

Data on soil carbon stock change, carbon stock and stock change in surface litter and in coarse dead wood prepared for the Swiss NIR 2020 (GHGI 1990–2018)

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Summary

Switzerland prepares annually a greenhouse gas inventory for reporting under the climate convention UNFCCC and the Kyoto Protocol (KP). 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 Swiss greenhouse gas inventory (GHGI) 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 has been developed further as documented in section 2.4. Since the previous submission, no methodological changes were implemented. In response to a recommendation of the expert review of the National Inventory Report (NIR) 2019 additional detail on the derivation of litter inputs has been provided.

In section 3, the results obtained for the Swiss GHGI 2020 (1990-2018) are presented and discussed. As reported in section 3.1, the total CSC in dead wood, litter, and mineral soil in Swiss forests from 2017 to 2018 was a gain of 0.003 ± 0.005 (2SE) $\text{Mg C ha}^{-1}\text{a}^{-1}$ or 3.320 ± 5.672 (2SE) Gg C a^{-1} (based on 1 156 146.4 ha of productive forest for the period NFI3-4 (2013-2017)). The dominating pools dead wood (gain of 0.042 ± 0.002 $\text{Mg C ha}^{-1}\text{a}^{-1}$) and litter (loss of -0.042 ± 0.001 $\text{Mg C ha}^{-1}\text{a}^{-1}$) cancelled each out. Mineral forest soils were responsible for minor gains of 0.003 ± 0.000 $\text{Mg C ha}^{-1}\text{a}^{-1}$. For the period 2012-2018, the uncertainty for total CSC was ca. 17.1%. For the same period Norway and Finland where a similar methodology is applied reported uncertainties for the net CSC in dead wood, litter and soil organic matter of 15.5% and 31.5%, respectively.

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 (IPCC 2006a):

- 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 \geq 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 (2006a), 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: the NFI4 is 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

- Change analyses (*Veränderungsauswertungen*):

- NFI1-2: 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
- NFI2-3: 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
- NFI3-4 (2013-2017): assumed to be representative of the period 2006 to 2017; the change is estimated based on the plots common to the inventories NFI3 and the 5-year window 2013-2017 of the NFI4

Units of carbon measurements:

- Carbon stocks:

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

- Carbon stock changes:

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

1 Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto-Protocol are international treaties to reduce greenhouse gas (GHG) emissions. As a signature state, Switzerland is required to maintain a comprehensive GHG inventory, including emissions and removals of CO₂-eq. from Land Use, Land-Use Change and Forestry (LULUCF). In the first commitment period (2008-2012), Switzerland elected to account for Forest management under Article 3.4. of the Kyoto Protocol; in the second commitment period, the accounting of Forest management under the Kyoto Protocol is mandatory for all parties. Thus, C stock changes (CSC) in above- and belowground living and dead biomass and in the soil have to be reported in Switzerland's Greenhouse Gas Inventory (GHGI). Starting with the Swiss GHGI 2013 (1990-2011; FOEN 2013), the C decomposition model Yasso07 (2011; Tuomi et al. 2009) was used for deriving estimates of 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 Swiss GHGI 2013, Switzerland committed to further improve the model implementation and the accuracy of the estimates of temporal changes in soil, litter, and dead wood. The GHGI-Submission 2020 (1990-2018) is based on the same methodology as the submission in 2019, including the improvements implemented there. Following a recommendation of the Expert Review of the National Inventory Report 2018 (UNFCCC 2018, ID#L.9), this report provides additional detail on litter inputs, including the treatment of tree stumps (section 2.3.3). The report further presents and discusses the estimates of C stocks and CSC for the year 2017/2018 published in the GHG-inventory submission of April 2020 (section 3).

1.1 TCCCA criteria and verification: specific information for UNCFFF/KP reviewers

The report addresses the criteria for transparency, consistency, comparability, completeness and accuracy (TCCCA):

Transparency is achieved by providing and explaining data sources, assumptions and methodologies that were used including relevant references and links to software that was applied. The methodology is described in detail to ensure that results can be reproduced. See section 2 on Methods. Consistent with decisions 6/CMP.9 and 24/CP19, the methodology was ensured to be consistent with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006b) and also with the “Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol” (IPCC 2014).

Consistency is obtained by relying on data sources 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. See section 2 on Methods.

Comparability is achieved by estimating removals by sinks and emissions by sources based on methodologies and formats agreed by the COP. The C cycling model Yasso07 was applied in a consistent manner with several other KP parties using the model, including Austria, Finland and Norway. See section 2 on Methods and section 3.1 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 sections 2 for methods and 3 for results and discussion.

Accuracy is achieved by employing reliable and accurate data and a methodology that is applied by other countries and in research, and which is consistent with the 2006 IPCC Guidelines. All results were verified with independent data and deviations were identified and discussed. This was 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. See sections 2 for methods and 3 for results and discussion.

2 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 GHGI 2013. In the following, the model is described (section 2.1) and supporting information on the validity of Yasso07 for conditions in Switzerland is provided (section 2.2). Section 2.3 presents in detail the implementation of the model for estimating carbon stocks and carbon stock changes in dead wood and litter (DOM) and in soils of forests in Switzerland. Methodological developments since 2013 are presented in section 2.4 demonstrating efforts of inventory development.

2.1 Yasso07

Yasso07 (2011; Tuomi et al. 2009) 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, Yasso07 requires information on C inputs from dead organic matter components (i.e. litter and dead wood) and climate (temperature, temperature amplitude and precipitation). Decomposition of the different components of C inputs is modeled based on their chemical composition, size of woody parts and climate (2011; Tuomi et al. 2009). 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 (Fig. 1, Tuomi et al. 2011) were derived from a global data set (2011; Tuomi et al. 2009). Parameters defining C decomposition rates and C cycling between carbon compartments (Fig. 1) are obtained probabilistically using Markov Chain Monte Carlo sampling and are fitted based on data from litterbag studies (Tuomi et al. 2009) and woody litter decomposition experiments (Tuomi et al. 2011). 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 24 correlated parameters. At the time of this study, three independent parameter sets, i.e. vectors of 24 parameters have been developed and published (Rantakari et al. 2012; 2011; Tuomi et al. 2009).

The Yasso07 release 1.0.1 was used in this report. More information and the source code are available on <http://code.google.com/p/yasso07ui/>. The Yasso07 Fortran source code was compiled for the Windows7 operating system. The statistical software R version 3.5.1 (64 bit; R Core Team 2018) was used for administrating the Yasso07 simulations.

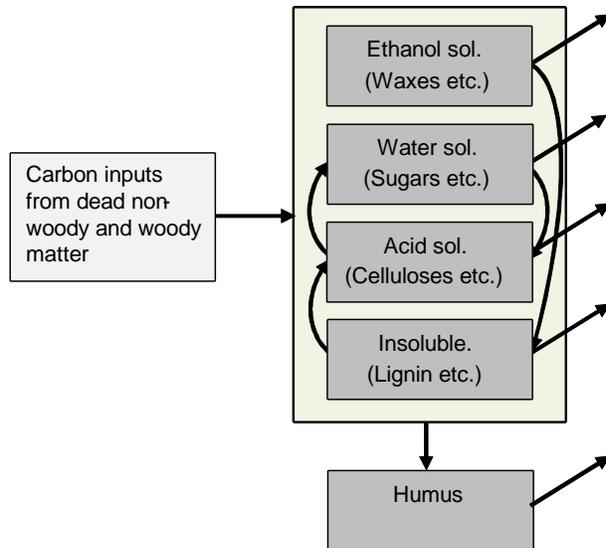


Figure 1. Flow chart of Yasso07 soil carbon model. The boxes represent soil carbon compartments, the arrows carbon flows; only those carbon flows are shown that deviate significantly from zero (adapted from Liski et al. 2009).

2.2 Verifying the suitability of Yasso07 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 altitudinal 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.

The best agreement of Yasso07 results with observed C decomposition was obtained with the parameter presented in Rantakari et al. (2012), which was obtained by restricting the global dataset on dead wood, litter, and soil decomposition set (2011; Tuomi et al. 2009) to European sites. Didion et al. (2014a) found that no 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 (Figs. 2 and 3).

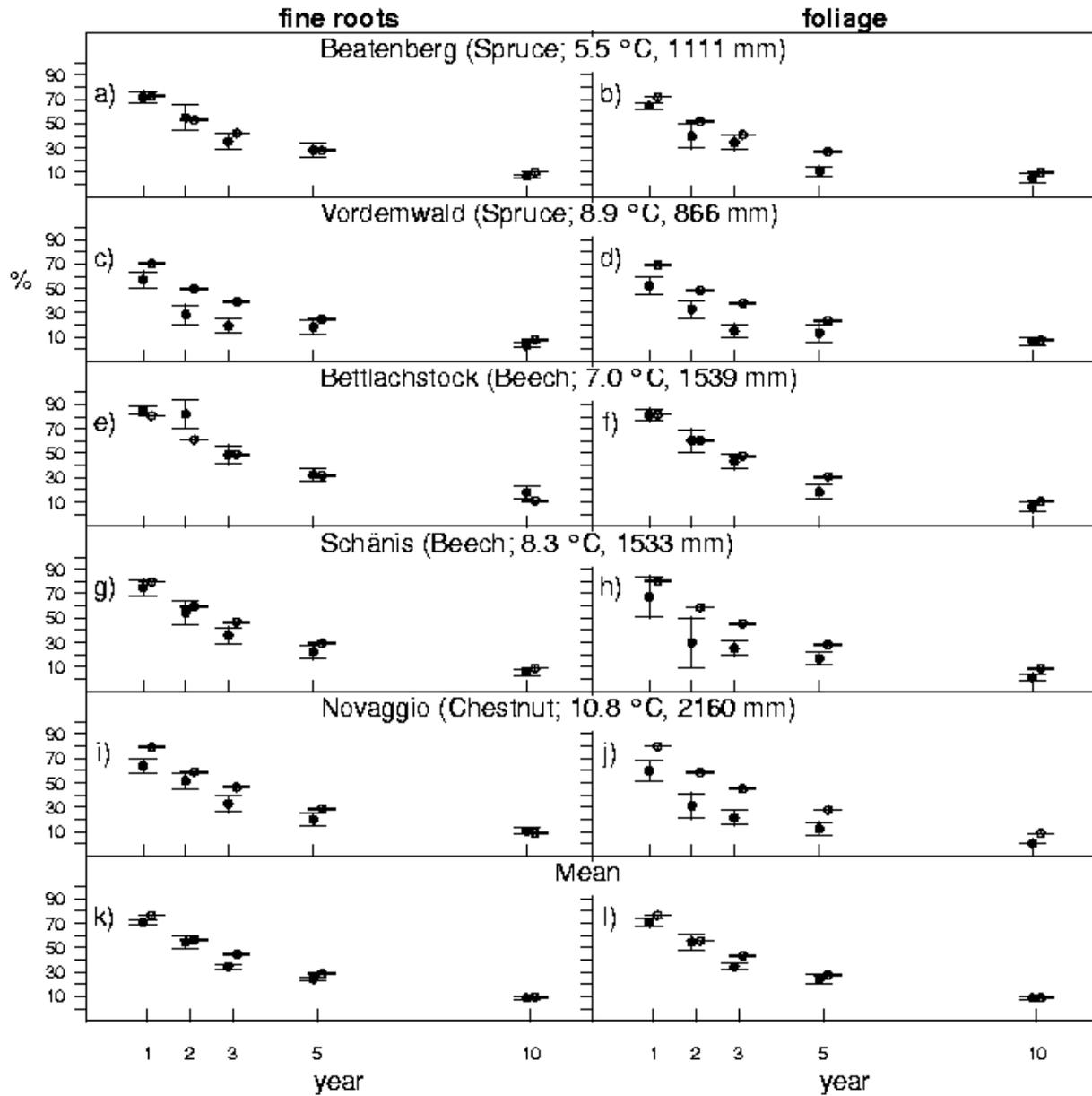


Figure 2. Mean and standard deviation for remaining mass of C [%] in fine root and foliage litter at five forest sites and the mean over all sites. Measured data were based on 20 replicate samples (filled circles). Simulated data were the result of 500 replicate simulations for parameter values of parameter set presented in Rantakari et al. (2012) (open circles). Note that the annual data points are slightly offset for better comparison. For each site the dominant species, annual mean soil temperature measured at 5 cm depth and annual mean throughfall precipitation are given. Figure based on Fig. 2 in Didion et al. (2014a).

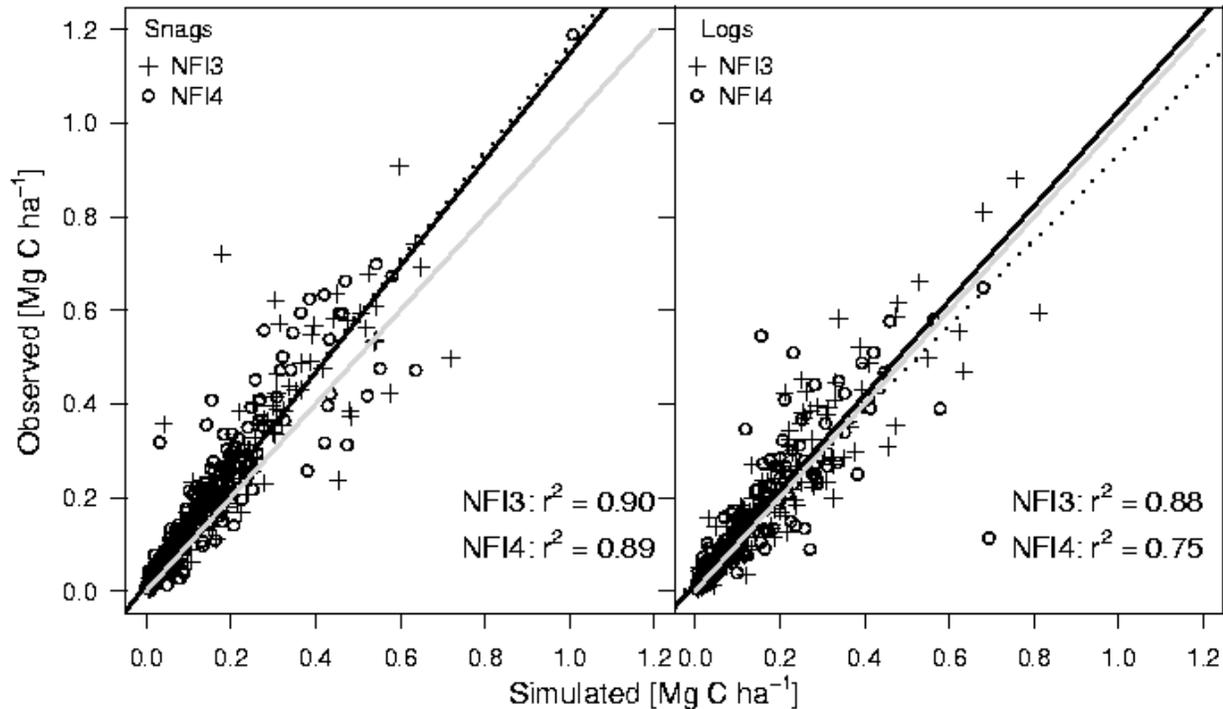


Figure 3. Observed and simulated C stores at NFIs 3 (2004-2006) and 4 (2009-2013) in dead trees that were a) standing ($n=379$), i.e. snags and b) lying ($n=209$), i.e. logs at the time of the NFI2 (1993-1995). The solid black line shows the fit at NFI3 and the dashed black line at NFI4. The solid grey line indicates a perfect fit. Reported is the adjusted r^2 . Regressions are significant with p -values <0.01 . The 95% confidence intervals for the slope of the regression line were a) for snags at NFI3 1.098 to 1.174 and at NFI4 1.113 to 1.193, and b) for logs at NFI3 0.960 to 1.063 and at NFI4 0.838 to 0.980. Figure based on Fig. 3 in Didion et al. (2014a).

2.3 Model implementation for estimating C stock changes in DOM and soil of productive forests in Switzerland

To estimate carbon stocks and carbon stock changes in DOM and soil of productive forests in Switzerland, Yasso07 was run on each sample plot of the Swiss national forest inventory (NFI) that was classified as accessible forest but not shrub forest (*gemeinsam zugänglicher Wald ohne Gebüschwald*) in two consecutive inventories following the definition “productive forest” (Combination Category 12, cf. Tab. 6-2 in FOEN 2019). Sample plots classified as productive forest were identified individually for each of the three NFI periods (i.e. defined as forest in two consecutive NFIs):

- NFI1-2 (from 1986 to 1995);

- NFI2-3 (from 1996 to 2005); and
- NFI3-4 (from 2006 to 2017)

With the NFI4, the methodology changed from a periodic to a continuous survey lasting 9 years during which annually one-ninth of all NFI plots are visited. To ensure accuracy and temporal consistency, for the period NFI3-4 only, sample plots common to NFI3 and sample plots in NFI4 visited in the years 2013 to 2017 were considered, i.e. 3211 of a total of 5824 plots common to the NFI3 and the 9-year NFI4. Also, due to changes in land use and cover, the number of sample plots classified as productive forest can vary between periods (Tab. 1 and A-1). In total, data from 5832 plots were considered in this GHGI consisting of the initial 5456 plots of the period NFI1-2, 211 plots converted to forest from NFI2-3, and 165 plots converted to forest from NFI3-4 (Tab. 1).

Table 1. Number of NFI sample plots in each NFI period where a period represents the common plots of two consecutive NFIs based on which litter production (section 2.3.3) is estimated and which are simulated with Yasso07.

NFI period	forest in previous period	Converted to forest since previous period	Total for period
	Number of sample plots		
NFI1-2	N/A ¹	N/A ¹	5456
NFI2-3	5370	211	5581
NFI3-4 (2013-2017) ²	3046	165	3211

¹not applicable in this first NFI period; ²for the period NFI3-4 only sample plots common to NFI3 and the sample plots in NFI4 visited in the years 2013 to 2017 were considered

To drive the Yasso07 simulation and to obtain C stock estimates for dead wood, litter and mineral soil in Swiss forests, a model parameter set was selected (section 2.3.1) and plot-specific annual inputs for a) for observed climate (section 2.3.2), and b) non-woody and woody C derived from measured data (section 2.3.3) were used. Section 2.3.3 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:

- 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- $C_{in1-2_{avg}}$; section 2.3.3) 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_{in1-2} ; section 2.3.3).
- 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 for 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- $C_{in1-2_{avg}}$;
 - forest in 1880 and 1915 but non-forest in 1940: 47 years simulation with Forest- $C_{in1-2_{avg}}$ (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_{in1-2} ;
 - forest in 1880 but non-forest 1915 and in 1940: 17 years simulation with Forest- $C_{in1-2_{avg}}$, and 43 years simulation with Non-Forest- C_{in1-2} (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- $C_{in1-2_{avg}}$, 30 years simulation with Non-Forest- C_{in1-2} (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- $C_{in1-2_{avg}}$;
 - 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_{in1-2} instead of Forest- $C_{in1-2_{avg}}$ and Forest- $C_{in1-2_{avg}}$ instead of Non-Forest- C_{in1-2} 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- $C_{in1-2_{avg}}$;

- 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}, i.e, 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), i.e, 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 NFI3-4-3: 32 years simulation with Non-Forest-C_{in}1-2 and 13 years simulation with constant, averaged forest C inputs based on NFI3-4 data (Forest-C_{in}3-4_{avg}; section 2.3.3), i.e, halfway of the period 1940 and start of NFI3-4 in 2006;
- c. **Forest development after 1985:** Sample plot-specific annual 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}2-2, Forest-C_{in}3-4 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; section 2.3.3).

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.

2.3.1 *Model parameters*

The model parameters presented in Rantakari et al. (2012) were used to drive the simulations. With this parameter set, Yasso07 reproduced observed C losses in decomposing dead wood and litter with a high degree of accuracy (section 2.2). Uncertainty in model parameter values was included in the simulations by random sampling from the distribution of possible parameter vectors (Tab. A-2).

2.3.2 *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 ca. 2.2 km with monthly data since 1961 (MeteoSwiss 2019).

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 2016a) and RhiresM v1.0 (MeteoSwiss 2016b). Annual mean temperature and precipitation were calculated as the mean and sum, respectively, of the monthly data extracted for NFI sample plots classified as productive forest in any of the three inventory periods. Annual temperature amplitudes were calculated following the Yasso-methodology (Rantakari et al. 2012) as the semi-amplitude:

$$Tamp_y = 0.5 \times (\text{max. monthly temperature}_y - \text{min. monthly temperature}_y)$$

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 Yasso07 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 three NFI periods (N=5832) and, in comparison, the long-term annual means calculated for the norm periods 1961-1990 and 1981-2010 indicating the increase in temperature. Table A-3 provides additional details.

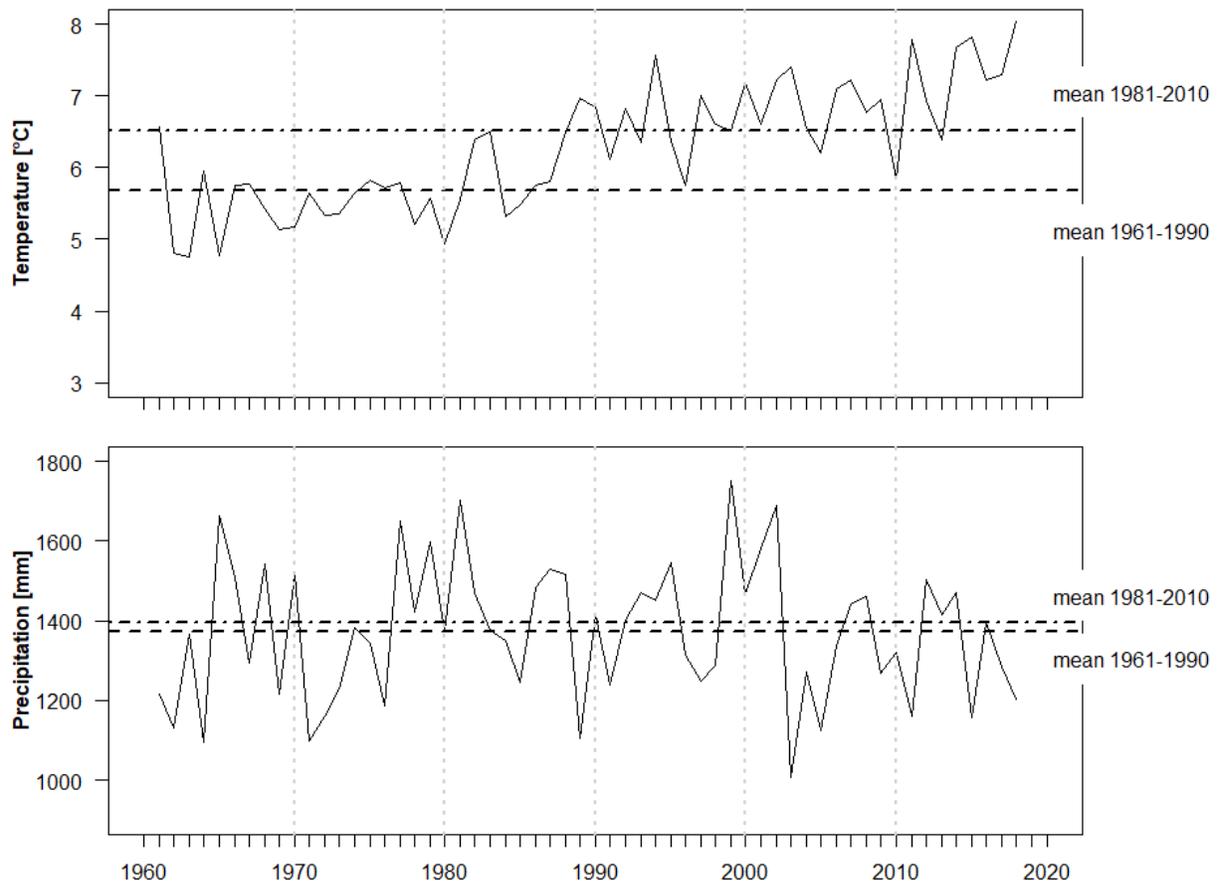


Figure 4. Annual means of temperature and precipitation sums since 1961 for all NFI sample plots classified as productive forest in any of the three NFI periods ($n=5832$). The long-term means of the norm periods 1961-1990 and 1981-2010 are indicated by the horizontal lines.

2.3.3 C inputs

Estimates of C inputs for the simulations with Yasso07 were obtained separately for all NFI sample plots classified as productive forests in any of the three NFI periods. 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) stemwood¹ of trees ≥ 12 cm (diameter at breast height; dbh), ii) large branches \geq ca. 7 cm in diameter, and iii) dead coarse roots $>$ ca. 5 mm in diameter;
- 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). 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 (Tab. 2).

Table 2. 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

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 (Fischer and Traub 2019).

Etzold et al. (2011) verified the accuracy of the estimates with independent data from long-term forest ecosystem research sites.

Current measured data have been available since the NFI 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- $C_{in1-2_{avg}}$, Forest- $C_{in2-3_{avg}}$, Forest- $C_{in3-4_{avg}}$. 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. These disturbances 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 (Tab. A-4), a distribution of possible inputs was created.

Annual above-ground C inputs on temporarily unstocked sample plots (Non-Forest- C_{in} ; Tab. 3) were estimated based on data from (Didion et al. 2018) 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 3 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 Yasso07 following experimentally derived fractions (Tab. 4) as discussed in Didion et al. (2014a).

Table 3. Mean and standard deviation of C inputs over all NFI sample plots simulated with Yasso07 for the GHGI 2019. C inputs are based on averaged (**Forest-C_{in}1-2_{avg}**, **Forest-C_{in}2-3_{avg}**, **Forest-C_{in}3-4_{avg}**) and plot-specific (**Forest-C_{in}1-2**, **Forest-C_{in}2-3**, **Forest-C_{in}3-4**) 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}	665 ±239	1014 ±441	312 ±130	259 ±154	54 ±36	48 ±31	2352 ±543
Forest-C_{in}1-2	721 ±644	1118 ±1194	337 ±322	278 ±664	60 ±180	53 ±158	2567 ±1563
Forest-C_{in}2-3_{avg}	707 ±252	1073 ±500	331 ±140	305 ±236	75 ±57	67 ±50	2558 ±628
Forest-C_{in}2-3	752 ±684	1158 ±1277	350 ±343	318 ±795	79 ±225	70 ±198	2727 ±1714
Forest-C_{in}3-4_{avg}	701 ±254	1099 ±591	324 ±130	291 ±220	80 ±50	71 ±44	2566 ±695
Forest-C_{in}3-4	737 ±711	1169 ±1393	339 ±356	312 ±843	86 ±287	76 ±253	2719 ±1852

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}	254 ±164	605 ±397	121 ±85	87 ±83	29 ±24	10 ±9	1106 ±446
Forest-C_{in}1-2	271 ±430	646 ±1248	127 ±177	92 ±315	31 ±160	11 ±52	1178 ±1379
Forest-C_{in}2-3_{avg}	287 ±183	681 ±440	127 ±85	90 ±96	38 ±37	12 ±10	1235 ±495
Forest-C_{in}2-3	302 ±487	717 ±1438	133 ±182	93 ±330	40 ±172	12 ±53	1297 ±1575
Forest-C_{in}3-4_{avg}	296 ±186	698 ±441	126 ±82	103 ±94	49 ±45	17 ±14	1289 ±497
Forest-C_{in}3-4	302 ±482	717 ±1332	127 ±171	105 ±380	51 ±302	17 ±80	1319 ±1509

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

Table 4. Initial fractions for the simulation of foliage and fine root litter and of dead wood separated into the four chemical compartments in Yasso07, 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 Methodological improvements

2.4.1 Methodological changes compared to GHGI 2019

No methodological changes were implemented for this submission.

2.4.2 List of methodological changes and further developments until GHGI 2019

GHGI 2018 (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 methodological changes were implemented.

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.

2.5 Analysis

Yasso07 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 five C input components (cf. Tab. 4). 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, seeds and fruits, 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) were calculated (cf. Appendix I in Didion et al. 2014a; Didion et al. 2012).

Annual estimates of carbon stocks in the soil, litter and dead wood (CWD) pools for each NFI plot were derived from Yasso07 simulations for the period 1989 to 2018. 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*: Soil_{csc}, Litter_{csc}, CWD_{csc} and the sum (ALL_{csc}); contained in result tables² A-7 to A-14 [Mg C ha⁻¹a⁻¹] and A-15 to A-22 [Mg C a⁻¹].
- 2) *annual carbon stocks*: Litter and CWD; result tables A-23 to A-26 [Mg C ha⁻¹] and A-27 to A-30 [Mg C].

2.5.1 Spatial stratification

The LULUCF sector in the Swiss GHGI uses a spatial stratification of land use categories with five production regions and three elevation classes (≤ 600 m, 601-1200 m, > 1200 m; ch. 6.2.2 in FOEN 2019). Consistent with this stratification, sample plot based estimates of C stocks and C stock changes in dead wood, litter and mineral soil in Swiss forests were aggregated by these 15 strata. Estimates of absolute stocks [Mg C] and total stock change [Mg C a⁻¹] were obtained based on the respective area of forest land remaining forest land calculated for commonly accessible forest of NFIs 3 and 4 based on sample plots of the NFI4 visited between 2013 and 2017 (Tab. A-5; note that for the final preparation of the Swiss GHGI activity data from aerial photographs of the Swiss land use statistics (AREA) are used; cf. ch. 6.3.1 in FOEN 2019).

3 Results and Discussion

The complete set of result tables of C stock and CSC that were prepared for the Swiss GHGI 2020 (1990-2018) can be found in Appendix II. In the following, the results for CSC and stocks are presented and additional data that are relevant for verification are documented. Results are presented for each of the three C pools, i.e. dead wood, litter, and mineral soil. This separation of simulation results is based on the source of the C inputs (section 2.3.3) and their separation into chemical compounds in the Yasso model (section 2.1). This separation 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).

3.1 Carbon stock change

The mean total CSC from 2017 to 2018 in dead wood, litter, and mineral soil in Swiss forests was estimated as a gain of ca. 0.003 ± 0.005 (2SE) Mg C ha⁻¹a⁻¹ (Total Switzerland in Tab. 5, ALL_{csc}

² see Appendix II for details and nomenclature.

in Fig. 5). This corresponded to a national gain of 3.320 ± 5.672 (2SE) Gg C a⁻¹ based on 1 156 146.4 ha of productive forest as derived for the period 2006-2017, i.e. the period between NFIs 3 and 4 (Tab. A-5). The decrease in the total CSC gain from 2016-2017 to 2017-2018 (Fig. 5) was primarily due to, on average, higher temperature in 2018 than in 2017 (cf. Fig. 4) that created favorable conditions for decomposition.

Temporal dynamics of annual total CSC since 1990 were dominated by the dead wood and litter pools (Fig. 5). The dead wood pool gained C in 2017/2018 (0.042 ± 0.002 Mg C ha⁻¹a⁻¹; Dead wood_{csc} in Fig. 5). The pool lost C during the period NFI1-2 and then gained in C as result of the storm Lothar, which occurred in 1999 (i.e. between NFIs 2 and 3). 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 will slowly release the stored C over the coming decades. The trend of decreasing harvesting rates for several years after NFI3 (Table 6-17 in FOEN 2019) 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.

The CSC in 2017/2018 in the litter pool constituted a loss of -0.042 ± 0.001 Mg C ha⁻¹a⁻¹ (Litter_{csc} in Fig. 5). The litter pool consists of easily decomposable non-woody material, and the dynamics in this C pool are largely driven by interannual variability in temperature and precipitation (Aerts 1997).

Mineral forest soils continuously gained in C at a comparably moderate rate (0.003 ± 0.000 Mg C ha⁻¹a⁻¹ in 2015; Soil_{csc} in Fig. 5).

Whether CSC corresponds to a gains (removal) or a loss (emission) depended on carbon pools and regions (Tabs. 5 and A-5 to A-8 and A-13 to A-16 for a complete time series of mean areal [Mg C ha⁻¹a⁻¹] and mean absolute CSC [Mg C a⁻¹]).

Table 5. Mean national total (sum of dead wood, litter and soil) carbon stock change \pm 2 standard error in 2016 stratified into 3 elevation classes and 5 NFI-production regions. Negative values C losses, positive values C gains.

Elevation class	Production region					Switzerland
	Jura	Plateau	Pre-Alps	Alps	Southern Alps	
	Mg C ha ⁻¹ a ⁻¹					
<601 m	0.047 \pm 0.022	0.025 \pm 0.014	0.083 \pm 0.019	0.064 \pm 0.020	0.080 \pm 0.024	0.036 \pm 0.011

601-1200 m	0.015 ±0.011	0.048 ±0.016	0.083 ±0.019	0.064 ±0.020	0.017 ±0.014	0.049 ±0.008
>1200 m	0.008 ±0.019	0.048 ±0.016	-0.121 ±0.019	-0.096 ±0.011	0.062 ±0.013	-0.066 ±0.008
Total	0.022 ±0.009	0.035 ±0.011	0.009 ±0.014	-0.049 ±0.010	0.047 ±0.009	0.003 ±0.005

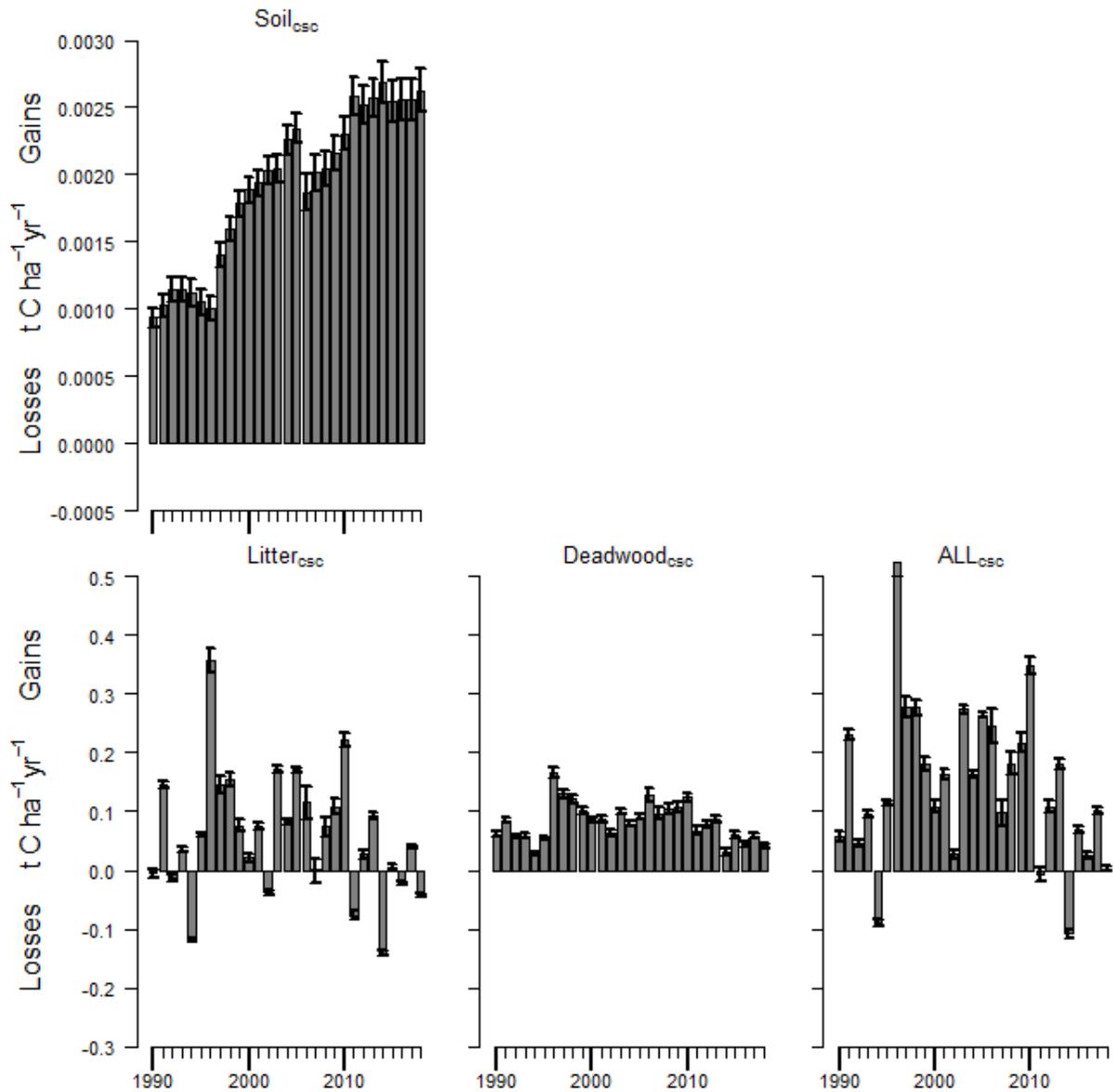


Figure 5. National mean carbon stock change (CSC) since 1990 for three pools soil, litter, dead wood and their sum (ALL) in t C ha^{-1} (equals Mg C ha^{-1}). Note the difference of the y-axis scale between Soil_{CSC} and $\text{Litter}_{\text{CSC}}$, $\text{Dead wood}_{\text{CSC}}$ and ALL_{CSC} , respectively. Negative values indicate C losses, positive values C gains. The error bars indicate the standard error (2SE).

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 2.3.3) as well as the uncertainty in the Yasso parameters (section 2.3.1) were by applying a Monte-Carlo approach

based on 100 replicate simulation (section 2.5). Following the change in the NFI4 from periodic to a continuous survey (section 2.3), dead wood and litter inputs for the period NFI3-4 were derived based on shifting sample of sample plots common to NFI3 and multi-annual NFI4 subsets, i.e. 2009-2011 (National Inventory Report 2013; ch. 7.3.4.1 in FOEN 2013), 2009-2012 ch. 7.3.4.1 (NIR 2014; ch. 7.3.4.1 in FOEN 2014), 2009-2013 (NIR 2015 and NIR2016; ch. 6.4.2.1 in FOEN 2015; 2016), 2011-2015 (2017; (NIR 2017 and NIR2018; ch. 6.4.2.1 in FOEN 2018), 2013-2017 (NIR2019; ch. 6.4.2.1 in FOEN 2019 and in this submission for NIR2020). This change in sample plots introduced additional variability, which was taken into account to obtain an uncertainty estimate corresponding to approximately the second commitment period of the Kyoto Protocol. 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 Yasso07 is also applied. For example, Norway reports an uncertainty of 15.5%, which applied to both the DOM and mineral soil pools (chapter 6.4.1.2 in Norwegian Environment Agency 2019), 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 2019)

3.2 Carbon stocks

Estimates of coarse dead wood C stocks based on measured tree volume are available since the NFI3. The simulated national mean dead wood C stock underestimates the national stock derived from the NFI by ca. 8% (Tab. 6). 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 change in coarse dead wood C stocks in Switzerland between NFIs 3 and 4 was reproduced accurately by the model (Tab. 6) considering the uncertainty in the stocks.

Table 6. Mean and standard error of carbon stored in dead wood based on observations in NFIs 3 and 4 and simulated dead wood carbon stock with Yasso07; the simulated stock was calculated as the mean of the annual stocks in years 2004-2006 for NFI3 and 2013-2018 for NFI4. Percent change was calculated based on the respective means.

NFI3		NFI4		Change	
Mg C ha ⁻¹				%	
NFI	Yasso07	NFI	Yasso07	NFI	Yasso07
7.34	±0.3	6.76	±0.1	7.99	±0.2
				7.35	±0.1
				8.7	8.8

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 and Nussbaum et al. report similar C stocks in the litter pool, i.e. 18.1 ±0.61 and 16.73 ±0.83 Mg C ha⁻¹a⁻¹, respectively.

The simulated national mean litter C stock was ca. 75% of the stock reported by Moeri (2007); cf. Tab.7. This difference is not surprising since the simulated values do not include litter from herbs, shrubs and trees <12 cm dbh. Currently these litter pools cannot be accurately estimated based on existing NFI data. Estimates of litter and shrub biomass on sample plots with forest cover based on data from Didion et al. (2018) are highly variable and work is ongoing to obtain more accurate data. A quantification of foliage litter produced by tree saplings with a measurable dbh, i.e. with height >130 cm is under investigation.

Table 7. 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 Yasso07; the simulated stock was calculated as the long-term mean over the period 1990-2018.

Moeri 2007	Yasso07
Mg C ha ⁻¹	
18.1 ±0.61	13.39 ±0.19

The variability in litter C stocks between regions is greater in the measured data from Moeri (2007) than in the simulated data. There are several explanations for this, including a) statistics (e.g., on harvest) that are used to derive inputs for the Yasso07 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 7.

Under the considerations explained previously, the estimates of dead wood and litter C stocks derived with Yasso07 agree with observations and are plausible, certainly at the national level.

Since observed C decomposition was reproduced highly satisfactory with Yasso07 (Didion et al. 2014a), 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 soil carbon stocks in Switzerland (Eckmeier et al. 2010; Nussbaum et al. 2012; Nussbaum et al. 2014; Zanelli et al. 2006), they cannot be reproduced by models yet. Hence, only changes in soil C stocks derived from the Yasso07 are used for reporting purposes under the UNFCCC and the Kyoto Protocol. 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 Yasso07 is ongoing at WSL and elsewhere. Planned and anticipated improvements to the application in Switzerland for the coming years include:

- Investigating opportunities for further development of the Yasso model. This occurs in close collaboration with other countries where currently Yasso07 is applied as well, i.e. Finland, Norway, and Austria (ongoing). An international workshop is scheduled for February 2020.
- Improving the completeness of the litter inputs by accounting for the contribution of litter from the trees <12 cm dbh and from the herb- and shrub layer. This extends on the study by (Didion et al. 2018) which provided first estimates on biomass turnover of plants in the herb- and dwarf shrub layer of NFI sites. These activities will improve the accuracy of the simulated estimates (planned for submission GHGI 2021).
- Review of the litter production estimates, including turnover rates (anticipated for submission GHGI 2021).
- 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 (anticipated for submission GHGI 2021).

Several opportunities for collaboration and further development of Yasso07 are arising from national and international projects, including

- “Carbon sources and sinks in agricultural soils” by C. Wüst und S. Keel, Agroscope Reckenholz-Tänikon Research Station (ART);
- “Bayesian methods and the dynamics of soil processes of forests” by M. Järvenpää, J. Liski, A. Akujärvi, M. Kaasalainen at Tampere University of Technology and Finnish Environment Institute; and
- ongoing research and collaboration between Finnish Environment Institute, Finnish Forest Research Institute, Norwegian Forest and Landscape Institute and WSL.

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Appendix I: Additional data

Table A-1. Number of NFI sample plots per subregion per NFI period in the category “productive forest CC12” as defined in the Swiss Greenhouse gas inventory (cf. Tab. 6-2 in FOEN 2019). Note that for the period NFI3-4 only sample plots common to NFI3 and the sample plots in NFI4 visited in the years 2013 to 2017 were considered.

Elevation class	NFI period	Production Region					Switzerland
		Jura	Plateau	Pre-Alps	Alps	Southern-Alps	
<601 m	NFI1-2	247	664	36	34	95	1076
	NFI2-3	247	665	35	39	96	1082
	NFI3-4	132	362	19	17	57	587
600 – 1200 m	NFI1-2	607	467	643	484	260	2461
	NFI2-3	612	470	642	485	265	2474
	NFI3-4	338	256	349	285	162	1390
>1200 m	NFI1-2	115	13	350	1155	286	1919
	NFI2-3	122	13	370	1207	313	2025
	NFI3-4	73	7	212	727	215	1234
Total	NFI1-2	969	1144	1029	1673	641	5456
	NFI2-3	981	1148	1047	1731	674	5581
	NFI3-4	543	625	580	1029	434	3211

References

FOEN (Federal Office for the Environment) (2019) Switzerland's Greenhouse Gas Inventory 1990–2017. National Inventory Report including reporting elements under the Kyoto Protocol. Submission of April 2019 under the United Nations Framework Convention on Climate Change and under the Kyoto Protocol. Federal Office for the Environment, Bern. avl. online at www.bafu.admin.ch/climate-reporting

Table A-2. Maximum a posteriori (MAP) estimators and standard errors for the parameter vectors of the parameter set developed by Rantakari et al. (2012) which was validated for simulating dead wood and litter decomposition in Swiss forests (Didion et al. 2014).

Parameter	MAP (\pm SE)	Unit	Interpretation
αA	0.517 (\pm 0.0004)	a^{-1}	Decomposition rate of A
αW	3.552 (\pm 0.003)	a^{-1}	Decomposition rate of W
αE	0.346 (\pm 0.0005)	a^{-1}	Decomposition rate of E
αN	0.266 (\pm 0.0002)	a^{-1}	Decomposition rate of N
$\rho 1$	0.0449 (\pm 0.0001)		Relative mass flow, W \rightarrow A
$\rho 2$	0.0029 (\pm 0.00009)		Relative mass flow, E \rightarrow A
$\rho 3$	0.978 (\pm 0.00006)		Relative mass flow, N \rightarrow A
$\rho 4$	0.637 (\pm 0.0001)		Relative mass flow, A \rightarrow W
$\rho 5$	0.312 (\pm 0.0002)		Relative mass flow, E \rightarrow W
$\rho 6$	0.0187 (\pm 0.00003)		Relative mass flow, N \rightarrow W
$\rho 7$	0.0225 (\pm 0.00002)		Relative mass flow, A \rightarrow E
$\rho 8$	0.0117 (\pm 0.00006)		Relative mass flow, W \rightarrow E
$\rho 9$	0.001 (\pm 0.00005)		Relative mass flow, N \rightarrow E
$\rho 10$	0.336 (\pm 0.0002)		Relative mass flow, A \rightarrow N
$\rho 11$	0.042 (\pm 0.00005)		Relative mass flow, W \rightarrow N
$\rho 12$	0.0899 (\pm 0.0001)		Relative mass flow, E \rightarrow N
$\beta 1$	0.0895 (\pm 0.00009)	$10^{-2} \text{ } ^\circ\text{C}^{-1}$	Temperature dependence
$\beta 2$	-0.0023 (\pm 0.000005)	$10^{-4} \text{ } ^\circ\text{C}^{-2}$	Temperature dependence
γ	-2.94 (\pm 0.001)	m^{-1}	Precipitation dependence
αH	0.24 (\pm 0.001)	$10^{-3} \text{ } a^{-1}$	Humus decomposition rate
ρH	0.15 (\pm 0.0002)	10^{-2}	Mass flow to humus
$\phi 1$	-0.539 (\pm 0.0003)	cm^{-1}	First order size dependence
$\phi 2$	1.186 (\pm 0.0005)	cm^{-2}	Second order size dependence
r	-0.263 (\pm 0.000002)		Size dependence power

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Table A-3. Mean annual temperature and precipitation sum of the norm-period 1981-2010 calculated from the plot-specific data within each region for NFI sample plots in the category “productive forest CC12” as defined in the Swiss Greenhouse gas inventory (cf. Tab. 6-2 in FOEN 2019). Source: MeteoSwiss (2016a; 2016b).

a) Temperature [°C]

Elevation class		Production region					Switzerland
		Jura	Plateau	Pre-Alps	Alps	Southern Alps	
<601 m	Min	6.8	7.5	7.4	4.2	5.2	4.2
	Mean	9.2	9.2	8.8	8.3	10.2	9.2
	Max	10.8	11.2	10.1	10.2	12.6	12.6
601-1200 m	Min	4.7	5.8	1.7	0.2	2.2	0.2
	Mean	7.7	8.6	6.9	5.9	8.2	7.3
	Max	10.3	10.9	10.5	10.2	12.6	12.6
>1200 m	Min	4.8	4.9	1.7	-2.4	-1.5	-2.4
	Mean	6.4	6.6	5.2	3.2	5.5	4.2
	Max	8.8	9.3	9.2	10.1	11.2	11.2
Total	Min	4.7	4.9	1.7	-2.4	-1.5	-2.4
	Mean	7.9	8.9	6.3	4.1	7.2	6.5
	Max	10.8	11.2	10.5	10.3	12.6	12.6

b) Precipitation sum [mm]

Elevation class		Jura	Plateau	Pre-Alps	Alps	Southern Alps	Switzerland
		Min	840	834	1089	714	1358
<601 m	Mean	1098	1099	1389	1192	1745	1171
	Max	1391	1662	1816	2065	2343	2442
	Min	912	906	1081	521	864	521
601-1200 m	Mean	1365	1260	1601	1292	1812	1441
	Max	1936	1894	2278	2275	2391	2543
	Min	1251	1467	1243	534	864	534
>1200 m	Mean	1741	1914	1802	1242	1744	1456
	Max	2113	2064	2371	2374	2408	2597
	Min	840	834	1058	521	864	521
Total	Mean	1347	1173	1665	1255	1770	1395
	Max	2113	2079	2371	2380	2416	2604

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FOEN (Federal Office for the Environment) (2019) Switzerland's Greenhouse Gas Inventory 1990–2017. National Inventory Report including reporting elements under the Kyoto Protocol. Submission of April 2019 under the United Nations Framework Convention on Climate Change and under the Kyoto Protocol. Federal Office for the Environment, Bern. avl. online at www.bafu.admin.ch/climate-reporting

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MeteoSwiss (Federal Office of Meteorology and Climatology). 2016b. Monthly and Yearly Precipitation: RhiresM and RhiresY. Federal Office of Meteorology and Climatology MeteoSwiss, Zurich.

Table A-4. Uncertainty in litter inputs (%).

	Conifers	Broadleaves
Allometry¹	11	11
Biomass Conversion and Turnover²	18	18
Carbon content³	0.35	0.25
Total⁴	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 A-5. Area of productive forest in Switzerland based on the area of forest land remaining forest land calculated for commonly accessible forest of NFIs 3 and 4 (annual tranches 2013 to 2017). Shaded in grey are strata which were combined due to a low number of sites in NFI3-4: a) elevation classes 601-1200m and >1200m in production region 2 'Central Plateau'; b) elevation classes <601m and 601-1200m in production region 3 'Pre-Alps'; and c) elevation classes <601m and 601-1200m in production region 4 'Alps' (cf. ch. 6.4.2.2 in FOEN 2019).

Elevation class	Jura			Central Plateau			Pre-Alps			Alps			Southern Alps			Switzerland		
	ha	± %	N	ha	± %	N	ha	± %	N	ha	± %	N	ha	± %	N	ha	± %	N
<601 m	47527.7	7	132	130341.0	4	362	6841.1	22	19	6121.0	23	17	20523.3	12	57	211354.1	3	587
601-1200 m	121699.6	4	338	92174.9	5	256	125660.3	3	349	102616.6	5	285	58329.4	6	162	500480.7	2	1390
>1200 m	26284.2	10	73	2520.4	38	7	76332.3	5	212	261762.2	2	727	77412.5	5	215	444311.6	2	1234
Total	195511.5	1	543	225036.3	1	625	208833.7	2	580	370499.7	1	1029	156265.2	2	434	1156146.4	1	3211

References

FOEN (Federal Office for the Environment) (2019) Switzerland's Greenhouse Gas Inventory 1990–2017. National Inventory Report including reporting elements under the Kyoto Protocol. Submission of April 2019 under the United Nations Framework Convention on Climate Change and under the Kyoto Protocol. Federal Office for the Environment, Bern. avl. online at www.bafu.admin.ch/climatereporting

Appendix II: Data prepared for Switzerland's GHGI 2020 (1990-2018)

Table A-6. List of result tables that were included in the data delivery from 10.07.2019. The associated Excel file presents the relevant data based on averaged annual stocks and stock changes.

Table	Table name	Content
A-7	Annual C stock change [Mg C ha ⁻¹ a ⁻¹]	Mean CWD pool stock change
A-8		Mean LFH pool stock change
A-9		Mean Soil pool stock change
A-10		Mean stock change for ALL pools
A-11		Standard error CWD pool stock change
A-12		Standard error LFH pool stock change
A-13		Standard error Soil pool stock change
A-14		Standard error stock change for ALL pools
A-15	Annual absolute C stock change [Mg C a ⁻¹]	Mean CWD pool stock change
A-16		Mean LFH pool stock change
A-17		Mean Soil pool stock change
A-18		Mean stock change for ALL pools
A-19		Standard error CWD pool stock change
A-20		Standard error LFH pool stock change
A-21		Standard error Soil pool stock change
A-22		Standard error stock change for ALL pools
A-23	Annual C stock [Mg C ha ⁻¹]	Mean CWD pool stock
A-24		Mean LFH pool stock
A-25		Standard error CWD pool stock
A-26		Standard error LFH pool stock
A-27	Annual absolute C stock [Mg C]	Mean CWD pool stock
A-28		Mean LFH pool stock
A-29		Standard error CWD pool stock
A-30		Standard error LFH pool stock

NOTE:

1) The following strata were combined due to a low number of sites in NFI3-4; for time series consistency the strata were combined for the complete time series: a) elevation classes 601-1200m and >1200m in production region 2 'Central Plateau'; b) elevation classes <601m and 601-1200m in production region 3 'Pre-Alps'; and c) elevation classes <601m and 601-1200m in production region 4 'Alps' (cf. ch. 6.4.2.2 in FOEN 2019).

2) Table values were rounded to 6 decimal places.

3) Tables of absolute CSC and stock contain national estimates based on the area of productive forest between NFIs 3 and 4 of 1 161 140.4 ha (cf. Tab. A-3).

4) Negative values for CSC indicate a C sink, positive values a C source.

References

FOEN (Federal Office for the Environment) (2019) Switzerland's Greenhouse Gas Inventory 1990–2017. National Inventory Report including reporting elements under the Kyoto Protocol. Submission of April 2019 under the United Nations Framework Convention on Climate Change and under the Kyoto Protocol. Federal Office for the Environment, Bern. avl. online at www.bafu.admin.ch/climatereporting