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Modeling soil carbon stock including dead wood and L, F, H-horizon using the models Massimo and Yasso07

Final Report

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1 Introduction

Forests cover a large proportion of the earth's land surface and they can act both as important sources or sinks of atmospheric carbon (Liski et al. 2006). The importance of forests as carbon pool has been recognized in the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. As a result, Parties to the Kyoto Protocol committed to account for all changes in forest carbon pools due to afforestations, deforestation (Art. 3.3.) and forest management (Art. 3.4; accounting on a voluntary basis) in their annual greenhouse gas inventory. These carbon pools are the above and below ground biomass, dead wood, litter and soil organic carbon. Carbon in living biomass is the largest pool and it is usually estimated on the basis of a vast amount of inventory data.

The amount of carbon in forest soils is also a significant carbon pool that is almost equal to the carbon stored in biomass (Perruchoud et al. 2000). However, readily available methods for estimating carbon change of the non-living organic matter pools are still lacking (Liski et al. 2006). Soil carbon changes are generally not measured in national forest inventories (Tomppo et al. 2010). Measuring the carbon changes of soils is particularly difficult, because the expected changes are one or two orders of magnitude smaller than spatial variability of carbon stocks at forest sites (Liski 1995; Liski et al. 1998; Tuomi et al. 2011a). Therefore models are often used to estimate soil carbon stocks and their changes (Peltoniemi et al. 2006; Peltoniemi et al. 2007; Mäkipää et al. 2008).

Based on the assumption that changes in forest conditions may also affect the carbon stock of forest soils, the Yasso model was developed to calculate the carbon stock and stock changes of forest soils from basic forest resource and climate information (Liski et al. 2005; Liski et al. 2003). Yasso and also the advanced version Yasso07 (Tuomi et al. 2009) consist of five chemical decomposition compartments. Each material input to a modeled site is subdivided into these decomposition compartments. Yasso and Yasso07 simulate decomposition processes within model compartments and material fluxes between those compartments. Both processes are driven by a set of parameters. Moreover, the model output of both models is a summary of organic carbon up to 1 m depth, including carbon from dead wood, L, F and H-horizon and soil organic carbon. Beside those similarities, Yasso and Yasso07 also feature important differences.

One difference concerns the parameterization of the models. To parameterize a model empirical data are required. However, soil organic carbon pools defined in a model and fluxes between those pools cannot easily be determined by measurements (Tuomi et al. 2009). Therefore it is a common practice to first define possible fluxes between model pools and then quantify the parameters determining the magnitude of these fluxes based on measurement data (Tuomi et al. 2009). This was the case when the model Yasso was developed. When designing Yasso07, the developers wanted to reduce the uncertainty arising from prefixed model fluxes and thus they assumed that all carbon fluxes between the decomposition compartments of the model were possible. No decision about the direction of carbon fluxes was taken beforehand. Fluxes and model parameters were determined directly from a global data set of litter mass loss experiments (Tuomi et al. 2009). Due to the difference in parameterization, the model Yasso07 and its parameters are not directly comparable with the previous model Yasso.

As Yasso07 model output summarizes organic carbon up to 1 m depth, including carbon from dead wood, L, F and H-horizon and soil organic carbon, the model results are not appropriate to be separated into dead wood, litter and soil organic carbon. In this report we therefore call the summation of soil organic carbon, L, F and H-horizon and dead wood *Yasso07-output*.

Up to now, there are two different parameter sets published for Yasso07. A global dataset of litterbag studies with predominately boreal and temperate sites was used to develop the parameters published in Tuomi et al. (2009) called P09 in this report. A second parameter set was published in 2011, which is also included in the graphical user interface of Yasso07 (Tuomi et al. 2011a) called P11 in this report. Both parameter sets have been applied in publications (Thum et al. 2011; Tuomi et al. 2011a). The main difference between the two parameter sets P09 and P11 is the parameterisation process. During the parameterisation of P11 the two different mesh sizes encountered in litter bag studies were taken into account differently than during the parameterisation for P09. Advantages and drawbacks of those two approaches are numerous and for further interest the reader is referred to Tuomi et al. (2011a). To establish the validity under Swiss climatic conditions, we applied both parameter sets and compared the simulated non woody litter mass loss with measured data from local litter bag studies (Frey 2010).

Soil carbon estimates are required for the present as well as for the near future since a potential change in forest management or climate may affect changes in soil carbon stock. To model soil carbon stock change for future years, future litter input and climate attributes are required. The IPCC has modeled a number of possible future climate scenarios (IPCC 2000), which have been downscaled for Switzerland. For this study we applied the scenarios A2 and B2. Future litter input can be modeled using the model Massimo (Kaufmann 2001). Massimo is a dynamic single tree model, which can estimate annual litter input information under different management scenarios. The semi-empirical model is based on NFI data from Switzerland and takes into account tree species, stand structure and some environmental attributes. Massimo was initially developed to assess the effect of forest management on future forest wood production. The model output is wood volume. Additional allometric functions and turnover rates have been added to estimate biomass and litter production based on diameter at breast height (DBH).

Combining climate scenarios from IPCC and litter scenarios from Massimo with the decomposition model Yasso07 allows estimating changes in soil carbon stocks including dead wood and L, F and H-horizon for the near future. In this report we present (1) a validation of model components to estimate soil carbon stock including dead wood and L, F and H-horizon (called Yasso07-output in this study), (2) estimates of Yasso07-output based on current scientific knowledge and a basic forest management scenario required for greenhouse gas accounting under UNFCCC and the Kyoto Protocol. (3) We assess to what degree forest management can affect the modeled Yasso07-output. (4) We investigate the effect of varying climate data on Yasso07-output. (5) We shortly discuss possibilities to differentiate soil organic carbon, dead wood and L, F and H-horizon in Yasso07 for greenhouse gas accounting under UNFCCC and the Kyoto Protocol. (5) We present an outlook of planed research for the improvement of the estimation of soil carbon stock, dead wood and L, F and H-horizon changes in the Swiss Greenhouse Gas Inventory.

2 Material and Methods

The model Yasso07 requires basic climate information and information about litter input quantity and quality. Based on a constant litter input quantity and average climate values Yasso07 generates equilibrium values for different soil carbon fractions per site. This first step is called spin-up phase. The equilibrium values are usually reached after 10 000 years.

In the so-called simulation phase, the actual as well as prospective soil carbon stocks (including dead wood and L, F and H-horizon) are then calculated based on the initial equilibrium values from the spin-up phase together with the actual measured or predicted yearly litter and climate input values.

The input information used for this project is described in separate sections: section 2.1 climate data, section 2.2 litter type and quantity, and section 2.3 Yasso07 specific chemical fractions of litter and initial state of the soil.

2.1 Climate data

Climate information was required for the spin-up phase (10 000 years) and the simulation phase (1956 to 2055). Climate data from the Federal office of meteorology and climatology of Switzerland (MeteoSwiss) were used to calculate climate variables at a spatial resolution of 100 m. Therefore daily values of MeteoSwiss weather stations were interpolated using the *daymet software* from Thornton et al. (1997). The annual temperature was calculated from mean monthly temperature data and annual rainfall from the sum of monthly rainfall data. The temperature amplitude was calculated as half of the difference between the highest and lowest means of monthly temperature data per year.

2.1.1 Spin-up phase

For the spin-up phase (10 000 years) the climate information was taken from the mean annual temperature and rainfall of the period 1960 to 1990 from the surface data calculated with *daymet* (see Table 1).

Table 1 Climate input data for model spin-up. Annual average temperature, annual precipitation sum and annual temperature amplitude for 4726 NFI 3 sample plots, as measured between 1960 to 1990, stratified by NFI production region.

Production region	Annual av. temperature (°C)	stdev	Annual precipitation (mm)	stdev	Annual temp. amplitude (°C)	stdev
Jura	6.94	1.41	1334	241	8.5	0.42
Plateau	8.19	0.79	1178	158	9.0	0.25
Pre-Alps	5.85	1.45	1717	295	8.5	0.35
Alps	4.40	2.08	1305	350	8.5	0.45
S. Alps	6.42	2.79	1833	226	8.7	0.39

2.1.2 Simulation phase

For the first part of the simulation phase (the period from 1956 to 2000) again the meteorological surface data calculated with *daymet* were used. For each year the mean annual temperature, rainfall and temperature amplitude were taken as input information. For the second simulation phase (the period from 2001 to 2055) IPCC climate scenarios were used. The projected climate data for Switzerland were calculated from anomalies of CRU (Climatic Research Unit, UK, http://www.cru.uea.ac.uk/) data and the output data from *daymet*. Thereby the CRU data that are based on the Hadley model (HadCM3) were used. The monthly means of the years 1961 to 1990 served as reference data. Two scenarios were included in the Yasso07 modeling: IPCC emission scenario A2 and B2 (IPCC 2000).

The main difference between these two IPCC scenarios is the expected development of future anthropogenic greenhouse gas emissions (see Fig. 1, IPCC 2000). While the A2 scenario is based on the assumption of a steady increase of anthropogenic greenhouse gas emissions, the B2 scenario assumes that the global anthropogenic greenhouse gas emissions increase continuously until a peak is reached around the year 2050. After this peak, a sustained decline of the greenhouse gas emission is expected. The A2 scenario forecasts a temperature increase of 2 to 5.4° C until the year 2100, whereas the B2 Scenario forecasts a temperature increase of 1.4 and 3.8° C for the same period. Detailed information about the different „families“ of climate scenarios is listed in the IPCC special report – „Emission Scenarios“ (IPCC 2000). The average values of the predicted climate attributes for the 4726 National Forest Inventory (NFI) sample plots over time according to the scenarios A2 and B2 are shown in Table 2.

Due to considerable inter annual fluctuations in climate we used a five year running mean of the climate attributes as the default in the simulation process. To explore the effect of different approaches to the averaging of the climate data, we also run simulations based on not averaged inputs and for 3 and 10 year running means. If not noted otherwise, the presented results refer to simulations with climate data based on the default running mean of 5 years.

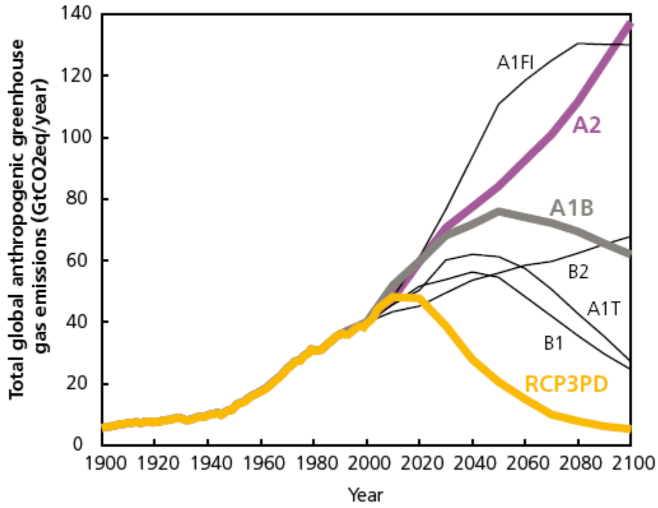


Figure 1 Green house gas emissions for different IPCC scenarios from 1990 to 2100. In this Study scenario A2 and B2 are used. One CO_2-equivalent (CO_2-eq) is a reference unit, with which other green house gases are indicated as a CO_2-measurement unit as well (IPCC 2000).

Table 2. Average decadal temperature, annual precipitation and annual temperature amplitude over all 4726 NFI sample plots for 2 climate scenarios A2 and B2.

Period	Average annual temperature (°C)	Sum annual rainfall (mm)	Annual temperature amplitude (°C)	Average annual temperature (°C)	Sum annual rainfall (mm)	Annual temperature amplitude (°C)
1956-65	6.40	1352	9.85	6.40	1352	9.85
1966-75	6.39	1367	9.13	6.39	1367	9.13
1976-85	6.26	1456	9.56	6.26	1456	9.56
1986-95	6.98	1352	9.47	6.98	1352	9.47
	Climate scenario A2			*Climate scenario B2*		
1996-05	7.09	1422	9.60	7.07	1422	9.62
2006-15	7.39	1385	9.28	7.38	1386	9.32
2016-25	7.68	1440	9.05	7.72	1441	9.13
2026-35	8.01	1507	10.06	8.01	1509	10.16
2036-45	8.06	1413	10.17	8.06	1414	10.25
2046-55	9.06	1373	10.03	9.06	1373	10.09

2.2 Litter type and quantity (NFI data, Massimo simulations)

Site specific litter input information for the years 1986-2005 are estimated based on NFI data (Brändli 2010), litter input information for the years 2006-2055 are based on Massimo simulations.

Both NFI and Massimo data report wood volume as major attribute. Allometric functions are applied to estimate the amount of annual litter based on standing volume, cut and mortality data (Kaufmann 2001, Thürig et al. 2005, Perruchoud et al. 1999, Wirth et al. 2004, Wutzler et al. 2008, Rohmeder

1972). The allometric functions and additional assumptions to estimate litter input per site from wood volume over bark are listed in Table 3. The carbon concentration and density of litter are required to convert volume of litter into carbon contained in litter. A carbon concentration of 50% was assumed for all litter types (IPCC 2003). Values of wood density of living trees published in Assmann (1961) were used to estimate carbon content for each woody litter fraction.

Table 3 Allometric functions and assumptions[1] to estimate litter input per site (CT=coniferous trees, DT=deciduous trees).

Tree part	Biomass-Volume (m^3)	Biomass Mass (kg)	Source	Turnover time (years)	Source
Wood vol. over bark	Function		Kaufmann, 2001	% Biom.	NFI12
Coarse branches (DT)	Function		Kaufmann, 2001		NFI12
Small branches	Function		Kaufmann, 2001	25	(Kaufmann pers. comm.)
Leaves/needles		Function	Perruchoud et al 1999	1 DT 3 Pinus 7 Picea 10 Abies	(Kaufmann pers. comm.) (Kaufmann pers. comm.) (Kaufmann pers. comm.) (Kaufmann pers. comm.)
Coarse roots		CT: function DT: function	Wirth et al 2005 Wutzler et al 2008		NFI12
Fine roots		5% of coarse roots	Perruchoud et al 1999	1.36	Perruchoud et al 1999
Fruits		Function (dbh, region)	Rohmeder, 1972	1	(Kaufmann pers. comm.)

[1]Conversion: Volume to weight (Wood density according to Assmann, 1961)
Conversion: Weight to carbon (constant conversion factor = 0.5, IPCC, 2003)

Four different management scenarios (Table 4) have been simulated with the help of the model Massimo (Kaufmann 2001). Table 5 shows wood volume, cut and mortality as measured in NFI1- NFI3 and further simulated by Massimo in Scenario 400 (steady harvest). The resulting estimates of litter input for the period 1986 - 2055 are given in Table 6. The impact of a change in forest management on litter quantity and litter fractions were modeled using Massimo. Current forest management, as deduced from NFI 2-3 measurements, is represented by scenario 400 (steady harvest). Three additional forest management scenarios were modeled representing lower and higher harvest intensities compared to scenario 400. For the Swiss Forest Management Reference Level (FMRL; used for net-net accounting in the second commitment period), scenario 425 is taken as the business as usual harvesting scenario.

Table 4 Forest management scenarios used in Massimo to simulate litter input to soils.

Number of scenario	Name of scenario	Definition of scenario
400	steady harvest (baseline)	Harvest volume (stemwood over bark): 6.7 m3 * ha^{-1}*y^{-1}
411	steady living biomass	Mean increase of 11%
485	reduced harvest	Harvest reduction compared to Sc. 400: 2006-2015: -10% 2016-2055: -30%
425	increased harvest	Harvest increase compared to Sc. 400: 2006-2015: +15%

	2016-2055: +30%

Table 5 Forest management affected attributes cut (i.e. harvest) and mortality as measured in the NFI 1, 2, 3 (1985-2005; Massimo baseline information) and as simulated in the Massimo baseline scenario 400: 2006-2035 (data units in stem wood over bark).

Data source	Year	Volume $m^3\ ha^{-1}$	Volume m^3/tree	Cut $m^3 ha^{-1} y^{-1}$	Mortality $m^3 ha^{-1} y^{-1}$	Cut+ Mortality $m^3 ha^{-1} y^{-1}$
NFI 1	1985	337	0.78			
				5.7	1.0	6.7
NFI 2	1995	352	0.84			
				6.5	1.8	8.3
NFI 3	2005	361	0.89			
				6.6[1]	1.3	7.9
Base sc.	2015	365	0.81			
				6.7[1]	1.3	8.0
Base sc.	2025	378	0.82			
				6.6[1]	1.4	8.0
Base sc.	2035	393	0.82			

[1] Due to model intrinsic single-tree implementation of harvesting scenarios, the modeled amount of cut varies slightly.

The litter input for the Yasso07 simulation is calculated based on estimates for the following 6 pools with distinct litter fractions:

a. Non-woody litter above ground (**nwlo**): foliage, needles, fruits
b. Non-woody litter below below ground (**nwlu**): fine roots
c. Fine woody litter (**fwl**): twigs with diameter < 7cm and bark
d. coarse woody litter small below ground (**cwlsu**): coarse roots
e. coarse woody litter small above ground (**cwlso**): branches with diameter > 7cm
   stem wood with diameter < 20 cm
f. coarse woody litter large (**cwll**): stem wood with diameter > 20 cm

As the current implementation of Yasso07 does not distinguish between above- and belowground pools, inputs for the model consist of non-woody litter (i.e., sum of a and b), fine woody litter, and coarse woody litter (sum of d, e and f).

Table 6 shows the estimated amount of litter per year in those categories. The litter input per year for each estimated litter fraction for scenario 400 (steady harvest) in the period 2006-2015 is given in Figure 2.

Table 6 Estimated average amount of litter for NFI 1-2 (1986-1995), NFI 2-3 (1996-2005) and for the Massimo scenarios 400 (steady harvest), 411 (steady living biomass), 485 (reduced harvest) and 425 (increased harvest) for the period 2006-2055.

data	period	nwlo	nwlu	fwl	cwlso	cwlsu	cwll	**sum**
					(t C ha^{-1} $year^{-1}$)			
NFI 1-2	1986-95	1.80	1.13	0.49	0.02	0.45	0.13	4.02
NFI 2-3	1996-05	1.96	1.25	0.53	0.03	0.55	0.23	4.54
Sc.400	2006-15	1.94	1.25	0.50	0.03	0.68	0.22	4.63
	2016-25	2.00	1.31	0.51	0.03	0.73	0.19	4.77
	2026-35	2.07	1.35	0.52	0.04	0.71	0.19	4.89
	2036-45	2.14	1.40	0.53	0.05	0.72	0.21	5.05
	2046-55	2.21	1.44	0.54	0.05	0.74	0.23	5.22
Sc.411	2006-15	1.93	1.24	0.50	0.03	0.77	0.22	4.68
	2016-25	1.94	1.25	0.49	0.03	0.83	0.18	4.71
	2026-35	1.94	1.24	0.48	0.03	0.80	0.17	4.68
	2036-45	1.96	1.24	0.48	0.04	0.82	0.19	4.72
	2046-55	1.97	1.23	0.48	0.04	0.79	0.20	4.72
Sc.425	2006-15	1.93	1.24	0.50	0.03	0.77	0.22	4.68
	2016-25	1.94	1.24	0.48	0.03	0.89	0.18	4.76
	2026-35	1.91	1.21	0.47	0.03	0.84	0.18	4.64
	2036-45	1.90	1.18	0.46	0.04	0.85	0.18	4.62
	2046-55	1.88	1.15	0.45	0.04	0.87	0.20	4.59
Sc.485	2006-15	1.95	1.26	0.51	0.03	0.62	0.22	4.59
	2016-25	2.04	1.35	0.53	0.04	0.61	0.19	4.75
	2026-35	2.17	1.45	0.55	0.04	0.62	0.21	5.06
	2036-45	2.29	1.53	0.57	0.05	0.75	0.24	5.42
	2046-55	2.37	1.60	0.59	0.06	0.61	0.27	5.48

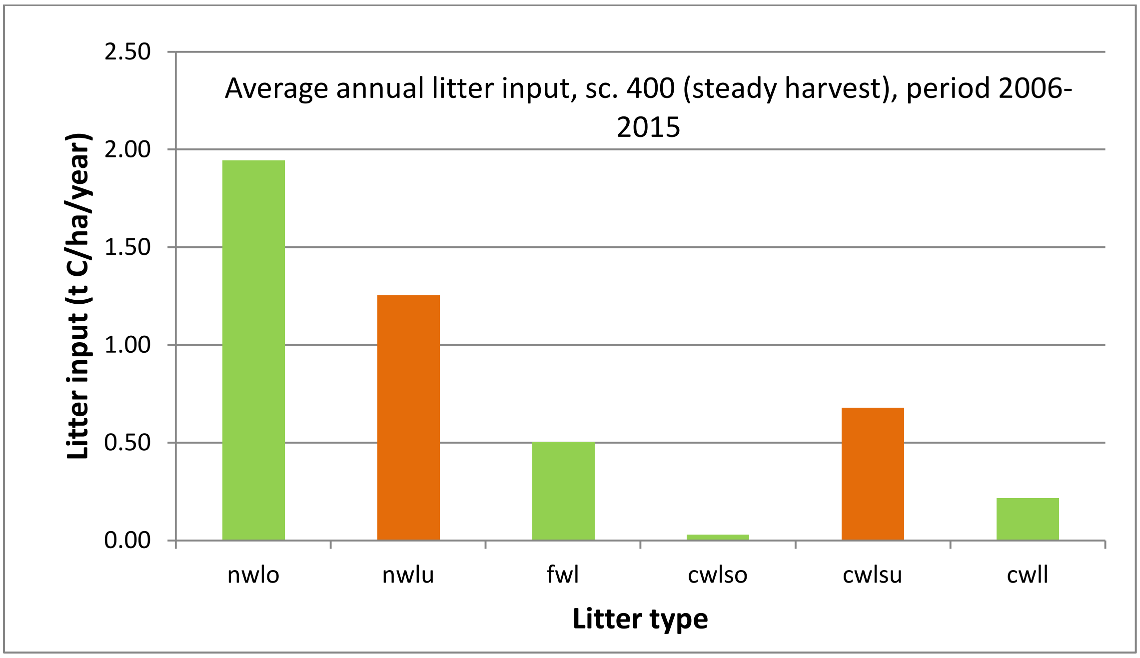


Figure 2 Estimated amount of litter input of scenario 400 (steady harvest) in the period 2006-2015.

2.3 Yasso07 specific input information

2.3.1 Parameter set

Unless noted otherwise, we have used the Yasso07 parameter set as published by Tuomi et al (2009) in combination with parameters for wood decomposition as published in Tuomi et al (2011b). In this report we will call this combined parameter set P09 (Table 7). The parameter set published by Tuomi et al (2011a), here called P11, is listed in Table 7. Reasons for using P09 in our calculations are outlined in the sections Results and Discussion.

Table 7 Yasso07 parameter set P09, as published by Tuomi et al (2009) (P09) for non woody debris and Tuomi et al (2011b) for woody debris(*), was used for this study. For comparison, also the Yasso07 parameter set P11 as published by Tuomi et al (2011a) is shown.

	P09	P11	Interpretation
Alpha A	0.66	-0.72	Decomposition rate
Alpha W	4.3	-5.90	Decomposition rate
Alpha E	0.35	-0.28	Decomposition rate
Alpha N	0.22	-0.031	Decomposition rate
P1	0.32	0.48	
P2	0.01	0.01	
P3	0.93	0.83	
P4	0.34	0.99	
P5	0.00	0.00	
P6	0.00	0.01	
P7	0.00	0.00	
P8	0.00	0.00	
P9	0.01	0.02	
P10	0.00	0.00	
P11	0.00	0.015	
P12	0.92	0.95	
Betta 1	0.076	0.095	Temperature dependance
Betta 2	-0.00089	-0.0014	Temperature dependance
Gamma	-1.27	-1.21	Precipitation dependance
p_H	0.04	0.0045	Mass flow to H
Alpha H	0.0033	-0.0016	H decomposition rate
Tetta 1*	-1.71	-1.71	Size, first order
Tetta 2*	0.86	0.86	Size, sec. order
r*	-0.306	-0.306	Size dep.power

2.3.2 Model initialization

For the spin-up phase the litter input estimates of the period NFI 1-2 for each NFI sample plot were used as base values (termed NFI12). To minimize the bias introduced by short term events such as harvesting, plot values have been calculated as moving averages (average of a surrounding area of 20 km*20 km for each plot, termed NFI12_20).

Climate data for the spin-up phase are described in section 2.1.1.

2.3.3 Litter quality

The model Yasso07 contains five decomposition compartments representing four different chemical fractions plus the humus fraction. Each litter type entering the system has to be divided into four chemical fractions differing in solubility to acid, water, and ethanol. The solubility is measured by a sequential extraction procedure as described in Berg et al. (1982). The chemical fractions of each litter type are therefore a) acid soluble (A), b) water soluble (W) c) ethanol soluble (E), d) non soluble

(N) and e) humus (H). The humus fraction is set to zero for litter input. Those chemical AWEN fractions need to be determined for each litter type.

The AWEN fractions of non woody litter from local tree species, grown at five sites in Switzerland have been analyzed by Frey (2010). Results from this study are used for AWEN fractions of needles, leaves and fine roots from *P. abies* and *F. Sylvatica* (Table 8). The AWEN fractions of branches or stems of locally grown species were not available. Therefore we used the AWEN fractions as listed on the Yasso07 website (SYKE 2011). For *F. sylvatica* stem litter, the AWEN fractions of *B. pendula* were used. For *P. abies* stem litter, the chemical fractions of two independent studies are provided on the Yasso07 website. For *P. abies* and *F. sylvatica* fwl the AWEN fractions from *P. sylvestris* branches were used as input values. Since the AWEN fractions from litter from local tree species other than *P. abies* and *F. sylvatica* were not listed on the Yasso07 website, we used the AWEN fractions from *P. abies* for coniferous and those of *F. sylvatica* for deciduous tree litter. A summary of chemical fractions used in the Yasso07 simulations are listed in Table 8.

The mean diameter of each woody litter fraction has to be provided as input information for Yasso07. The mean diameter for fine woody litter (fwl) was set to be 5 cm and the mean diameter of coarse woody litter (cwl) was set to be 20 cm (Table 8). These diameters are based on observed diameter distributions from woody debris measured with the line intersect method LIS (NFI 3) and coarse woody debris measured with the standard method at the NFI 3 sites (data not shown).

Table 8 Chemical fractions in percent of different litter types and mean diameter of woody litter types, used for modeling in Yasso07. Abreviations used: acid soluble (A), water soluble (W), ethanol soluble (E) and non soluble (N), non woody litter (nwl), fine woody litter (fwl), coarse woody litter (cwl).

Litter type[1]	*Chemical fraction (%)*				*Dia-meter (cm)*	*Source*	*Tree Species applied*[3]
	A	*W*	*E*	*N*			
Foliage,f.R. (nwl) *P. abies*	42.8	19.1	9.6	26.0	0	Frey 2010	C
Foliage,f.R. (nwl) *F. sylvatica*	45.8	9.6	4.9	37.7	0	Frey 2010	D
Branches (fwl) *P. sylvestris*	46.3	1.9	7.8	43.0	5	Manual[2]	C,D
Stem (cwl) *P. abies*	66.5	1.5	0.3	30.5	20	Manual	C
Stem (cwl) *B. pendula*	71.5	1.5	0.0	27.0	20	Manual	D

[1]f.R = fine roots

[2] Chemical composition of litter types, as provided in the Yasso07-UI Manual on the webpage (http://www.ymparisto.fi/default.asp?node=21594&lan=en.

[3] Input information used for tree species: coniferous trees (C), deciduous trees (D).

2.3.4 Litter data used – quantity

For the simulation phase (1956-2055), we used spatially averaged data from NFI 1 and 2 measurements (NFI12_20), measured plot specific data from NFI 1 and 2 (NFI12) and NFI 2 and 3 (NFI23), respectively, and simulated data from Massimo (MA). The spatially averaged NFI12_20 data were used from 1956 to 1985, NFI12 data from 1986-1995, NFI23 data from 1996 to 2005, MA from 2006-2055. An overview of litter and climate input information used in Yasso07 is provided in Table 9.

Table 9 Litter and climate information used in the different phases of Yasso07 simulation. NFI12_20 data refers to spatially averaged data from NFI12; NFI12, NFI23 and MA (data from the Massimo model) refer to plot specific data. Starting in 1956. 5 year mean of climate data were used.

Year	Mode	Litter information	Climate information
10 000 years	Spin up	NFI12_20	Annual mean of period 1960-1990
1956-1965	Simulation	NFI12_20	
1966-1975		NFI12_20	Annual data
1976-1985		NFI12_20	Annual data
1986-1995		NFI12	Annual data
1996-1999		NFI23	Annual data
2000-2005		NFI23	Annual data, sc. A2, B2
2006-2015	Simulation	MA	Annual data, sc. A2, B2
2016-2025		MA	Annual data, sc. A2, B2
2026-2035		MA	Annual data, sc. A2, B2
2036-2045		MA	Annual data, sc. A2, B2
2046-2055		MA	Annual data, sc. A2, B2

3 Results

In the excel file *CarbChange100year_400_27_04_12.xlsx* time series of average Yasso07-output (soil organic carbon including dead wood and L, F and H-horizon) for Switzerland are given for the years 1956 to 2055 for different scenarios.

3.1 Validation of Yasso07

In October 2011, an international Audit with Experts was organized by WSL and BAFU to present and discuss results of Yasso07 validations in Switzerland. The presented slides (Audit_WSL_4_10_11.pdf) and the protocol of the discussion approved by the international attendees (Protocol_Audit_WSL_04_10_11_approved.pdf) build an integral part of this final report. Additionally, we present the validation of different Yasso07 parameter sets, the comparison with measured soil carbon values and a review of different fine root turnover rates. A scientific publication of all validation results including the validation of litter estimation is in preparation and will be handed in after submission of this report in Autumn 2012.

3.1.1 Validation of decomposition parameters

We compared the measured litter mass loss after 5 years (Frey 2010) with Yasso07 modeled litter mass loss (Table 10, Figures 3, 4, and 5) for 5 sites. For the simulation phase, we used P09 and P11 in independent runs. Litter input was the amount of litter placed in a litter bag. Site specific climate data, averaged for the period 1960-1990 from the *daymet* data set were used in the simulation.

Modeled mass loss of litter after 5 years using Yasso07-P09 (see section 2.1) was quite similar to measured values at 4 out of 5 sites (Table 10). Modeled and measured mass loss agreed well for all litter types irrespective of species, although litter mass loss from *F. sylvatica* was slightly overestimated by Yasso07. At the site Schänis, modeled and measured values did not agree. However, this is most likely due to a measurement artefact at this site (Frey, pers. comm.): fine clay particles may have contaminated the litter sample.

The Yasso07 modeled litter mass loss using P11 was considerably lower than modeled mass loss using P09 (Table 10) and also lower than measured values.

Table 10 Percentage of litter mass still present after 5 years of field exposure as estimated by Yasso07 and as measured in litter bag studies at five sites in Switzerland. Yasso07 was used with the parameter set as published by Tuomi et al (2009) (P09) or Tuomi et al (2011) (P11). The percentage of mass remaining after 5 years was calculated as 100% minus the percentage of mass decomposed within 5 years.

Site	Species	Litter type	Frey 2010	Yasso07 P09	Yasso07 P11
			Percentage of mass remaining after 5 years		
Beatenberg	*Picea abies*	f.roots, needles	19.5	21	40.2
Vordemwald	*Picea abies*	f.roots, needles	15.5	17	37.4
Bettlachstock	*F. sylvatica*	f.roots, leaves	25.0	21	44.7
Schänis	*F.sylvatica*	f.roots, leaves	27.0[1]	17	40.4
Novaggio	*C. sativa*	f.roots, leaves	16.0	15	37.3

[1] Litter bag samples may have been contaminated with fine clay particles.

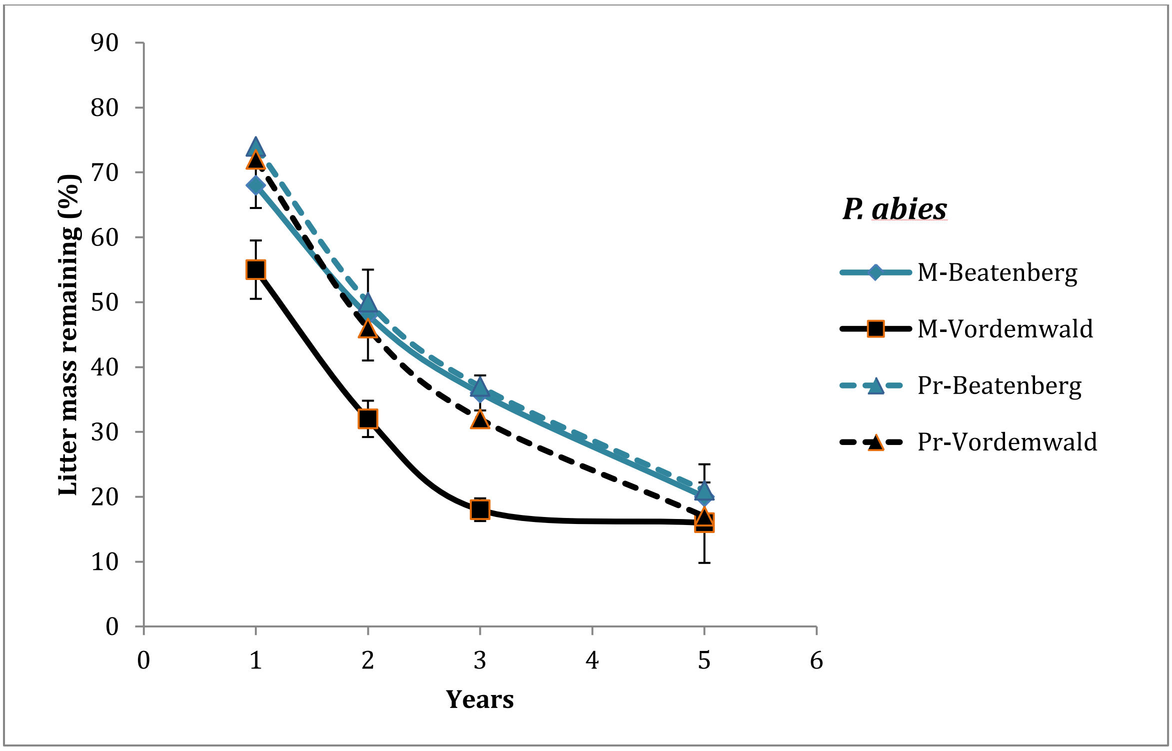


Figure 3 Litter mass remaining after five years for *Picea abies* litter (fine roots and needles) at two sites as measured in a litter bag study (Frey 2010: prefix M —) and as modeled (Yasso07-P09: prefix Pr - - -).

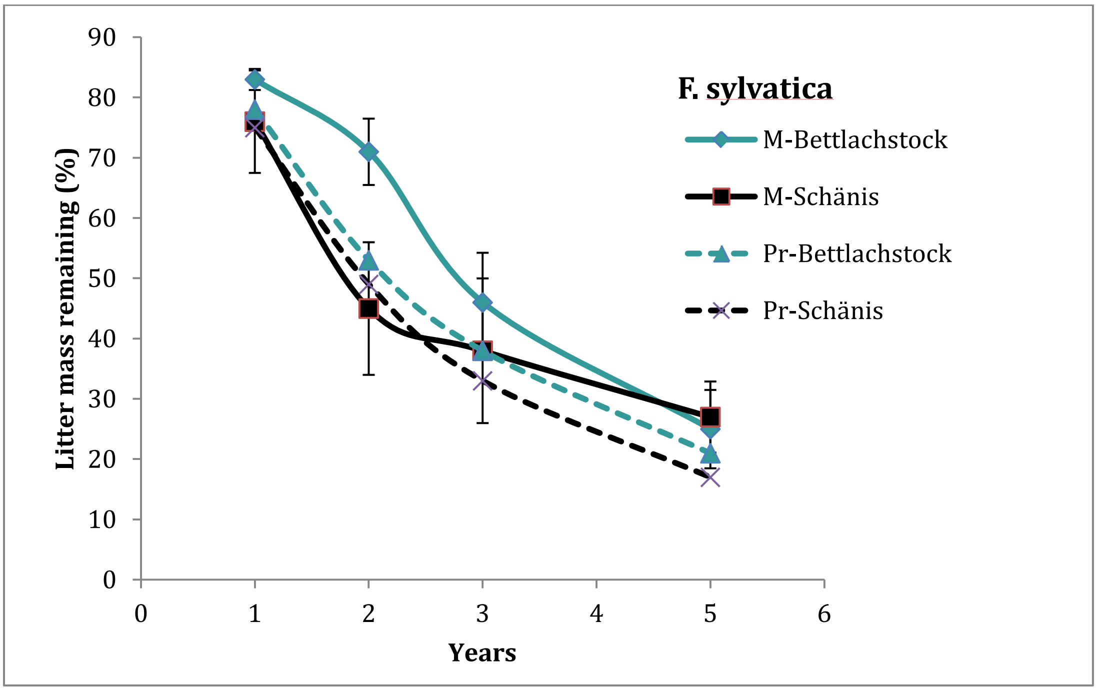


Figure 4 Litter mass remaining after five years for *Fagus sylvatica* litter (fine roots and leaves) at two sites as measured in a litter bag study (Frey 2010: M —) and as modeled (Yasso07-P09: prefix Pr - - -).

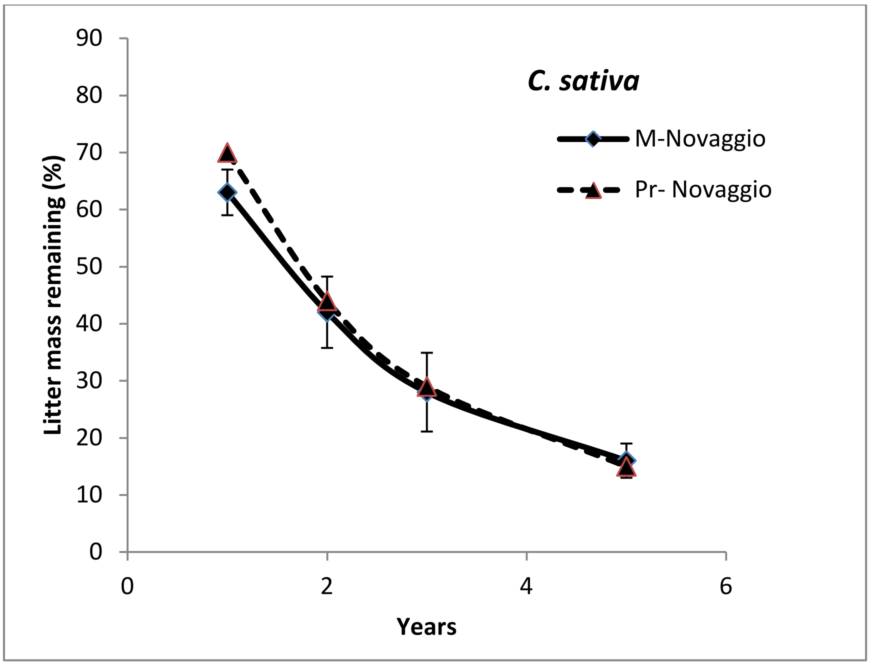


Figure 5 Litter mass remaining after five years for *Castanea sativa* litter (fine roots and leaves) at one sites, as measured in a litter bag study (Frey 2010: M —) and as modeled (Yasso07-P09: prefix Pr - - -).

3.1.2 Comparison with measured soil carbon values

Average estimated Yasso07-output, stratified by production region, for the years 1986, 1996 and 2006 and measured soil carbon stock values from 167 NFI sites (subset of NFI sample plots) are listed in Table 11. Those soil C measurements origin from the 8 km x 8 km grid of the *Waldzustandsinventar* from Lüscher et al. (1994). Yasso07-output is generally lower than measured soil carbon stock values. This is particularly the case for sites in the Jura and to a lesser degree for sites in the Alps. Yasso07-output and measured values agree best in the Plateau region, whereas estimates for Southern Alpine sites are not in agreement with measured values.

Table 11 Yasso07_P09 estimated soil carbon stock including deadwood and L, F and H -horizon for the years 1986, 1996 and 2006 (Massimo sc. 400; climate scenario A2 averaged over 5 years).

Production region	*Average Yasso07-output ($t\ C\ ha^{-1}$)*			
	1986	*1996*	*2006*	*Measured*[1]
Jura	80.72	80.2	82.00	144
Plateau	93.02	91.3	91.75	86
Pre Alps	96.71	96.4	98.33	135
Alps	99.47	99.2	100.46	147
S. Alps	57.30	57.6	59.2	198
Switzerland	89.22	88.64	90.00	141
Without S. Alps	93.73	93.07	94.40	113

[1]Average measured soil carbon content from 167 NFI sites (Soil database, Soil Science Unit)

3.1.3 Comparison of different fine-root turnover rates

Fine root longevity, or the inverse of it the fine root turnover rate, is an important factor that determines fine root litter input, the second biggest source of litter after leave litter input to most sites. Fine root longevity has been under discussion recently and is still the centre of ongoing research since measuring it is complicated and includes many obstacles.

A number of methods were developed over the years to determine fine root longevity such as the indirect calculation method using the ratio between standing biomass and annual production, minirhizotrons measurements and more recently the stable or labile C isotope measurement (^{14}C, ^{13}C). In essence all the various methods yield estimates for fine root longevity that can differ significantly by the applied method: Estimates range from a few months (minirhizotron methods; Trumbore and Gaudinski 2003) to 1-3 years (indirect method of biomass/fine root production; Trumbore and Gaudinski 2003) up to 4-11 years (radiocarbon method (^{14}C); Trumbore et al. 2006). A recent study used three methods in combination to estimate fine root lifespan and they suggested the fine root lifespan to be 3 years (Gaudinski et al 2010).

The oldest method is the indirect calculation method (standing biomass/annual production) and thus it has been applied numerous times. However, even within this framework different methods of estimation exist. For example, the annual production of fine roots can be measured using in growth cores or root nets. Alternatively fine root production can be measured using sequential coring over a period of at least a year. Furthermore, several methods exist to calculate the fine root production from the measured change in fine root biomass and necromass, such as Maximum-Minimum formula, Decision Matrix, Compartment flow method (Brunner et al. pers. comm. 2011)

So far most published estimates for fine root life span for *P. abies* and *F. sylvatica* were conducted using the indirect calculation method (standing biomass/annual production) measuring fine root growth and using the Decision matrix formula to estimate fine root production (Brunner et al. pers. comm. 2011). Since this is an accepted method with a reasonable data base these estimates for fine root lifespan were deemed to be acceptable for the modeling process. The suggested values for fine root life span for *P. abies* and *F. sylvatica* of 1.16 and 1.16 years (Brunner et al. pers. comm. 2011) were quite close to the previous estimate of 1.36 years (Perruchoud et al 1999) (Table 12).

Table 12 Different estimates of fine root lifespan and fine root turnover and method of determination.

Fine root life span (year)	Fine root turnover ($year^{-1}$)	Source	Year	Method of analysis
4-11	0.25-0.09	Trumbore et al.	2006	^{14}C
3	0.33	Gaudinski et al.	2010	Isotopes, minirhizotrons, radix model
1.36	0.74	Perruchoud et al.	1999	
1.16	0.87	Brunner et al. *(P. abies)*	2011	sequ.coring, ingrowth cores
1.16	0.86	Brunner et al. *(F. sylv.)*	2011	sequ.coring, ingrowth cores
1.43	0.70	Hickler et al.	2008	

3.2 Comparison of forest management scenarios

The four forest management scenarios modeled for all NFI sample plots are driven by different forest management regimes. The effects of forest management on Yasso07-output are shown in Figure 6, those on the change of Yasso07-output in Table 13. Negative values refer to a decrease in carbon stocks (source) whereas positive values refer to an increase in carbon stocks (sink).

It can be seen in Table 13 that estimated change of Yasso07-output is a source of C (-50 kg C ha^{-1} $year^{-1}$) during the period NFI12 (1986-1995) and a sink of C (117.4 kg C ha^{-1} $year^{-1}$) for the period NFI23 (1996-2005). The fluctuations in the subsequent periods are considerable. Most values indicate an increase of C with only a few exceptions in the scenarios 411 (steady living biomass) and 425 (increased harvest). Under all four forest management scenarios, there is a strong increase in Yasso07-output in the period 1996 to 2005 (NFI23, storm activity) and in the scenarios 400 (steady harvest) and 485 (reduced harvest) also a relatively strong increase in the period 2036-2045. In these two scenarios, the carbon stock is continuously increasing (Figure 6). The value of the period 1996-2005 (NFI23) is considerable higher than values of the subsequent periods, especially for the scenarios 411 and 425 . The differences between all scenarios become evident, when averages of the whole time period 1986-2055 are considered: The values range from -3.2 kg C ha^{-1} $year^{-1}$ in scenario 425 (increased harvest) to 51.0 kg C ha^{-1} $year^{-1}$ in scenario 485 (reduced harvest) for the period 1986-2055.

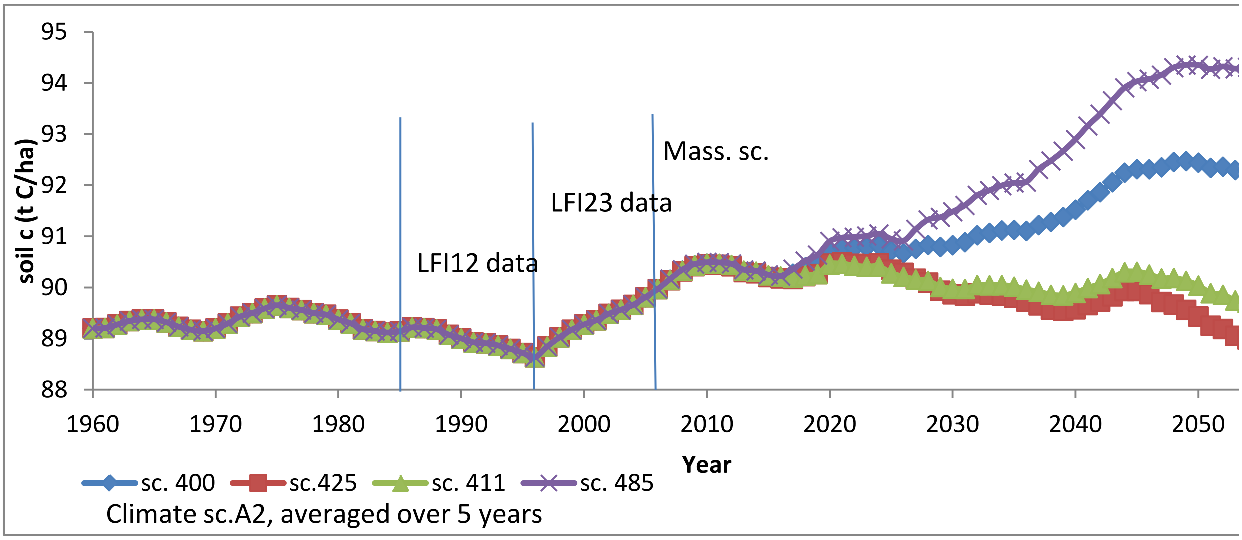


Figure 6 Yasso07_P09 estimated soil carbon stock including deadwood and L, F and H-horizon for four different forest management scenarios, using IPCC climate scenario A2. (Climate data averaged over 5 years).

Table 13 Change of Yasso07_P09 estimated soil carbon stock including deadwood and L, F and H-horizon over different time frames under two climate scenarios (A2 and B2) and four different forest management scenarios, using 5-year averages of annual climate data. Climate scenarios B2 is only calculated for management scenario 400. The stock change is estimated by the Yasso07 model output based on the P09 parameterization. Negative values refer to a decrease in carbon stocks whereas positive values refer to an increase in carbon stocks.

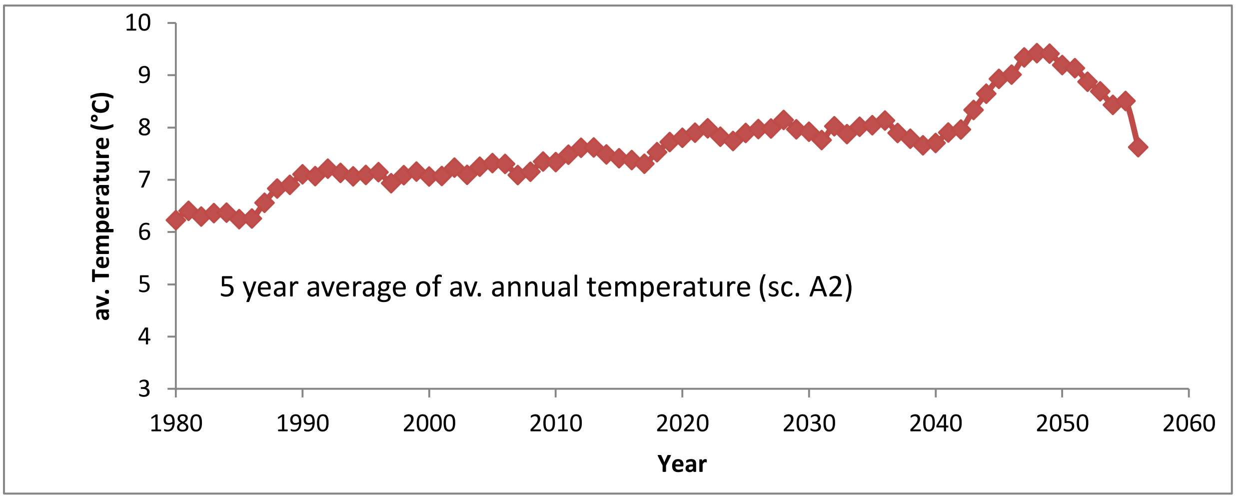
		Annual change of Yasso07-output[1] (kg C ha^{-1} $year^{-1}$)			
Period of Years	**Climate B2**	**Climate A2**			
start - end	Sc. 400	Sc.400	Sc.411	Sc.425	Sc.485
1986 - 1995	-50.0	-50.0	-50.0	-50.0	-50.0
1996 - 2005	120.0	117.4	117.4	117.4	117.4
2006 - 2015	22.7	24.6	26.9	23.5	27.8
2016 - 2025	48.9	52.7	6.1	16.8	72.8
2026 - 2035	45.9	45.7	-19.3	-48.8	113.4
2036 - 2045	121.0	120.8	34.9	20.5	196.6
2046 - 2055	-1.7	-2.7	-61.0	-96.9	24.8
1986 -2055	30.5	30.7	4.2	-3.2	51.0
1996 -2055	40.3	40.5	11.2	2.9	63.2
2008 -2012	19.6	20.1	23.2	20.0	22.6
2013-2020	42.7	51.2	15.0	20.5	69.5

[1] Yasso07 estimate of soil carbon including dead wood and L, F and H-horizon.

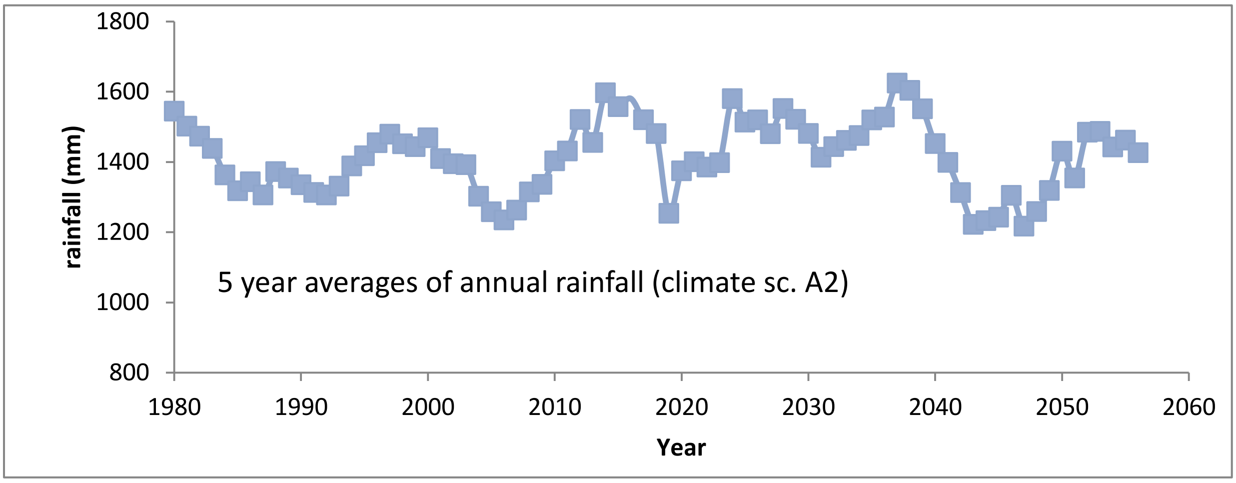
Annual change of Yasso07-output in scenario 400 (steady harvest) estimated for the period 1986 to 2055 is given in Figure 7C. Average annual temperature and annual rainfall is given for comparison in Figure 7A and 7B. Change of Yasso07-output is very variable between years. The strong increase in stored soil carbon during the period NFI23 is a result of storm occurrences. Figure 7 suggests that annual temperature is negatively, annual rainfall is positively correlated with carbon stock change.

When a time delay of change of Yasso07-output of about 5 years compared to annual rainfall is considered, the strength of the correlation between these two variables increases (data not shown).

A)



B)



C)

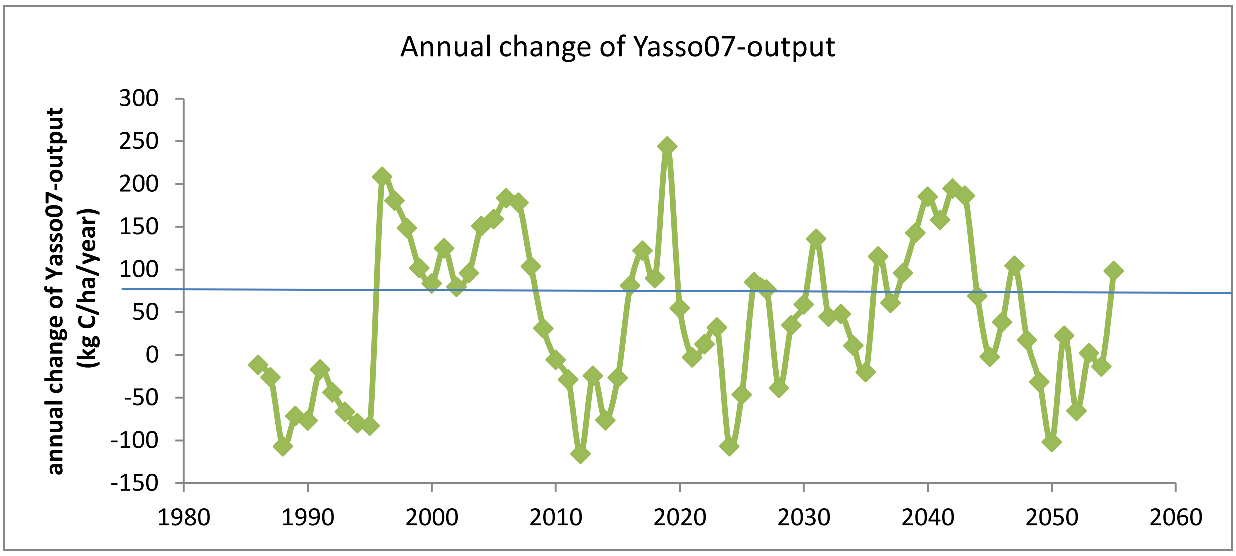


Figure 7 Five year average of average annual temperature (A), annual rainfall (B) and annual change of Yasso07-output simulated with parameter set P09 (C) , for forest management scenario 400 (climate data including IPCC climate sc. A2, climate data averaged over 5 years). The change in soil carbon stock including dead wood and L, F and H-horizon over the period 1996 to 2055 is indicated by the blue line.

3.3 Effect of climate on changes of Yasso07-output

Differences in changes of Yasso07-output between climate scenarios A2 and B2 are small and range between -4 to +3 kg C ha^{-1} $year^{-1}$ (Table 13). However, larger effects can be seen by averaging annual climate data over a varying time period (3, 5 or 10 years, Table 14). Changes of Yasso07-outputs based on annual (i.e. not averaged), 3, 5 and 10 year average climate data are shown in Table 14. Differences based on 5 versus 10 year averaged climate are considerable in most presented time periods (final column, Table 14). If the whole period between 1986 and 2055 is considered, the difference is ca. 14% . Strong differences exist between the averaging method for the (relatively short) commitment periods of the Kyoto protocol and range from ca. -46% to 113%.

Table 14 Estimated changes in soil C, dead wood and L, F and H-horizon (Yasso07-output) over different time frames using climate data averaged over 3, 5 or 10 years and forest management scenario 400 (Climate scenario A2 used). The stock change is estimated by the Yasso07 model output based on the P09 parameterization.

Period			Climate data averaged over				
			A 1 year[1]	B 3 year[2]	C 5 year[3]	D 10 year[4]	Difference C to D [%][5]
start		end		Annual change of Yasso07-output (kg C ha^{-1} $year^{-1}$)			
1986	-	1995	-39.7	-51.6	-50.0	50.6	N/A*
1996	-	2005	136.6	120.0	117.4	122.4	4.3
2006	-	2015	49.1	35.1	24.6	34.7	41.1
2016	-	2025	78.2	64.5	52.7	43.8	-16.9
2026	-	2035	23.8	42.2	45.7	37.1	-18.8
2036	-	2045	142.1	132.6	120.8	97.7	-19.1
2046	-	2055	24.7	12.7	-2.7	51.9	N/A*
1986	-	2055	35.3	32.3	30.7	34.9	13.7
1996	-	2055	47.6	43.1	40.5	45.0	11.1
2008	-	2012	21.7	-11.0	20.1	42.8	112.9
2013	-	2020	33.4	31.9	51.2	27.9	-45.5

[1]Annual data; not averaged

[2] Three year climate data: averaged 1 year ahead and 1 past the actual year of interest

[3] Five year climate data: averaged 2 years ahead and 2 past the actual year of interest

[4] Ten year climate data: averaged 4 years ahead and 5 year past the actual year of interest

[5]Percentage difference calculated as: (D-C)/C x 100

*Differing can't be expressed in percentage

Table 15 Yearly values of changes in Yasso07-output for 2005-2013 estimated using Yasso07_P09, sc. 400, stratified according to altitude class and production region of Switzerland (climate A2, averaged over 5 years). Negative values refer to a decrease in carbon stocks whereas positive values refer to an increase in carbon stocks.

Altitude	Annual change of Yasso07-output (kg C ha^{-1} $year^{-1}$) Jura	Plateau	Pre-Alps	Alp	S.Alp	Switz.
			2005-2006			
0-600	263	82	-41	21	18	*112*
601-1200	193	136	205	126	-17	*151*
>1200	91	158	171	231	174	*202*
mean	*201*	*105*	*185*	*193*	*71*	*159*
			2006-2007			
0-600	2	-31	320	238	465	*37*
601-1200	183	64	-1	392	818	*214*
>1200	152	182	-183	242	725	*235*
mean	*132*	*10*	*-44*	*290*	*723*	*183*
			2007-2008			
0-600	-25	-20	246	165	355	*24*
601-1200	134	79	44	348	686	*195*
>1200	124	156	-67	264	649	*255*
mean	*92*	*22*	*18*	*289*	*619*	*178*
			2008-2009			
0-600	-79	-79	116	37	300	*-38*
601-1200	50	15	-1	220	596	*117*
>1200	44	72	-61	164	570	*179*
mean	*16*	*-40*	*-15*	*179*	*539*	*104*
			2009-2010			
0-600	-93	-85	60	-53	169	*-60*
601-1200	-4	-16	-39	114	434	*50*
>1200	-14	7	-92	30	397	*63*
mean	*-29*	*-56*	*-51*	*55*	*377*	*31*
			2010-2011			
0-600	-117	-126	-42	-100	134	*-99*
601-1200	-13	-50	-79	41	372	*11*
>1200	2	30	-87	-13	349	*31*
mean	*-39*	*-94*	*-80*	*3*	*325*	*-6*
			2011-2012			
0-600	-121	-137	-82	-123	91	*-112*
601-1200	-29	-63	-89	0	306	*-13*
>1200	-28	-7	-89	-42	289	*2*
mean	*-53*	*-105*	*-89*	*-30*	*266*	*-29*
			2012-2013			
0-600	-175	-204	-170	-250	28	*-178*
601-1200	-81	-144	-180	-116	219	*-96*
>1200	-69	-56	-163	-168	199	*-103*
mean	*-104*	*-178*	*-175*	*-153*	*181*	*-116*

3.4 Stratification by altitude and production region

Changes of Yasso07-output per hectare and year stratified by altitude and production region are shown in Table 15. In this report, values are provided on an annual basis for the period 2005 to 2013. Regional differences in Yasso07-output are apparent in the simulated results. In the Plateau and Pre Alpine regions, a predominantly decreasing carbon stock is estimated, whereas a strong increase in the sink in the Southern Alpine regions is indicated. In the Alps and the Jura initially soil is a sink and becomes a source after 2007. A pattern in carbon stock change by altitudinal range is not apparent in the data.

The forest area stratified by altitude and production region is given in Table 16.

Table 16 Forest area of Switzerland stratified by production region and altitude.

Altitude	*Jura*	*Plateau*	*Pre Alps*	*Alps*	*S. Alps*	*Switzerland*
			Forest area (ha)			
0-600 m	49 276	132 304	7 345	8 515	19 773	217 214
601-1200 m	125 168	95 213	132 784	101 792	56 987	511 944
>1200 m	26 741	2 496	78 466	260 534	74 810	443 048
Sum	201 185	230 014	218 596	370 842	151 570	1 172 206

4 Discussion

4.1 Model validation

For the model Yasso07, at least two quite different parameter sets have been published (P09 and P11, see section 2.3.1), which cause a notable difference in the Yasso07-output. The good agreement between measured and modeled mass loss using P09 could indicate that the P09 is more appropriate under local conditions than P11. However, the lower mass loss values estimated using P11, would make sense if one accepts the view that organic material may have been leached out of the litter bags in the field trial, but are still in the soil system. This point of view is suggested by Tuomi et al (2011a). Since we were not in the position of verifying the statement that organic matter that leached out of litter bags is still in the soil at the site, we opted for the cautious approach and thus favoured P09. This approach was supported by the results of the comparison of modeled non woody litter mass loss with measured litter bag mass loss: Results of the Yasso07 simulation with P09 of non-woody litter (nwl) mass decay corresponded better with measured nwl mass loss over 5 years than results obtained with P11. We concluded that medium term decay patterns of non-woody litter (nwl) are well represented when using P09 with Yasso07.

The Yasso07 development team recently published three further parameter sets developed for Scandinavian, European and global climatic conditions. Implementing the European parameter set reduced estimated soil carbon stock changes somewhat compared to using P09, but did not change values substantially (data not shown). Since Yasso07_P09 has also been applied successfully in other research studies (e.g., Thum et al. 2011), for estimating current and future soil carbon stock change in Swiss forest soils., we opted to use P09 rather than the more recently published P11.

4.2 Change of Yasso07-output for sc. 400 and climate A2

Over the period 1996 to 2055 the change Yasso07-output increased by 40.5 kg C ha^{-1} $year^{-1}$, when climate scenario A2 and Massimo scenario 400 are used. Changes of Yasso07-output varied considerably between years. This is partly due to a change in litter input and partly due to weather fluctuations. For example, the simulated strong increase in carbon stock between 1996 and 2006 is comparatively high and most likely due to increased litter input during this period after storm activity. Estimated carbon stock change for sc. 400 varies considerably in the period 2010 and 2050, although estimated litter input slowly but gradually increases in that time. This could be due to fluctuations in the modeled climate conditions (Figure 7). Changes of Yasso07-output correlate with fluctuations in rainfall and temperature. Particularly changes in rainfall pattern seem to align with carbon stock changes during 2015 to 2040. However, in the period after 2042 a notable increase in mean annual temperature is modeled and carbon stock change gets measurably reduced at the same time. Even carbon stock losses are estimated to occur at that time under sc. 400. Climate factors like precipitation and temperature are very important drivers that determine Yasso07-output almost to the same extent as the massive increase in litter input after storm activity.

4.3 Forest management scenarios

Variations in forest management cause changes in the litter input and consequently in the Yasso07-output. So, the amount of changes in Yasso07-output for the period 1996 to 2055 is estimated to be highest for sc. 485 (63.2 kg C ha^{-1} $year^{-1}$), intermediate for scenario 400 (40.5 kg C ha^{-1} $year^{-1}$) and lowest for scenario 425 (2.9 kg C ha^{-1} $year^{-1}$).

Together with an increase in harvest activity (scenario 425), changes of Yasso07-output are estimated to be increasing in the period 1996 to 2025, but decreasing in the periods 2026-36 and 2046-55. Initially, after increased harvest activity has started, there is an increase in litter from dead root carbon. In later years the lower input of non woody litter from the reduced standing biomass outweighs this factor and the estimated carbon stock change gets close to zero or even negative. This is the case for scenario 425 and to a lesser degree for scenario 411 (reduced harvest). When increased harvesting intensity coincides with higher mean annual temperatures, carbon is lost from the soil, dead wood and L, F and H-horizon and thus the C stock decreases. However, the effect of increased temperature has only been implemented in Yasso07 (carbon mineralisation) but not in Massimo (carbon acquisition) yet. Increased temperature could increase growth and thus carbon acquisition but it could also increase drought stress and affect the system adversely. This is an unsolved issue which needs to be addressed in the future. Adaptive forest management (cf. Lindner et al. 2010) may be applied to minimize adverse effects.

4.4 Annual, 3 year , 5 year, 10 year or long term average of climate data

Changes of Yasso07-output are significantly affected by the way the climate data is entered into the modeling process, whether as annual data or as the running mean over 3, 5 or 10 years. Those modeled changes over small time frames can be altered notably by the way climate data is entered. However, changes of Yasso07-output over longer periods are much less affected (cf. Table 14. This shows, that changes of Yasso07-output are quite similar when using different averages of climate data, only the timing when changes occur are altered by the way that climate data is entered. This is, however, very important, especially when data are used for political reasons (e.g. reporting greenhouse gas emissions under UNFCCC and the Kyoto Protocol) and information is needed for a specific time period.

4.5 Yasso07-output for Kyoto commitment periods

In the first commitment period (2008-2012) a gross-net accounting approach is used, meaning that the absolute values of changes in all carbon pools can be accounted for. During the period 2008-2012 changes of Yasso07-output show an increase of soil carbon and deadwood between 16.6 and 42.8 kg C ha^{-1} $year^{-1}$ in all but one scenarios (Table 13 and 14). Merely management scenario 400 combined with climate scenario A2 averaged over 3 years simulates a decrease of -11 kg C ha^{-1} $year^{-1}$ (Table 14).

In the period 2013-2020 changes of Yasso07-output show an increase of soil carbon, organic layers and deadwood in all scenarios between 15.0 and 51.2 kg C ha^{-1} $year^{-1}$ (Table 13 and 14). For the second commitment period (2013-2020) forest management is accounted for on a net-net basis using a so called Forest Management Reference Level (FMRL), which reflects the expected changes in carbon pools under a certain forest harvesting scenario. This means, that only the difference in the changes of Yasso07-output between the expected and the actual harvesting rate will be accounted for. For example, if harvesting rates 2013-2020 remain at the same level as during 1985-1996 (scenario 400), yasso07 shows an increase of 30.7 kg C ha^{-1} $year^{-1}$ (51.2 kg C ha^{-1} $year^{-1}$ for scenario 400 and 20.5 kg C ha^{-1} $year^{-1}$ for scenario 425 chosen for setting FMRL; date displayed in Table 13).

It is important to note that those figures are *not the final ones* as they will be independently checked for accuracy by a second person.

4.6 Initial estimate of soil carbon including dead wood and L, F and H-horizon

Another point that needs to be focused on in the future is the initial estimation of the stock of soil carbon including dead wood and L, F and H-horizon. The focus of this study was put on assessing the magnitude of temporal changes in Yasso07-output and not the absolute level of carbon stock. This differentiation is important, since stock and stock changes often have to be presented together, although reliability of both estimates are not necessarily the same. Modeled soil carbon stocks and soil carbon stock changes, although dependent, are measured on substantially different time scales and on a substantially different knowledge base. Carbon stock modelled by Yasso07-output assumes litter data for 5 000 to 10 000 years, whereas stock changes assessed by changes of Yasso07-output require data for a period of about 100 years. Therefore, soil carbon stock is arguably much harder to estimate than soil carbon stock change since forest/land management, climate and soil forming processes of the last 10 000 years are more difficult to model than forest management and climate of the last 100 years. Hence, good agreement between measured and modeled soil carbon stock change values does not necessarily imply that modeled and measured soil carbon stock values have to agree equally well and vice versa. Short term decay processes (up to 50 years) are arguably most important to model soil carbon stock change in the timescale of 50 to 100 years, whereas long term forest/land management, past climate and soil forming processes may be more important on a time scale of 10 000 years. Short term decay processes of non woody litter, as modeled by Yasso07, were validated successfully with results from a local litter bag study conducted by Frey (2010). For details see section 3.1.1. Modeled soil carbon stock values did not match equally well with the measured soil carbon stock values at 167 NFI sites, as provided by the Soil Science Unit at WSL (cf. Section 3.1.2). Compared with the data from those sites, the Yasso07_P09 modeled soil carbon stock values are lower (Table). The results from these two comparisons suggest that modeling of soil carbon stock needs to be improved.

4.7 International comparison

The estimated amount of soil carbon stock change including dead wood and L, F and H-horizon over the period 1996-2055 for forest management sc. 400 and climate scenario A2 was 40.5 kg C ha^{-1} year^{-1}. This increase in carbon is in the broad range of values reported for other climatically comparable countries. For example for European countries, Luyssaert et al (2010) estimated that about 220 kg C ha^{-1} year^{-1} were sequestered in the forest soil in the period between 1990 to 2005 (51.4 kg C ha^{-1} year^{-1} in this study over the same period). For Swedish forest soils Agren et al (2008) estimated soil carbon stock change to be 120 kg C ha^{-1} year^{-1} for the period 1926-2000.

Our estimate of soil carbon stock change including dead wood and L, F and H-horizon of 40.5 kg C ha^{-1} year^{-1} tends to be somewhat lower than in those comparable studies. This could be due to the reason that we included future temperature increases in the modeling process, whereas temperature increases were less pronounced in the period prior to 2000.

Up to now, two other countries apply Yasso or Yasso07 for reporting carbon stock changes in forest soils to the UNFCCC. Finland applies Yasso without separating dead wood and soil organic matter due to model limitations. Norway applies Yasso07 and reports dead wood and soil organic matter separately based on specific assumptions. As far as we know, only Germany, Belgium and Czech Republic report carbon stock changes based on repeated measurements of soil carbon.

4.8 Separating of Yasso07-output in deadwood, organic layers and soil carbon

According to the Marakesh Accords, which are used for Reporting under the Kyoto Protocol, 5 carbon pools have to be accounted for separately: above and below ground living biomass, dead wood, L, F and H-horizon, and soil organic carbon. However, Yasso07-output summarises organic carbon up to 1 m depth, including carbon from dead woody debris, L, F and H-horizon and soil organic carbon. Therefore assumptions need to be taken to allow separate accounting of these 3 pools included in the Yasso07-output. Three alternative options were considered for further investigation:

1. The Yasso07-output is **subdivided based on the chemical fractions** AWENH. This subdivision is technical feasible but somehow artificial. Nevertheless, it can be conducted in order to fulfil IPCC reporting requirements.
2. Dead wood as **measured in NFI 3** and published in Weggler et al. (2012) is subtracted from Yasso07-output. This approach is strongly limited by the fact, that measured values of dead wood only exists for the period NFI 3. Management scenarios will therefore not be reflected in future estimations.
3. The carbon content of the annual amount of litter modeled by Massimo is subtracted from the Yasso07-output. This has the advantage that different forest management scenarios can be reflected and that also simulations for the future are possible. However, the amount of dead wood and L, F and H-horizon in the field is the result of accumulation over years. Decay of

deadwood takes years and thus the annual input of litter needs to be multiplied by a factor to take into account this accumulation. Such a factor could be established on the basis of decay functions, but these are difficult to be determined due to the lack of local data.

4. Dead wood is subtracted from Massimo litter prior to using it as input in Yasso07.

From the current stage of knowledge, it seems to us that the only viable option is option 1 as this is the only method not mixing measured and modeled values. Option 1 and 4 will be further discussed with international Yasso07 experts in Finland in May 2012 and be published in the next report.

5 Conclusion

Combining the forest management model Massimo, allometric functions and the soil decomposition model Yasso07 allowed estimating soil carbon stock change including dead wood and L, F and H-horizon for the current years and the near future (2055).

During the first commitment period (2008-2012) changes of Yasso07-output show an increase of soil carbon and deadwood between 16.6 and 42.8 kg C ha^{-1} $year^{-1}$ in all but one scenarios. During the second commitment period (2013-2020) changes of Yasso07-output show an increase of soil carbon and deadwood in all scenarios between 15.0 and 51.2 kg C ha^{-1} $year^{-1}$.

Those estimates appear reliable, since they are mainly based on short to medium time frame, litter decay mechanisms and they are the broad range of values published for other European countries. However, those figures are *not the final ones* as quality control is still under progress. Moreover, any projections of future C stocks in forest soils are subject to the uncertainties related to the extent of the change in climate and the resulting impact on disturbances, particularly storms and pests. The practice of adaptive forest management and continuous monitoring of forest may be used to minimize potential adverse effects on C stocks of forests and forest soils.

6 Outlook and deliverables

The following aspects of Yasso07-output will be investigated in further detail.

1. For quality control, the simulation results from Yasso07 will be implemented independently by a new colleague. All model results will be replicated with identical input and parameter values.
2. Litter values from NFI 4 data will be applied to estimate soil carbon stocks including dead wood and L, F and H-horizon of the years 2009 to 2011.
3. All scenarios will be calculated based on climate data averaged over 10 years.
4. A possible separation of dead wood and soil organic matter will be assessed. We try to develop suggestions for a methodologically possible and thematically meaningful separation of model output from Yasso07 into dead wood and soil organic matter taking into account experiences from Finland and Norway. First discussions will take place during the Yasso07 seminar in Helsinki in Mai 2012.
5. Reporting methods of soil carbon stock changes of other countries as reported in their NIRs will be analyzed.
6. Uncertainty of Massimo model stochasticity and Yasso07 parameter uncertainty will be assessed.

7. All results of model validation will be published.
8. Results from the project KliWaWa (influence of environmental factors and climate change on forest growth) will be incorporated in the Yasso07-output as soon as available (not before 2014).

The deliverables agreed upon by WSL and BAFU for soil carbon stock changes until September 2012 are described in Table 19.

Table 19 Deliverables of WSL in soil carbon modeling agreed upon with BAFU until September 2012.

Date	Deliverables of WSL
31.3.2012	Final report of the project **Modeling soil carbon stock change using the models Massimo and Yasso07** including data.
31.07.2012	Assessment of possible separation of model output Yasso07 into dead wood and soil organic carbon (step 4).
30.09.2012	Soil carbon stocks and soil carbon stock changes simulated with Yasso07 and litter from NFI 4 data (steps 1 to 6).

For this tasks and further analysis for the Swiss Greenhouse Gas Inventory, WSL committed Markus Didion for the next three years. He brings along experience in Greenhouse Gas Inventories from Alterra (Netherlands) and worked for the Joint Research Centre in Ispra supporting scientific forest modeling and data compilation for LULUCF. Markus Didion started working at WSL the first of April 2012.

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