Data on soil carbon stock change, carbon stock and stock change in surface litter and in coarse deadwood prepared for the Swiss GHGI 2014 (1990-2012)

20. December 2013

Prepared by Markus Didion, Edgar Kaufmann and Esther Thürig

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

Commissioned by the Federal Office for the Environment FOEN

Swiss Federal Institute for Forest,
Snow and Landscape Research WSL

Summary

Switzerland prepares annually a greenhouse gas inventories 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 data for forest management, 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 deadwood, 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 advancements included a) implementing a new model parameter set, b) improving the estimation of uncertainties in model parameters and in model inputs, and c) refining the simulation of C decomposition in litter and deadwood. Accordingly, the accuracy of the estimates of C stocks and CSC was improved. As a result the a-posteriori calibration of deadwood stocks (chapter 7.3.4.9 in FOEN 2013) became redundant and, hence, a source of uncertainty was eliminated.

In section 3, the results obtained for the Swiss GHGI 2014 (1990-2012; FOEN 2014) are presented and discussed. As reported in section 3.1, the total CSC in soil, litter and deadwood from 2011 to 2012 produced a small source of +0.25 Mg C ha^{-1} or +295,213 Mg C (based on 1,165,344 ha of productive forest between NFIs 3 and 4). The standard error of the estimates for CSC originating from uncertainty in C inputs and in model parameters varied between 2-20% for the individual pools and ca. 26% for total CSC. In comparison, Finland reports an uncertainty of 24.1% for the net CSC in 2011 in dead wood, litter and soil organic matter. For the first KP commitment period 2008-2012, aggregated values encompassing deadwood, litter and soil constituted a C source of +0.287 Mg C ha^{-1}a^{-1} ±8%. A minor source effect also resulted in comparison to the KP base year 1990 when the mean total C stock was 60.202 Mg C ha^{-1} ±1% compared to 60.199 ± Mg C ha^{-1} ±1% in 2012.

Based on the improved methods, the national estimate for mean total CSC in 2010-2011 was a source of +0.269 Mg C ha^{-1} compared to a sink of -0.029 Mg C ha^{-1} that was estimated with the implementation used in the previous GHGI.

Section 3.3 presents ongoing and planned projects to further improve the estimates of C stocks and CSC in deadwood, litter and soil on forest lands in Switzerland and which are expected to

increase the transparency, consistency, comparability, completeness and accuracy of the reported data for 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 2003):

- Soil organic carbon
- Litter
- Deadwood

Following the convention used by Switzerland in its previous National Inventory Reports (NIR), the reported pools are

- Soil
- LFH (Litter - Fermenting - Humified) layer
- Deadwood (corresponding to TDW as used in Switzerland's NIR 2013 (chapter 7.3.4.8 in FOEN 2013): wood of dead trees >12 cm, lying dead wood >7 cm and dead coarse roots)
- Total as the sum of the above pools

Dead organic matter (DOM): Term is used as defined in IPCC (2003), i.e., deadwood and litter.

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

- State analyses (*Zustandsauswertungen*):

- NFI1: assumed to be representative of the year 1985
- NFI2: assumed to be representative of the year 1995
- NFI3: assumed to be representative of the year 2005
- NFI4a: assumed to be representative of the year 2012

- Change analyses (*Veränderungsauswertungen*)

- NFI12: assumed to be representative of the period 1986 to 1995
- NFI23: assumed to be representative of the period 1996 to 2005
- NFI34a: assumed to be representative of the period 2006 to 2012

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). From the activities in the LULUCF sector, Switzerland elected to account for forest management under the Kyoto Protocol. Thus, the country is required to report on C stock changes in above- and belowground living and dead biomass and in the soil. Starting with the Swiss GHGI 2013 (1990-2011; FOEN 2013), the C decomposition model Yasso07 (Tuomi et al. 2009, Tuomi et al. 2011) was used for deriving estimates of C stock change in deadwood (incl. stems, branches and roots), non-woody litter and in soils on productive forest lands (Didion et al. 2012, FOEN 2013).

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 deadwood. For the GHGI-Submission 2014 (1990-2012), several methodological improvements of the Yasso07 application on Swiss forest lands were made, including a) increased accuracy of climate and litter input data, b) model parameterization and c) uncertainty estimation, which resulted in greater accuracy and elimination of sources of uncertainty. The purpose of this report is to a) give details of the improved methods (section 2.3) and b) to present and discuss the estimates of C stocks and C stock changes for use in the GHG-inventory submission of April 2014 (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.

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, deadwood 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 described in detail in Didion et al. (2012). 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, Tuomi et al. 2011) is a model of C cycling in mineral soil, litter and deadwood. 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 deadwood 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, Tuomi et al. 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, Tuomi et al. 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 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 3.0.1 (64 bit) was used for administrating the Yasso07 simulations.

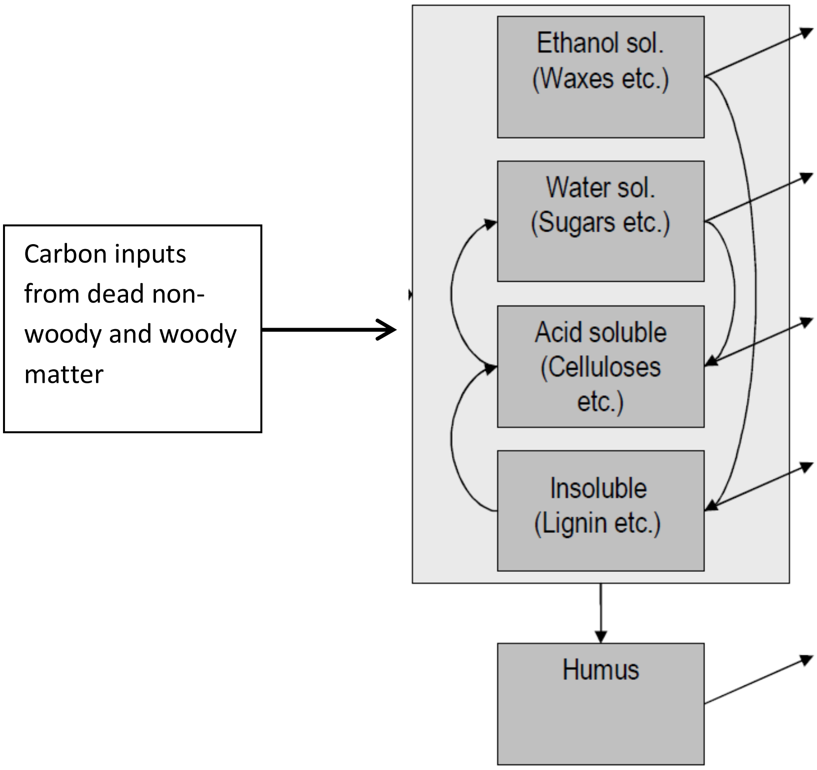

Figure 1. Flow chart of Yasso07 soil carbon model. The boxes represent soil carbon compartments, the arrows carbon flows; only those carbon flows are shown that deviate significantly from zero (adapted from Liski et al. 2009).

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 throughout the 4 NFIs (Tab. 1), i.e., forests that were considered forest remaining forest. To drive the Yasso07 simulation, plot-specific annual inputs for a) non-woody and woody C derived from measured data and 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) and constant, aggregated C inputs from the first NFI (NFI12avg; 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 (NFI12avg; 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 to 2; Tab. 3), plot-specific carbon inputs from the 4 NFIs and annual, site-specific climate data until 2012 are used to obtain the time series of annual C stocks. The time series of C inputs since 1986 (Fig. 2) is derived by backwards-averaging inputs over three years, i.e., the input of the current year was calculated as the mean over the inputs of the current year and the two preceding years.

Table 1. Number of NFI sampling sites per subregion that were available for the Yasso07 simulation. Only plots were included that were classified as accessible forest but not shrub forest. These areas represent the "productive forest CC12", as it is used in the Swiss Greenhouse gas inventory (FOEN 2013).

Elevation	Production Region					Switzerland
	Jura	Plateau	Pre-Alps	Alps	Southern-Alps	
<601 m	103	229	34	47	54	467
600 – 1200 m	173	118	204	186	80	761
>1200 m	18	3	60	204	35	320
Total	294	350	298	437	169	1,548

2.2.1 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 2012a, 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

(Tab. 2 for long-term national means). Annual mean temperature and precipitation sum were calculated as the mean and sum, respectively, of the monthly data. Annual temperature amplitudes were calculated as

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

Table 2. Long-term (1961-1990) mean annual temperature and precipitation sum calculated from the plot-specific data within each region (source: MeteoSwiss 2012a, b).

a) Temperature

		Production region					Switzerland [°C]
Elevation class		**Jura** [°C]	**Plateau** [°C]	**Pre-Alps** [°C]	**Alps** [°C]	**Southern Alps** [°C]	
<601 m	*Min*	5.9	6.5	5.1	3.4	4.4	3.4
	Mean	8.2	8.3	7.8	7.5	9.5	8.4
	Max	10.0	10.4	9.4	9.9	11.7	11.7
601-1200 m	*Min*	4.3	5.4	0.6	-1.0	0.4	-1.0
	Mean	7.0	7.7	6.0	5.0	7.3	6.5
	Max	9.5	10.0	9.7	9.6	11.7	11.7
>1200 m	*Min*	4.2	4.4	0.6	-5.0	-2.4	-5.0
	Mean	5.9	6.1	4.4	2.4	4.4	3.3
	Max	8.6	8.4	8.3	9.3	11.0	11.0
Total	*Min*	4.2	4.4	0.6	-5.0	-2.4	-5.0
	Mean	7.2	8.0	5.5	3.2	6.2	5.6
	Max	10.0	10.4	9.7	9.9	11.7	11.7

b) Precipitation

Elevation class		**Jura** [mm]	**Plateau** [mm]	**Pre-Alps** [mm]	**Alps** [mm]	**Southern Alps** [mm]	**Switzerland** [mm]
<601 m	*Min*	814	804	1062	687	1361	684
	Mean	1066	1080	1375	1207	1757	1154
	Max	1467	1603	1785	2044	2265	2382
601-1200 m	*Min*	871	890	1061	580	861	580
	Mean	1324	1236	1593	1275	1805	1421
	Max	1862	1838	2273	2324	2322	2538
>1200 m	*Min*	1210	1378	1241	602	861	602
	Mean	1650	1794	1780	1240	1718	1442
	Max	2046	1936	2390	2454	2365	2639
Total	*Min*	813	804	1045	576	861	576
	Mean	1303	1151	1652	1249	1755	1380
	Max	2046	1967	2395	2456	2370	2640

2.2.2 C inputs

Estimates of C inputs (Tab. 3; Fig. 2) for the simulations with Yasso07 were obtained separately for coniferous and broadleaved tree species for:

- Coarse-woody material from trees >7 cm in diameter separately for roots, branches and stem; and
- Non-woody material separately for foliage (incl. fruits) and fine roots < ca. 5 mm.

The annually accumulating mass in these 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 4a). 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 estimates of C inputs were obtained separately for each NFI plot to account for local conditions including the prevalent forest management 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 (Tab. 3): Estimates of fine root and foliage production change with a change in tree number and volume. Estimates of coarse-woody production change with a change in the rate of tree mortality due to a disturbance and in the amount of residues that remain after a disturbance.

Table 3. Mean C inputs for all NFI plots simulated with Yasso07 (n=1,548): Mean 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. Standard deviations in brackets.

a) conifers

Simulation period	NFI data	DOM component				
		Fine roots	Foliage	Coarse-woody (>7 cm diameter)		
				Roots	Branches	Stems
Spin-up and 1961-1985	NFI12avg (moving window)	741 (±271)	1080 (±505)	297 (±170)	56 (±39)	50 (±34)
1986-1995	NFI12	734 (±659)	1069 (±1142)	283 (±667)	44 (±167)	48 (±148)
1996-2005	NFI23	785 (±689)	1130 (±1228)	375 (±873)	110 (±284)	97 (±251)
2006-2012	NFI34a	727 (±683)	1021 (±1174)	176 (±591)	32 (±139)	29 (±123)

b) broadleaves

Simulation period	NFI data	DOM component				
		Fine roots	Foliage	Coarse-woody (>7 cm diameter)		
				Roots	Branches	Stems
Spin-up and 1961-1985	NFI12avg (moving window)	281 (±167)	671 (±409)	98 (±84)	30 (±24)	10 (±10)
1986-1995	NFI12	292 (±386)	691 (±898)	114 (±344)	38 (±179)	12 (±50)
1996-2005	NFI23	328 (±423)	772 (±983)	106 (±330)	57 (±220)	17 (±64)
2006-2012	NFI34a	327 (±406)	769 (±941)	68 (±284)	21 (±124)	6 (±32)

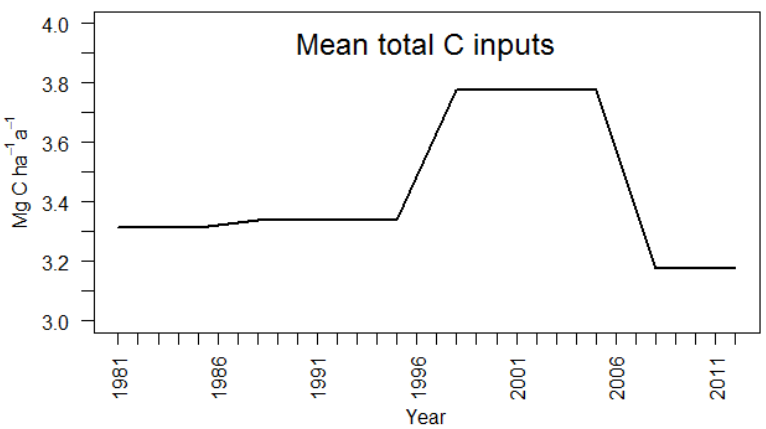

Figure 2. Time series since 1986 of mean total C inputs (i.e., sum of five dead organic matter components; cf. Tab. 3).

2.3 Methodological improvements

Following the aim to continuously improve the methods, several developments were made to the Yasso07 application for reporting to the Swiss GHGI 2014 (1990-2012; FOEN 2014).

2.3.1 Model parameters

Didion et al. (2014) examined the validity of different published parameter sets (incl. the set used for the simulations for the Swiss GHGI 2013) based on measured C decomposition in foliage, fine roots and deadwood. They found that estimates obtained with the parameter set presented in Rantakari et al. (2012) agreed better with observed data than estimates obtained with the parameters in Tuomi et al. (2009) that were used for the simulations for the Swiss GHGI 2013. Didion et al. (2014) concluded that with the parameters from Rantakari et al. (2012), Yasso07 reproduced measured C decomposition with a high degree of accuracy.

2.3.2 Climate input data

MeteoSwiss recalculated precipitation data at a number of climate stations resulting in changes in the spatially interpolated precipitation data at NFI sites which improved the accuracy since unrealistically high values were replaced.

2.3.3 Litter input data

A primary driver of the soil C budget in forests is C from decomposing dead organic matter (Amundson 2001, Jandl et al. 2007). Several improvements to the estimation of the litter and deadwood production were made:

a. Improved estimation of stand age on NFI plots resulting in changes to litter production;
b. Finer separation of inputs into five DOM components (cf. Tab. 3) allowing for i) source-specific partitioning into four chemical compartments (AWEN, cf. section 2.1 'Yasso07') using measured information (Tab. A-1) and ii) more precise estimates of the size of deadwood, i.e., 19 cm for stems (based on NFI data), 4 cm for branches (based on Mäkinen et al. 2003) and 7 cm for roots;

c. More accurate conversion of biomass to carbon content of litter inputs by replacing the IPCC default conversion factor 0.5 with local data (Dobbertin and Jüngling 2009) for conifers (0.493) and broadleaves (0.476);
d. More accurate estimation of conifer root biomass by replacing the allometric relationship (Zell and Thürig 2013); and
e. Uncertainty of litter inputs deriving from different sources was estimated. Based on the mean inputs at each NFI site and estimates of uncertainty, a distribution of possible inputs was created; a combined uncertainty was derived for (Tab. A-2)
    - 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.

Items a-d clearly contribute to improving the estimation of LFH and deadwood C stocks compared to the previous Swiss GHGI. The effect of these efforts are presented in the results section 3.2 'Carbon stocks'. As a result of the improvements the a-posteriori calibration of deadwood stocks (chapter 7.3.4.9 in FOEN 2013) became redundant and, hence, a source of uncertainty was eliminated.

2.3.4 Uncertainty estimation

Uncertainty in model parameter values and in the size of litter inputs was estimated following a Monte-Carlo approach. From both, the distribution of possible parameter values (Tab. A-3) and of possible NFI plot-specific litter inputs (cf. Tab. A-2), 10 random samples were drawn and simulated independently, resulting in 100 replicate simulations. The plot-specific estimates from the replicates were used to obtain a measure of variance in the estimated carbon stocks and stock changes for the three carbon pools.

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), the litter-fermented humus (LFH) layer (i.e., sum C in the AWEN compartments of fine roots and foliage) and in deadwood (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. 2014). For consistency with previous submissions of Switzerland's NIR (chapter 7.3.4.8 in FOEN 2013), C stocks and C stock changes were estimated for a) the LFH layer pool rather than the litter pool (sensu IPCC 2003) and b) the CWD pool based on coarse-woody inputs only.

Annual estimates of carbon stocks in the soil, LFH and CWD pools for each NFI plot were derived from Yasso07 simulations for the period 1989 to 2012. Averaged annual estimates of C stocks were derived from annual estimates by averaging over three years, i.e. the mean over the current year and the two preceding years. For both resulting time series, the annual change in carbon stock between consecutive years was calculated. Thus, for each pool a total of four time series was obtained giving the mean and the uncertainty estimate (standard error (SE) derived from 100 replicate simulations for each NFI plot) for:

1) *annual carbon stock change based on annual stocks*: SO_{csc}, LFH_{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 stock change based on averaged annual stocks*: $SO_{avg, csc}$, $LFH_{avg, csc}$, $CWD_{avg, csc}$ and the sum ($ALL_{avg, csc}$); result tables 3 [Mg C $ha^{-1}a^{-1}$] and 4 [Mg C a^{-1}].
3) *annual carbon stocks*: LFH, CWD; result tables 5 [Mg C ha^{-1}] and 6 [Mg C].
4) *averaged annual carbon stocks*: LFH_{avg}, CWD_{avg}; result tables 7 [Mg C ha^{-1}] and 8 [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 4a (Tab. A-4; 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 7.2.2.1 in FOEN 2013)

3 Results and Discussion

The complete set (cf. section 2.4 ‘Analysis’) of C stock and C stock change (henceforth CSC) that were prepared for the Swiss GHGI 2014 (1990-2012) can be found in Appendix II. In the following, the results for CSC and stocks are presented and additional data that are relevant for

[1] Nomenclature following data submission from 13.08.2013; see also Appendix II for details.

verification are documented. If not otherwise noted, the stock and CSC data are based on the 3-year-averaged annual results.

3.1 Carbon stock change

For the mean total CSC 2011-2012 in soil, LFH and deadwood, a small source effect of ca. +0.25 Mg C ha^{-1} (±3%) was estimated ($ALL_{csc,avg}$ in Fig. 3, Tab. 4). This corresponded to a national source effect of +295,213 Mg C calculated based on the area of productive forest of 1,165,344 ha (Tab. A-4) as derived for the period between NFIs 3 and 4.The dynamics in deadwood and, to a lesser extent, LFH dominated total CSC (Fig. 3), alternating between source and sink between the different NFIs. Soil acted continuously as a comparably moderate sink. The standard error resulting from uncertainty in C inputs and in model parameters was generally in the range of ca. 2 to 20% of the pool means, which was comparable to reported uncertainties (e.g., Keller et al. 2006, Schöning et al. 2006, Luyssaert et al. 2010). The uncertainty in total combined CSC was estimated as ca. 26%. In comparison, Finland reports an uncertainty of 24.1% for the net CSC in 2011 in dead wood, litter and soil organic matter (cf. chapter 7.2.4.2 in Statistics Finland 2013). In few cases uncertainty was larger when uncertainty reached across 0 (e.g., LFH pool in year 2010, Fig. 3). Whether CSC resulted in a source or sink effect varied between pools and regions (Tabs. 4 and A-6 to A-9 and A-14 to A-17 for a complete time series of areal [Mg C $ha^{-1}a^{-1}$] and absolute CSC [Mg C a^{-1}]).

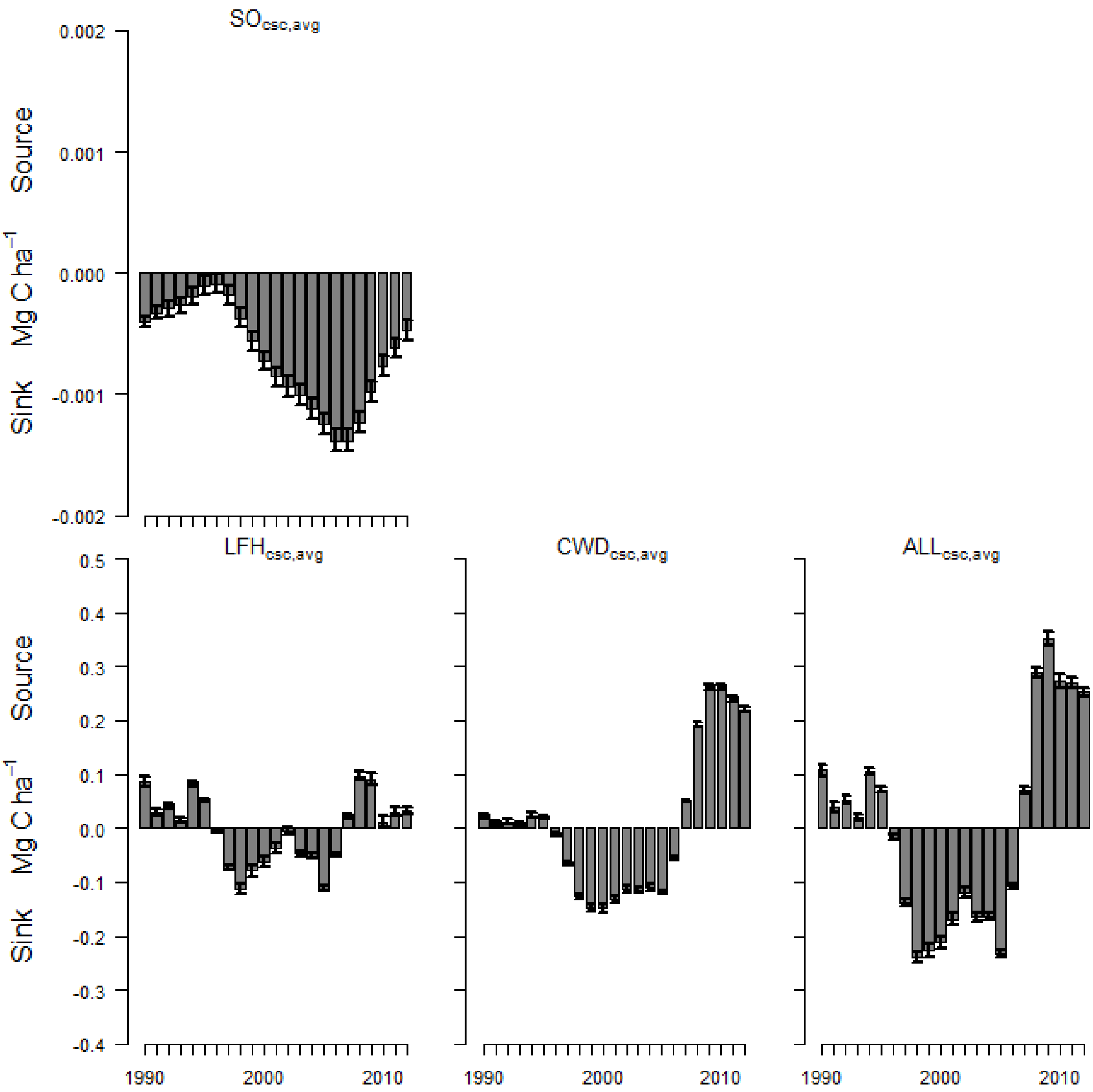

Figure 3. National mean carbon stock change (CSC) based on 3-year averaged annual carbon stocks for 3 pools soil (SO), litter (LFH), dead wood (CWD) and their sum. Note the difference of the y-axis scale for $SO_{csc,avg}$ and for $LFH_{csc,avg}$, $CWD_{csc,avg}$ and $ALL_{csc,avg}$, respectively. Negative values indicate a sink of C, positive values a carbon source.

Table 4. Carbon stock change [Mg C ha^{-1}] between 2011 and 2012 stratified into 3 elevation classes and 5 NFI-production regions. Rel. standard error (%) in brackets. 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	0.274 (12.3)	0.349 (6.0)	-0.006 (1726.7)	0.323 (31.4)	0.006 (627.1)	0.293 (5.5)
601-1200 m	0.071 (22.9)	0.287 (10.0)	0.575 (4.0)	0.290 (8.3)	-0.043 (69.2)	0.277 (3.8)
>1200 m	0.266 (12.0)	0.287 (10.0)	0.166 (20.1)	0.264 (8.5)	-0.101 (45.6)	0.188 (8.9)
Total	0.142 (10.0)	0.324 (5.2)	0.428 (4.3)	0.274 (6.1)	-0.061 (39.8)	0.253 (3.2)

For comparing the effect on CSC estimates of the improved method applied in the GHGI 2014 (1990-2012) with the method used in the GHG 2013 (1990-2011; FOEN 2013), C stocks and CSC were recalculated for the complete time series since 1990. The difference in methods was negligible for CSC in the soil C pool in the long-term (i.e., a minor sink), although the results were more variable following the methods from 2011 (Fig. 4). The largest differences were in the estimates for LFH and CWD. While the temporal dynamics between NFIs (i.e., 1996 and 2006) remained similar, the improved methodology resulted in a shift towards a small C source. The national estimate for mean total CSC 2010-2011 reported in the previous GHGI was a sink of -0.029 Mg C ha^{-1} compared to a source of +0.269 Mg C ha^{-1} (Fig. 4) calculated for the same period based on the improved methodology.

In 2012 the first commitment period of the Kyoto Protocol ended. Over the period 2008 to 2012 mean total C stock in soil, LFH and CWD in Swiss forests decreased from 61.633 Mg C ha^{-1} ±1% to 60.199 ± Mg C ha^{-1} ±1% with a mean CSC of +0.287 Mg C $ha^{-1}a^{-1}$ ±8% (i.e., a source of C). A minor source effect also exists in comparison to 1990 when the mean total C stock was 60.202 Mg C ha^{-1} ±1%.

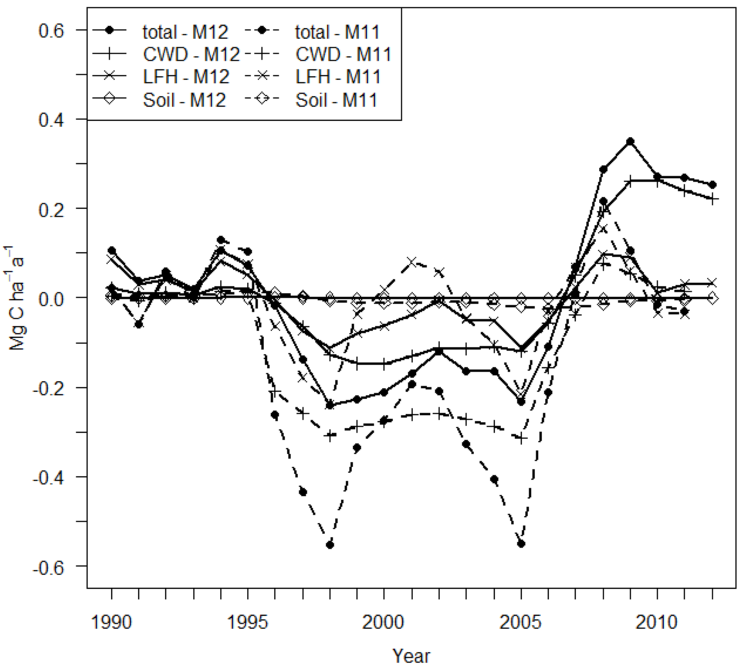

Figure 4. National mean carbon stock change based on averaged annual carbon stocks for 3 pools soil (SO), litter (LFH), dead wood (CWD) and their sum (total) estimated with the improved methodology applied for the GHGI 2014 (1990-2012; "M12") and based on the method applied for the GHGI 2013 (1990-2011; "M11"). Negative values indicate a sink of C, positive values a carbon source.

3.2 Carbon stocks

Due to the improvements in the methods (cf. section 2.3 'Methodological improvements'), the accuracy of simulated LFH and CWD stocks increased significantly from the GHGI 2013 (1990-2011; FOEN 2013) where there was only moderate agreement between simulated stocks and reported data from the literature (cf. Didion et al. 2012). For an overview, figure 5 presents the time series of the estimated national mean C stock in LFH and CWD, respectively.

For verification, the simulated LFH and deadwood stocks were compared with observed data from Moeri (2007) for LFH (Tab. 6) and from the NFI for deadwood (Tab. 7). The simulated national mean LFH C stock was ca. 60% of the reported stock (Tab. 6). This difference is not surprising since the simulated values did 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 experimental data from Muukkonen and Mäkipää (2006), the C inputs from herb- and shrub vegetation in Finnish forests was estimated to be in the range of 500 to 660 Kg C $ha^{-1}a^{-1}$. This would contribute additional 15-25% to the currently used non-woody C inputs used for the Swiss GHGI. Thus, the simulated value for the national mean LFH C stock can be considered as a reliable and plausible estimate, which was also indicated by the overlapping ranges of the standard deviations (Tab. 6). An estimate of the contribution of the herb and shrub layer to carbon inputs on NFI sites may become available with the project 'The carbon cycle of LWF-sites in Switzerland' (P. Waldner, WSL) for the GHGI 2015 (1990-2013).

Table 6. Carbon stock in the litter pool based on observed (sum of L, F and H horizons from Tab. 5.3 in Moeri 2007) and estimated LFH carbon stock with Yasso07; the estimated stock was calculated as the long-term mean over the period 1989-2012. Standard deviation in brackets.

Region	**Moeri 2007**	**Yasso07**
	Mg C ha^{-1}	
Jura	9.71 (±15.1)	9.11 (±0.08)
Central Plateau	9.5 (±13.3)	9.10 (±0.08)
Pre-Alps	17.3 (±28.4)	10.61 (±0.1)
Alps	33.4 (±43.3)	12.32 (±0.1)
Southern-Alps	22.3 (±29.9)	10.09 (±0.15)
Switzerland	18.1 (±30.0)	10.41 (±0.04)

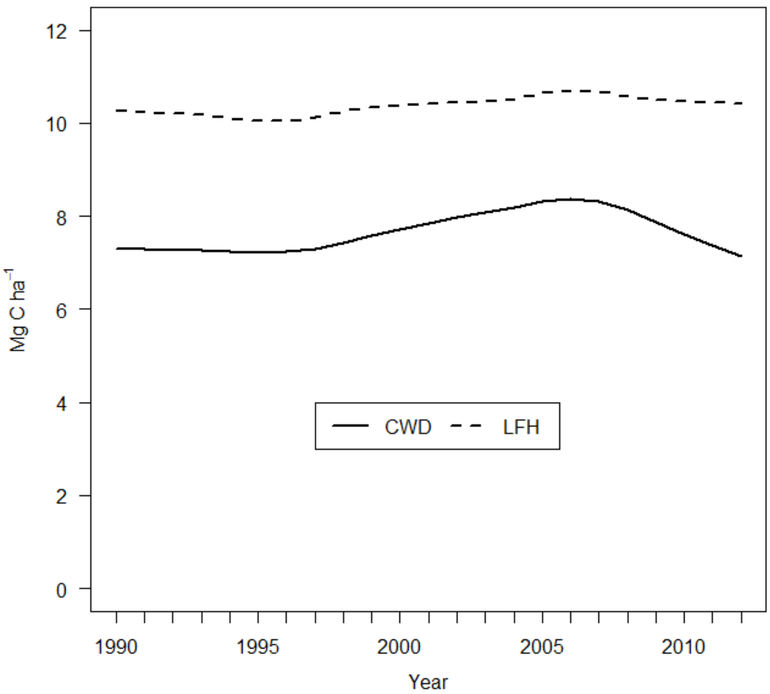

Figure 5. National mean of 3-year averaged annual LFH and CWD carbon stocks estimated with Yasso07 for the Swiss GHGI 2014 (1990-2012).

The variability between LFH C stocks between regions is greater in the measured data from Moeri (2007) than in the simulated data (Tab. 6). 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 spatially aggregated, and b) the measured data are based on a limited number of observations and thus the means are more uncertain as indicated by the large standard deviations in Table 6.

In the Swiss NFI, estimates of coarse deadwood C stocks based on measured tree volume are available since the NFI3. The simulated national mean deadwood C stock overestimates stocks derived from the NFI by 30 to 40% (Tab. 7). This is expected because NFI data are associated with high uncertainty (cf. Didion et al. 2014), especially regarding the measurement of the decay class, which is important for applying the correct wood density. Furthermore, NFI data are based on details that are not available for the model estimates, including calculation of C stock on the basis of individual trees. This allows a more accurate estimate of tree volume and thus the amount of stored carbon than is possible in the derivation of the input data for Yasso07. 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, and diameter and length of a piece of deadwood. Nevertheless, the simulated stocks are plausible since they agree well with NFI estimates of national mean deadwood C stocks that are based on the observed full volume of deadwood pieces (i.e., not accounting for observed damage), i.e., 7.04 (±0.19) Mg C ha^{-1} at NFI3 and 7.01 (±0.3) Mg C ha^{-1} at NFI4a.

Table 7. Carbon stored in deadwood (CWD) based on observations in NFIs 3 and 4a and estimated deadwood carbon stock with Yasso07; the estimated stock was calculated as the mean in years 2004-2006 for NFI 3 and 2009-2011 for NFI 4a. Standard error (standard deviation of the sampling distribution) in brackets.

Region	**NFI 3**		**NFI 4a**	
	Mg C ha^{-1}			
	NFI	**Yasso07**	**NFI**	**Yasso07**
Jura	4.79 (±0.32)	6.37 (±0.08)	4.67 (±0.43)	5.90 (±0.08)
Central Plateau	4.19 (±0.27)	11.05(±0.13)	4.49 (±0.47)	10.30 (±0.12)
Pre-Alps	8.14 (±0.53)	11.05 (±0.15)	8.65 (±0.90)	10.04 (±0.14)
Alps	7.06 (±0.33)	7.87 (±0.10)	6.15 (±0.43)	7.09 (±0.09)
Southern-Alps	5.60 (±0.43)	2.15 (±0.04)	5.34 (±0.60)	2.09 (±0.05)
Switzerland	6.01 (± 0.17)	8.29 (±0.05)	5.94 (± 0.26)	7.61 (±0.05)

Between the NFI3 and NFI4, C stocks decreased both in the simulated data and in the NFI estimates, which was due, particularly, to lower C inputs deriving from CWD for the period NFI34 compared to NFI23 (cf. Tab. 3, Fig. 2). The decrease in C inputs can be explained by the large-scale windthrow damage following the storm Lothar in 1999. The fact that simulated C stocks showed a higher reduction than C stocks based on NFI data was due to the limitations of the assessment of deadwood decay classes. While a piece of deadwood remains for several years in one decay class and thus has a constant C store, simulated C decay occurs on an annual time step. Due to the short period between measurements in the NFI3 and the ongoing NFI4 (less than 5 years), for the majority of deadwood pieces that derived from the storm event in 1999 the same decay class was observed in the two NFIs. However, the decay of these deadwood pieces continued in reality, which is also reflected in the simulated decomposition in Yasso07.

The data in tables 6 and 7 indicate that the estimated LFH and deadwood C stocks agree well with observations and are plausible, certainly at the national level. Since observed C decomposition was reproduced highly satisfactory with Yasso07 (Didion et al. 2014), confidence can be placed in the reported stocks and stock changes in the LFH and CWD pools.

Due to the incomplete knowledge of the origin of the high soil carbon stocks in Switzerland (Nussbaum et al. 2012, in review), they cannot be reproduced by models yet. Hence, only changes in soil C stocks were reported. 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 in the soil is very stable (e.g., Preston and Schmidt 2006), b) variability in measured changes due to methodological errors is large (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 0.7 Mg C ha^{-1}. This was less than the of 2.3 Mg C ha^{-1} reported by Hagedorn (2010). However, the correlation of the Yasso07 estimates with elevation was stronger, i.e. $r=0.36$ ($p=0$) 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. Improvements to the application in Switzerland that are planned include:

- Investigating the validity of the forthcoming new version of Yasso07 for application in Switzerland. The new model version and a new parameter set that are currently developed at the Finnish Environment Institute and Tampere University of Technology (http://www.syke.fi/en-US/Research__Development/Research_and_development_projects/Projects/Soil_carbon_model_Yasso/News) are expected to result in improvements to the Swiss Yasso07 implementation.

- Examining the suitability of Yasso07 for estimating CSC on lands converted to forests, where we can build 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 deadwood, 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.

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

- Active participation in the European task force on forest soil modeling with Yasso07, which includes experts from Austria, Finland, France, Switzerland and the European Joint Research Centre.
- National Research Programme project "Sustainable use of Soil as a Resource" by F. Hagedorn, WSL;
- "Deadwood pools and drivers in Swiss and European forests" by S. Herman., WSL;
- "Kernfäule" (heart rot) by J. Wunder, WSL; and
- "Carbon sources and sinks in agricultural soils" at the Agroscope Reckenholz-Tänikon Research Station (ART).

4 Conclusions

The methodology for estimating carbon stocks and carbon stock changes in deadwood, litter and soil for the Swiss GHGI has been further improved. Carbon stocks in deadwood and litter (LFH layer in the Swiss inventory) can now be estimated accurately within the limits of missing information on the contribution of the herb- and shrub layer. The carbon decomposition in deadwood and litter has been shown to be accurate (cf. Didion et al. 2014) and, thus, a high degree of confidence can be placed in the accuracy of the reported carbon stock changes in all pools.

The comprehensive analysis of uncertainties, which included uncertainty in the deadwood and litter inputs and in the model parameters, presented a further advancement. The uncertainties and variability in the C stock changes in soil, litter and deadwood were within reported error margins (e.g., Luyssaert et al. 2010).

Current limitations such as lack of data and source of the high soil C stocks are under investigation in ongoing and planned, respectively, research projects.

Acknowledgements

We are grateful to Nele Rogiers and Andreas Schellenberger at FOEN for valuable discussions and comments on this report. Jari Liski, Finnish Environment Institute and Aleksi Lehtonen, Finnish Forest Research Institute provided support with the implementation of Yasso07. We also appreciate the support of Massimiliano Zappa and Käthi Liechti, Mountain Hydrology and Mass Movements, WSL with the conversion of the climate data.

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Appendix I: Additional data

Table A-1. Initial values for the simulation of foliage and fine root litter and of deadwood 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
Deadwood	**Conifers**	0.675	0.0175	0.0025	0.305
	Broadleaves	0.715	0.015	0	0.27

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).

[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 6.4 in chapter 'Quantifying Uncertainties in Practice' in the IPCC (2000) report on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (avl. at: www.ipcc-nggip.iges.or.jp/public/gp/english/).

Table A-3. Maximum a posteriori (MAP) estimators and standard errors for the parameter set developed by Rantakari et al. (2012), which was used in the Yasso07 application for the Swiss GHGI 2014 (1990-2012).

Parameter	Parameter set			Unit	Interpretation
	P09	P11	P12		
αA	0.66 (±0.11)	0.72 (±0.09)	0.517 (±0.0004)	a-1	Decomposition rate of A
αW	$\mathbf{4.3^{+1.6}_{-1.0}}$	5.9 (±0.8)	3.552 (±0.003)	a-1	Decomposition rate of W
αE	0.35 (±0.08)	$\mathbf{0.28^{+0.07}_{-0.04}}$	0.346 (±0.0005)	a-1	Decomposition rate of E
αN	0.22 (±0.06)	$0.031^{+0.011}_{-0.004}$	0.266 (±0.0002)	a-1	Decomposition rate of N
ρ1	0.32 (±0.08)	0.48 (±0.06)	0.0449 (±0.0001)		Relative mass flow, W → A
ρ2	$\mathbf{0.01^{+0.14}_{-0.01}}$	$\mathbf{0.01^{+0.15}_{-0.01}}$	0.0029 (±0.00009)		Relative mass flow, E → A
ρ3	$\mathbf{0.93^{+0.03}_{-0.11}}$	$\mathbf{0.83^{+0.16}_{-0.23}}$	0.978 (±0.00006)		Relative mass flow, N → A
ρ4	$\mathbf{0.34^{+0.18}_{-0.15}}$	$\mathbf{0.99^{+0.01}_{-0.05}}$	0.637 (±0.0001)		Relative mass flow, A → W
ρ5	$\mathbf{0.00^{+0.07}_{-0.00}}$	$\mathbf{0.00^{+0.08}_{-0.00}}$	0.312 (±0.0002)		Relative mass flow, E → W
ρ6	$\mathbf{0.00^{+0.07}_{-0.00}}$	$\mathbf{0.01^{+0.2}_{-0.01}}$	0.0187 (±0.00003)		Relative mass flow, N → W
ρ7	$\mathbf{0.00^{+0.01}_{-0.00}}$	$\mathbf{0.00^{+0.01}_{-0.00}}$	0.0225 (±0.00002)		Relative mass flow, A → E
ρ8	$\mathbf{0.00^{+0.01}_{-0.00}}$	$\mathbf{0.00^{+0.01}_{-0.00}}$	0.0117 (±0.00006)		Relative mass flow, W → E
ρ9	$\mathbf{0.00^{+0.07}_{-0.01}}$	$\mathbf{0.02^{+0.23}_{-0.02}}$	0.001 (±0.00005)		Relative mass flow, N → E
ρ10	$\mathbf{0.00^{+0.01}_{-0.00}}$	$\mathbf{0.00^{+0.01}_{-0.00}}$	0.336 (±0.0002)		Relative mass flow, A → N
ρ11	$\mathbf{0.00^{+0.06}_{-0.00}}$	0.015 (±0.015)	0.042 (±0.00005)		Relative mass flow, W → N
ρ12	$\mathbf{0.92^{+0.04}_{-0.15}}$	$\mathbf{0.95^{+0.05}_{-0.16}}$	0.0899 (±0.0001)		Relative mass flow, E → N
β1	7.6 (±2.0)	9.5 (±2.0)	0.0895 (±0.00009)	10-2 °C-1	Temperature dependence
β2	-8.9 (±6.5)	$\mathbf{-1.4^{+0.6}_{-0.9}}$	-0.0023 (±0.000005)	10-4 °C-2	Temperature dependence
γ	-1.27 (±0.2)	-1.21 (±0.14)	-2.94 (±0.001)	m-1	Precipitation dependence
αH	$\mathbf{3.3^{+0.6}_{-0.7}}$	$\mathbf{1.6^{+0.3}_{-0.2}}$	0.24 (±0.001)	10-3 a-1	Humus decomposition rate
ρH	4 (±0.9)	0.45 (±0.08)	0.15 (±0.0002)	10-2	Mass flow to humus
φ1	NA	-1.71 (±0.16)	-0.539 (±0.0003)	cm-1	First order size dependence
φ2	NA	0.86 (±0.1)	1.186 (±0.0005)	cm-2	Second order size dependence
r	NA	-0.306 (±0.013)	-0.263 (±0.000002)		Size dependence power

Table A-4. 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 4a.

Elevation class	Production region										Switzerland	
	Jura		Plateau		Pre-Alps		Alps		Southern Alps			
	ha	± %	ha	± %	ha	± %	ha	± %	ha	± %	ha	± %
<601 m	52718.92	9	133226.3	5	6059.865	31	10396.56	23	20065.22	16	222466.9	4
601-1200 m	125621.2	4	91608.64	6	135066.7	4	100957.7	7	53490.88	9	506745.1	3
>1200 m	21976.44	16	2378.83	50	78063.02	7	260370.4	3	73343.08	7	436131.8	3
Total	200316.5	2	227213.8	1	219189.6	2	371724.7	2	146899.2	3	1165344	1

Appendix II: Data prepared for Switzerland's GHGI 2014 (1990-2012)

Table A-5. List of result tables that were included in the data delivery from 9.12.2013. The associated Excel file presents the relevant data based on averaged annual stocks and stock changes.

Table	Table name	Submitted table	Content
	Annual C stock change [Mg C $ha^{-1}a^{-1}$]	1a	Mean CWD pool stock change
		1b	Mean LFH pool stock change
		1c	Mean Soil pool stock change
		1d	Mean stock change for ALL pools
		1e	Standard error CWD pool stock change
		1f	Standard error LFH pool stock change
		1g	Standard error Soil pool stock change
		1h	Standard error stock change for ALL pools
	Annual absolute C stock change [Mg C a^{-1}]	2a	Mean CWD pool stock change
		2b	Mean LFH pool stock change
		2c	Mean Soil pool stock change
		2d	Mean stock change for ALL pools
		2e	Standard error CWD pool stock change
		2f	Standard error LFH pool stock change
		2g	Standard error Soil pool stock change
		2h	Standard error stock change for ALL pools
A-6	Average annual C stock change [Mg C $ha^{-1}a^{-1}$]	3a	Mean CWD pool stock change
A-7		3b	Mean LFH pool stock change
A-8		3c	Mean Soil pool stock change
A-9		3d	Mean stock change for ALL pools
A-10		3e	Standard error CWD pool stock change
A-11		3f	Standard error LFH pool stock change
A-12		3g	Standard error Soil pool stock change
A-13		3h	Standard error stock change for ALL pools
A-14	Average annual absolute C stock change [Mg C a^{-1}]	4a	Mean CWD pool stock change
A-15		4b	Mean LFH pool stock change
A-16		4c	Mean Soil pool stock change
A-17		4d	Mean stock change for ALL pools
A-18		4e	Standard error CWD pool stock change
A-19		4f	Standard error LFH pool stock change
A-20		4g	Standard error Soil pool stock change
A-21		4h	Standard error stock change for ALL pools
	Annual C stock [Mg C ha^{-1}]	5a	Mean CWD pool stock
		5b	Mean LFH pool stock
		5c	Standard error CWD pool stock
		5d	Standard error LFH pool stock
	Annual absolute C stock [Mg C]	6a	Mean CWD pool stock
		6b	Mean LFH pool stock
		6c	Standard error CWD pool stock
		6d	Standard error LFH pool stock
A-22	Average annual C stock [Mg C ha^{-1}]	7a	Mean CWD pool stock
A-23		7b	Mean LFH pool stock
A-24		7e	Standard error CWD pool stock
A-25		7f	Standard error LFH pool stock
A-26	Average annual absolute C stock [Mg C]	8a	Mean CWD pool stock
A-27		8b	Mean LFH pool stock
A-28		8e	Standard error CWD pool stock
A-29		8f	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 4 of 1,165,344 ha.
4) Negative values for CSC indicate a C sink, positive values a C source.