Data on soil carbon stock change, carbon stock and stock change in surface litter and in coarse dead wood prepared for the Swiss GHGI 2016 (1990-2014)

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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 (FOEN 2013), 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 was further developed as documented in section 2.3. The improvements increased particularly the consistency and transparency of the estimates of C stocks and CSC since the previous submission.

In section 3, the results obtained for the Swiss GHGI 2016 (1990-2014) are presented and discussed. As reported in section 3.1, the total CSC in soil, litter and dead wood from 2013 to 2014 produced emissions of 0.158 ±0.004 Mg C ha^{-1} or 183 396 ±4 649 Mg C (based on 1 157 624 ha of productive forest between NFIs 3 and 4b) with a dominant effect of litter (emissions of 0.16 ±0.002 Mg C ha^{-1}) and minor removals in dead wood (-0.001 ±0.004 Mg C ha^{-1}) and in soil (-0.001 ±0.0001 Mg C ha^{-1}). The double standard error (2SE) of the estimates for CSC originating from uncertainty in C inputs and in model parameters was ca. 25% for the litter and soil pools, ca. 60% for the dead wood pool and ca. 40% for total CSC. In comparison, Finland reports a uncertainties (2SE) of 46.8% (North) and 26.2% (South) for the net CSC in 2012 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
- 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; corresponds to LFH (Litter - Fermenting - Humified) layer, i.e. excludes fine woody material <7 cm
- **Dead wood (CWD)**: stemwood of standing dead trees ≥12 cm, lying dead stemwood and branchwood ≥7 cm and dead coarse roots > ca. 5 mm; (corresponds to TDW as used in previous NIRs)
- **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*):

- NFI 1: assumed to be representative of the year 1985
- NFI 2: assumed to be representative of the year 1995
- NFI 3: assumed to be representative of the year 2005
- NFI 4b: assumed to be representative of the year 2013

- Change analyses (*Veränderungsauswertungen*)

- NFI 1-2: assumed to be representative of the period 1986 to 1995
- NFI 2-3: assumed to be representative of the period 1996 to 2005

- NFI 3-4b: assumed to be representative of the period 2006 to 2014

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 $ha^{-1}a^{-1}$)

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 2016 (1990-2014), two modifications were made relating to time series consistency and compliance with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006b). The purpose of this report is to a) give details on methodological revisions (section 2.3) and b) to present and discuss the estimates of C stocks and CSC published in the GHG-inventory submission of April 2016 (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 detailing the various data sets that were used and by providing 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 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 applying the Yasso07 model 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 reached by calculating annual estimates since 1989 for the litter, dead wood and soil pools for all 15 forest regions in Switzerland. See sections 2 for methods and 3 for results and discussion.

Accuracy is obtained by employing reliable and accurate data and a methodology that is applied by other countries and in research. All results were verified with independent data and deviations were identified and discussed. 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) and further elaborated in Didion et al. (2013, 2014b). The model was validated for conditions in Switzerland by Didion et al. (2014a) who found that Yasso07 reproduced observed C losses in dead wood and litter very accurately. In the following, a) the most important aspects of the model and the implementation are summarized, and b) the methodological changes are presented in detail.

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 compartments, 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 (R Core Team 2013) version 3.0.2 (64 bit) was used for administrating the Yasso07 simulations.

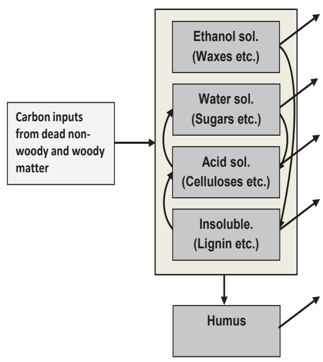

Figure 1. Flow chart of Yasso07 soil carbon model. The boxes represent soil carbon compartments, the arrows carbon flows; only those carbon flows are shown that deviate significantly from zero (adapted from Liski et al. 2009).

2.2 Model implementation for estimating C stock changes in Switzerland

Yasso07 was run on each plot of the Swiss national forest inventory (NFI) that was assessed as accessible forest but not shrub forest (*gemeinsam zugänglicher Wald ohne Gebüschwald*) and as productive forest (Combination Category 12, cf. Tab. 6-6 in FOEN 2015) throughout the four NFIs (Tab. 1), i.e., forests that were considered forest remaining forest. To drive the Yasso07 simulation, a model parameter set was selected and plot-specific annual inputs for a) non-woody and woody C derived from measured data and for b) observed climate were used as follows:

a. Initial C stocks are estimated in a spin-up procedure (cf. Liski et al. 2009) based on mean climate 1961 to 1990 (Tab. 2, Fig. 2) and constant, aggregated C inputs from the first NFI (NFI 1-2_{avg}; Tab. 3) assuming that current C stocks in the soil have accumulated over centuries (cf. Gimmi et al. 2013).
b. 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 25 years with regionally aggregated, constant C input data (NFI 1-2_{avg}; Tab. 3) but with annual climate data for the period 1961 to 1985.
c. For the period after 1986 (i.e., start of the period NFI 1-2; Tab. 3), plot-specific carbon inputs from the four NFIs and annual, plot-specific climate data until 2014 (Fig. 2) are used to obtain the time series of annual C stocks.

Table 1. Number of NFI sampling plots per subregion that were available for the Yasso07 simulation. Only plots were included that were classified as accessible forest but not shrub forest throughout the four NFIs. These areas represent the "productive forest CC12", as it is defined in the Swiss Greenhouse gas inventory (cf. Tab. 6-6 in FOEN 2015).

Elevation class	Production Region					Switzerland
	Jura	Plateau	Pre-Alps	Alps	Southern-Alps	
<601 m	129	346	18	17	40	550
600 – 1200 m	306	253	330	241	116	1246
>1200 m	46	4	145	488	128	811
Total	481	603	493	746	284	2607

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.

2.2.1 *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 (Didion et al. 2014a). Uncertainty in model parameter values was included in the simulations by random sampling from the distribution of possible parameter vectors (Tab. A-1).

2.2.2 *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 with a spatial resolution of 2.2 km with monthly data since 1961 (MeteoSwiss 2013a, b).

For the location of each NFI sampling plot, data for mean monthly absolute temperature [°C] and for monthly precipitation sum [mm] since 1961 were extracted from the respective gridded data. Annual mean temperature and precipitation were calculated as the mean and sum, respectively, of the monthly data. Annual temperature amplitudes were calculated as

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

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.

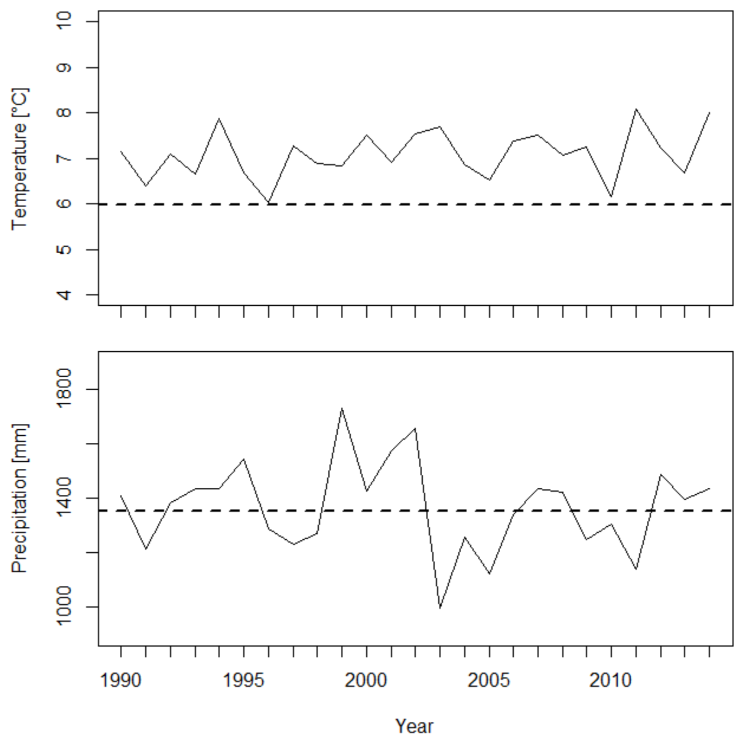

Figure 2. Annual means of temperature and precipitation sums since 1990 compared to the long-term (1961-1990) mean (dashed line) for all considered NFI plots.

Table 2. Long-term (1961-1990) mean annual temperature and precipitation sum calculated from the plot-specific data within each region (source: MeteoSwiss 2013a, b).

a) Temperature

		Production region					Switzerland [°C]
Elevation class		**Jura [°C]**	**Plateau [°C]**	**Pre-Alps [°C]**	**Alps [°C]**	**Southern Alps [°C]**	
<601 m	**Min**	6.6	6.6	6.8	3.4	4.3	3.4
	Mean	8.3	8.3	8.0	7.6	9.4	8.4
	Max	9.9	10.3	9.3	9.8	11.5	11.5
601-1200 m	**Min**	3.8	6.1	0.6	-0.6	1.3	-0.6
	Mean	6.9	7.7	6.0	5.1	7.6	6.5
	Max	9.6	9.4	9.7	9.6	11.7	11.7
>1200 m	**Min**	3.8	4.0	0.7	-2.8	-1.0	-2.8
	Mean	5.4	5.2	4.4	2.7	4.5	3.5
	Max	8.0	6.7	8.3	9.3	10.4	10.4
Total	**Min**	3.7	4.0	0.6	-2.8	-1.0	-2.8
	Mean	7.2	8.1	5.6	3.6	6.5	6.0
	Max	9.9	10.3	9.7	9.9	11.7	11.7

b) Precipitation sum

Elevation class		**Jura [mm]**	**Plateau [mm]**	**Pre-Alps [mm]**	**Alps [mm]**	**Southern Alps [mm]**	**Switzerland [mm]**
<601 m	**Min**	817	827	1062	687	1388	684
	Mean	1059	1079	1361	1124	1759	1134
	Max	1349	1599	1724	1552	2106	2148
601-1200 m	**Min**	877	895	1076	592	999	592
	Mean	1320	1233	1585	1286	1815	1412
	Max	1753	1731	2240	2231	2293	2480
>1200 m	**Min**	1295	1695	1288	592	1050	592
	Mean	1640	1824	1787	1212	1681	1416
	Max	1978	1924	2342	2307	2273	2528
Total	**Min**	817	827	1049	580	999	580
	Mean	1281	1148	1636	1234	1747	1355
	Max	1978	1944	2348	2314	2311	2542

2.2.3 *C inputs*

Estimates of C inputs (Tab. 3) for the simulations with Yasso07 were obtained separately 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; and
- Non-woody material comprising iv) foliage incl. fruits, and v) fine roots < ca. 5 mm.

The annually accumulating mass in these five DOM components (Tab. 3) 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 (NFI 1 through 4b). 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).

The uncertainty related to the estimation of dead wood and litter inputs was estimated to account for uncertainties in

- applying allometric functions (biomass expansion factors, turnover rates; Wutzler and Mund 2007);
- carbon concentration (Dobbertin and Jüngling 2009); and
- measurement errors in the NFI data.

Based on the mean inputs at each NFI site and estimates of uncertainty, a distribution of possible inputs was created and a combined uncertainty was derived (Tab. A-2).

The estimates of 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 five 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.

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. C inputs over all NFI plots simulated with Yasso07 for the GHGI 2016 (n=2 607): Mean and standard deviation of carbon content [Kg C $ha^{-1}a^{-1}$] in five dead organic matter (DOM) components for coniferous and broadleaved tree species for different simulation periods and for the spin-up procedure.

a) conifers

Simulation period	NFI data	DOM component					Total
		Fine roots	Foliage	Coarse-woody (>7 cm diameter)			
				Roots	Branches	Stems	
Spin-up and 1961-1985	**NFI 1-2$_{avg}$ (moving window)**	745 ±269	1110 ±507	294 ±165	62 ±43	54 ±38	2264 ±826
1986-1995	**NFI 1-2**	749 ±653	1115 ±1155	285 ±653	60 ±180	53 ±159	2263 ±2174
1996-2005	**NFI 2-3**	799 ±702	1168 ±1226	347 ±815	89 ±239	79 ±210	2482 ±2417
2006-2014	**NFI 3-4b**	751 ±683	1093 ±1197	346 ±1078	98 ±376	87 ±333	2375 ±2744

b) broadleaves

Simulation period	NFI data	DOM component					Total
		Fine roots	Foliage	Coarse-woody (>7 cm diameter)			
				Roots	Branches	Stems	
Spin-up and 1961-1985	**NFI 1-2$_{avg}$ (moving window)**	280 ±166	667 ±407	97 ±84	33 ±27	11 ±11	1089 ±655
1986-1995	**NFI 1-2**	281 ±371	666 ±866	100 ±316	36 ±171	12 ±55	1095 ±1466
1996-2005	**NFI 2-3**	319 ±416	749 ±964	103 ±336	48 ±187	13 ±47	1233 ±1619
2006-2014	**NFI 3-4b**	321 ±398	752 ±922	121 ±469	61 ±334	18 ±89	1273 ±1735

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).

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

2.3 Methodological improvements

Gridded monthly climate data are continuously prepared by the Federal Office of Meteorology and Climatology MeteoSwiss. Before the data are used in the simulations with Yasso07, they are examined for consistency with the data from previous years. This examination revealed inconsistencies of the data on monthly mean temperature and precipitation sums. The inconsistencies could be linked to i) an update by MeteoSwiss to the applied interpolation algorithm for temperature, and ii) the implementation of the algorithms for temperature and precipitation in the regions near the Swiss borders. Thus new time series of monthly mean temperature and precipitation sums since 1961 were obtained which were derived consistently with the current version of the interpolation algorithm TabsM v1.4 (MeteoSwiss 2013a) and with consistent implementations in the border regions. While the effect on the national means was negligible, moderate changes occurred at individual NFI sites which consequently resulted in changes to the simulated decomposition dynamics with Yasso07.

Following 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 2006a). As a result, the i) C inputs to Yasso07 and ii) simulated C stocks from which the reported C stock changes in dead wood, litter and soil were derived, are no longer averaged as done in previous inventories (cf. chapter 2.4 in Didion et al. 2014b and chapter 6.4.2.8 in FOEN 2015).

2.4 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, 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 6.4.2.8 in FOEN 2015), C stocks and 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 2014. 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*: SO_{csc}, $Litter_{csc}$, CWD_{csc} and the sum (ALL_{csc}); contained in result tables[1] 1 [Mg C $ha^{-1}a^{-1}$] and 2 [Mg C a^{-1}].
2) *annual carbon stocks*: Litter and CWD; result tables 3 [Mg C ha^{-1}] and 4 [Mg C].

Estimates of absolute stocks [Mg C] and total stock change [Mg C a^{-1}] stratified for five production regions and three elevation classes (≤600 m, 601-1200 m, >1200 m) were obtained based on the respective area of forest land remaining forest land calculated for commonly accessible forest of NFIs 3 and 4b (Tab. A-3; 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. chapter 6.3.1 in FOEN 2015).

3 Results and Discussion

The complete set of result tables (cf. section 2.4) of C stock and CSC that were prepared for the Swiss GHGI 2016 (1990-2014) 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.

3.1 Carbon stock change

The mean total CSC 2013-2014 in soil, litter and dead wood, was estimated as an emission of ca. 0.158 ±0.004 Mg C ha^{-1} (ALL_{csc} in Fig. 2, Tab. 5). This corresponded to a national emission of 183 396 ±4 649 Mg C based on 1 157 624 ha of productive forest as derived for the period 2006-2013, i.e. the period between NFIs 3 and 4b (Tab. A-3).

This distinct source 2013-2014 was the result of the comparatively large C emissions from the litter layer (0.16 ±0.002 Mg C ha^{-1}; $Litter_{csc}$ in Fig. 2). For reporting purposes, the litter pool corresponds to the LFH layer and consists of only non-woody material, the dynamics in this C pool are largely driven by interannual variability in temperature and precipitation (Aerts 1997). In Switzerland, 2014 was the warmest year on record (MeteoSwiss 2015) which largely explained the emission spike in the litter pool. The effect of weather on the litter C pool is more transparent now that CSC is derived from annual rather than from averaged annual stocks (cf. section 2.3).The dynamics in the litter pool dominated total CSC over the entire time series (Fig. 2).

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[1] see Appendix II for details and nomenclature.

Soil acted continuously as a comparably moderate sink (-0.001 ±0.0001 Mg C ha^{-1} in 2013-2014; $Soil_{csc}$ in Fig. 2) and dead wood formed a persistent sink since NFI 2 (-0.001 ±0.004 Mg C ha^{-1} in 2013-2014; Dead $wood_{csc}$ in Fig. 2), which was due to two reasons:

- In 1999 (i.e. between NFIs 2 and 3), the storm Lothar caused large scale mortality across Swiss forests. 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 harvest rates starting after NFI 3 resulted in more volume of dead wood remaining in the forest compared to the years before. This lead to an increase in the C stock in dead wood.

Whether CSC were net emissions or removals depended on carbon pools and regions (Tabs. 5 and A-6 to A-9 and A-14 to A-17 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 ± standard error [Mg C ha^{-1}] between 2013 and 2014 stratified into 3 elevation classes and 5 NFI-production regions. Negative values indicate a sink of C, positive values a carbon source.

Elevation class	Production region					Switzerland
	Jura	Plateau	Pre-Alps	Alps	Southern Alps	
<601 m	0.141 ±0.018	0.185 ±0.011	0.074 ±0.049	0.049 ±0.051	0.049 ±0.015	0.157 ±0.008
601-1200 m	0.092 ±0.009	0.174 ±0.014	0.269 ±0.013	0.153 ±0.011	0.052 ±0.014	0.163 ±0.006
>1200 m	0.223 ±0.011	0.174 ±0.014	0.217 ±0.018	0.170 ±0.010	-0.022 ±0.019	0.151 ±0.008
Total	0.117 ±0.007	0.181 ±0.009	0.246 ±0.011	0.162 ±0.008	0.018 ±0.010	0.158 ±0.004

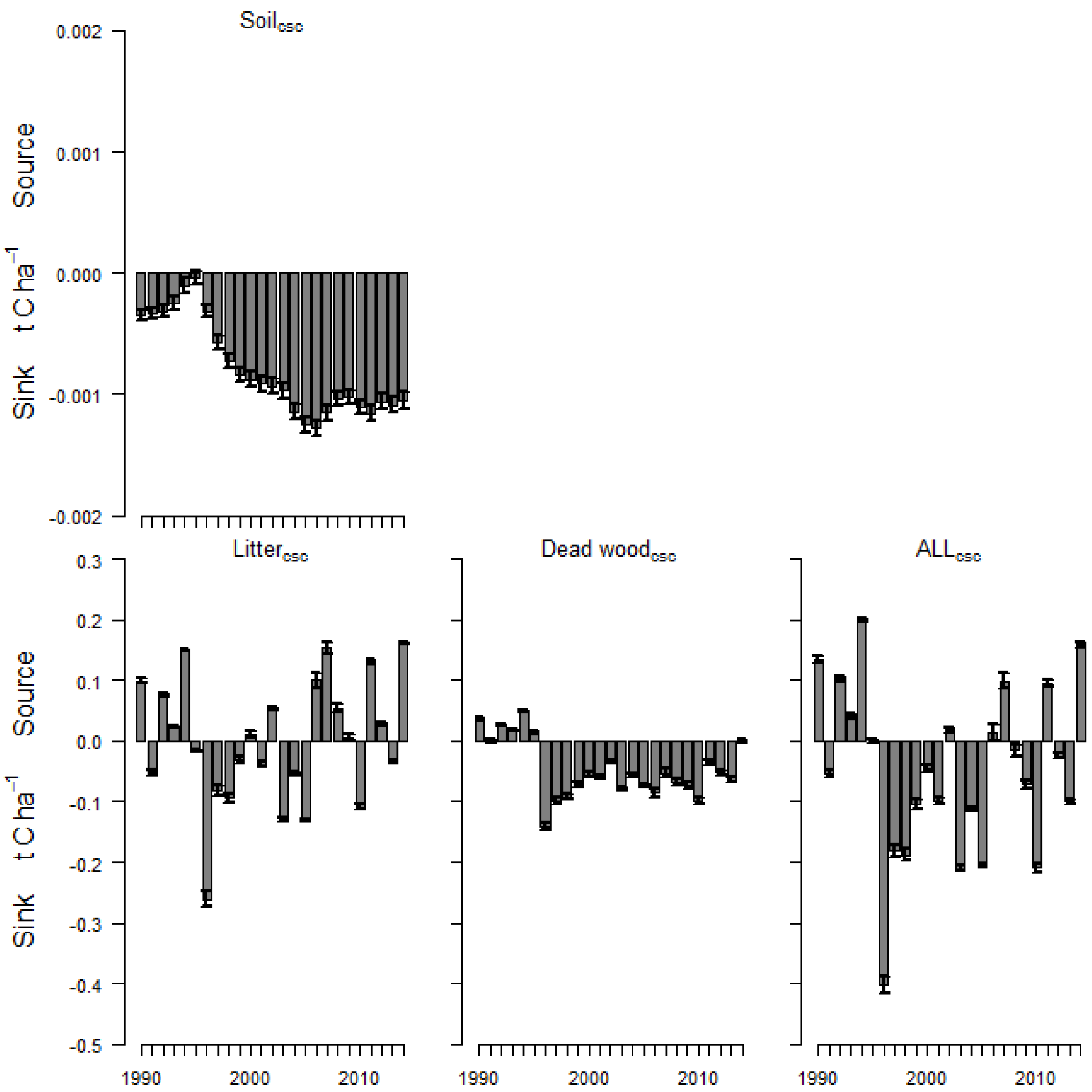

Figure 2. National mean carbon stock change (CSC) for three pools soil, litter, dead wood and their sum (ALL) in t C ha^{-1} (equals Mg C ha^{-1}). Note the difference of the y-axis scale between $Soil_{csc}$ and $Litter_{csc}$, Dead $wood_{csc}$ and ALL_{csc}, respectively. Negative values indicate a sink of C, positive values a carbon source. The error bars indicate the standard error.

The double standard error resulting from uncertainty in C inputs and in model parameters was ca. 25% litter and soil pools, ca. 60% for the dead wood pool and ca. 40% for total CSC. This is comparable to reported uncertainties (e.g., Keller et al. 2006, Schöning et al. 2006, Luyssaert et al. 2010). For the net CSC in 2011 in dead wood, litter and soil organic matter Finland reports an uncertainty of 46.8% in South Finland, 26.2% in North Finland and 24.1% for the whole country (double standard error; cf. chapter 7.2.4.2 in Statistics Finland 2014).

For evaluating the effect on CSC estimates resulting from the improved method applied for the GHGI 2016 (cf. section 2.3), C stocks and CSC were recalculated for the complete time series since 1990.

- The effect of the revised climate data (cf. section 2.3) on the estimates of CSC was negligible as the results based on the new data were mainly within one and consistently within two standard errors of results based on annual stocks in the GHGI 2015, i.e., not the reported CSC which was based on averaged stocks.
- In comparison with the CSC reported in the GHGI 2015, the shift from estimating CSC based on averaged stocks (Didion et al. 2014b, FOEN 2015) to using annual stocks (this report) resulted in a higher variability and larger differences between years as expected. However, the change in the method is consistent with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006a) and improves transparency.

3.2 Carbon stocks

For verification of the simulation approach, estimated C stocks are presented. With the exception of the estimated C stock in the mineral soil in forests, the differences to the annual stocks calculated for the GHGI 2015 were negligible.

In the Swiss NFI, estimates of coarse dead wood C stocks based on measured tree volume are available since the NFI 3. The simulated national mean dead wood C stock overestimates the national stock derived from the NFI by ca. 30% (Tab. 6). The C stocks are also overestimated in four of the five production regions. In the Southern-Alps, the particular climate characterized by highly variable precipitation pattern with extended periods of drought interrupted by heavy rainfall events (cf. Didion et al. 2011) limits the accuracy of model results. This is not surprising since 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. Also, 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. Nevertheless, the simulated stocks are plausible since they agree well with NFI estimates of national mean dead wood C stocks that are based on the observed full volume of dead wood pieces (i.e., not accounting for observed damage), i.e., 7.16 (±0.26) Mg C ha^{-1} at NFI 3 and 7.75 (±0.26) Mg C ha^{-1} at NFI 4b.

The observed change in coarse dead wood C stocks in Switzerland between NFIs 3 and 4b was reproduced accurately by the model (Tab. 6). Considering the lower number of available plots within a region (cf. Tab. 1), the simulated change in the production regions also agreed well with observations. With the exception of the Central Plateau, the model reproduced the trends in individual production regions quite well (Tab. 6). One reason for the inconsistency on the Central Plateau may be an overestimation of C inputs for the Yasso07 simulation. This may be due to inaccuracies in the estimation of harvest residuals as the forests in this region are the most intensively used forests in Switzerland.

Table 6. Mean and standard error of carbon stored in dead wood (CWD) based on observations in NFIs 3 and 4b 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 NFI 3 and 2009-2014 for NFI 4b.

Region	**NFI 3**		**NFI 4b**		**Change**	
	Mg C ha^{-1}				**%**	
	NFI	**Yasso07**	**NFI**	**Yasso07**	**NFI**	**Yasso07**
Jura	**4.49 ±0.38**	**6.65 ±0.13**	**5.28 ±0.46**	**7.37 ±0.20**	**17.6**	**10.8**
Central Plateau	**4.81 ±0.47**	**10.86 ±0.16**	**4.51 ±0.35**	**11.49 ±0.25**	**-6.2**	**5.8**
Pre-Alps	**8.28 ±0.66**	**10.73 ±0.19**	**8.93 ±0.69**	**10.87 ±0.29**	**7.76**	**1.3**
Alps	**7.18 ±0.44**	**7.37 ±0.11**	**7.46 ±0.39**	**7.59 ±0.18**	**3.9**	**3.0**
Southern-Alps	**4.85 ±0.50**	**2.34 ±0.08**	**5.64 ±0.49**	**2.91 ±0.22**	**16.3**	**24.4**
Switzerland	**6.16 ±0.23**	**8.13 ±0.07**	**6.54 ±0.22**	**8.56 ±0.10**	**6.2**	**5.3**

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 #1799} are used since Nussbaum et al. {, 2012 #1799} place 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, respectively.

The simulated national mean litter C stock was ca. 70% of the stock (Tab. 7) reported by Moeri (2007). This difference is not surprising since the simulated values do not include non-woody litter inputs from the herb and shrub layers. Carbon 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 (cf. de Wit et al. 2006). Based on preliminary data from Etzold et al. (2014), understory vegetation contributed on average ca. 12% (0.1 to 36.8%) to the total observed annual C turnover at six sites of the Long-term Forest Ecosystem Research Programme LWF. This value compares well with experimental data from Muukkonen and Mäkipää (2006), who estimated the C inputs from herb- and shrub vegetation in Finnish forests to be in the range of 500 to 660 Kg C ha^{-1} a^{-1}. This would correspond to 15-25% of the currently used C inputs used for the Swiss GHGI (Tab. 3). Thus, the simulated value for the national mean litter C stock can be considered as a reliable and plausible estimate (Tab. 7).

Table 7. 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 1990-2014. Standard error in brackets.

Region	Moeri 2007	Yasso07
	Mg C ha^{-1}	
Jura	9.71 (±1.78)	9.11 (±0.31)
Central Plateau	9.5 (±0.57)	9.57 (±0.30)
Pre-Alps	17.3 (±1.02)	10.90 (±0.39)
Alps	33.4 (±2.37)	12.31 (±0.40)
Southern-Alps	22.3 (±3.67)	9.65 (±0.59)
Switzerland	18.1 (±0.61)	10.53 (±0.17)

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.

The data in tables 6 and 7 indicate that the estimated dead wood and litter C stocks agree well with observations in the case of dead wood 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), b) the simulated CSC including standard error is less than the mimimum detection limit of repeated SOC measurements (e.g., Keller et al. 2006), and c) observed environmental gradients are reproduced by the model, including the increase in soil C stocks with elevation. The increase in soil C per 100 m increase in elevation was 1.07 Mg C ha^{-1}. This was less than the 2.3 Mg C ha^{-1} reported by Hagedorn (2010). However, the correlation of the Yasso07 estimates with elevation was stronger, i.e. $r = 0.35$ ($p = 0$) than in the analysis by Hagedorn (2010), i.e. $r = 0.12$ (p value not reported).

3.3 Further development

Research to improve Yasso07 is ongoing at WSL and elsewhere. Planned improvements to the application in Switzerland include:

- Investigating the validity of the forthcoming new version of Yasso07 for application in Switzerland. The new model version Yasso15 includes, among other, a new parameter set that improves the sensitivity of the simulated decomposition to temperature and precipitation. Yasso15 is currently tested at the Finnish Environment Institute and Tampere University of Technology. A beta-version will be available for testing in Switzerland in fall 2015. Yasso15 is expected to improve the estimates for C stocks and C stock changes in Swiss forests.
- Examining the suitability of Yasso07 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.
- Improving the derivation of C inputs from litter and dead wood, including a) interpolating between two consecutive NFIs and b) accounting for the contribution of fine-woody litter <7 cm and of litter from the herb- and shrub layer; the latter in collaboration with S. Etzold, WSL. These activities will improve the accuracy of the Yasso07 estimates and result in an increase in completeness.
- Quantifying the effect of uncertainty associated with the spatially interpolated temperature and precipitation data on CSC estimates. MeteoSwiss is currently developing ensembles of the gridded climate data that will allow to address this source of uncertainty in the simulations with Yasso07. The ensembles are expected to become available in 2016.

It is also anticipated that the previously completed European task force on forest soil modeling with Yasso07 (LULUCF MRV project: "Analysis of and proposals for enhancing Monitoring, Reporting and Verification (MRV) of land use, land use change and forestry (LULUCF) in the EU"; http://forest.jrc.ec.europa.eu/activities/lulucf/) will provide new insights and stimulate further improvements of the Yasso07 application. The project demonstrated strengths and weaknesses of Yasso07 for estimating the C balance of dead wood, litter and soil in forests along a wide environmental gradient. Contributors to the task force came from Austria, Estonia, Finland, France, Romania, Spain and Switzerland representing a large variety of forest types. The implications and further research needs were discussed in a workshop at WSL on 15 December 2014 and are currently summarized in two manuscripts:

- Didion, M., V. Blujdea, G. Grassi, L. Hernández, R. Jandl, K. Kriiska, A. Lehtonen, and L. Saint-Andre. Models for reporting forest litter and soil C pools in national greenhouse

gas inventories: methodological considerations and requirements. Under revision in *Carbon Management*.

- Hernández, L., I. Alberdi, V. Blujdea, I. Cañellas, M. Didion, R. Jandl, K. Kriiska, A. Lehtonen, G. Marin, D. Moreno-Fernández, and L. Saint-Andre. Towards global assessment of soil carbon stocks and balance: the ability of Yasso07 model across a wide gradient of climatic and forest conditions in Europe. In preparation.

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

- National Research Programme project "Sustainable use of Soil as a Resource" by F. Hagedorn, WSL;
- “Kernfäule” (heart rot) by J. Wunder, WSL;
- “Carbon sources and sinks in agricultural soils” at the 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.

4 Conclusions

The methodology for estimating carbon stocks and carbon stock changes in dead wood, litter and soil for the Swiss GHGI has been further improved since Switzerland’s latest GHGI (FOEN 2015). In particular, the time series consistency was improved as a result of the revision in the climate data that were identified in the QA/QC process. Transparency of the estimated C stock changes was increased by applying the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006b) and refraining from using averaged time-series data.

Current limitations such as not accounting for C inputs from fine-woody and understory litter and improving the uncertainty estimate are under investigation in ongoing and planned research projects.

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Appendix I: Additional data

Table A-1. 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.

Paramet er	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

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Table A-2. Uncertainty in litter inputs (%).

	Conifers	Broadleaves
Wood density[1]	25.9	23.6
Spatial uncertainty in the NFI[2]	3	3
Litter turnover[3]	17	4
Total[4]	31.1	27.6

[1] 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.

[2] Approximated based on the estimation error for tree volume reported for the NFI; cf. chapter 1.4 in Brändli, U.-B., editor. 2010. Schweizerisches Landesforstinventar: Ergebnisse der dritten Erhebung 2004-2006. [Results of the third Swiss National Forest Inventory 2004-2006]. Swiss Federal Research Institute for Forest, Snow and Landscape Research, Birmensdorf (ZH) and Federal Office for the Environment (FOEN), Bern.

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

[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-3. 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 4b.

Elevation class	**Production region**										**Switzerland**	
	Jura		**Plateau**		**Pre-Alps**		**Alps**		**Southern Alps**			
	ha	**± %**	**ha**	**± %**	**ha**	**± %**	**ha**	**± %**	**ha**	**± %**	**ha**	**± %**
<601 m	51944.01	8	131845.7	4	7233.055	25	9999.95	21	19916.59	14	220939.3	4
601-1200 m	124512.4	4	93816.63	5	133776.2	4	98174.97	6	52458.94	8	502739.2	2
>1200 m	23325.2	13	2627.465	41	77225.62	6	257593.2	3	73174.27	6	433945.7	2
Total	199781.7	1	228289.8	1	218234.9	2	365768.1	2	145549.8	2	1157624	1

Appendix II: Data prepared for Switzerland's GHGI 2016 (1990-2014)

Table A-5. List of result tables that were included in the data delivery from 14.07.2014. The associated Excel file presents the relevant data based on averaged annual stocks and stock changes.

Table	Table name	Content
A-6	Annual C stock change [Mg C $ha^{-1}a^{-1}$]	Mean CWD pool stock change
A-7		Mean LFH pool stock change
A-8		Mean Soil pool stock change
A-9		Mean stock change for ALL pools
A-10		Standard error CWD pool stock change
A-11		Standard error LFH pool stock change
A-12		Standard error Soil pool stock change
A-13		Standard error stock change for ALL pools
A-14	Annual absolute C stock change [Mg C a^{-1}]	Mean CWD pool stock change
A-15		Mean LFH pool stock change
A-16		Mean Soil pool stock change
A-17		Mean stock change for ALL pools
A-18		Standard error CWD pool stock change
A-19		Standard error LFH pool stock change
A-20		Standard error Soil pool stock change
A-21		Standard error stock change for ALL pools
A-22	Annual C stock [Mg C ha^{-1}]	Mean CWD pool stock
A-23		Mean LFH pool stock
A-24		Standard error CWD pool stock
A-25		Standard error LFH pool stock
A-26	Annual absolute C stock [Mg C]	Mean CWD pool stock
A-27		Mean LFH pool stock
A-28		Standard error CWD pool stock
A-29		Standard error LFH pool stock

NOTE:
1) Elevation classes 601-1200m and >1200m in production region 2 were combined in the calculations and have the same value reported.
2) Table values were rounded to 3 decimal places.
3) Tables of absolute CSC and stock contain national estimates based on the area of productive forest between NFIs 3 and 4b of 1 157 624 ha.
4) Negative values for CSC indicate a C sink, positive values a C source.