2024 (GHGI 1990-2022). The Swiss National Forest Inventory (NFI) is the primary data source, and for the NIR 2024 revisions and new information from the fifth NFI were applied for updating the time series of C stocks and C stock changes since 1990.

The estimated national mean C gains and losses resulting from tree biomass growth and drain in the reporting year 2022 were 2.86 ±0.08 (2SE) t C ha^{-1} a^{-1} and -2.82 ±0.24 t C $ha^{-}1$ a^{-1}, respectively. These estimates correspond to a net change of 0.04 ±0.26 t C ha^{-1} a^{-1} in 2022. The mean national C stock in above- and belowground tree biomass was 117.80 ±2.55 t C ha^{-1}. For the year 2021 the estimates were a gain of also 2.86 ±0.08 t C $ha^{-}1$ a^{-1} and for losses 2.73 ±0.24 t C $ha^{-}1$ a^{-1}. Compared to the estimates of total biomass gains for the reporting year 2021 presented in the previous NIR submission 2023 (3.02 ±0.12 t C ha^{-1} a^{-1}), the values were lower. For total biomass losses, i.e. including fellings and natural mortality the values were higher compared to the NIR 2023 (2.52 ±0.34 t C ha^{-1} a^{-1}). The differences in growth and drain between the two NIR submissions can be attributed primarily to the new NFI5 data and reflect the increased stress on Swiss forests due to extended drought conditions and warming climate. The estimated biomass growing stock derived for the NIR 2024 (2022: 117.80 ±2.55 t C ha^{-1} and 2021: 117.76 ±2.55 t C ha^{-1}) are lower than previously (132.24 ±2.48 t C ha^{-1}). This was expected as the revised estimation approach accounts for sample plots converted to forest since the previous inventory.

There was no statistically significant difference between the time series of gains and losses prepared for the NIR 2024 and the NIR 2023, except for the years since 2018. Since 2018 growth in Swiss forests declined while mortality increased due to increased stress from drought and insects, which was not apparent yet in the NFI data representing the period 2006 to 2019 that were the basis for the NIR submissions 2021, 2022, and 2023. The effect of the application of updated historic NFI data before 2006, i.e. accounting for updates in the database was negligible for the entire time series since 1990.

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Glossary

The terminology used in this report follows the definitions listed in Annex 4A.1 in Volume 4 of IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2006); country-specific modifications noted where applicable.

basic wood density: Ratio between oven dry mass and fresh stem-wood volume without bark.

carbon (C) fraction: Tonnes of carbon per tonne of biomass dry matter.

dbh: diameter at breast height

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

state and change components in biomass and carbon:

- growth: increment in total biomass of all tally trees between two forest inventories. In the Swiss NFI, the increment is based on all surviving and ingrowing trees and the predicted increment of the felled or mortality trees for half of the measuring interval. Growth estimates are attributed to C gains in the GHGI.
- Cut and mortality (here simplified to drain): decrease in total biomass due to fellings and natural mortality of tally trees between two forest inventories. In the Swiss NFI, fellings

refers to trees that were harvested and removed from the forest between two consecutive inventories identified in the field by cutting marks on remaining stumps, and natural mortality refers to trees that died naturally between two consecutive inventories. Drain is attributed to C losses in the GHGI.

- growing stock: total tree biomass of all living and standing tally trees estimated for a particular forest inventory.

tally tree: Tree that is part of the sample of an inventory. In the Swiss NFI, tally trees have a dbh ≥12 cm and are located on a sample plot within the forest area according to the Swiss NFI forest definition.

total tree biomass: incl above-ground and below-ground elements of tally trees.

- above-ground: all biomass of trees above the soil including stems, stumps, branches, bark, seeds, and foliage;
- below-ground: all biomass of live roots > 5 mm diameter

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 from Land Use, Land-Use Change and Forestry (LULUCF). Thus, C stock changes in living tree biomass (including above- and belowground parts), dead organic matter, and soil have to be reported in Switzerland's National Inventory Report (NIR).

The Swiss National Forest Inventory (NFI) is the primary source of data for estimating the C balance of Swiss forests. The NFI provides data since 1984 collected in different measurement campaigns. Sections 2.1 and 2.2 of this report provide background information on the NFI data. Sections 2.3 to 2.5 document the methodology to obtain estimates on C gains, losses, and stocks in living biomass from the NFI data that are used for reporting CO_2 emissions and removals in the Forest Land category in the LUUCF sector of Switzerland's NIR 2024 (GHGI 1990-2022). The estimates for the NIR 2024 are based on updated NFI data representing the most current forest dynamics. Section 2.6 presents the approach to ensure time series consistency and accuracy. Changes in methods and input data are documented in section 2.7. Section 3 of the report presents the estimates obtained from the NFI data and a discussion of the impact of the methodological changes on the results compared to the estimates prepared for the NIR submission 2023 (FOEN 2023).

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 section 2.6 of this 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 2006). 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 as regulated by law. It was ensured that the methods were applied consistently, including data per unit area which are independent of temporal changes in the underlying forest area. Regular updated NFI data are used to represent the most current forest dynamics.

Comparability is achieved by estimating carbon stocks and stock changes based on methodologies and formats agreed by the COP and CMA and following the inventory guidelines.

Completeness is achieved by addressing all changes in forest carbon stocks due to growth and drain and by including all tree elements associated with above- and belowground C pools. Full geographical coverage was ensured by relying on data from the Swiss National Forest Inventory, which provides a representative random sample for the forest regions in Switzerland.

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 using independent data (section 3.4).

2 Data and Methods

2.1 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 1). While the sample plots in the NFI1 were based on a 1x1 km grid, a 1.41x1.41 km grid that intersected the 1x1 km grid was used in later inventories (Brändli and Hägeli 2019)**.** 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.

Table 1. 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 1.41x1.41 km grid (Brändli and Hägeli 2019). Note that the NFI5 is carried out in the years 2018 to 2026, and that for the NFI1 the number of sample plots and tally trees based on the initially used 1x1 km grid is given in brackets.

	NFI1	NFI2	NFI3	NFI4	NFI5
Inventory cycle	1983-1985	1993-1995	2004-2006	2009-2017	2018-2022
Terrestrial sample plots	5517 (10’981)	5'679	5'920	6'042	3'435
Tally trees	64’414 (128’441)	67'297	70'061	71'962	40'537

Allometries and wood densities were developed using country-specific estimates where possible. Table 2 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).

The estimates of biomass growth and drain that are used for reporting C gains and losses in the Swiss NIR are 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 2023). Biomass growing stock for reporting in the NIR is based on all on all sample plots visited in one particular inventory classified as accessible forest but not shrub forest (*zugänglicher Wald ohne Gebüschwald*), i.e. including sample plots converted to forest since the previous inventory (Table 1).

Table 2. 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, basic 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, basic 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)

2.2 Spatial stratification and temporal aggregation

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 2023):

- 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). An analysis of variance showed that this spatial stratification and additionally tree species type as a further explanatory variable all significantly explain differences in gross growth (Thürig et al. 2005, re-confirmed in 2017 for data of the period NFI34; Table 3).

Table 3. Analysis of variance of gross growth of data from NFI2 and NFI3. Explanatory variables: Tree species type, NFI production region, and elevation

Strata	Gross growth	
	F-value	p-value
Tree species type: coniferous / broadleaved	421	<0.0001
NFI Production region	45	<0.0001
Elevation classes	34	<0.0001

With the change to a continuous inventory in the NFI4, the number of sample plots within a spatial stratum that are common to two consecutive inventories in a particular inventory period resulted in a limited accuracy and representativity of smaller spatial strata for estimating growth and drain. 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 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 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, 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.

Table 4. Number of NFI sample plots of accessible forest plots without brush forest in each NFI period where the total for a period represents the common plots of two consecutive NFIs based on which biomass growth and drain are 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. This results in different sample plot numbers for NFI periods, which are based on the common plots between two consecutive inventories. 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	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[1]	5’456
1996–2005	**NFI23**	N/A[1]	5’370	211	5’581
2006-2017	**NFI34**	N/A[1]	5’521	303	5’824
2018-2022[2]	**NFI45**	2018 - 2022	3’242	95	3’337

[1]not applicable in this first NFI period

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

2.3 Biomass growth, drain, and growing stock

Estimates of biomass growth, drain, and growing stock are derived from measurements of individual tally trees on NFI sample plots. Estimates of growth and drain are based on the common plots of two consecutive NFIs. Stocks are estimated on all sample plots visited in one particular inventory or within a moving window in the continuous NFIs, i.e. including sample plots converted to forest since the previous inventory. This ensures that for each inventory the most representative and accurate stocks are used to obtain stock changes for forest and converted to other land categories. Growth, drain, and growing stock estimates comprise the total tree biomass including stemwood of the entire stem over bark, branches over bark, and coarse roots (Table 2). Growth is calculated as the change in total tree biomass between two consecutive inventories considering the state of a tree as follows:

- A tree is alive and measured in both inventories: difference between the biomass calculated based on the dbh in the first and second inventory.
- A tree is alive and measured in the first inventory and dead (and still present on a sample plot) or harvested (and removed from a sample plot) in the second inventory: difference between the biomass calculated based on the dbh in the first inventory and the modelled dbh (Herold et al. 2019) at the half point of the NFI period as the exact date of tree death or harvest is not known.

Drain correspond to the total biomass of trees that were alive in the first inventory and were dead or harvested in the second inventory estimated based on the modelled dbh (Herold et al. 2019) at the half point of the NFI period. Mean annual values for growth and drain are derived based on the number of vegetation periods calculated separately for each repeatedly visited sample plot (Lanz et al. 2019). Estimates of the biomass of growth and drain for each NFI period are shown in Table S. 1, and for stocks for each NFI in Table S. 2.

2.4 Conversion of growth, drain, and growing stock from biomass to carbon

The estimated growth, drain, and growing stock in biomass are converted to carbon using a mean C fraction of 0.5 in dry matter based on estimates for broadleaved and coniferous trees in table 4.3 in Volume 4 of the 2006 IPCC guidelines.

2.5 Annualizing C drain and growing stock

The annual volume of harvested trees in Swiss forests (Table 5, Figure S. 1) are quantified accurately in the Swiss harvest statistics database (FSO 2023). The harvest statistic provides data stratified by tree species type (broadleaved and coniferous), assortments, production region, and ownership. These data are used to derive annual estimates of drain based on the fraction of the mean annual drain data obtained from the NFI that corresponds to fellings, i.e. the fraction affected by natural mortality is not annualized as this process is not associated with the harvest statistic. To annualize the mean annual fellings estimate from the NFI (i.e. a constant value for a period between two consecutive NFIs), the harvest statistic data are used to calculate annual weighting factors based on the ratio between the harvested volume in a particular year and the mean of the annual harvests falling within a NFI period (Table 5). This is done separately for broadleaves and conifers using only the national total volume, i.e. disregarding the production regions as they are not further stratified by elevation, which may introduce a bias in the reported data that are stratified by production region and elevation (section 2.2). The annual weighting factors are multiplied with the fellings estimate for the NFI period to produce annual estimates (Figure 1). This approach corresponds broadly to the logging factor method proposed by Röhling et al. (2016).

Annual values of C stocks are derived based on the growing stock in 1985 determined from all sample plots of the NFI1 and forward calculation using the net change of the growth estimated for a NFI period and annualized drain (eq. 1) where y is number of years since 1985. Since the growth and drain estimates are based on plots common to two inventories and thus do not account for sample plots converted to forest between two inventories, forward calculated stocks are scaled to the observed stocks in subsequent inventories (Figure 2).

$$f_{stock}(y) = stock_{1985} + \sum_{n=1985}^{y-1} (growth_n + drain_n) \qquad \text{(equation 1)}$$

Table 5. Annual harvested volume in m³ for broadleaves, conifers, and the total based on the Swiss harvest statistics database (FSO 2023) and the derived annual weighting factors per NFI period. The weighting factors are given in full decimal places for reproducibility.

Year	NFI period	broadleaves		conifers		total	
		Harvest [m³]	factor	Harvest [m³]	factor	Harvest [m³]	factor
1986	NFI12	1176795	1.0095388	3451249	0.973562	4628044	0.982464
1987	NFI12	1158445	0.9937969	3411672	0.962397	4570117	0.970167
1988	NFI12	1162122	0.9969513	3332952	0.940191	4495074	0.954237
1989	NFI12	1167474	1.0015426	3374532	0.951921	4542006	0.9642
1990	NFI12	1196011	1.026024	5065667	1.428972	6261678	1.32926
1991	NFI12	1075864	0.922953	3461045	0.976325	4536909	0.963118
1992	NFI12	1172136	1.005542	3274417	0.923679	4446553	0.943937
1993	NFI12	1164931	0.9993611	3172844	0.895027	4337775	0.920845
1994	NFI12	1160618	0.9956611	3449297	0.973011	4609915	0.978616
1995	NFI12	1222362	1.0486295	3456046	0.974915	4678408	0.993156
1996	NFI23	1198861	0.9661648	2796054	0.689283	3994915	0.75414
1997	NFI23	1228819	0.9903081	3154339	0.777607	4383158	0.82743
1998	NFI23	1364530	1.0996779	3480517	0.858016	4845047	0.914623
1999	NFI23	1319610	1.0634767	3408099	0.840164	4727709	0.892473
2000	NFI23	1627567	1.31166	7610407	1.876116	9237974	1.743898
2001	NFI23	1186951	0.9565665	4474629	1.103085	5661580	1.068764
2002	NFI23	1057085	0.8519072	3499532	0.862704	4556617	0.860175
2003	NFI23	1073649	0.8652562	4047322	0.997745	5120971	0.966711
2004	NFI23	1091964	0.8800163	4068558	1.00298	5160522	0.974177
2005	NFI23	1259416	1.0149663	4025234	0.9923	5284650	0.997609
2006	NFI34	1456314	0.9072585	4245213	1.257088	5701527	1.144379
2007	NFI34	1481202	0.9227633	4209356	1.24647	5690558	1.142177
2008	NFI34	1538955	0.9587424	3723244	1.102523	5262199	1.056199
2009	NFI34	1519050	0.9463419	3360646	0.995151	4879696	0.979425
2010	NFI34	1617344	1.007577	3511655	1.039868	5128999	1.029464
2011	NFI34	1663556	1.036367	3411532	1.010219	5075088	1.018643
2012	NFI34	1578854	0.9835988	3079530	0.911907	4658384	0.935005
2013	NFI34	1683797	1.0489765	3094531	0.916349	4778328	0.959079
2014	NFI34	1735880	1.0814233	3177339	0.94087	4913219	0.986154
2015	NFI34	1666104	1.037954	2885793	0.854538	4551897	0.913632
2016	NFI34	1647437	1.0263248	2811554	0.832554	4458991	0.894984
2017	NFI34	1673678	1.0426725	3013864	0.892462	4687542	0.940857
2018	NFI45	1590271	1.02285	3607931	1.060095	5198202	1.048416
2019	NFI45	1484211	0.954633	3129827	0.919617	4614038	0.930597
2020	NFI45	1433876	0.9222579	3368349	0.9897	4802225	0.968552
2021	NFI45	1549832	0.9968399	3448051	1.013118	4997883	1.008014
2022	NFI45	1715536	1.103419	3462863	1.01747	5178399	1.044422

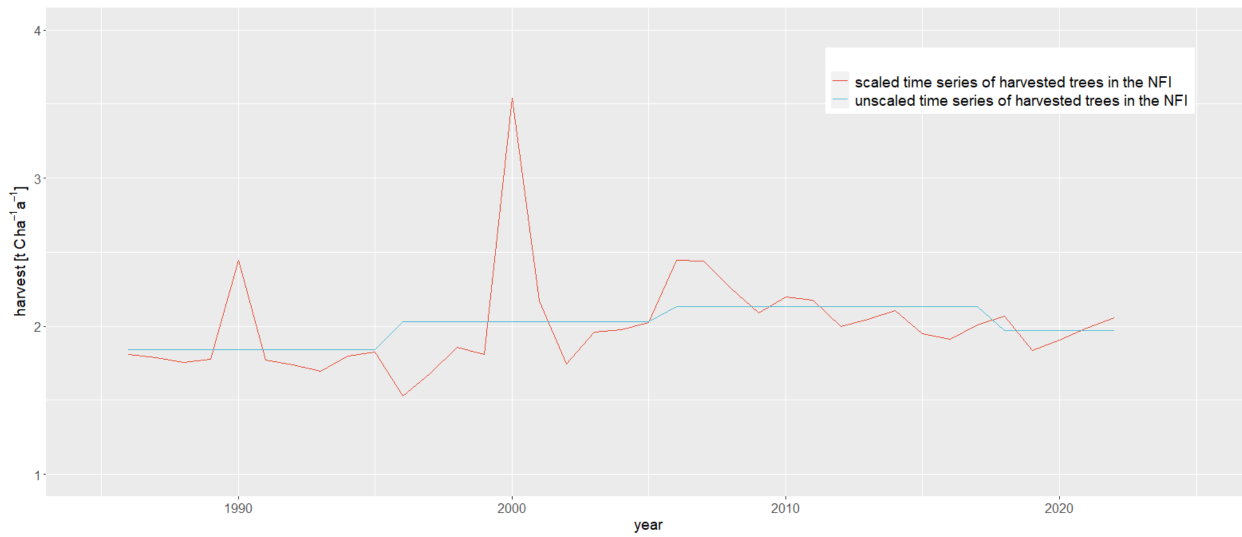

Figure 1. Time series of harvest - unscaled based on the observed state change between two NFI periods and scaled using annual weighting factors derived from the Swiss harvest statistics database (Table 5).

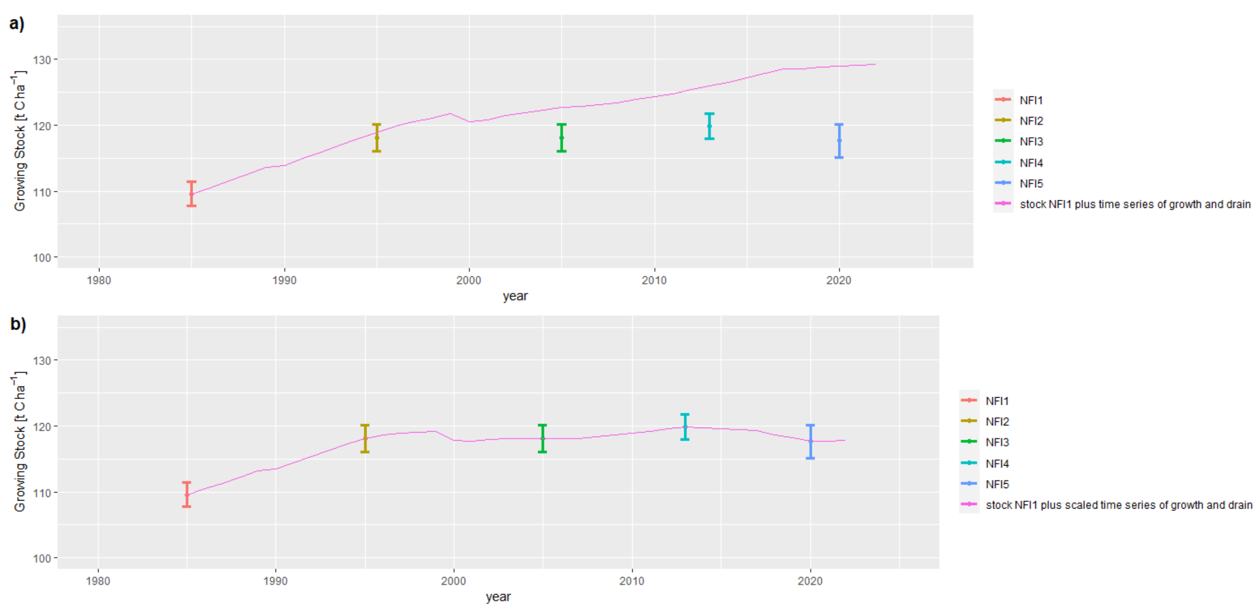

Figure 2. Time series of growing stock. a) growing stock (mean + 2SE) observed in different NFIs and forward calculation based on the stock observed in the NFI1 and growth and drain estimates in subsequent inventories, and b) growing stock (mean + 2SE) observed in different NFIs and scaled time series of stocks to account for plots converted to forest between two inventories.

2.6 QA/QC

The preparation of the data on biomass and C growth, drain and growing stock 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.

2.6.1 *Time series consistency*

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 growth, drain, and growing stock 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.

The approach to regularly update the estimates based on the most current NFI data that are available from the continuous survey approach implemented with NFI4 may introduce differences in the time series of growth, drain, and growing stock estimated for annual NIR submissions. In addition, the annually updated weighting factors for fellings (section 2.5) may also contribute to variability in the reported values. Nevertheless, this approach ensures that C gains and losses reported in a NIR are based on the most current and accurate NFI data on growth, drain, and growing stock.

To analyze time series consistency and accuracy, current estimates of growth, drain, and growing stock are compared with data derived for use in previous NIR submissions. Following the revisions of methods and data since the first NFI (section 2.7), the entire time series since 1985 was recalculated and was compared at the national level with the data prepared for reporting in the NIR 2023 (section 3.1).

2.6.2 *Completeness*

Estimates of growth, drain, and growing stock include all above- and belowground tree parts. The approach to separately estimate growth, and drain ensures that all changes in the C stocks of the living biomass are addressed. The approach implicitly accounts for C that accumulated in trees before they reached the measurement threshold of 12 cm used in the Swiss NFI. The approach ensures accuracy as the country-specific allometries to estimate total tree biomass do not apply to trees < 12 cm dbh. Furthermore, trees with dbh < 12 cm contribute only little to total forest biomass and C stock (Peichl and Arain 2006). Dunger et al. (2012) estimated this contribution to 1-2% for forests with similar forest structure as Switzerland.

In the productive forest in Switzerland, understory vegetation presents only a small component of the above-ground biomass carbon pool, i.e. < 1% based on estimates for herbaceous vegetation in the Swiss NFI in Didion (2020b). Consistent with the inventory guidelines (Annex 4A.1, Vol. 4, IPCC 2006), this vegetation layer was not included in the living biomass estimates for Switzerland's GHGI. It was ensured that the exclusion was used in a consistent manner throughout the inventory time series. This approach also ensures consistency with the model based forest reference level where understory vegetation cannot be estimated and predicted accurately.

2.6.3 *Verification*

Based on the estimates of total above-ground tree biomass growing stock and the corresponding estimates of stemwood volume, biomass conversion and expansion factors are calculated and compared with IPCC 2006 default values (Table 4.5, Vol. 4).

2.6.4 *Uncertainty*

The NFI methodology calculates the statistical random sampling error (ch. 2.5 in Lanz et al. 2019) and reports it by default. In the results section, this error is reported for comparability with NFI publications. The total uncertainty of the net C stock change of tree biomass on forest land reported in the NIR additionally considers uncertainties related to the temporal aspect of sampling from different 5-year subsets of the period NFI45 (section 2.2), allometric relationships, basic wood density, and C fraction (ch. 6.4.3.1 in FOEN 2023). For the allometric relationship to estimate volume and the conversion to total tree biomass, a sampling uncertainty of 21.2% and a model uncertainty of 22.2% is assumed based on Lehtonen and Heikkinen (2016). For carbon content in solid wood an uncertainty of 2% is assumed based on 2% relative standard deviation (RSD) in Monni et al. (2007), and 4-8% RSD in Lamlom and Savidge (2003). The uncertainty associated with the harvest statistics, which are used for annualizing C stocks and losses (section 2.5), is not addressed as it cannot be derived mathematically (cf. Röhling et al. 2016). However, any bias is minimized by applying a national factor to harvested trees only.

2.6.5 *Documentation*

The NFI estimates are retrieved from the NAFIDAS database (Traub et al. 2017; https://www.wsl.ch/en/projects/the-data-analysis-system-nafidas.html). The procedure to parametrize the database analyses to obtain reproducible estimates, and the methodology to produce the estimates of biomass stocks, growth, and drain are documented in (Didion 2020a). Separate copies of the documentation and the estimates used for reporting are maintained at WSL and FOEN.

Forest statistics data are maintained by the Federal Statistical Office and are available online at https://www.pxweb.bfs.admin.ch/pxweb/de/.

2.7 Methodological improvements and updates of input data

2.7.1 *Improvements and updates compared to the GHGI 1990-2021 (NIR 2023)*

Methodological improvements

For this submission several methodological improvements were implemented to increase the accuracy of the C stock and change estimates. Following the findings by Didion et al. (in prep) that the previously applied model to estimate foliage biomass and turnover overestimated the contribution of *Larix decidua* and *Fagus sylvatica*, a revised model was applied. This affected stocks but had a negligible effect on growth and drain.

Also, the derivation of annual estimates of stocks was revised. The estimates now also account for sample plots that were converted to forest between two inventories (Figure 2). As the forest on such plots is typically young, the growing stock per hectare is lower as compared to the previous GHGI data. This is thus a more accurate representation of actual stocks which are used for estimating C gains and losses due to land use changes to and from forest land (stock-difference approach).

Further, the annual estimates of stocks are affected by the revision of the annualization of the drain, i.e. applying single national weighting factors to fellings as opposed to the previous approach using factors stratified by production region but not by elevation classes. This was done to minimize any bias resulting from the annualization (section 2.5).

Updates of input data

For this submission NFI data of the first 5 years of the fifth NFI were available comprising the measurements in the period 2018 to 2022. This is the first occasion to have sufficient data from the NFI5 to derive robust estimates of growth and drain (section 2.2) between NFI4 and NFI5. This allowed to conclude the period between NFI3 and NFI4 (Table 4), which was the basis of data in the previous NIRs (cf. Didion et al. 2020). This provided the opportunity to consistently derive data for the entire time series since 1990, i.e. including data from the periods NFI12 and NFI23, which were derived for the NIR submission 2014 (Thürig and Herold 2013), and thereby accounting for

- minor corrections and updates in the NFI database;
- revised allometry for coarse roots (Zell and Thürig 2013); and
- aggregation of spatial strata with the start of the NFI4 (section 2.2.).

Further, the harvest statistics data for 2022 were included in the derivation of annual values of drain (section 2.5).

2.7.2 *List of improvements and updates until GHGI 1990-2021 (NIR 2021 to 2023)*

GHGI 1990-2019 to GHGI 1990-2021 (section 2.7.1 in Didion et al. 2020)

- Update of NFI sites to derive estimates of C inputs between NFIs 3 and 4.
- Addressing minor error in the bias correction for measured trees.

3 Results and discussion

3.1 C growth, drain, and growing stock

Figure 3 shows the time series of national estimates of C growth, drain, and growing stocks since 1990 for reporting in the NIR 2024. For comparison, the corresponding estimates reported in the NIR (Didion et al. 2020; FOEN 2023) are shown. The time series data for drain and growing stock include the effects of annualizing drain (section 2.5). Growth varied moderately by < 10% between NFI periods during which it is assumed constant. This observation applies equally to the time series in the NIR 2023 and NIR 2024. The exception is the latest NFI45 period covering the years 2018 to 2022 which were available for the NIR 2024 for the first time (section 2.7.1). Data before 2018 for the two NIR submissions differed by less than two standard errors, i.e. it can be assumed that the difference between estimates in the two NIR submissions is not significant. This observation is further supported by the fact that the uncertainty around the means shown in Figure 3 is not accounting for uncertainty related to allometric relationships, basic wood density, and C fraction (section 2.6.4). This indicates that the revisions to growth data that were made in preparation for the NIR 2024, i.e. accounting for updates in the database and root allometries also in the first three NFIs, had a negligible effect. The drop in growth in 2018 that is visible in the data for the NIR 2024 resulted from the transition from the period NFI34 to the period NFI45. Growth in Swiss forests declined since 2018 due to increased stress from drought and insects (Allgaier Leuch and Fischer 2023). This process was not apparent yet in the data reported in the NIR 2023 as the growth estimates for the years 2018 to 2021 were based on constant NFI data covering the period 2006 to 2021 (section 2.2).

Drain also varied moderately by < 10% between NFI periods with the exception of two peaks in 1990 and 2000. These were the result of exceptionally high harvests in 1990 after the storm Vivian (February 1990) and in 2000 after the storm Lothar (December 1999). The annual fluctuations reflect the temporal dynamics in the harvested volume (Figure S. 1), which were the basis of the annualization of the drain estimates for NFI periods (section 2.5). Estimates prepared for reporting in the NIR 2024 are within 2 standard errors of the mean of the data reported in the NIR 2023, with exception of the years 2000 and from 2018 onwards. In 2000 this was due to the revised derivation of the drain, i.e. only fellings are annualized while previously this was done for fellings and natural mortality. The reasons for the differences in the data after 2018 were the same as for growth, i.e. the new NFI45 period.

Estimates of biomass growing stock derived for the NIR 2024 were lower than previously. This was expected as the new data account for sample plots converted to forest since the previous inventory (section 2.3). The annual variability resulted from the application of annualized drain data to obtain annual stocks (section 2.5).

As identified above, significant differences in the estimates of growth between the NIR 2023 and the NIR 2024 existed only in the years 2018 to 2021 as a result of the new NFI45 data. The new data also affected the estimates of drain in those years although less pronounced. For transparency, a detailed comparison at the level of spatial strata was done comparing the data prepared for this submission, i.e. based on NFI45 subset 2018-2022 and data prepared based on the NFI34/5 subset 2015-2019 that were the basis of the NIR submissions in 2021 to 2023 (FOEN 2021, 2022, 2023).Table 6 and Table 7 present quantitatively the differences between the estimates from both NFI datasets for all 11 spatial strata (section 2.2); note that the unmodified estimates in biomass, i.e. not annualized stocks and drain, are shown (section 2.5). Compared to the estimates prepared for the previous NIR submissions (Didion et al. 2020), the values for biomass growth were in the majority of strata including the national level, lower (i.e. negative difference value in Table 6). For total biomass drain, i.e. including fellings and natural mortality, the values were in the majority of strata including the national level, higher (i.e. positive difference value in Table 7). Means based on the NFI45 subset 2018-2022 were generally within 2 SE of the mean values of the NFI34/5 subset 2015-2019. As expected, this was not the case at the national level with the exception of drain estimated for coniferous species. Table 8 shows the same information for C stocks indicating also that significant differences between the two datasets occurred primarily in strata with larger number of sample plots, which lead to lower standard errors.

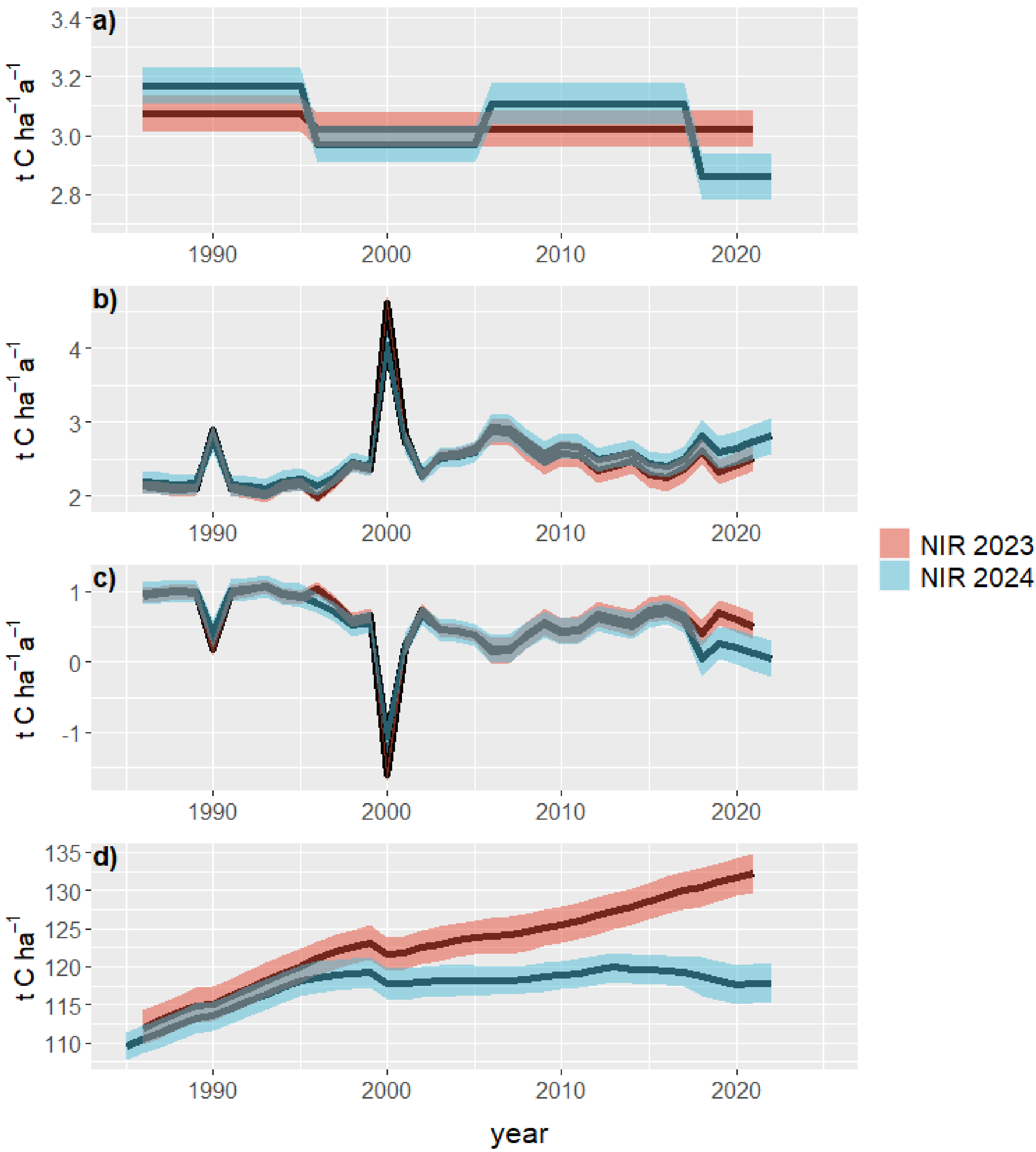

Figure 3. Estimates of a) growth, b) drain, c) their net change, and d) growing stock reported in the NIR2023 and prepared for the NIR2024. The ribbons indicate 2 standard errors of the mean. Note that for the net change positive values indicate gains and negative values losses.

3.2 Net change of C growing stock

The national net C stock change is calculated as the difference between C growth and drain, i.e. in the reporting year 2022 2.86 ±0.08 (2SE) t ha^{-1} a^{-1} and 2.82 ±0.24 t ha^{-1} a^{-1}, respectively. The uncertainty associated with the net change is estimated based on the statistical random sampling error reported with NFI estimates for growth and drain:

$$SE_{net-change} = \sqrt{0.08^2 + 0.24^2}$$

The net C stock change for 2022 is thus a sink of 0.04 ±0.26 t C ha^{-1} a^{-1}.

The approach to calculate the standard error of the net change assumes the random variables growth and drain to be independent, and may results in a small overestimation of the uncertainty estimate for the net change. This can be assumed to compensate here for excluding errors associated with allometric relationships, basic wood density, and C fraction (cf. section 2.6.3).

In the NIR (ch. 6.4.3.1 in FOEN 2023) uncertainties related to random sampling error, as well as the temporal aspect, allometric relationships, basic wood density, and C fraction are combined by adding relative uncertainties using equation 3.1 in Volume 1 of the IPCC 2006 guidelines.

Table 6. Mean ± 2 SE of estimated C gross growth of living trees for the periodic NFI data (i.e. NFI34/5 subset 2015-2019 and the NFI45 subset 2018-2022; section 2.6.4) that were the basis for the reporting years 2019 to 2021 in NIR submissions 2021 to 2023 (Didion et al. 2020) and 2022 in NIR 2024 presented in this report. The table gives further the differences between the latest and previous estimates. Shaded strata indicate cases where the mean value of the NFI45 subset 2018-2022 is not within 2 SE of the mean value of the NFI34/5 subset 2015-2019 (i.e. a statistically significant difference exists). The number of available sample plots in each stratum based on the NFI45 subset 2018-2022 is given in brackets.

Spatial stratum	**Species**	**Data NIR 2024**		**Data NIR 2023**		**Difference**
		t C ha^{-1} a^{-1}	**2 SE**	**t C ha^{-1} a^{-1}**	**2 SE**	**t C ha^{-1} a^{-1}**
Jura <=600m (N=146)	conifers	0.98	0.26	0.99	0.26	-0.02
	broadleaves	1.79	0.30	2.32	0.42	-0.53
	Total	2.77	0.34	3.31	0.40	-0.55
Jura >600m-1200m (N=341)	conifers	1.57	0.19	1.67	0.20	-0.10
	broadleaves	1.31	0.16	1.54	0.19	-0.23
	Total	2.88	0.22	3.20	0.26	-0.32
Jura >1200m (N=68)	conifers	1.42	0.32	1.58	0.41	-0.16
	broadleaves	0.47	0.18	0.46	0.18	0.01
	Total	1.89	0.39	2.04	0.45	-0.15
Plateau <=600m (N=375)	conifers	1.68	0.21	1.88	0.23	-0.20
	broadleaves	2.34	0.24	2.41	0.24	-0.08
	Total	4.01	0.25	4.29	0.26	-0.28
Plateau >600m (N=286)	conifers	2.35	0.27	2.52	0.61	-0.17
	broadleaves	2.19	0.34	2.35	0.61	-0.17
	Total	4.53	0.38	4.87	0.88	-0.33
Pre-Alps <=1200m (N=393)	conifers	2.36	0.23	2.52	0.25	-0.16
	broadleaves	1.50	0.23	1.49	0.21	0.01
	Total	3.86	0.28	4.01	0.24	-0.15
Pre-Alps >1200m (N=227)	conifers	1.96	0.27	2.11	0.26	-0.15
	broadleaves	0.24	0.11	0.19	0.10	0.06
	Total	2.21	0.28	2.30	0.28	-0.09
Alps <=1200m (N=337)	conifers	1.25	0.18	1.38	0.20	-0.13
	broadleaves	1.24	0.20	1.24	0.23	-0.01
	Total	2.49	0.23	2.62	0.26	-0.13
Alps >1200m (N=818)	conifers	1.93	0.14	1.99	0.12	-0.06
	broadleaves	0.17	0.05	0.14	0.05	0.03
	Total	2.10	0.14	2.13	0.13	-0.03
Southern Alps <=1200m (N=211)	conifers	0.24	0.17	0.22	0.20	0.03
	broadleaves	1.89	0.29	0.92	0.22	0.97
	Total	2.13	0.31	1.13	0.32	1.00
Southern Alps >1200m (N=233)	conifers	1.48	0.21	1.50	0.24	-0.02
	broadleaves	0.52	0.18	0.50	0.17	0.03
	Total	2.00	0.24	1.99	0.28	0.01
Switzerland (N=3453)	conifers	1.70	0.07	1.79	0.07	-0.09
	broadleaves	1.16	0.06	1.24	0.08	-0.08
	Total	2.86	0.08	3.03	0.06	-0.17

Table 7. Mean ±2 SE of estimated C drain including fellings and natural mortality for the periodic NFI data (i.e. NFI34/5 subset 2015-2019 and the NFI45 subset 2018-2022; section 2.6.4**)** that were the basis for the reporting years 2019 to 2021 in NIR submissions 2021 to 2023 (Didion et al. 2020) and 2022 in NIR 2024 presented in this report. The table gives further the differences between the latest and previous estimates. Shaded strata indicate cases where the mean value of the NFI45 subset 2018-2022 is not within 2 SE of the mean value of the NFI34/5 subset 2015-2019 (i.e. a statistically significant difference exists). The number of available sample plots in each stratum based on the NFI45 subset 2018-2022 is given in brackets.

		Data NIR 2024		**Data NIR 2023**		**Difference**
Spatial stratum	**Species**	**t C ha^{-1} a^{-1}**	**2 SE**	**t C ha^{-1} a^{-1}**	**2 SE**	**t C ha^{-1} a^{-1}**
Jura <=600m (N=146)	conifers	1.56	0.61	1.30	0.50	0.26
	broadleaves	2.39	0.68	1.41	0.43	0.99
	Total	3.95	0.85	2.70	0.64	1.25
Jura >600m-1200m (N=341)	conifers	1.91	0.52	1.53	0.34	0.38
	broadleaves	1.59	0.43	1.24	0.35	0.35
	Total	3.51	0.68	2.77	0.50	0.73
Jura >1200m (N=68)	conifers	1.28	0.50	1.70	0.83	-0.42
	broadleaves	0.58	0.48	0.32	0.25	0.27
	Total	1.86	0.75	2.02	0.90	-0.15
Plateau <=600m (N=375)	conifers	2.41	0.49	2.42	0.45	-0.02
	broadleaves	2.27	0.50	2.22	0.48	0.06
	Total	4.67	0.68	4.63	0.66	0.04
Plateau >600m (N=286)	conifers	2.81	0.63	2.52	0.59	0.30
	broadleaves	1.98	0.52	2.35	0.61	-0.37
	Total	4.79	0.83	4.87	0.83	-0.08
Pre-Alps <=1200m (N=393)	conifers	2.68	0.60	2.71	0.55	-0.03
	broadleaves	1.43	0.44	1.18	0.39	0.25
	Total	4.11	0.77	3.89	0.73	0.22
Pre-Alps >1200m (N=227)	conifers	1.46	0.51	1.55	0.69	-0.10
	broadleaves	0.08	0.06	0.10	0.07	-0.02
	Total	1.54	0.52	1.66	0.70	-0.12
Alps <=1200m (N=337)	conifers	1.34	0.43	1.16	0.31	0.19
	broadleaves	0.98	0.34	0.85	0.30	0.13
	Total	2.32	0.56	2.00	0.46	0.32
Alps >1200m (N=818)	conifers	1.05	0.22	1.04	0.22	0.02
	broadleaves	0.12	0.05	0.09	0.04	0.03
	Total	1.17	0.23	1.12	0.22	0.05
Southern Alps <=1200m (N=211)	conifers	0.17	0.19	0.22	0.05	-0.05
	broadleaves	1.15	0.26	0.92	0.01	0.23
	Total	1.31	0.33	1.13	0.02	0.18
Southern Alps >1200m (N=233)	conifers	1.06	0.50	0.63	0.36	0.43
	broadleaves	0.18	0.15	0.15	0.10	0.03
	Total	1.24	0.52	0.78	0.37	0.46
Switzerland (N=3453)	conifers	1.65	0.15	1.55	0.13	0.10
	broadleaves	1.07	0.11	0.95	0.10	0.12
	Total	2.72	0.18	2.50	0.17	0.22

Table 8. Mean and 2 SE of estimated C growing stock of living trees for the periodic NFI data (i.e. NFI34/5 subset 2015-2019 and the NFI45 subset 2018-2022; section 2.6.4) that were the basis for the reporting years 2019 to 2021 in NIR submissions 2021 to 2023 (Didion et al. 2020) and 2022 in NIR 2024 presented in this report. The table gives further the differences between the latest and previous estimates. Shaded strata indicate cases where the mean value of the NFI45 subset 2018-2022 is not within 2 SE of the mean value of the NFI34/5 subset 2015-2019 (i.e. a statistically significant difference exists). The number of available sample plots in each stratum based on the NFI45 subset 2018-2022 is given in brackets.

		Data NIR 2024		Data NIR 2023		Difference
Spatial stratum	**Species**	**t C ha^{-1}**	**2 SE**	**t C ha^{-1}**	**2 SE**	**t C ha^{-1}**
Jura <=600m (N=146)	conifers	32.50	8.61	36.12	8.96	-3.63
	broadleaves	77.80	10.90	96.48	13.37	-18.68
	Total	110.30	12.24	132.61	13.56	-22.31
Jura >600m-1200m (N=341)	conifers	64.20	6.57	72.49	8.26	-8.29
	broadleaves	64.25	6.09	71.12	7.08	-6.85
	Total	128.45	7.20	143.60	8.44	-15.14
Jura >1200m (N=68)	conifers	72.40	12.58	67.36	13.16	5.04
	broadleaves	20.79	7.83	24.27	9.72	-3.49
	Total	93.20	13.28	91.63	14.56	1.55
Plateau <=600m (N=375)	conifers	46.65	6.14	51.41	6.48	-4.76
	broadleaves	75.55	8.34	76.49	7.84	-0.93
	Total	122.20	8.40	127.90	7.96	-5.69
Plateau >600m (N=286)	conifers	70.65	8.58	60.54	8.41	10.13
	broadleaves	74.25	10.82	80.48	12.16	-6.23
	Total	144.90	11.75	141.02	12.76	3.90
Pre-Alps <=1200m (N=393)	conifers	87.30	7.87	96.93	9.41	-9.65
	broadleaves	62.10	7.62	62.06	7.90	0.04
	Total	149.40	8.97	158.98	9.42	-9.60
Pre-Alps >1200m (N=227)	conifers	111.85	10.99	106.46	10.69	5.41
	broadleaves	15.52	5.16	11.86	4.34	3.67
	Total	127.40	11.49	118.31	11.16	9.08
Alps <=1200m (N=337)	conifers	58.00	7.27	68.31	9.26	-10.31
	broadleaves	51.15	6.86	54.06	8.06	-2.91
	Total	109.15	8.58	122.37	10.45	-13.22
Alps >1200m (N=818)	conifers	95.85	5.08	100.40	5.51	-4.52
	broadleaves	6.05	1.45	4.77	1.28	1.28
	Total	101.90	5.05	105.17	5.39	-3.25
Southern Alps <=1200m (N=211)	conifers	15.30	9.46	17.09	9.07	-1.80
	broadleaves	87.90	9.30	89.61	10.13	-1.69
	Total	103.20	13.02	106.70	12.95	-3.49
Southern Alps >1200m (N=233)	conifers	73.40	8.76	72.98	9.56	0.44
	broadleaves	17.03	4.89	19.63	5.12	-2.60
	Total	90.45	8.30	92.60	9.35	-2.16
Switzerland (N=3453)	conifers	72.00	2.36	74.98	2.58	-2.99
	broadleaves	45.66	2.05	48.69	2.21	-3.04
	Total	117.65	2.55	123.67	2.68	-6.02

3.3 Verification

Based on the estimates of C growing stock derived for the reporting year 2022 (Table 8) and corresponding estimates of stemwood volume, biomass conversion and expansion factors (BCEF) were calculated and compared with default values for temperate forests from Table 4.5 in Vol.4 of the IPCC 2006 guidelines. Note that for technical reasons biomass growing stock and stemwood volume in the Swiss NFI include bark. The resulting national mean BCEF of 0.619 ±0.001 t m^{-3} for conifers and 0.829 ± 0.003 t m^{-3} for broadleaves compares well with the default values for a growing stock level > 200 m^3 ha^{-1} of 0.7 (0.35-0.9) and 0.8 (0.55-1.1).

3.4 Identified potential improvements

Consistent with IPCC 2006 good practice, areas of possible improvement are identified for future implantation, including

- Annualizing growth and drain data based on annual NPP obtained from MODIS to improve consistency in the growth and drain time series. This requires a thorough evaluation, including a consideration of the spatial level to implement this (i.e. at plot level or larger) and of the consistency with the national harvest statistics data that are currently used for annualizing drain (section 2.5). Relevant information for implementing this is expected to results result from collaborations within the EU Horizon project Pathfinder (https://pathfinder-heu.eu) including financial support from the State Secretariat for Education, Research and Innovation for Task 3.3 on modelling carbon flux between living biomass, DOM and soil pools.

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Supplemental data

Table S. 1. Mean growth and drain (consisting of fellings and natural mortality) in biomass for each NFI period. Note that the data for the period NFI45 are based on the annual tranches 2018 to 2022. The data were derived from the NFI database.

NFI period	Growth	Drain - fellings	Drain – natural mortality	Drain – total
	$t\ ha^{-1}\ a^{-1}$			
NFI12	6.336	3.698	0.778	4.476
NFI23	5.939	4.081	1.14	5.221
NFI34	6.217	4.292	0.983	5.275
NFI45	5.716	3.962	1.501	5.463

Table S. 2. Mean stock in biomass for each NFI. Note that the data for the NFI5 are based on the annual tranches 2018 to 2022. The data were derived from the NFI database.

NFI	Stock
	$t\ ha^{-1}$
NFI1	219.169
NFI2	236.224
NFI3	236.301
NFI4	239.812
NFI5	235.295

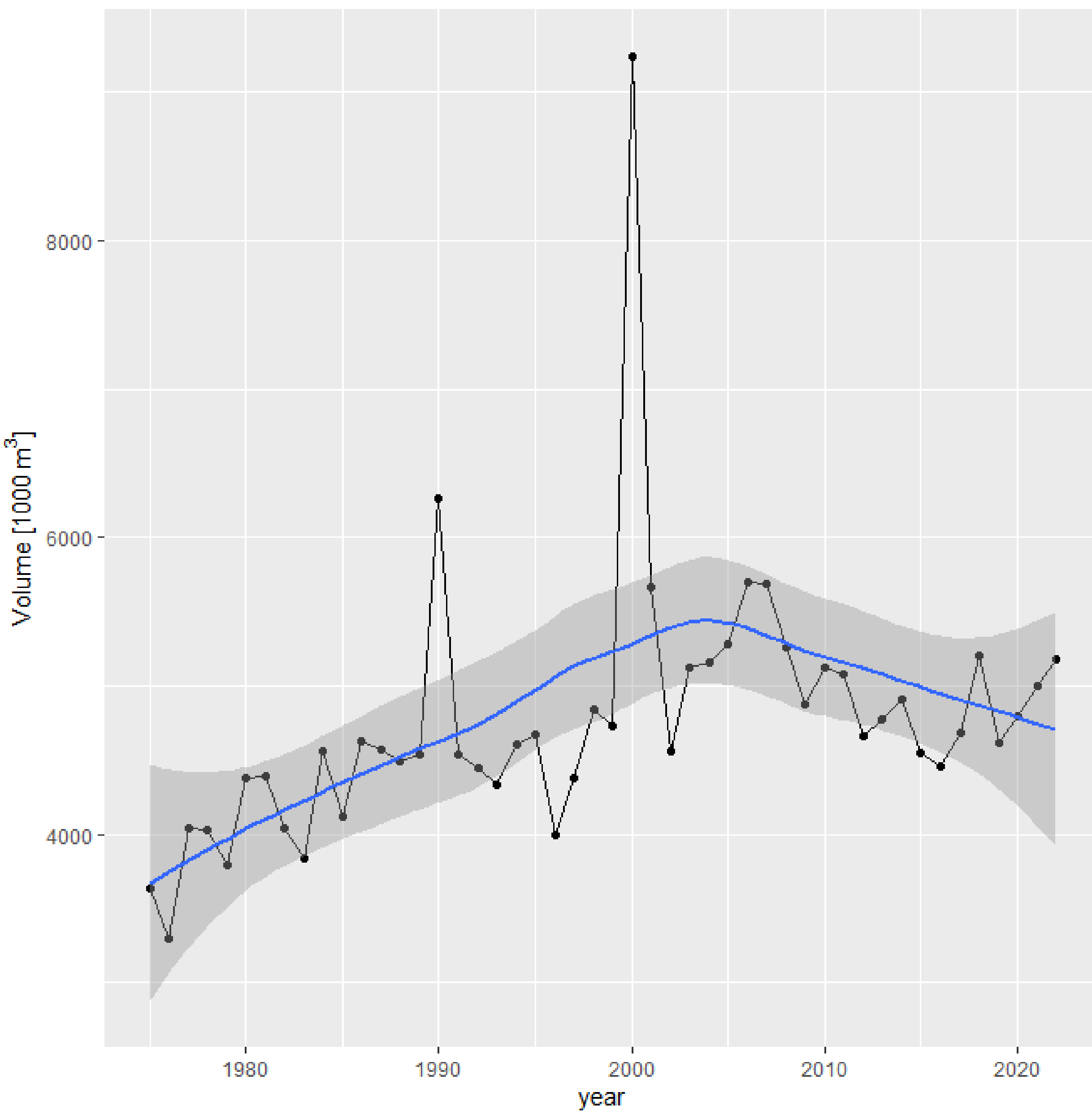

Figure S. 1. Annual total harvested volume in 1000 m^3 since the start of the start of the Swiss harvest statistics database in 1975 (FSO 2023). The black line shows the annual values, the blue line the trendline based on the LOESS method, and the grey band indicates the 95% confidence interval..