# Data on soil carbon stock change, carbon stock and stock change in surface litter and in coarse dead wood prepared for the Swiss GHGI 2019 (1990-2017)

28 June 2018

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Commissioned by the Federal Office for the Environment FOEN

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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, the derivation of annual dead wood and litter production estimates was improved to achieve greater accuracy and completeness of the stock and stock change estimates in dead wood, litter, and soil in Swiss forests. Further the methodology was revised for consistency with the procedure of the stock and stock change estimates of living biomass in Swiss forest.

In section 3, the results obtained for the Swiss GHGI 2019 (1990-2017) are presented and discussed. As reported in section 3.1, the total CSC in soil, litter and dead wood from 2016 to 2017 was a gain of 0.100 ±0.003 (1SE) Mg C $ha^{-1}a^{-1}$ or 116.442 ±3.338 Gg C $a^{-1}$ (based on 1 161 140.4 ha of productive forest for the period NFI3-4 (2013-2017) with dominant effects of the dead wood (gain of 0.059 ±0.002 Mg C $ha^{-1}a^{-1}$) and the litter pool (gain of -0.039 ±0.002 Mg C $ha^{-1}a^{-1}$). Mineral forest soils were responsible for minor gains of 0.003 ±0.000 Mg C $ha^{-1}$ $a^{-1}$. The double standard error (2SE) of the estimates for CSC originating from uncertainty in C inputs and in model parameters was ca. 8.0% for dead wood ca. 8.1% for litter, and ca. 6.0% for mineral soil. The Uncertainty for total CSC was estimated as ca. 12.9%. For the period 2012-2016, the uncertainty for total CSC was ca. 35.4%. For the same period Finland reported an uncertainty (2SE) of 31.5% for the net CSC in dead wood, litter and soil organic matter.

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 previous National Inventory Reports (NIR), the reported pools comprise

- **Soil**: organic C in mineral soil up to a depth of ca. 100 cm
- **Litter**: non-woody material including foliage, bark, fine roots < ca. 5 mm, and fine woody litter, including twigs and small branches <7 cm; corresponds to LFH (Litter - Fermenting - Humified) layer
- **Dead wood (CWD)**: stemwood of standing dead trees ≥12 cm, lying dead stemwood and branchwood ≥7 cm and dead 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 (Kg $ha^{-1}a^{-1}$) = 0.1 g $m^{-2}a^{-1}$
- Megagram per hectare and year (Mg $ha^{-1}a^{-1}$) = 1000 Kg $ha^{-1}a^{-1}$
- Gigagram per hectare and year (Gg $ha^{-1}a^{-1}$) = 1000 Mg $ha^{-1}a^{-1}$

# 1 Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) and the 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 $CO_2$-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 (Tuomi et al. 2009, 2011) 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. For the GHGI-Submission 2019 (1990-2017), several improvements were implemented resulting in greater accuracy, enhanced completeness and consistency with the estimation procedure of the living biomass pools (section 2.4). The primary purpose of this report is to present and discuss the estimates of C stocks and CSC published in the GHG-inventory submission of April 2019 (section 3). Additional information on the methodology, including validity of the Yasso07 model for conditions in Switzerland is provided in section 2.

## 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 changes for the current inventory are presented in detail in section 2.4. This section also lists aspects of further development of the model implementation realized in the previous inventories since the GHGI 2013 demonstrating efforts of inventory development.

## 2.1 Yasso07

Yasso07 (Tuomi et al. 2009, 2011) 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., non-woody inputs, incl. foliage and fine roots, and woody inputs, incl. standing and lying dead wood and dead roots) 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 (Tuomi et al. 2009, 2011). 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 (Tuomi et al. 2009, 2011). 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 paramamters have been developed and published (Tuomi et al. 2009, 2011, Rantakari et al. 2012).

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 3.4.3 (64 bit; R Core Team 2017) was used for administrating the Yasso07 simulations.

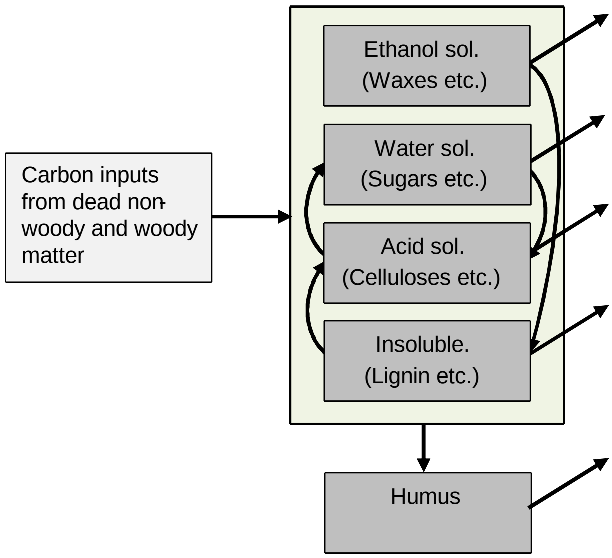


**Figure 1.** Flow chart of Yasso07 soil carbon model. The boxes represent soil carbon compartments, the arrows carbon flows; only those carbon flows are shown that deviate significantly from zero (adapted from Liski et al. 2009).

## 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 (Tuomi et al. 2009, 2011) 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).

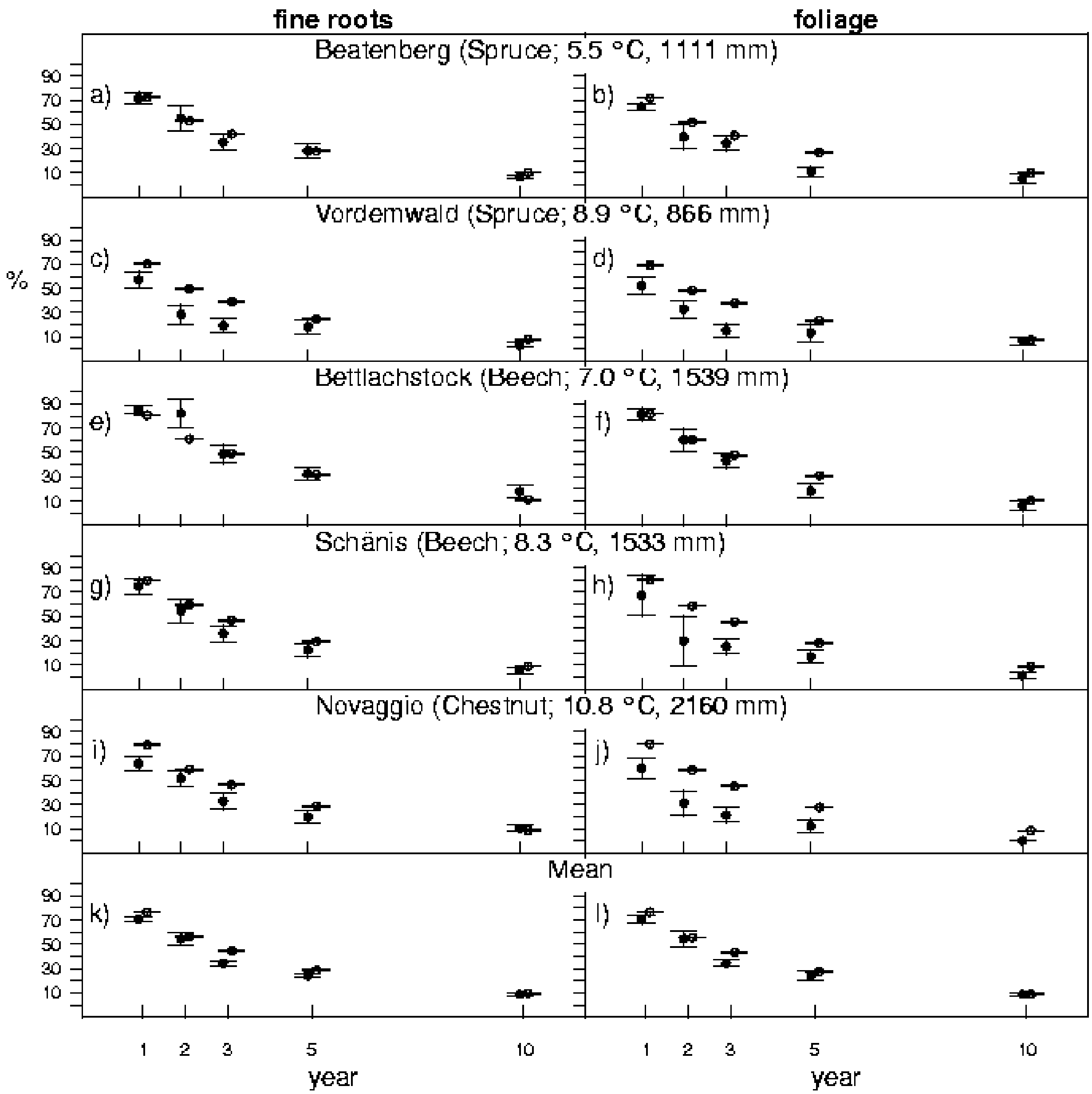


**Figure 2.** Mean and standard deviation for remaining mass of C [%] in fine root and foliage litter at five forest sites and the mean over all sites. Measured data were based on 20 replicate samples (filled circles). Simulated data were the result of 500 replicate simulations for parameter values of 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).

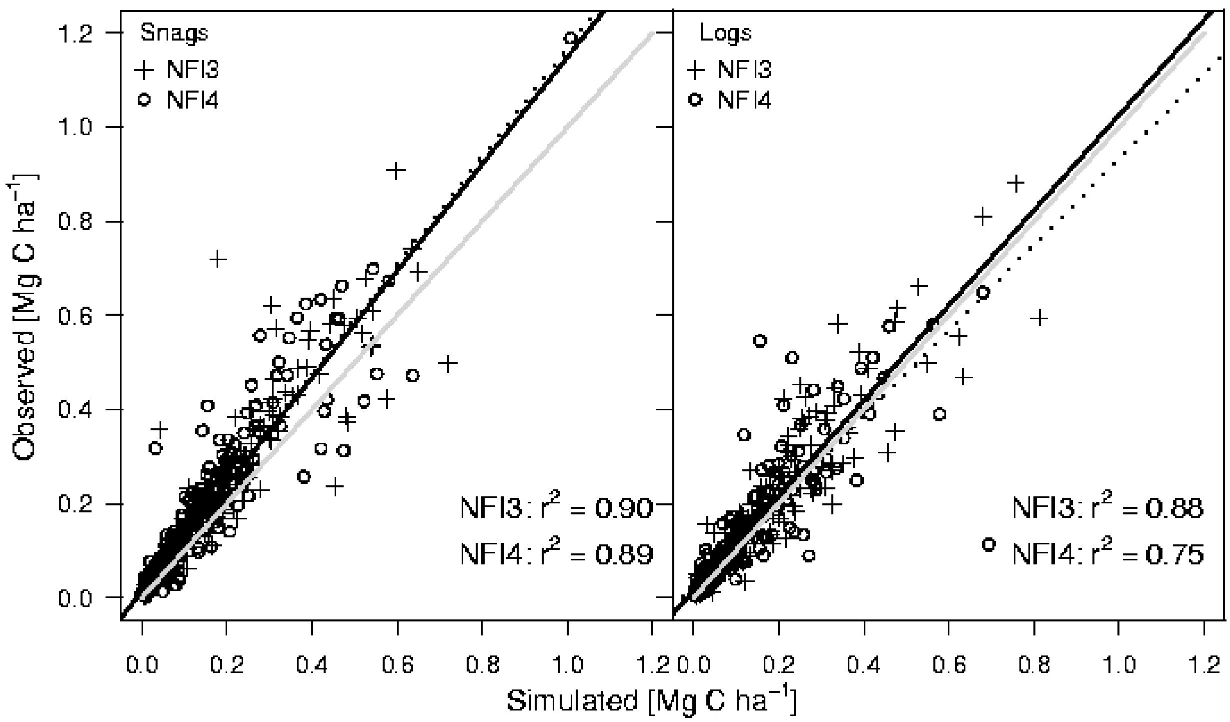


**Figure 3.** Observed and simulated C stores at NFIs 3 (2004-2006) and 4 (2009-2013) in dead trees that were a) standing (n=379), i.e., snags and b) lying (n=209), i.e., logs at the time of the NFI2 (1993-1995). The solid black line shows the fit at NFI3 and the dashed black line at NFI4. The solid 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 2018). 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)

This ensures accuracy by considering the maximum number of plots per period as opposed to the approach in previous inventories which considered only plots defined as productive forest in all three periods (cf. ch. 2.3 in Didion and Thürig 2017). The revised approach thus accounts for land use changes following conversion from or to forest between two NFI periods. Further, the method is now consistent with the estimation procedure of the living biomass pools (cf. ch. 6.4.2.5 in FOEN 2018).

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** |

[1]not applicable in this first NFI period; [2]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

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. The derivation of C inputs was revised for this inventory (section 2.4.1) by extending the intermediate phase between conditions after spin-up (historic C stocks below) and the time of availability of measured data (forest development until 1985 below). The simulation of current C stocks based on the available climate and C inputs was implemented as follows:

a. **Historic C stocks assumed to represent the conditions in 1880**: Established based on the assumption that forest soils C stocks are the result of long-term processes. The year 1880 was used because it corresponds to the first year with a robust estimate of whether a NFI sample plot was forested (Ginzler et al. 2011).
    - Long-term equilibrium soil C stocks: Estimated in a spin-up procedure (cf. Liski et al. 2009) based on mean climate 1961 to 1990 and constant, averaged forest C inputs based on NFI1-2 data (Forest-$C_{in}$1-$2_{avg}$; section 2.3.3) 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. (2017); (Non-Forest-$C_{in}$1-2; 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_{in}$1-2 $_{avg}$;
        - forest in 1880 and 1915 but non-forest in 1940: 47 years simulation with Forest-$C_{in}$1-2 $_{avg}$ (i.e., 35 years between 1880 and 1915 and 12 years between 1916 until halfway of the period 1916 to 1940) and 13 years simulation with Non-Forest-$C_{in}$1-2;
        - forest in 1880 but non-forest 1915 and in 1940: 17 years simulation with Forest-$C_{in}$1-2 $_{avg}$, and 43 years simulation with Non-Forest-$C_{in}$1-2 (i.e., 18 years between from halfway between 1880 and 1915 and 25 years from 1916 to 1940);
        - forest in 1880 but non-forest 1915 and forest again in 1940: 17 years simulation with Forest-$C_{in}$1-2 $_{avg}$, 30 years simulation with Non-Forest-$C_{in}$1-2 (i.e., 18 years from halfway between 1880 and 1915 and 12 years from halfway between 1916 and 1940), and 13 years simulation with Forest-$C_{in}$1-2 $_{avg}$;
        - non-forest in 1880 the procedure was the same as all above listed alternatives in the case of forest in 1880 but with reversed C inputs, ie., Non-Forest-$C_{in}$1-2 instead of Forest-$C_{in}$1-2 $_{avg}$ and Forest-$C_{in}$1-2 $_{avg}$ instead of Non-Forest-$C_{in}$1-2 in the respective periods.

- State 1985: Depending on the classification in 1940 and the NFI period when a sample plot was first classified as forest, the simulation after 1940 was continued based in mean climate 1961 to 1990 until 1960 and annual climate from 1961 onward in case of
    - forest in 1940 and in NFI1-2: 45 years simulation with Forest-$C_{in}$1-2 $_{avg}$;
    - forest in 1940 and non-forest in NFI1-2: 22 years simulation with Non-Forest-$C_{in}$1-2 and 23 years simulation with Forest-$C_{in}$1-2 $_{avg}$, 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_{in2}$-2 , Forest-$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 2017).

For the location of each NFI sampling 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:

$$Tamp_y = 0.5 \times \left(max.monthly\ temperature_y - min.monthly\ temperature_y\right)$$

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 period 1961-1990. Table A-3 provides additional details.

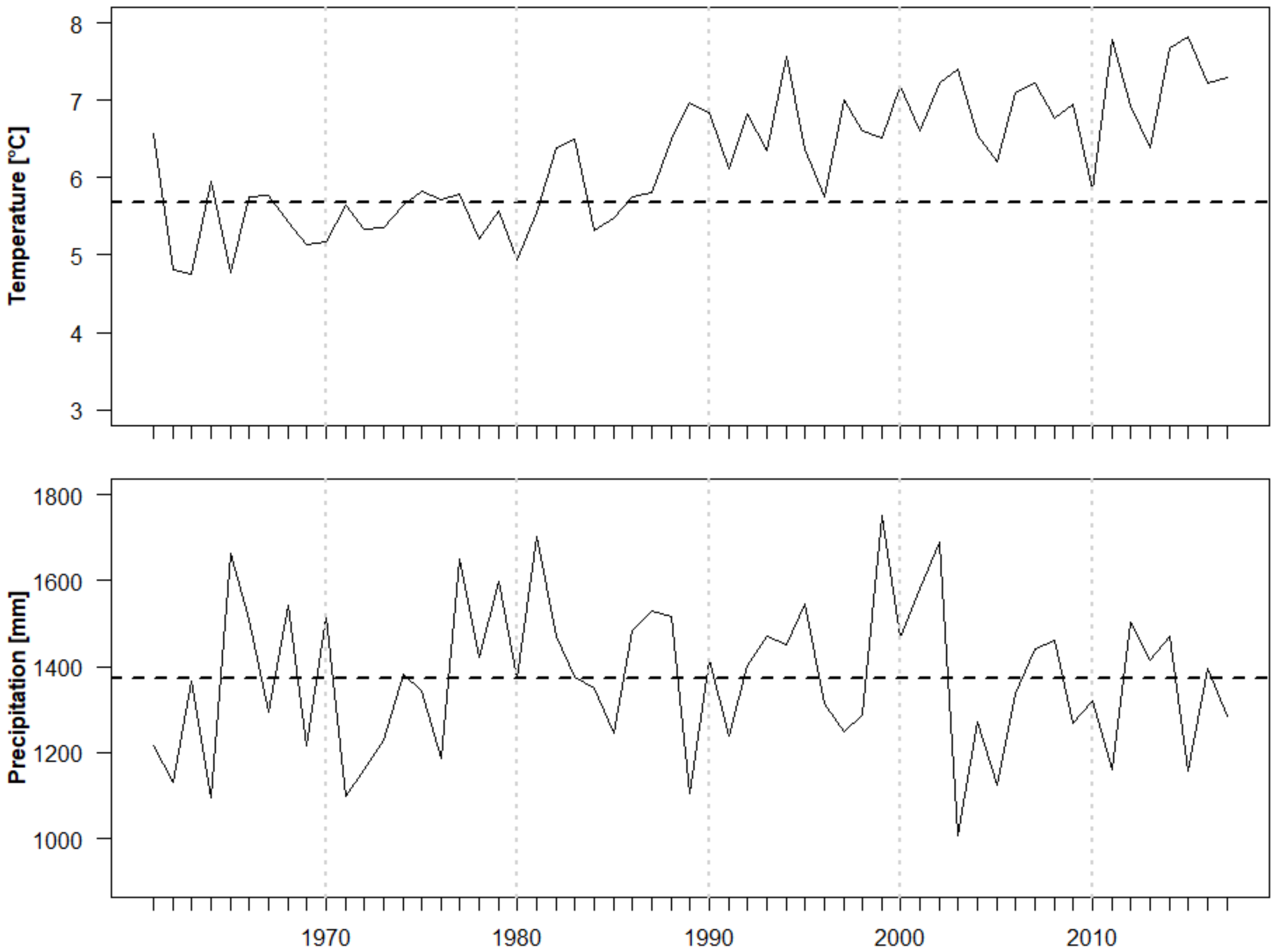


**Figure 4.** Annual means of temperature and precipitation sums since 1961 for all NFI sample plots classified as productive forest in any of the three NFI periods (n=5832). The long-term mean (1961-1990) is indicated by the dashed horizontal line.

### 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:

- Coarse-woody material comprising i) stemwood of standing dead trees ≥12 cm (diameter at breast height; dbh) and of lying dead trees ≥7 cm dbh, ii) branchwood ≥7 cm in diameter, and iii) dead coarse roots > ca. 5 mm in diameter;
- Fine-woody material comprising iv) small branches and twigs <7 cm in diameter; and
- Non-woody material comprising v) foliage incl. fruits, and vi) fine roots < ca. 5 mm.

The annually accumulating mass in these six DOM components was derived through allometric relationships to the volume of living standing and removed (harvest and mortality) trees (cf. Thürig et al. 2005). The volume of living and removed trees was obtained from NFI data (NFI1 through NFI4). Etzold et al. (2011) verified the accuracy of the estimates with independent data from long-term forest ecosystem research sites. The conversion to C was based on measured carbon densities (Dobbertin and Jüngling 2009).

Current measured data have been available since the NFI1 in 1985. For the spin-up, the development until 1940, and sample plots that were non-forest in 1940 but became forest after 1985 (i.e., classified as productive forest in a NFI period), C inputs of individual sample plots were obtained by using a spatial moving window including data from all forested plots within a 10x10km quadrat. Based on this procedure averaged C inputs were obtained for each plot included in an inventory period, i.e. Forest-$C_{in}1\text{-}2_{avg}$, Forest-$C_{in}2\text{-}3_{avg}$, Forest-$C_{in}3\text{-}4_{avg}$ . 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 background 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 six DOM components: Estimates of fine root and foliage 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 components such as branches and result in an increase in the amount of dead wood, NFI measurements will show this increase. Since the input of C (i.e., the volume of dead wood which is produced in one year) to the model is derived from NFI dead wood 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. 2) were estimated based on data from Didion et al. (2017) 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 2 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. 3) as discussed in Didion et al. (2014a).

**Table 2.** 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 3.** 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 2018*

In the past only NFI sample plots classified as productive forest throughout all NFIs were considered. Although this approach reduced the variability in litter production estimates between NFI periods, it excluded plots that were afforested after the first NFI. Under the new approach, sample plots that conformed to the productive forest definition in any of the NFIs were selected for each individual NFI period. This change in sample plot selection improved the accuracy of the C stock and C stock change estimates because for each NFI period all available sample plots are considered and young afforested sample plots are included. Following this change in methodology, also the previous restriction to exclude sample plots with degraded forest such as found in forest aisles was lifted. Due to this methodological change, the sample plot selection is fully consistent with the sample plot selection for estimating growth and mortality of living biomass in Swiss forests (cf. ch. 6.4.2.5 in FOEN 2018).

As a consequence of considering all sample plots with productive forest in any NFI inventory period including newly afforested and temporarily unstocked plots, C inputs representative of non-forest vegetation had to be estimated. Since biomass on temporarily unstocked sample plots without tree cover is not measured in the Swiss NFI, data from Didion et al. (2017) were used to obtain an estimate representative of dense shrub- and herbaceous vegetation. This assumption was based on NFI data on herb- and shrub cover estimates on such sample plots indicating that unstocked plots have a herb- and shrub cover >51 %. Using non-forest estimates of C inputs for simulating C stocks and C stock changes on temporarily unstocked sample plots rather than considering that there are no C inputs on such plots further improved the accuracy of the C inventory.

In recent Swiss GHGIs, C stock and C stock change estimates did not include the contribution of fine woody litter in order to maintain consistency with the initial definition of the dead organic matter pools in FOEN (2012), which excluded this pool due to poor data; cf. also section 2.4 in Didion et al. (2012). Since estimates of fine woody litter including small branches and twigs <7 cm in diameter for trees with dbh > 12cm are available in the Swiss NFI, this material is now included as C input contributing to the estimates of the litter pool. Including fine woody litter in the C stock and C stock change estimates improves accuracy and completeness of the Swiss GHGI.

The implementation of the methodological improvements regarding the selection of sample plots and the consideration of plots without tree cover, also required a revision of the simulation of historic forest development establishing initial C stocks. Current C stocks are assumed to have accumulated over centuries to millennia (Schlesinger 1990). Similar to the approach in previous inventories, initial C stocks were established in a spin-up procedure with Yasso07 based on average climate and C input data (e.g., Didion and Thürig 2017). In order to cancel out the steady-state conditions after the spin-up phase (cf. Peltoniemi et al. 2007), the spin-up simulation in recent inventories was followed by simulating C dynamics with average C inputs but annual climate data for 25 years. Ginzler et al. (2011) examined forest development over the last century in Switzerland and provided robust estimates of whether a NFI sample plot was forested in 1880, 1915, and 1940. Using this information the intermediate phase between initial conditions and the availability of current, measured forest inventory data with the start of the Swiss NFI in 1986 was extended from 25 to 105 years removing any artefacts of the spin-up simulation.

As a consequence of all the methodological changes, the entire time series of C stocks and C stock changes in dead wood, litter and mineral soils in productive forests in Switzerland was recalculated. To demonstrate the effect of the recalculation, figure 5 shows total C stock changes (i.e., sum of the changes in dead wood, litter, and soil) reported in the GHGI 2018 and the corresponding estimates obtained with the improved methodology for the GHGI 2019:

- The fine woody contribution has a minimal effect on estimates and is generally within the range of general uncertainty as shown by the data for the GHGI 2018 without (i.e., as reported) and with fine woody share (i.e., recalculated with the same methodology).
- The effect of the revised methodology was considerable and was the result of, primarily, two causes:
    i. Increased number of NFI sample plots: This explained particularly the difference over much of the period NFI1-2 (i.e., until ca. 1994) and again over parts of the period NFI2-3 (i.e., ca. 1997 to 2001) when the number of sample plots increased from 2616 in the GHGI 2018 to 5456 in the period NFI1-2, and to 5581 in the period NFI2-3 (cf. Tab. 1).Further, the effect in period NFI1-2 was exacerbated by the revised spin-up and simulation until 1985, which after the revision also include

historically or temporarily unstocked plots with a high C sequestration potential after afforestation.

ii. Forest conditions on previously not considered sample plots. The restriction in the previous inventories to include only sample plots classified as productive forest in all three NFI periods introduced a bias towards mature, comparatively undisturbed stands. The revised methodology of the GHGI 2019 considers also younger stands aged ca. 20 to 30 years and stands with higher disturbance intervals such as in forest aisles with higher turnovers of particularly non-woody and fine woody litter.

The overall effect of these changes were lower emissions, or greater gains, respectively as shown by the data using the revised methodology of the GHGI 2019 on the same sample plots as in the GHGI 2018 (Fig. 5).

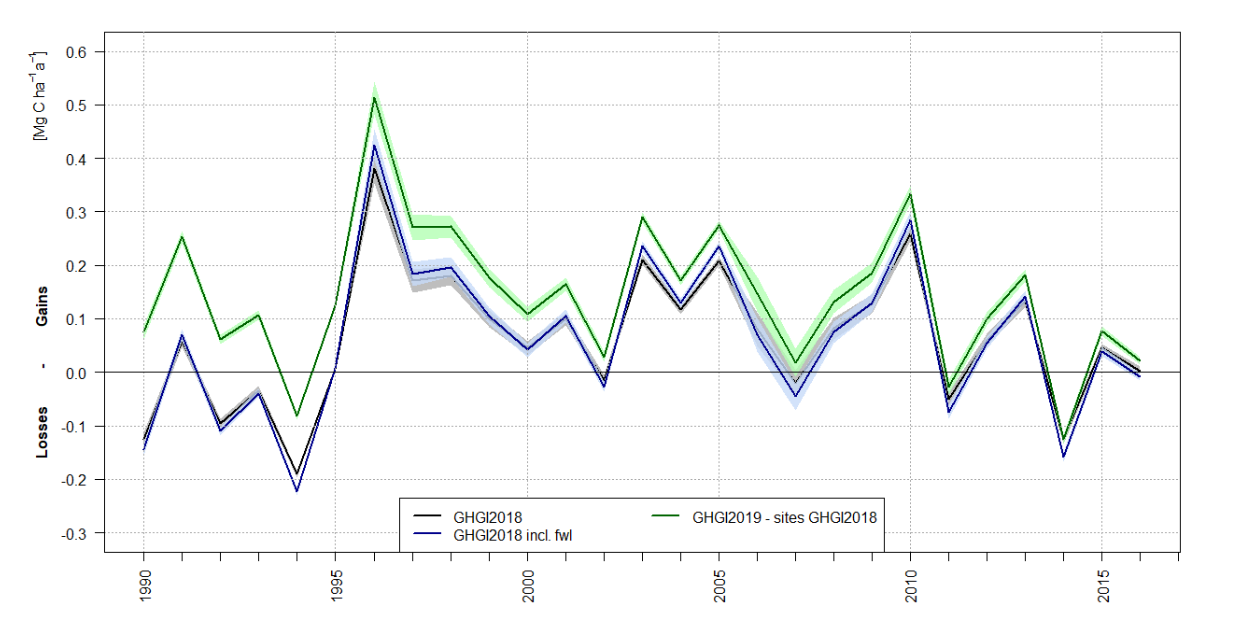


**Figure 5.** Time series of total C stock changes (i.e., sum of the changes in dead wood, litter, and soil) reported in the GHGI 2018 ('GHGI2018'), using the methodology of the GHI 2018 but including the contribution of fine woody litter ('GHGI2018 incl. fwl'), and using the revised methodology of the GHGI 2019 on the same sample plots as in the GHGI 2018 ('GHGI2019 - sites GHGI2018'). Lines show mean values, shaded areas indicate uncertainty based on 2 SE.

### 2.4.2 *List of methodological changes and further developments until GHGI 2018*

*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. 3). 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 components), in litter (i.e., sum C in the AWEN compartments of fine roots and foliage) and in dead wood (CWD; i.e., sum C in the AWEN compartments of stem, branches and roots) were calculated (cf. Appendix I in Didion et al. 2012, Didion et al. 2014a). For consistency with previous submissions of Switzerland's NIR (cf. chapter 6.4.2.6 in FOEN 2018) , C stock changes were estimated for a) the litter pool representing the Litter - Fermenting – Humified (LFH) layer and b) the CWD pool based on coarse-woody inputs.

Annual estimates of carbon stocks in the soil, litter and CWD pools for each NFI plot were derived from Yasso07 simulations for the period 1989 to 2017. 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 tables[1] A-7 to A-14 [Mg C $ha^{-1}a^{-1}$] 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 2018). 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 2018).

# 3 Results and Discussion

The complete set of result tables of C stock and CSC that were prepared for the Swiss GHGI 2019 (1990-2017) 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

[1] see Appendix II for details and nomenclature.

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 2016 to 2017 in dead wood, litter, and mineral soil in Swiss forests was estimated as a gain of ca. 0.100 ±0.003 (1SE) Mg C $ha^{-1}a^{-1}$ (Total Switzerland in Tab. 4, $ALL_{csc}$ in Fig. 6). This corresponded to a national gain of 116.442 ±3.338 Gg C $a^{-1}$ based on 1 161 140.4 ha of productive forest as derived for the period 2006-2017, i.e. the period between NFIs 3 and 4 (Tab. A-5). The approximately fourfold increase in the total CSC gain from 2015-2016 to 2016-2017 (Fig. 6) was primarily due to, on average, higher temperature and moderately lower precipitation in 2017 than in 2016 (cf. Fig. 4), which slowed decomposition.

Temporal dynamics of annual total CSC since 1990 were dominated by the dead wood and litter pools (Fig. 6). The dead wood pool gained C in 2016/2017 (0.059 ±0.002 Mg C $ha^{-1}a^{-1}$; Dead $wood_{csc}$ in Fig. 6). 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 CSC in 2016/2017 in the litter pool constituted a gain of -0.039 ±0.002 Mg C $ha^{-1}a^{-1}$ ($Litter_{csc}$ in Fig. 6). 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 ±0.0001 Mg C $ha^{-1}a^{-1}$ in 2015; $Soil_{csc}$ in Fig. 6).

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 $ha^{-1}a^{-1}$] and mean absolute CSC [Mg C $a^{-1}$]).

**Table 5.** Mean national total (sum of dead wood, litter and soil) carbon stock change ± 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 | 0.141 | ±0.025 | 0.095 | ±0.016 | 0.159 | ±0.021 | 0.174 | ±0.023 | 0.125 | ±0.028 | 0.109 | ±0.012 |
| 601-1200 m | 0.157 | ±0.014 | 0.129 | ±0.019 | 0.159 | ±0.021 | 0.174 | ±0.023 | 0.042 | ±0.017 | 0.143 | ±0.009 |
| >1200 m | 0.118 | ±0.023 | 0.129 | ±0.019 | -0.056 | ±0.022 | 0.057 | ±0.013 | 0.088 | ±0.015 | 0.047 | ±0.009 |
| Total | 0.148 | ±0.011 | 0.109 | ±0.012 | 0.080 | ±0.016 | 0.091 | ±0.012 | 0.076 | ±0.010 | 0.100 | ±0.006 |

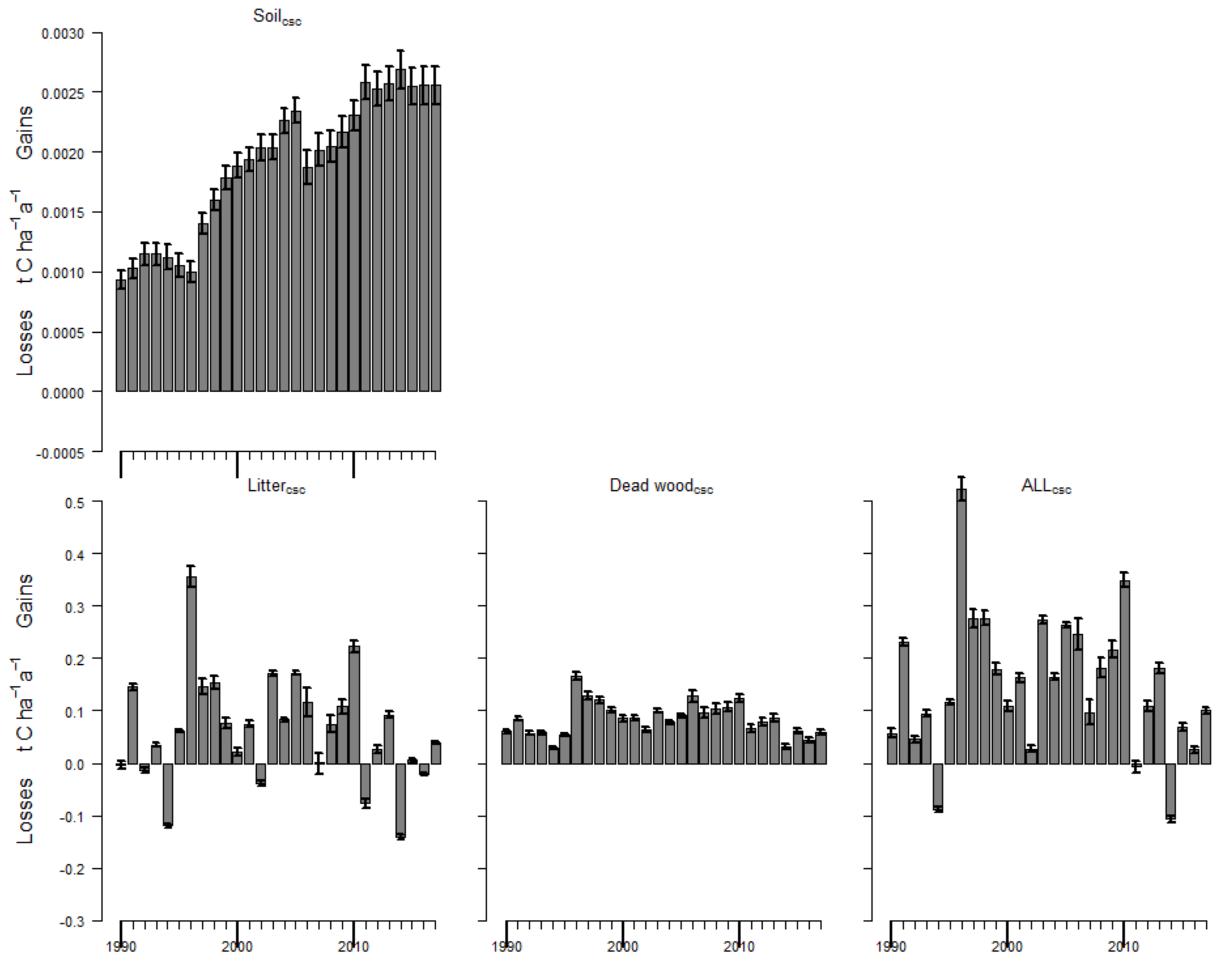


**Figure 6.** National mean carbon stock change (CSC) since 1990 for three pools soil, litter, dead wood and their sum (ALL) in t C ha$^{-1}$ (equals Mg C ha$^{-1}$). Note the difference of the y-axis scale between Soil$_{csc}$ and Litter$_{csc}$, Dead wood$_{csc}$ and ALL$_{csc}$, respectively. Negative 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 taken into account in the estimation of C stock changes in Swiss forests. The double standard error resulting from uncertainty in C inputs and in model parameters was estimated over the length of the first commitment period of the Kyoto Protocol in order to account for annual variability. The double standard error for the dead wood, litter and mineral soil C in the Swiss GHGI were 21.2%, 40.4, %, and 13.6%, respectively. The total uncertainty of the carbon stock change in DOM and mineral soil was estimated as 40.3%. This is in the range of uncertainty estimates in countries where Yasso07 is also applied.

For example, Norway reports an uncertainty of 15.5% (1SE), which applied to both the DOM and mineral soil pools (chapter 6.4.1.2 in Norwegian Environment Agency 2017), and Finland reports an uncertainty of 31.5% (2SE) in the net CSC in DOM and mineral soil (Lehtonen and Heikkinen 2016, chapter 6.4.3.2 in Statistics Finland 2017).

## 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. 10% (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 (CWD) 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 2013-2017 for NFI4. Percent change was calculated based on the respective means.

| NFI3 | | | | NFI4 | | | | Change | |
|---|---|---|---|---|---|---|---|---|---|
| Mg C ha$^{-1}$ | | | | | | | | % | |
| NFI | | Yasso07 | | NFI | | Yasso07 | | NFI | Yasso07 |
| 7.45 | ±0.2 | 6.76 | ±0.1 | 7.97 | ±0.2 | 7.33 | ±0.1 | 6.9 | 8.4 |

For verification of the litter C stocks, the simulated data were compared with observed data from Moeri (2007). These data rather than data from Nussbaum et al. (2012) are used since Nussbaum et al. (2012) placed little confidence in their method. At the national level Moeri 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$^{-1}$a$^{-1}$, 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. (2017) 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 1990-2016.

| 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 (Tab. 7). 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 large standard deviations 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 (Zanelli et al. 2006, Eckmeier et al. 2010, Nussbaum et al. 2012, 2014), 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). Simulates 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 the validity of the further development of Yasso07 for application in Switzerland. The new model version Yasso15 includes, among other, a new parameter set that is expected to improve the sensitivity of the simulated decomposition to temperature and precipitation. This occurs in close collaboration with other countries where currently Yasso07 is applied as well, i.e. Finland, Norway, and Austria (ongoing).
- Implementing knowledge gained in the project "Drivers of C stabilization in Swiss Forest soils" (Gosheva et al. 2018; anticipated for submission GHGI 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. (2017) 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 2020).
- 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 2020).
- Examining the suitability of Yasso07 and Yasso15 for estimating CSC on lands converted to forests, based on the experience from Finland and Norway, where Yasso07 is already applied on afforested lands. This would improve the consistency in methods in the Swiss GHGI (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.

## Acknowledgements

We are grateful to Nele Rogiers at FOEN for valuable discussions and comments on this report. The NFI team at WSL is acknowledged for data collection, data base management and general support with NFI data-related questions.

## References

Aerts, R. 1997. Climate, Leaf Litter Chemistry and Leaf Litter Decomposition in Terrestrial Ecosystems: A Triangular Relationship. Oikos **79**:439-449.

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.

de Wit, H. A., T. Palosuo, G. Hylen, and J. Liski. 2006. A carbon budget of forest biomass and soils in southeast Norway calculated using a widely applicable method. Forest Ecology and Management **225**:15-26.

Didion, M., M. Baume, F. Giudici, and J. Schneuwly. 2017. Long-term dynamics of herbaceous layer biomass in Swiss forests. [Final Report on Project: *Schätzung Biomasse Kraut- und Strauchschicht basierend auf LFI-Deckungsgrad*]. Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf.

Didion, M., B. Frey, N. Rogiers, and E. Thürig. 2014a. Validating tree litter decomposition in the Yasso07 carbon model. Ecological Modelling **291**:58-68.

Didion, M., E. Kaufmann, and E. Thürig. 2012. Estimation of carbon stocks and fluxes in soil, LFH layer and deadwood in Swiss forests with Yasso07. Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf. avl. online at www.bafu.admin.ch/climatereporting.

Didion, M., E. Kaufmann, and E. Thürig. 2013. Data on soil carbon stock change, carbon stock and stock change in surface litter and in coarse deadwood prepared for the Swiss GHGI 1990-2012. Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf. avl. online at www.bafu.admin.ch/climatereporting.

Didion, M., E. Kaufmann, and E. Thürig. 2014b. Data on soil carbon stock change, carbon stock and stock change in surface litter and in coarse deadwood prepared for the Swiss GHGI 2015 (1990-2013). Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf. avl. online at www.bafu.admin.ch/climatereporting.

Didion, M., and E. Thürig. 2015. Data on soil carbon stock change, carbon stock and stock change in surface litter and in coarse deadwood prepared for the Swiss GHGI 2016 (1990-2014). Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf. avl. online at www.bafu.admin.ch/climatereporting.

Didion, M., and E. Thürig. 2016. Data on soil carbon stock change, carbon stock and stock change in surface litter and in coarse deadwood prepared for the Swiss GHGI 2017 (1990-2015). Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf. avl. online at www.bafu.admin.ch/climatereporting.

Didion, M., and E. Thürig. 2017. Data on soil carbon stock change, carbon stock and stock change in surface litter and in coarse deadwood prepared for the Swiss GHGI 2018 (1990-2016). Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf. avl. online at www.bafu.admin.ch/climatereporting.

Dobbertin, M., and E. 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.

Eckmeier, E., M. Egli, M. W. I. Schmidt, N. Schlumpf, M. Nötzli, N. Minikus-Stary, and F. Hagedorn. 2010. Preservation of fire-derived carbon compounds and sorptive stabilisation promote the accumulation of organic matter in black soils of the Southern Alps. Geoderma **159**:147-155.

Etzold, S., M. Dobbertin, P. Waldner, A. Thimonier, and M. Schmitt. 2011. Interim Report: The carbon cycle of LWF-sites in Switzerland. p 22. Swiss Federal Research Institute for Forest, Snow and Landscape Research, Birmensdorf.

Etzold, S., J. Helfenstein, A. Thimonier, M. Schmitt, and P. Waldner. 2014. Final Report: The role of the forest understory within the forest nutrient and carbon cycle of LWF sites. p 32. Swiss Federal Research Institute for Forest, Snow and Landscape Research, Birmensdorf.

FOEN (Federal Office for the Environment). 2012. Switzerland's Greenhouse Gas Inventory 1990–2010. National Inventory Report 2012 including reporting elements under the Kyoto Protocol. Submission of 13 April 2012 under the United Nations Framework Convention on Climate Change and under the Kyoto Protocol. Federal Office for the Environment, Bern.

FOEN (Federal Office for the Environment). 2013. Switzerland's Greenhouse Gas Inventory 1990–2011. National Inventory Report 2013 including reporting elements under the Kyoto Protocol Submission of 15 April 2013 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.

FOEN (Federal Office for the Environment). 2018. Switzerland's Greenhouse Gas Inventory 1990–2016. National Inventory Report including reporting elements under the Kyoto Protocol. Submission of April 2018 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.

Freschet, G. T., W. K. Cornwell, D. A. Wardle, T. G. Elumeeva, W. Liu, B. G. Jackson, V. G. Onipchenko, N. A. Soudzilovskaia, J. Tao, and J. H. C. Cornelissen. 2013. Linking litter decomposition of above- and below-ground organs to plant–soil feedbacks worldwide. Journal of Ecology **101**:943-952.

Gao, Y., J. Cheng, Z. Ma, Y. Zhao, and J. Su. 2014. Carbon storage in biomass, litter, and soil of different plantations in a semiarid temperate region of northwest China. Annals of Forest Science **71**:427-435.

Ginzler, C., U.-B. Brändli, and M. Hägeli. 2011. Waldflächenentwicklung der letzten 120 Jahre in der Schweiz. Schweizerische Zeitschrift fur Forstwesen **162**:337-343.

Gosheva, S., F. Hagedorn, and M. Didion. 2018. Drivers of C stabilization in surface horizons of mineral forest soils in Switzerland [Final Report on Project: *Kohlenstoffstabilisierung in Mineralböden im Schweizer Wald*]. Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf.

Hoffmann, U., T. Hoffmann, G. Jurasinski, S. Glatzel, and N. J. Kuhn. 2014. Assessing the spatial variability of soil organic carbon stocks in an alpine setting (Grindelwald, Swiss Alps). Geoderma **232-234**:270-283.

IPCC. 2006a. 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use. Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html.

IPCC. 2006b. 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.

IPCC. 2014. 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). IPCC, Switzerland. Available at: http://www.ipcc-nggip.iges.or.jp/public/kpsg/.

Keller, A., A. Desaules, P. Schwab, P. Weisskopf, S. Scheid, and H.-R. Oberholzer. 2006. Monitoring Soil Quality in the long-term: Examples from the Swiss National Soil Monitoring Network. Mitteilungen der Österreichischen Bodenkundlichen Gesellschaft **73**:5-12.

Lehtonen, A., and J. Heikkinen. 2015. Uncertainty of upland soil carbon sink estimate for Finland. Canadian Journal of Forest Research:1-13.

Lehtonen, A., and J. Heikkinen. 2016. Uncertainty of upland soil carbon sink estimate for Finland. Canadian Journal of Forest Research **46**:310-322.

Liski, J., M. Tuomi, and J. Rasinmäki. 2009. Yasso07 user-interface manual. Finnish Environment Institute, Helsinki.

MeteoSwiss (Federal Office of Meteorology and Climatology). 2016a. Monthly and Yearly Mean Temperature: TabsM and TabsY. Federal Office of Meteorology and Climatology MeteoSwiss, Zurich. avl. online at www.meteoschweiz.admin.ch/content/dam/meteoswiss/de/service-und-publikationen/produkt/raeumliche-daten-temperatur/doc/ProdDoc_TabsM.pdf.

MeteoSwiss (Federal Office of Meteorology and Climatology). 2016b. Monthly and Yearly Precipitation: RhiresM and RhiresY. Federal Office of Meteorology and Climatology MeteoSwiss, Zurich. avl. online at www.meteoschweiz.admin.ch/content/dam/meteoswiss/de/service-und-publikationen/produkt/raeumliche-daten-niederschlag/doc/ProdDoc_RhiresM.pdf.

MeteoSwiss (Federal Office of Meteorology and Climatology). 2017. Produkte [*Products*] (avl. in German, French and Italian only). Retrieved 07.05. from http://www.meteoschweiz.admin.ch/home/service-und-publikationen/produkte.html.

Moeri, A. C. 2007. Kohlenstoffvorräte in Schweizer Waldböden unter besonderer Berücksichtigung der organischen Auflage. Universität Zürich, Zürich. avl. online at www.bafu.admin.ch/climatereporting.

Norwegian Environment Agency. 2017. Greenhouse Gas Emissions 1990-2015, National Inventory Report.

Nussbaum, M., A. Papritz, A. Baltensweiler, and L. Walthert. 2012. Organic Carbon Stocks of Swiss Forest Soils. Final Report. p 51. Institute of Terrestrial Ecosystems, ETH Zürich and Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Zürich and Birmensdorf.

Nussbaum, M., A. Papritz, A. Baltensweiler, and L. Walthert. 2014. Estimating soil organic carbon stocks of Swiss forest soils by robust external-drift kriging. Geosci. Model Dev. Discuss. **6**:7077-7116.

Peltoniemi, M., E. Thürig, S. Ogle, T. Palosuo, M. Schrumpf, T. Wutzler, K. Butterbach-Bahl, O. Chertov, A. Komarov, A. Mikhailov, A. Gärdenäs, C. Perry, J. Liski, P. Smith, and R. Mäkipää. 2007. Models in country scale carbon accounting of forest soils. Silva Fennica **41**:575–602.

R Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rantakari, M., A. Lehtonen, T. Linkosalo, M. Tuomi, P. Tamminen, J. Heikkinen, J. Liski, R. Mäkipää, H. Ilvesniemi, and R. Sievänen. 2012. The Yasso07 soil carbon model – Testing against repeated soil carbon inventory. Forest Ecology and Management **286**:137-147.

Schlesinger, W. H. 1990. Evidence from chronosequence studies for a low carbon-storage potential of soils. Nature **348**:232-234.

Statistics Finland. 2017. Greenhouse gas emissions in Finland 1990-2015. National Inventory Report under the UNFCCC and the Kyoto Protocol. Statistics Finland.

Thürig, E., T. Palosuo, J. Bucher, and E. Kaufmann. 2005. The impact of windthrow on carbon sequestration in Switzerland: a model-based assessment. Forest Ecology and Management **210**:337-350.

Tuomi, M., R. Laiho, A. Repo, and J. Liski. 2011. Wood decomposition model for boreal forests. Ecological Modelling **222**:709-718.

Tuomi, M., T. Thum, H. Järvinen, S. Fronzek, B. Berg, M. Harmon, J. A. Trofymow, S. Sevanto, and J. Liski. 2009. Leaf litter decomposition—Estimates of global variability based on Yasso07 model. Ecological Modelling **220**:3362-3371.

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

Zanelli, R., M. Egli, A. Mirabella, M. Abdelmoula, M. Plötze, and M. Nötzli. 2006. `Black' soils in the southern Alps: clay mineral formation and transformation, X-ray amorphous Al phases and Fe forms. Clays and Clay Minerals **54**:703-720.

# Appendix I: Additional data

**Table A-1.** Number of NFI sampling 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 2018). 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 |

**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 (±SE)** | **Unit** | **Interpretation** |
|---|---|---|---|
| **αA** | 0.517 (±0.0004) | $a^{-1}$ | Decomposition rate of A |
| **αW** | 3.552 (±0.003) | $a^{-1}$ | Decomposition rate of W |
| **αE** | 0.346 (±0.0005) | $a^{-1}$ | Decomposition rate of E |
| **αN** | 0.266 (±0.0002) | $a^{-1}$ | Decomposition rate of N |
| **ρ1** | 0.0449 (±0.0001) | | Relative mass flow, W → A |
| **ρ2** | 0.0029 (±0.00009) | | Relative mass flow, E → A |
| **ρ3** | 0.978 (±0.00006) | | Relative mass flow, N → A |
| **ρ4** | 0.637 (±0.0001) | | Relative mass flow, A → W |
| **ρ5** | 0.312 (±0.0002) | | Relative mass flow, E → W |
| **ρ6** | 0.0187 (±0.00003) | | Relative mass flow, N → W |
| **ρ7** | 0.0225 (±0.00002) | | Relative mass flow, A → E |
| **ρ8** | 0.0117 (±0.00006) | | Relative mass flow, W → E |
| **ρ9** | 0.001 (±0.00005) | | Relative mass flow, N → E |
| **ρ10** | 0.336 (±0.0002) | | Relative mass flow, A → N |
| **ρ11** | 0.042 (±0.00005) | | Relative mass flow, W → N |
| **ρ12** | 0.0899 (±0.0001) | | Relative mass flow, E → N |
| **β1** | 0.0895 (±0.00009) | $10^{-2}$ °$C^{-1}$ | Temperature dependence |
| **β2** | -0.0023 (±0.000005) | $10^{-4}$ °$C^{-2}$ | Temperature dependence |
| **γ** | -2.94 (±0.001) | $m^{-1}$ | Precipitation dependence |
| **αH** | 0.24 (±0.001) | $10^{-3}$ $a^{-1}$ | Humus decomposition rate |
| **ρH** | 0.15 (±0.0002) | $10^{-2}$ | Mass flow to humus |
| **φ1** | -0.539 (±0.0003) | $cm^{-1}$ | First order size dependence |
| **φ2** | 1.186 (±0.0005) | $cm^{-2}$ | Second order size dependence |
| **r** | -0.263 (±0.000002) | | Size dependence power |

**References**


Didion, M., B. Frey, N. Rogiers, and E. Thürig. 2014. Validating tree litter decomposition in the Yasso07 carbon model. Ecological Modelling **291**:58-68.

Rantakari, M., A. Lehtonen, T. Linkosalo, M. Tuomi, P. Tamminen, J. Heikkinen, J. Liski, R. Mäkipää, H. Ilvesniemi, and R. Sievänen. 2012. The Yasso07 soil carbon model – Testing against repeated soil carbon inventory. Forest Ecology and Management **286**:137-147.

**Table A-3.** Long-term (since 1990) mean annual temperature and precipitation sum calculated from the plot-specific data within each region for NFI sampling plots in the category "productive forest CC12" as defined in the Swiss Greenhouse gas inventory (cf. Tab. 6-2 in FOEN 2018). Source: MeteoSwiss (2016a, b).

a) Temperature [°C]

| | | Production region | | | | | Switzerland |
|---|---|---|---|---|---|---|---|
| **Elevation class** | | **Jura** | **Plateau** | **Pre-Alps** | **Alps** | **Southern Alps** | |
| **<601 m** | **Min** | 7.1 | 7.9 | 7.8 | 4.5 | 5.5 | 4.5 |
| | **Mean** | 9.6 | 9.5 | 9.2 | 8.6 | 10.6 | 9.6 |
| | **Max** | 11.1 | 11.5 | 10.5 | 10.5 | 13.0 | 13.0 |
| **601-1200 m** | **Min** | 5.0 | 6.1 | 2.0 | 0.6 | 2.5 | 0.6 |
| | **Mean** | 8.1 | 8.9 | 7.2 | 6.2 | 8.6 | 7.7 |
| | **Max** | 10.7 | 11.2 | 10.7 | 10.7 | 13.0 | 13.0 |
| **>1200 m** | **Min** | 5.1 | 5.2 | 2.0 | -2.1 | -1.1 | -2.1 |
| | **Mean** | 6.7 | 6.9 | 5.6 | 3.6 | 5.8 | 4.5 |
| | **Max** | 9.2 | 9.7 | 9.6 | 10.5 | 11.6 | 11.6 |
| **Total** | **Min** | 5.0 | 5.2 | 2.0 | -2.1 | -1.1 | -2.1 |
| | **Mean** | 8.3 | 9.2 | 6.7 | 4.4 | 7.5 | 6.9 |
| | **Max** | 11.1 | 11.5 | 10.8 | 10.7 | 13.0 | 13.0 |

b) Precipitation sum [mm]

| **Elevation class** | | **Jura** | **Plateau** | **Pre-Alps** | **Alps** | **Southern Alps** | **Switzerland** |
|---|---|---|---|---|---|---|---|
| **<601 m** | **Min** | 821 | 823 | 1087 | 698 | 1330 | 696 |
| | **Mean** | 1077 | 1081 | 1383 | 1178 | 1720 | 1152 |
| | **Max** | 1357 | 1684 | 1812 | 2060 | 2300 | 2418 |
| **601-1200 m** | **Min** | 900 | 893 | 1072 | 499 | 867 | 499 |
| | **Mean** | 1331 | 1240 | 1582 | 1279 | 1780 | 1418 |
| | **Max** | 1892 | 1864 | 2247 | 2252 | 2354 | 2539 |
| **>1200 m** | **Min** | 1229 | 1488 | 1240 | 514 | 867 | 514 |
| | **Mean** | 1713 | 1867 | 1780 | 1226 | 1709 | 1435 |
| | **Max** | 2086 | 2009 | 2332 | 2356 | 2371 | 2584 |
| **Total** | **Min** | 821 | 823 | 1046 | 499 | 867 | 499 |
| | **Mean** | 1316 | 1155 | 1645 | 1240 | 1738 | 1374 |
| | **Max** | 2086 | 2035 | 2332 | 2362 | 2382 | 2595 |

MeteoSwiss (Federal Office of Meteorology and Climatology). 2016a. Monthly and Yearly Mean Temperature: TabsM and TabsY. Federal Office of Meteorology and Climatology MeteoSwiss, Zurich.

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 |
|---|---|---|
| **Allometry**[1] | 11 | 11 |
| **Biomass Conversion and Turnover**[2] | 18 | 18 |
| **Carbon content**[3] | 0.35 | 0.25 |
| **Total**[4] | 21.1 | 21.1 |

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

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

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

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

**Table 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. NIR ch. 6.4.2.2).

| 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 | 46477.6 | 7 | 132 | 131280.6 | 4 | 362 | 7472.0 | 22 | 19 | 6000.9 | 23 | 17 | 20962.0 | 12 | 57 | 212193.1 | 3 | 587 |
| 601-1200 m | 122973.4 | 4 | 338 | 93373.8 | 5 | 256 | 131459.7 | 3 | 349 | 102180.2 | 5 | 285 | 57374.5 | 6 | 162 | 507361.6 | 2 | 1390 |
| >1200 m | 28141.2 | 10 | 73 | 2556.2 | 38 | 7 | 75323.0 | 5 | 212 | 262297.7 | 2 | 727 | 73267.6 | 5 | 215 | 441585.7 | 2 | 1234 |
| Total | 197592.3 | 1 | 543 | 227210.6 | 1 | 625 | 214254.7 | 2 | 580 | 370478.8 | 1 | 1029 | 151604.0 | 2 | 434 | 1161140.4 | 1 | 3211 |

# Appendix II: Data prepared for Switzerland's GHGI 2019 (1990-2017)

**Table A-6.** List of result tables that were included in the data delivery from 15.05.2018. 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. NIR ch. 6.4.2.2).
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.