NFI 4 module: WSL contribution to the Swiss GHG and Kyoto Tables focused on carbon gains and losses in Swiss forests.

Estimating carbon stock changes in living and dead biomass and soil for Switzerland's Forest Management Reference Level – modeling methodology and results

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Summary

In February 2011, Switzerland submitted its Forest Management Reference Level (FMRL) to the UNFCCC-secretariat for accounting of forest management impacts on the forest C budget during the second commitment period under the Kyoto Protocol (2013 to 2020). The FMRL encompasses mean carbon stock changes (CSC) of living biomass, dead wood, the organic layer, soil and HWP for the period 2013-2020. CSC in HWP is not treated in this report.

Since 2011, the implementation of the models used for modelling carbon stock changes in living biomass (Massimo) and dead wood, litter, and soil (Yasso07) in Swiss forest have been continuously improved. In this report, the applied models, the improvements since February 2011 and the modeling results are transparently presented.

The empirical forest scenario model Massimo was used for simulating forest development starting from observed conditions in the third National Forest Inventory (ie. 2006) until 2026 forced by the harvest levels as defined in Switzerland's business-as-usual harvesting scenario (BAU). The results were used to estimate carbon stock (CS) and carbon stock changes (CSC) in living biomass and to obtain data on deadwood and litter production. The estimates for dead biomass were used to derive inputs for the C decomposition model Yasso07. Yasso07 is directly linked with Massimo and was used for estimating CS and CSC in deadwood, incl. stems, branches and roots, in non-woody litter, incl. foliage and fine roots and in soils.

The Swiss BAU scenario defined an increase in harvested timber volume by ca. 30% for the period 2013-2020 compared to 1990-2007. This increase was simulated following a linear and an exponential pathway and the resulting CSC in living biomass, deadwood, litter, and soil were been analyzed. For both management scenarios, the recalculation provided a time-series of the expected CSC of the forest pools. The data in this report have been used for compiling and recalculating the Swiss FMRL.

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Glossary

Biomass losses: Biomass can be removed from the forest following:

- Harvest: use of trees for producing timber. It includes all merchantable wood, i.e., bole wood and branches ≥ 7 cm excluding bark and stump (*Derbholz*).
- Mortality: trees dying due to natural causes, incl. senescence, storm, etc.
- Total loss: Sum of harvest and mortality

Carbon pools: Terminology follows the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2003):

- Living Biomass
  - Aboveground biomass, incl. stem, stump, branches, bark, seeds, and foliage
  - Belowground biomass, incl. all living biomass of live roots
- Soil organic carbon
- Litter
- Deadwood

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

- Living Biomass, incl. above- and belowground compartments
- 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

Carbon stock (CS): Stock of organic carbon stored in the biomass of trees, deadwood or litter, and mineral soil, respectively.

Carbon stock change (CSC): Change between carbon stocks over a specified time interval.

Carbon dioxide equivalent (CO_2-eq): Carbon mass multiplied by the ratio 44/12, which is the ratio of their atomic weights.

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

Forest management reference level (FMRL): Mean projected C stock changes of living biomass, deadwood, litter, soil and HWP for 2013-2020 following the Swiss business-as-usual harvesting scenario (BAU) harvesting scenario. This value is used for accounting for forest management in the second Kyoto-commitment period (2013-2020).

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 2006
- NFI4b: assumed to be representative of the year 2013

- Change analyses (*Veränderungsauswertungen*)

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

Units of carbon measurements:

- Carbon stocks:

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

- Gigagram (Gg) = 10^3 metric ton = 10^6 Kg
- Teragram (Tg) = 10^6 metric tons = 1 Mio tons = 10^9 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). For reporting under the Kyoto Protocol, the accounting of forest management impacts on the forest C budget has been changed and is in effect for the second commitment period (CP2) from 2013 to 2020 (Grassi et al. 2012). Prior to the start of CP2 Annex 1 parties were required to construct a so-called Forest Management Reference Level (FMRL) for the period 2013-2020 taking into account forest characteristics and actual forest policy implemented until the end of 2009, which were to represent a so-called business-as-usual (BAU) harvesting scenario

The BAU scenario in Switzerland's submission of the FMRL assumed an increase in timber harvest of on average 30% over the period 2013-2020 compared to 1990-2007 (FOEN 2011). In this submission, it was not specified how the increase is distributed over time. This report presents two alternative pathways of the development of harvest rates until 2020 to reach the defined increase in timber harvest. The first alternative is based on the assumption of a linear increase in harvests from 2007 to 2020. For the second alternative, a different pattern was assumed describing an exponential development where initially harvest rates rise little and intensify towards the end of CP2.

Similar to the majority of Annex 1 parties, Switzerland opted for a model-based approach for preparing its FMRL (IPCC 2014). The objectives of this report were to present (i) the models used for calculating parts of Switzerland's FMRL (i.e., forest management scenario model Massimo and litter decomposition and soil carbon model Yasso07), and the model improvements which were made since the time of the submission on Switzerland's FMRL in February 2011, (ii) the model implementation to simulate the two alternative pathways to reach the increase in harvesting rates as defined in the BAU-scenario, and (iii) the resulting time series of CSC in the living biomass, DOM, and soil.

Based on the IPCC guidelines (IPCC 2014), the report considers five carbon pools that are elements of the Swiss FMRL: above and below-ground living biomass, dead wood, litter and soil organic carbon; the pool harvested wood products is not addressed in this report (see FOEN 2015a). The changes in living biomass and the production of litter and deadwood over the period 2013-2020 were simulated with a modified version of the forest management scenario model Massimo (Fischer et al. 2015, Kaufmann 2011, Kaufmann 2001a, Kaufman 2001b). The litter decomposition and soil carbon model Yasso07 (Tuomi et al. 2009, Tuomi et al. 2011) was used for deriving estimates of CSC in deadwood (incl. stems, branches and roots) and non-woody litter (dead organic matter, DOM), and in soils on productive forest lands over the same period based on simulated data on forest development obtained from Massimo.

The report is structured as follows: The section on methods provides i) descriptions of both applied models and model improvements implemented since 2011, and ii) details on the model implementation to simulate the alternatives of a linear and an exponential increase in harvest rates to obtain a time series of CSC for the BAU-harvesting scenario. The following chapter presents and discusses results of the simulations. The report concludes with a discussion on the implications of this study, specifically on model application and further development.

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 measured and maintained in a consistent manner (Swiss NFI) and that will be available in the future (regulated by law). 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 models Massimo and Yasso07 in a consistent manner that is similar to modeling approaches by other countries to construct their FMRL (cf. IPCC 2014, Böttcher et al. 2012). See section 2 on Methods, section 3 for results, and section 4 for discussion.

Completeness is reached by calculating annual estimates for all required C pools including living biomass, litter, deadwood and soil for all 15 forest regions in Switzerland. See sections 2 for methods and 3 for results.

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

2.1 Business as usual (BAU) harvesting scenario with linear and exponential increase in harvest rates

Switzerland's FMRL submitted in February 2011 (FOEN 2011) was based on a business-as-usual (BAU) harvesting scenario derived from extrapolation of historical data and Switzerland's Wood Policy defining that the level of the "Potential Sustainable Wood Supply" (PSWS) should be exhausted until 2020 (FOEN 2008). The BAU-harvesting scenario is described in detail in FOEN (2011) and in Switzerland's National Inventory Report (FOEN 2015b, Chapter 11.7.2). It defined an increase in harvested timber volume by ca. 30% for the period 2013-2020 compared to 1990-2007. To achieve the increase, more wood needs to be harvested on an annual basis.

In order to obtain a time-series of annual harvest rates for Switzerland's FMRL, two possible pathways were identified: a linear and an exponential increase between 2007 and 2020 represent plausible alternatives. In absence of knowledge about future forest development and the ability for harvesting interventions, the linear increase presents a pragmatic alternative. The exponential pathway assumes that policies, adopted and implemented no later than December 2009, only have a moderate impact at the beginning of the second commitment period and take stronger effect at the end of the commitment period. Both options were implemented in the forest management scenario model Massimo (following section 2.2) assuming typical background mortality estimated from NFI data and storm intensity based on observed events in the past. To ensure the longer-term plausibility of the increasing harvest rates, the prescribed time-series was extended and simulated until 2026.

2.2 Living Biomass: Massimo

Carbon stock changes in living biomass are modeled with the stochastic, empirical single tree forest management scenario model Massimo (Kaufmann 2011, 2001a, 2001b). The model version applied in this study was based on «MASSIMO 3» which was described in Fischer et al. (2015) and Kaufmann (2011). To meet the requirements for constructing the FMRL, minor modifications were made as described in section 2.2.2.

2.2.1 Model description

Massimo is to large extents based on NFI data. It therefore runs on every NFI site in Switzerland. The model projects the development of tree growth by updating single tree information diameter at breast height (dbh, measured at 1.3 m height from the floor) of all sites. DBH is expanded to biomass by applying allometric functions to the estimated dbh (Thürig and Herold 2013; Perruchoud 1999). Five different tree compartments can be estimated i) twigs, ii) branches, iii) bole wood, iv) stump, and v) roots. By aggregating estimates for single trees, the following stand variables can be projected:

- growing stock: living biomass of all trees including roots,
- gross growth: growth of all living biomass and growth of trees cut or died between two inventories,
- total loss: biomass of all trees that were commercially cut (i.e. harvested for producing timber) or died due to natural mortality between two inventories.

Massimo (Figure 1) consists of three major modules (i) single tree growth module, ii) cut and mortality module, and iii) regeneration module and two sub-modules (increment after thinning and ingrowth).

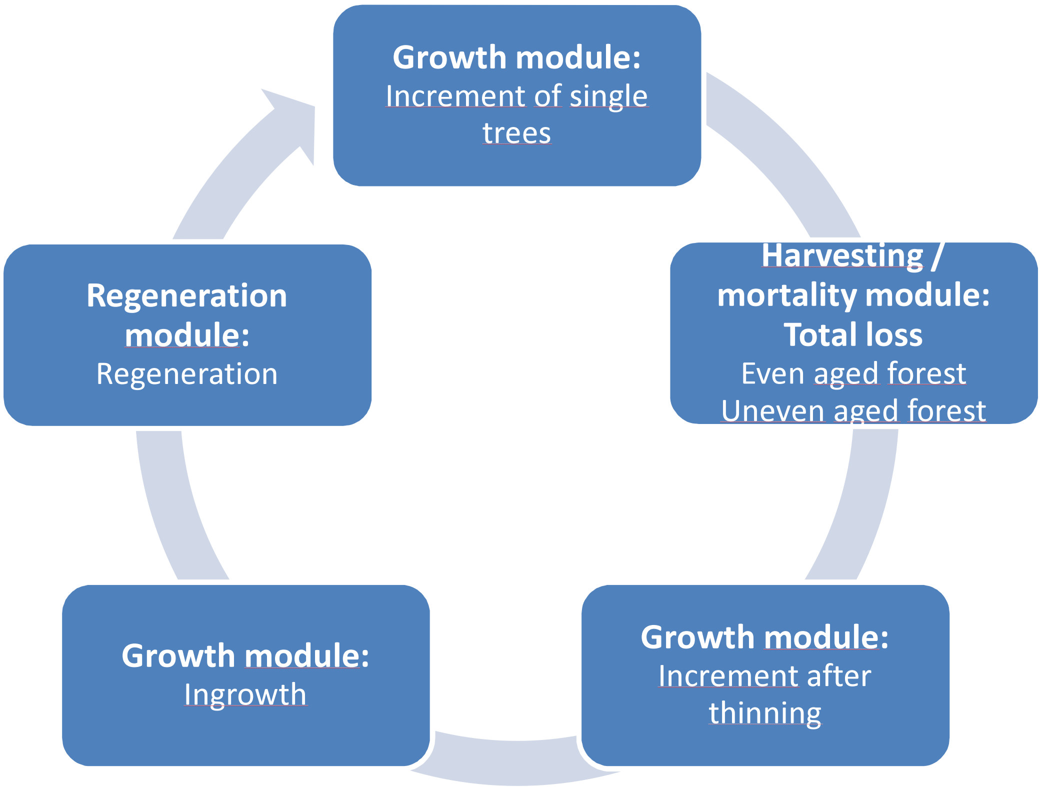

Figure 1. Schematic overview of «MASSIMO 3», adapted from Fischer et al. 2015.

The growth module integrates a single tree basal area increment model, based on a growth function using dbh as explanatory variable. Further explanatory variables are basal area per hectare, basal area of trees with a larger diameter than the subject tree (serving as competition index), fertility, altitude, stand age, a growth boost factor to account for the increase in growth after thinning operations (Thürig et al. 2005b). For uneven aged forests the diameter of the 100 thickest trees per ha is used instead of stand age (Kaufmann 2011).

The wood harvesting and mortality module calculates the annual harvested and natural mortality amounts based on several assumptions. All assumptions and rules about losses are empirically derived from NFI data. Natural mortality was based on empirical data from the NFI1 and NFI2 and amounts to ca. 14-15 % of total losses (Brassel and Brändli, 1999 Kaufmann 2011). Rotation periods for even aged forests as well as thinning criteria for all types of forests are defined. It is assumed that a rotation period largely depends on the site conditions: 90-110 years rotation periods on very good sites, 110-130 years on good sites, and 130-150 years on poor sites. As clear cutting practices are forbidden in Switzerland, mature stands are harvested over a time span of 20-30 years, promoting natural regeneration; in Switzerland, 90% of the forests are regenerated naturally (Brändli 2010). It is assumed that thinning takes place when a basal area increment of 10% has been reached compared to the basal area before the previous thinning. In Massimo, thinning - methods are differentiated between even aged and uneven aged forests. Basal area reductions of 30% and 25% are assumed for even aged and uneven aged forests, respectively (Kaufmann 2011). Trees to be thinned are selected according to their diameter, which is ascribed based on the diameter distribution of the selected forest stand. To define different forest management scenarios, the effective date of regeneration cuts and the periodicity of thinning can be modified.

The regeneration module is also based on NFI data. It randomly selects a plot with similar site conditions out of the NFI database and assigns it the corresponding regeneration data as well as other stand variables for further calculations within Massimo.

2.2.2 Model development since 2011

Since Switzerland submission of the FMRL in 2011 (FOEN 2011), the Massimo model was further developed. The model version applied in this study contains several modifications in comparison to model version «MASSIMO 3» (Fischer et al. 2015). General improvements were first, the implementation of more accurate harvest interventions. In even aged forests, rejuvenation by clear-cut was replaced by shelterwood system. In coppice, thinning interventions were displaced by rotation periods. Second, more realistic tree regeneration was implemented in protection forests. Third, the usability of the model has been improved.

Following modifications were made to meet the specific needs for constructing the FMRL. The time step of 10 years in the base version of the model was shortened to 5 years. This represents a reasonable approach to obtain a finer temporal resolution required for constructing, and future accounting based on the FMRL, which does not compromise the accuracy of the model (cf. results of the validation in the following section). After each time step, forest stand variables influencing forest development and harvesting interventions of the subsequent time step are updated. Since Massimo is based on NFI data which until the NFI3 in 2006 were collected at 10-year intervals, further changes to the model time step would result in a loss of accuracy.

2.2.3 Model validation

The model was initialized with NFI 3 data. For the validation, it was driven by observed harvest rates in NFI 4b (Abegg et al. 2014). As NFI 4b data were not used for model calibration, this is an independent model validation. After the simulation run of 5 years (one time step), modelled values of growing stock and gross growth were compared with growing stock and gross growth measured in NFI 4b.

2.2.4 Model implementation for estimating C stock changes in living biomass for constructing the Swiss FMRL

Two different pathways were simulated to reach the BAU-increase in harvest rate of on average 30% over the period 2013-2020 compared to 1990-2007. As the model works on five-year periods, the increase could only be implemented in five steps (2007-2011; 2012-2016; 2017-2021; 2022-2026; Table 1).

The increase in harvest was implemented by shortening the rotation periods and by intensifying the frequency of thinning. In protection forests and uneven aged forests, following model assumptions limit the change of rotation periods and thinning frequency: to preserve the vertical and horizontal structure of those forests and to ensure their protection function in the future, the model allows only small changes in their management. The scenario also incorporates a constant natural mortality 14-15% of total drain as described in Kaufmann (2011) which includes damage caused by regular storm events but not of extreme events.

For the FMRL, the calculations are based on five year periods with the area restricted to accessible forest in Switzerland, not including shrub forest.

Linear increase of harvest rate (Lin)
The total amount of harvested timber in this scenario increases *linearly* to 8.5 Mio m^3 a^{-1} in 2022-2026. In Massimo, this was implemented as an average increase in harvest rate of approximately 0.5 Mio m^3 over every 5-year time step. Due to model stochasticity (e.g., storm), the simulated increase deviated by ±8-9% or ±0.6 Mio m^3 (Table 1).

Exponential increase of harvest rate (Exp)
As for the linear pathway, the total amount of harvested timber in this scenario increases to 8.5

Mio m^3 a^{-1} in 2022-2026. The *exponential* pathway however assumes that initially harvest rates rise little and intensify towards the end of the simulation in 2026 (Table 1).

Table 1. Simulated increase in harvest rates as a result of the linearly and exponentially increasing scenarios between 2007 and 2026. The values represent mean values for a respective 5-year period. All values are given in Mio m^3 a^{-1} in merchantable wood (*Derbholz*). Single standard error (%) is shown.

Scenario	**Simulation time-step**			
	2007-2011	2012-2016	2017-2021	2022-2026
Linear increase in harvest rates (Lin)	6.9±9%	7.4±9%	7.9±8%	8.5±8%
Exponential increase in harvest rates (Exp)	6.8±11%	7.1±10%	7.3±7%	8.5±10%

Both scenarios were implemented separately for the 5 production regions of Switzerland. Due to stochastic model components storm intensity, frequency and location, the model was run 20 times and estimates were calculated as average values.

Standard errors of the estimates include the variation of the random samples and the variation of the 20 model runs.

2.3 Deadwood, litter and soil: Yasso07

The C decomposition model Yasso07 (Tuomi et al. 2009, Tuomi et al. 2011) was used for deriving estimates of carbon stock change in deadwood (incl. stems, branches and roots), non-woody litter and in soils on productive forest lands following the methodology applied for previous Swiss greenhouse gas inventories (GHGIs; FOEN 2013, 2014).

2.3.1 Model description

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 (Figure 2, 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 (Figure 2) are obtained probabilistically using Markov Chain Monte Carlo sampling and are fitted based on data from litterbag studies (Tuomi et al. 2009) and woody litter decomposition experiments (Tuomi et al. 2011). The approach allows calculating the maximum a posteriori point estimate and confidence sets for the model parameter vector which consists of a unique combination of 24 correlated parameters.

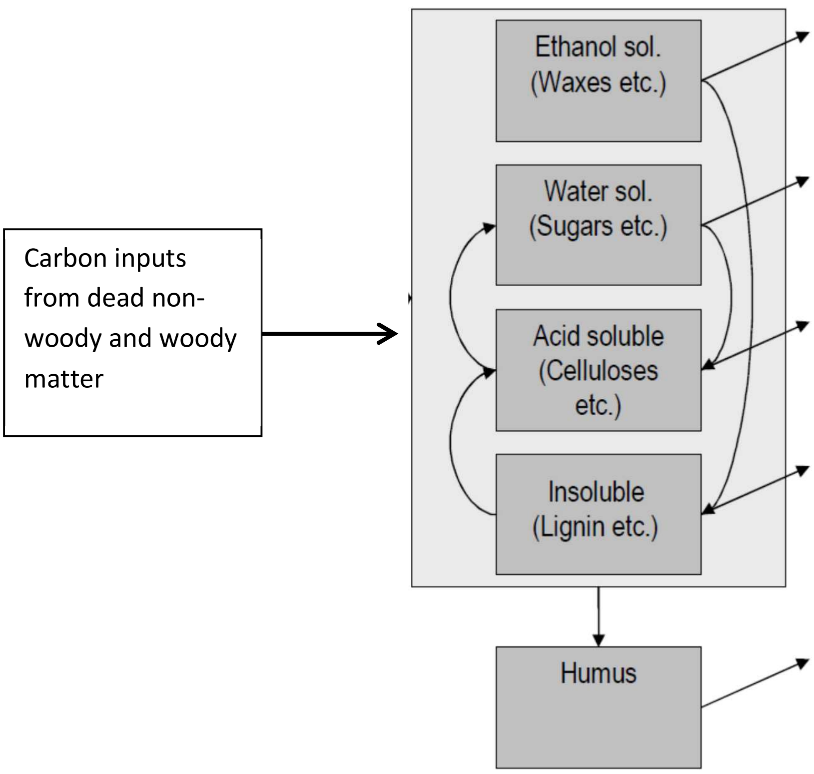

Figure 2. Flow chart of Yasso07 soil carbon model. The boxes represent soil carbon compartments, the arrows carbon flows; only those carbon flows are shown that deviate significantly from zero (adapted from Liski et al. 2009).

2.3.2 Model development since 2011 for application in Switzerland

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). The model and its application in the context of the Swiss GHGI was continuously improved since the initial use in 2012 (Didion et al. 2012, 2013, 2014b, FOEN 2013, 2014, 2015b).

2.3.3 Model validation

The model was validated for conditions in Switzerland by Didion et al. (2014a) who found that Yasso07 reproduced observed C losses in deadwood and litter very accurately. Didion et al. (2014b) showed that Yasso07 reproduced observed C stocks realistically.

2.3.4 Model implementation for estimating C stock changes in dead wood, litter and soil for constructing the Swiss FMRL

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 three subsequent NFIs until 2006, 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 (Table 2) and constant, aggregated C inputs from the first NFI (NFI12avg; Table 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; Table 3) but with annual climate data for the period 1961 to 1985.

c. For the time between 1986 (i.e., start of the period NFI 1 to 2; Table 3) and 2005 (i.e., end of the period NFI 2 to 3; Table 3), plot-specific carbon inputs from the three NFIs and annual, site-specific climate data are used.
d. Starting in 2006, the simulations were continued with projected C inputs that represent the two alternative assumptions for the increase in harvest rates between 2007 and 2026 (i.e., linear and exponential; cf. section 2.1).

The time series of C inputs since 1986 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.

The model parameters identified by Didion et al. (2014a) were used to drive the simulations. Uncertainty in model parameter values was included in the simulations by random sampling from the distribution of possible parameter vectors.

A Monte-Carlo approach was used to analyze the uncertainty related to C inputs and model parameters. The uncertainty was estimated based on independent simulations with five randomly sampled C input time series and five randomly sampled parameter vectors, i.e. a total of 25 simulations.

The Yasso07 release 1.0.1 was used in this report. More information and the source code are available on http://code.google.com/p/yasso07ui/. The Yasso07 Fortran source code was compiled for the Windows7 operating system. The statistical software R (R Core Team 2013) version 3.0.2 (64 bit) was used for administrating the Yasso07 simulations.

For harmonizing the Yasso07 simulation with the Massimo simulation a one-way link between the two models was implemented (Brandmeyer et al. 2000). The link was achieved via an interface which compiles the Massimo data to estimate the annual production of woody and non-woody litter for each simulated NFI plot. The data separated into the chemical compartments that are inputs for Yasso07 (cf. section 2.3.1) The interface is currently implemented in SAS. Further developments include a more flexible interface implemented in R to improve uncertainty estimation of Yasso07 inputs.

2.3.4.1 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 (Table 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

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

For the simulation the C balance in deadwood, litter and soil based on C inputs for the Swiss FMRL until 2026, observed climate data were used until the end of 2013. To obtain annual climate data for the years 2014 to 2026, means of randomly selected contiguous 3-year slices out of the norm-period 1981-2010 were used.

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

Elevation class		Production region					Switzerland [°C]
		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

2.3.4.2 C inputs

Estimates of C inputs (Table 3) 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 (representative of the deadwood pool); and

- Non-woody material separately for foliage (incl. fruits) and fine roots < ca. 5 mm (representative of the LFH pool, hereafter referred to as litter).

The annually accumulating mass in these DOM components (Table 3) was derived through allometric relationships to the volume of living standing and removed (harvest and mortality) trees (Thürig and Herold 2013) and specific lifespans of tree tissues (cf. Thürig et al. 2005a). The volume of living and removed trees was obtained from NFI data (NFI 1 through 3) and Massimo simulations for the linear and exponential increase in harvest rates between 2007 and 2026 which were assumed for the FMRL (cf. section 2.1). 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, lead to changes in 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 (Table 3): i) estimates of fine root and foliage production change with a change in tree number and volume; ii) 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 and standard error for C inputs for all NFI plots simulated with Yasso07 (n=4 726): 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. Starting 2007 inputs were derived from simulations with Massimo for a linear (Lin) and an exponential (Exp) increase in harvest rates between 2006 and 2026.

a) conifers

Simulation period	Input source	DOM component [Kg C $ha^{-1}a^{-1}$]									
		Fine Roots		Foliage		Coarse-woody (>7 cm diameter)					
						Roots		Branches		Stems	
Spin-up and 1961-1985	NFI12avg (moving window)	740 ±4		1109 ±7		289 ±2		61 ±1		54 ±1	
1986-1995	NFI12	750 ±10		1125 ±17		291 ±10		61 ±3		54 ±2	
1996-2006	NFI23	795 ±10		1171 ±18		347 ±12		89 ±3		79 ±3	
	Massimo	**Lin**	**Exp**	**Lin**	**Exp**	**Lin**	**Exp**	**Lin**	**Exp**	**Lin**	**Exp**
2007-2011		695 ±10	695 ±10	1018 ±17	1019 ±17	439 ±12	439 ±12	135 ±4	138 ±4	120 ±4	122 ±4
2012-2016		696 ±10	698 ±10	999 ±17	1001 ±17	476 ±12	463 ±12	138 ±4	138 ±4	70±2	72 ±2
2017-2021		689 ±10	697 ±10	969 ±17	985 ±17	507 ±12	467 ±13	143 ±4	141 ±4	72 ±2	72 ±2
2022-2026		673 ±10	687 ±10	935 ±16	966 ±17	534 ±12	523 ±14	144 ±4	144 ±4	75 ±2	74 ±2

b) broadleaves

Simulation period	Input source	Fine Roots		Foliage		Roots		Branches		Stems	
Spin-up and 1961-1985	NFI12avg	282 ±2		671 ±6		97 ±1		33 ±0		11 ±0	
1986-1995	NFI12	277 ±5		655 ±13		97 ±5		34 ±2		11 ±1	
1996-2006	NFI23	316 ±6		744 ±14		99 ±5		45 ±3		13 ±1	
	Massimo	**Lin**	**Exp**	**Lin**	**Exp**	**Lin**	**Exp**	**Lin**	**Exp**	**Lin**	**Exp**
2007-2011		297 ±6	298 ±6	695 ±14	696 ±14	193 ±7	192 ±7	91 ±4	91 ±4	35 ±1	35 ±1
2012-2016		301 ±6	302 ±6	699 ±14	702 ±14	206 ±6	199 ±6	96 ±4	100 ±4	19 ±1	19 ±1
2017-2021		300 ±6	305 ±6	695 ±14	706 ±14	221 ±7	202 ±6	103 ±4	101 ±4	20 ±1	20 ±1
2022-2026		297 ±6	303 ±6	684 ±14	698 ±14	233 ±7	233 ±7	104 ±4	109 ±4	20 ±1	20 ±1

The temporal dynamics of C inputs reflect the large scale tree mortality caused by the windstorm Lothar in 1999 and subsequent damage by bark beetle infestation. Litter and deadwood production increased significantly from the period NFI12 (1986-1995) to NFI23 (1996-2006; Table 3). Following the change from observation-based to simulation-based data, C inputs from fine root and foliage litter decrease and inputs from deadwood increase. This pattern was regardless of the assumed harvest rate increase and can be explained by i) the reduction in disturbance-related mortality compared to the period when Lothar occurred, and ii) the change in harvesting intensity. The differences in harvesting intensity between the period NFI23 and the subsequent periods as well as between the simulated management scenarios are responsible for the diverging pattern for inputs deriving from broadleaves and conifers on the one hand, and between litter and deadwood on the other hand.

3 Results

3.1 Validation of the Massimo model version for the FMRL

Total values of growing stock, gross growth and total losses simulated for Switzerland showed good agreement with measured NFI 4b values (Table 4). Values stratified for production regions showed larger deviations (not shown in this report). There was a slight overestimation of the modelled values compared to the measured values in NFI 4b. This is mainly caused by the restrictive model assumptions in protection forests and uneven aged forests: to preserve the vertical and horizontal structure of those forests and to ensure their protection function, harvesting amounts in uneven aged forests and protection forests could not be reduced in the definition of harvesting scenarios. However, all values were within two standard deviations of the combined standard error (95% confidence interval). The model Massimo therefore is assessed as a valuable tool to simulate short-term development of Swiss forests based on predefined management scenarios.

Table 4. Validation of Massimo with independent data. Positive values indicate an overestimation of the model compared to the measured NFI data.

	Growing stock	Gross growth	Total losses
Coniferous trees	+3%	+2%	+1%
Deciduous trees	+2%	+7%	+13%
Total	+3%	+4%	+4%

3.2 Living Biomass

Figure 3 shows Massimo results of the FMRL BAU-scenario for two alternative assumptions on future harvest rate development: "*linear increase*" and "*exponential increase*". All estimates are presented in Mg CO_2 eq. ha^{-1} a^{-1} with standard error of the mean. The overlapping range of the standard error indicates no statistical difference between the two scenarios. A combined error bar of total losses and gross growth was applied for CSC. As defined in the FMRL scenario (FOEN 2011), both scenarios end in the period of 2022-2026 with an increased harvest amount of 8.5 Mio m^3 a^{-1} or 12.9 Mg CO_2 eq. ha^{-1} a^{-1} in total losses. The mean CSC in living biomass after considering increment and losses over the period 2013-2020 for the two simulated pattern of harvest rate development were a source of +200.0 ±7.3% Kg CO_2 eq. ha^{-1} a^{-1} for the linear and a sink of -350.0 ±8.3% Kg CO_2 eq. ha^{-1} a^{-1} for the exponential development of harvest levels (Table 5).

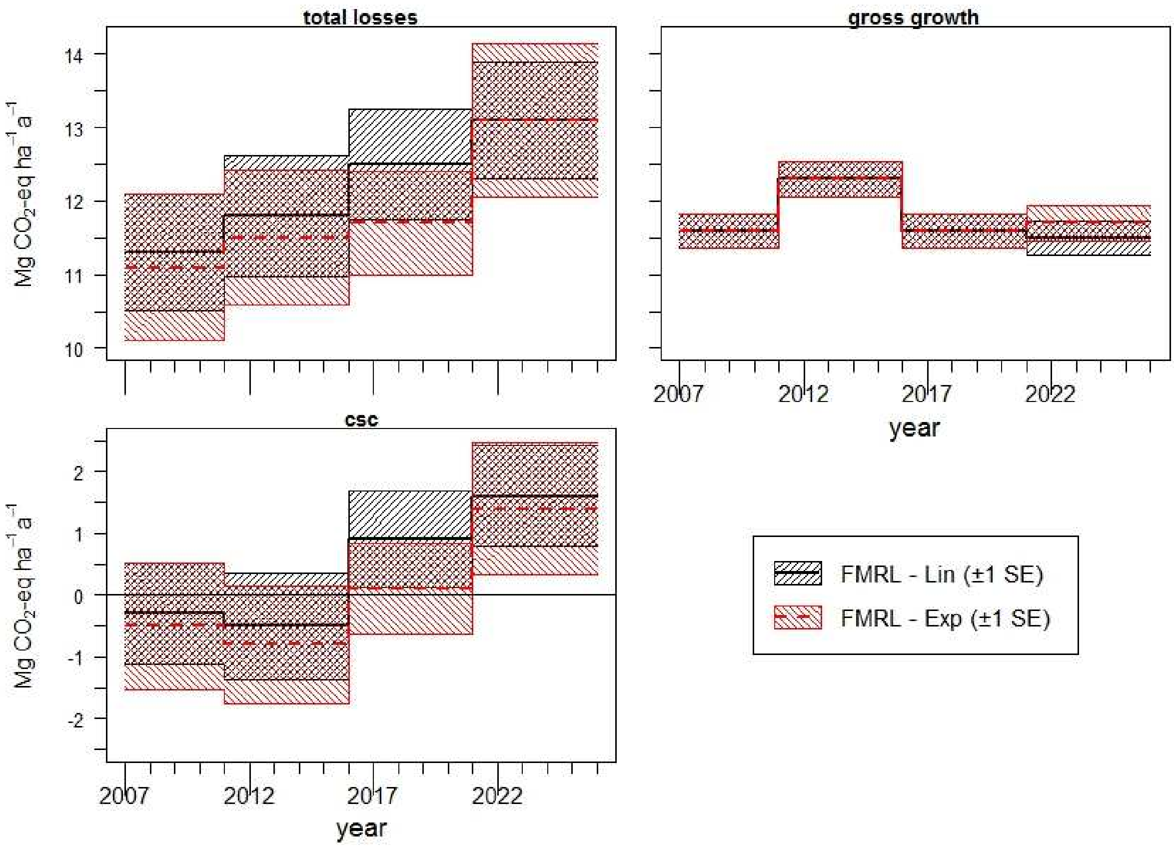

Figure 3. Carbon losses (total losses), gains (gross growth) and carbon stock changes (CSC) of living biomass in Swiss forests simulated with Massimo for two different pathways of the BAU-scenario (linear or exponential increase with storm).

Table 5. Mean CSC over the period 2013-2020 in the living biomass, CWD (deadwood), LFH and soil pools and mean total CSC for the BAU-scenario with two alternative pattern of harvest rate development: FMRL – Lin: linear development of harvest levels 2007-2026; FMRL – Exp: exponential development of harvest levels 2007-2026. Negative values indicate a sink, positive values a sink of CO_2.

	Living Biomass	**CWD**	**LFH**	**Soil**	**Total DOM and Soil**	**Total**
	Kg C ha^{-1} a^{-1} ±1SE%					
FMRL - Lin	+200.0 ±7.3%	-770.0 ±1.9%	+182.4 ±9.8%	-3.6 ±11.7%	-591.2 ±4.0%	-391.2 ±8.3%
FMRL - Exp	-350.0 ±8.3%	-692.6 ±2.1%	+153.5 ±11.6%	-3.6 ±11.5%	-542.7 ±4.3%	-892.7 ±9.3%

First results from the model simulations showed that the increase in harvest rates could not be distributed evenly among the five production regions due to the differences in forest structure with regards to, among other, dominant tree species, historic management, site type. To account for the differences in forest structure, the harvest rate in a production region may differ from the national average rate as required by the FMRL scenarios (Table 6).

Table 6. National mean increase in harvest according to the BAU-harvesting scenario with a linear or exponential pathway compared to measured harvest between NFI 2 and NFI 3. Positive values indicate an increase in harvest, negative values a decrease compared to mean harvest before 2007.

Time Period	Linear increase	Exponential increase
2007-2011	+6%	+3.0%
2012-2016	+12%	+6.0%
2017-2021	+18%	+13.0%
2022-2026	+25%	+25.0%

3.3 Deadwood, litter and soil

The dynamics in deadwood and litter dominated total CSC over the entire simulation period 1985-2026. Deadwood acted as a persistent sink as a legacy of the storm Lothar which occurred in 1999 (i.e., between NFI2 and 3). Lothar caused large scale mortality across Swiss forests. Although the majority of the felled trees were removed, the deadwood volume increased significantly. As particularly the larger sized felled trees decay slowly (Didion et al. 2014a), the storm resulted in a sustained C sink. Subsequent to the period NFI 2 to 3 (i.e., after 2006), the sink effect of deadwood increases strongly over a period of ca. 5 years until it starts to decrease again (Figure 4). This is due to the increase in C inputs from deadwood (Tab. 3).

The LFH pool alternated between source and sink, and reflects a high interannual variability (Figure 4) as the decomposition of the non-woody material proceeds fast and is highly dependent on the prevalent weather conditions. Soil acted continuously as a comparably moderate sink (Figure 4).

The difference between the results for linearly (FMRL – Lin) and exponentially (FMRL – Exp) increasing harvest rates (Figure 4) was noticeable only after a lag of ca. 6 years after the start of the time series with C inputs derived from Massimo simulations (i.e., 2007; cf. Table 3). The lag corresponds to the first time step in Massimo during which the harvest rates were still very similar (cf. Table 1). The mean CSC over the period 2013-2020 for the two simulated pattern of harvest rate development were sinks of -591.2 ±4.0% Kg C ha^{-1} a^{-1} for the linear and -542.7 ±4.3% Kg C ha^{-1} a^{-1} for the exponential development of harvest levels (Table 5).

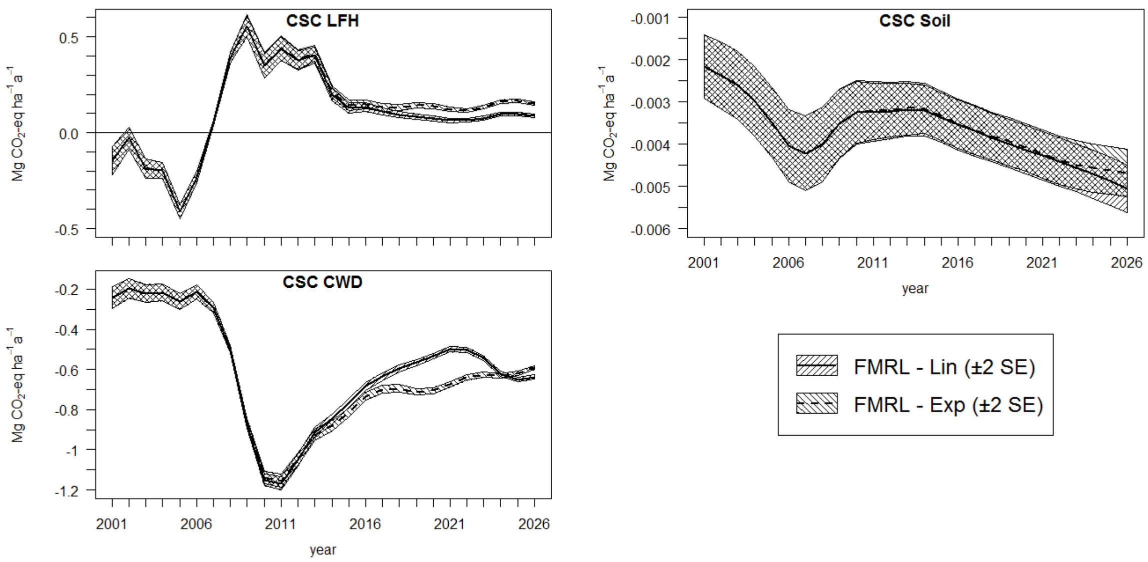

Figure 4. Carbon stock change in the deadwood (CWD), litter (LFH) and soil pool between 2011 and 2026 for observed C inputs from the Swiss NFI until 2006 and simulated C inputs from two management scenarios starting in 2007; FMRL – Lin: linear development of harvest levels 2007-2026; FMRL – Exp: exponential development of harvest levels 2007-2026.

4 Implications

The model-based approach to construct the Swiss FMRL relies on two well-documented models, i.e. Massimo (e.g., Schmid et al., 2006, Thürig and Kaufmann, 2010, Kaufmann, 2011) and Yasso07 (e.g., Rantakari et al., 2012, Ortiz et al., 2013, Didion et al., 2014a). The application of Yasso07 in GHGI reporting is well documented (FOEN 2013, Norwegian Climate and Pollution Agency, 2013, Statistics Finland, 2013, Umweltbundesamt, 2013). To ensure consistency between the results of the two models, Massimo and Yasso07 were spatially linked based on NFI plots (cf. section 2.3.4)

4.1 Living Biomass

Functional relationships in Massimo are derived from NFI data and reflect thus the heterogeneity of Swiss forests with regards to site- and stand-types as well as age-class and tree species distribution. A particular challenge is however, the reproduction of the typically extensive management of most forests in Switzerland which often varies on a small scale.

The heterogeneity of Swiss forests was also causing differences between production regions. As the productivity differs regionally, the contribution of individual regions towards achieving the national harvest target set in the FMRL needs to be considered.

In case of a linear pathway, harvesting values would be higher on average and thus result in positive balance over the period 2013-2020 (cf. Table 5). In comparison, the exponential scenario would produce a negative balance over this period. Thus, using a BAU-scenario with an exponential pathway would present a conservative way of accounting for Forest Management with FMRL (see also FOEN 2015b, Chapter 11.7.2).

Based on the comparison of NFI 4b data and model simulations with Massimo, the model is assessed to be a valuable tool to simulate short-term development of forests based on predefined management scenarios.

4.2 Deadwood, litter and soil

Yasso07 requires data on C inputs, which are estimated based on the production of non-woody and woody litter. The time series of C inputs for the Yasso07 implementation used for the Swiss FMRL is derived from observed NFI data and simulated data from Massimo 3. Therefore the temporal and spatial consistency of the C input data need to be maintained. Also, Yasso07 runs on an annual time step and requires annual inputs. The differences in the time intervals of NFI- and Massimo-data result in uncertainty in the C inputs for Yasso07 since there is the need to derive annual data. The temporal consistency of the C inputs is preserved by first, obtaining annual C inputs based on the time between two individual tree measurements (which varies in the NFI data and is 5 years in Massimo), and second, averaging C inputs over three years. The spatial consistency between Yasso07 simulations and NFI- and Massimo-data is ensured by running Yasso07 only on those NFI plots, that are common to all data sets, i.e. have been measured in all NFIs and are simulated with Massimo.

Based on the comparison between observed and simulated C stocks (Didion et al. 2014b) and the validation of simulated deadwood and litter decomposition under conditions in Switzerland (Didion et al. 2014a), the Yasso07 model can be considered to produce accurate estimates of C stock changes in deadwood, litter and soil in Swiss forests. The ability of the model to produce realistic estimates depends on the quality of the C inputs (Didion et al. 2014a). Based on Etzold et al. (2011) the functions to estimate the amount of C inputs reproduce observed data well.

4.3 Strength and limitations

The approach of coupling an empirical forest scenario model and a litter decomposition model is comparable with methodologies used in other countries (e.g., Böttcher et al. 2012). The methodology meets the requirement of completeness of the GHGI as the C balance of all relevant pools is covered. Since Massimo and Yasso07 run on the same NFI plots, spatial consistency is maintained.

While GHGIs need to be compiled annually, empirical forest scenario models typically use a time step greater than one year. Massimo and EFISCEN, which is used by most EU member states (cf. Böttcher et al., 2012) calculate forest development on 5-year time steps. Since empirical models by definition rely on observed data, the accurate representation of processes in the models is restricted to the temporal resolution of the available data.

4.4 Planned improvements

The models Massimo and Yasso07 are continuously further developed. For Massimo it is planned to improve the algorithms and assumptions (e.g. growth function, regeneration), the code, the usability and the documentation. The major aspects of the revision, which will occur over the coming years, include:

- Detailed review and revision of assumptions and implementation concerning the 5-year time step.
- Flexible implementation of natural mortality and natural disturbances.

Verification of allometries used to obtain estimates of whole tree volume and biomass, incl. branches, foliage, and roots.

Furthermore, the possibility of reporting annual gains and losses to the UNFCCC with the model Massimo and its implications to model assumptions will be discussed and analyzed. Verification of allometries will also result in more accurate estimates of C inputs for Yasso07. In addition, planned improvements for Yasso07 include:

- New model parameters which are developed at the Finnish Environment Institute and at Tampere University of Technology (http://www.syke.fi/en-US/Research__Development/Research_and_development_projects/Projects/Soil_carbon_model_Yasso/News).
- Quantifying the effect of uncertainty associated with the spatially interpolated temperature and precipitation data on CSC estimates. MeteoSwiss is currently developing ensembles of the gridded climate data that will allow to address this source of uncertainty in the simulations with Yasso07. The ensembles are expected to become available in 2016.

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