Estimating carbon stock changes in living and dead biomass and soil for the technical correction of Switzerland's Forest Management Reference Level for the Swiss NIR 2021 (1990–2019) – modeling methodology and results.

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Summary

In February 2011, Switzerland submitted its Forest Management Reference Level (FMRL) to the UNFCCC-secretariat (FOEN, 2011) for accounting of forest management on the forest greenhouse gas budget during the second commitment period under the Kyoto Protocol (2013 to 2020). The FMRL equals the projected mean annual greenhouse gas budget of the forest encompassing carbon stock changes (CSC) of living and dead biomass, mineral soil and harvested wood products (HWP) as well as non-CO2 greenhouse gas emissions from organic soils and fires for the period 2013-2020 under the assumption of a specific harvesting scenario. The quantification of CSC of living and dead biomass, litter, and mineral soils is treated in this report.

Since 2011, the technical implementation of the models used for modelling carbon stock changes in living biomass (Massimo), dead wood, litter, and soil (Yasso07) in Swiss forest have been continuously improved. In 2015 (FOEN, 2015) a first technical correction was submitted followed by a second technical correction in 2019 (FOEN 2019c).

From 2016 to 2018, the empirical forest scenario model Massimo was migrated in Java SE8 and several technical modifications and methodological improvements have been made. This has enabled us to achieve a better maintainability and reproducibility of the program code, a higher performance for more iterations, and an improved, empiric version of the regeneration. Yasso07 has been used to estimate carbon stock changes in dead wood, litter, and mineral soil in forests for the Swiss Greenhouse Gas Inventory since 2012. Major developments include improvements to accuracy, consistency, and transparency. These are documented in the annual National Inventory reports (e.g. FOEN 2019c, chapter 11.5.2.4.) as well as in the associated background reports (e.g. Didion 2020a). In 2021, Switzerland submitted a third technical correction of its FMRL (FOEN 2021, chapter 11.5.2.4). All technical changes related to this last technical correction are described in the present report.

To ensure methodological consistency between the newly implemented model version of Massimo and the historical data reported to UNFCCC, we show that the model can reproduce historical data. This newly implemented Massimo was used for simulating forest development starting from observed conditions in the third National Forest Inventory (i.e. 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 times series of carbon stock (CS) and carbon stock changes (CSC) in living biomass and to simulate the annual production of dead wood and litter. The annual estimates for dead wood and litter drove the C decomposition model Yasso07 used for estimating CS and CSC in dead wood, incl. stems, stumps, branches and roots, in non-woody litter, incl. foliage and fine roots and in mineral soils.

Switzerland's BAU for the FMRL defines an exponential increase from 2007 to the level of 8.2 million m^3 merchantable timber in the year 2020. After 2020, it is assumed that the harvesting amount remains constant (FOEN 2011). For this BAU management scenario, CSC in living biomass, dead wood, litter, and soil have been quantified with the updated models and the updated results in this report have been used for compiling and recalculating the Swiss FMRL.

Glossary

Biomass losses: Biomass removed from the living biomass includes:

- Harvest: use of trees for producing timber. It includes all merchantable timber removed from the forest.
- Mortality: trees dying due to natural causes, incl. senescence, storm, etc. Biomass normally not removed from the forest but carbon accounted under soil, litter, CWD and DOM.
- Total loss: Sum of harvest and mortality
- Merchantable timber: bole wood and branches ≥ 7 cm excluding bark and stump (*Derbholz)*

Carbon pools: Terminology follows the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (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
- Dead wood

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

- **Living Biomass**: above- and belowground compartments of alive trees;
- **Soil**: organic C in mineral soil up to a depth of ca. 100 cm;
- **Litter**: non-woody material including foliage, bark, fine roots < ca. 5 mm, and fine woody litter, including twigs and small branches <7 cm; corresponds to LFH (Litter - Fermenting - Humified) layer;
- **Dead wood (CWD)**: stemwood of standing dead trees ≥12 cm, lying dead stemwood and branchwood ≥7 cm and dead coarse roots > ca. 5 mm;
- ***Dead organic matter* (DOM)**: Term is used as defined in IPCC (2006), i.e., dead wood and litter.

Carbon stock (CS): Stock of organic carbon stored in the biomass of trees, dead wood or litter, and mineral soil, respectively. Harvested wood products (HWP) are also part of the CS, but are not included in this report.

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

Forest management reference level (FMRL): Projected mean yearly greenhouse gas budget expressed in CO_2-equivalents for 2013-2020 encompassing CSC of living biomass, dead wood, litter, mineral soil and harvested wood products (HWP) as well as non-CO_2 greenhouse gas emissions from organic soils and fires for the period 2013-2020 following the Swiss business-as-usual (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: field data collected 1983-1985; assumed to be representative of the year 1985
- NFI2: field data collected 1993-1995; assumed to be representative of the year 1995
- NFI3: field data collected 2004-2006; assumed to be representative of the year 2005
- NFI4: field data collected 2009-2017: the NFI4 is a continuous survey during which annually one-ninth of all NFI sample plots are visited; plots visited within each annual cycle provide a nationally representative sample

- Change analyses (*Veränderungsauswertungen*)

- NFI1-2: assumed to be representative of the period 1986 to 1995; the change is estimated based on all plots common to the inventories NFI1 and NFI2
- NFI2-3: assumed to be representative of the period 1996 to 2005; the change is estimated based on all plots common to the inventories NFI2 and NFI3
- NFI3-4/5 (2015-2019): assumed to be representative of the period 2006 to 2019; the change is estimated based on the plots common to the inventories NFI3 and the 3-year window 2015-2017 of the NFI4, and the plots common to the inventories NFI4 and NFI5 in the 2-year window 2018-2019

Stemwood over bark:
Volume of wood above ground from the base to the top of the stem (without the branches, but with bark) *(Schaftholz in Rinde, VMRD)*

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 rules for accounting of forest management have been changed 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 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

Switzerland's BAU for the FMRL defines an exponential increase from 2007 to the level of 8.2 million m^3 merchantable timber in the year 2020. After 2020, it is assumed that the harvesting amount remains constant (FOEN 2011). In 2015 Switzerland submitted a technical correction of its FMRL (FOEN, 2015, 2016), which addressed methodological improvements. In FOEN (2015), several planned improvements were described (chapter 11.7.8.) that would result in higher accuracy, transparency, and completeness of the Swiss FMRL. In 2019, Switzerland submitted a second technical correction of its FMRL (FOEN 2019c, chapter 11.5.2.4.). Technical corrections encompassed an improved accuracy, transparency, completeness, and usability as well as a better implementation of harvest interventions and more realistic tree regeneration. In 2021, Switzerland submitted a third technical correction of its FMRL (FOEN, 2021, chapter 11.5.2.4). All technical changes related to this last technical correction are described in the present report. Moreover, methodological consistency between the newly implemented model version of Massimo and the historical data reported to UNFCCC was shown by reproducing historical data.

Based on the IPCC guidelines (IPCC, 2014), this 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 as well as GHG-emissions from organic soils and fires are not addressed in this report. The pools of above and below-ground living biomass and its changes as well as the annual production of litter and dead wood over the period 2013-2020 were simulated with the forest management scenario model Massimo (Stadelmann et al., 2019). Pools and changes in dead wood and soil organic carbon were estimated with the soil carbon model Yasso07 (Tuomi et al., 2011; Tuomi et al., 2009), driven by the annual litter and dead wood production and annual climate data.

The report is structured as follows: The section on methods provides i) descriptions and evaluation of both applied models and model improvements implemented since FOEN (2019c),

ii) details on the Massimo model implementation to simulate the exponential increase in harvest rates to obtain a time series of CSC for the BAU-harvesting scenario, iii) resulting corrections of FMRL emissions factors. The result section presents, validates 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 modelling 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, dead wood 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 exponential increase in harvest rates

Scientific and political background documents

Switzerland's FMRL submitted in February 2011 (FOEN, 2011) is based on this business-as-usual (BAU) harvesting scenario defined in Switzerland's Wood Resource Policy 2020 (FOEN, 2008, p. 62). In this political forest management scenario the level of the "Potential Sustainable Wood Supply" (PSWS) should be exhausted until 2020 by reaching an annual harvesting amount of 8.2 million m^3 merchantable timber. Compared to historical harvesting values, this target reflects an average trend (Figure 1).

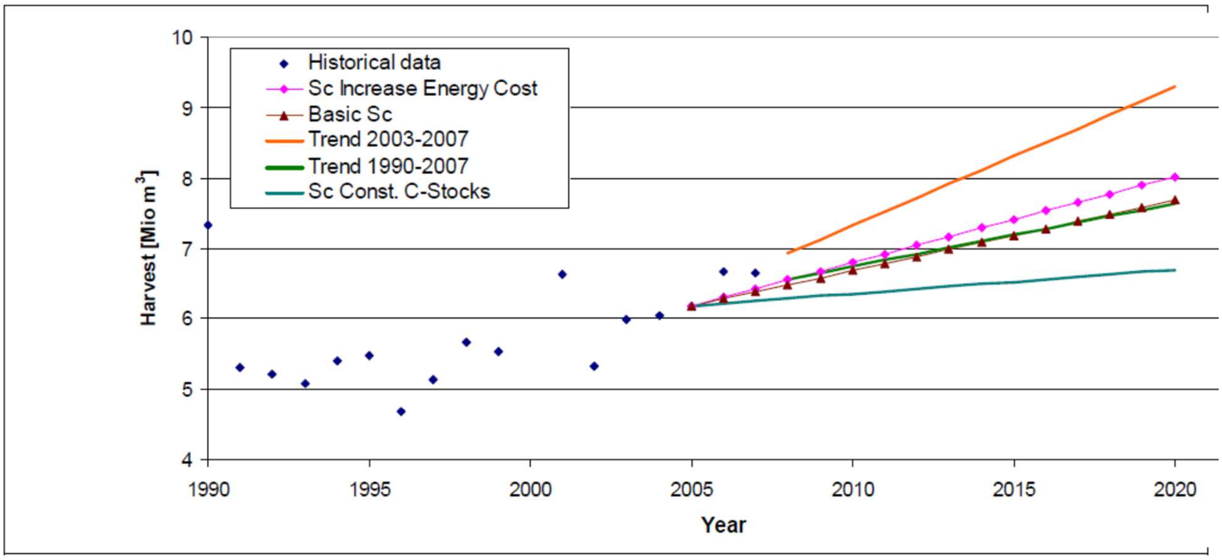

Figure 1 A comparison of future harvesting amounts until 2020 derived from linearly extrapolating historical harvesting data (Trend 1990-2007 and Trend 2003-2007) and from two scenarios from Pauli and Thees (2009) (Sc increase energy cost and basic scenario). Also the Scenario constant C-stocks) is shown. Sc – Scenario (FOEN, 2011, Fig. 6)

The harvesting target is also in the range of two scientific studies. In the first study, GeoPartner (2008) estimated a sustainable harvesting potential for Swiss forests considering gross growth data from the National Forest Inventory (NFI) 3. These results have been refined in Hofer et al. (2011) in which harvesting potentials were predicted by simulating forest development under different forest management scenarios using the individual tree growth simulator Massimo (Stadelmann et al., 2019). The second study by Pauli and Thees (2009) confirmed these results.

In the study of GeoPartner (2008), the figure 8.2 million m^3 merchantable timber can be found (S25 and Table 3-21, 8.23, of which 5.27 million m^3 coniferous wood and 2.96 million m^3

broadleaves). Figure 2 on page 211 of Hofer et al. (2011) shows that this total harvesting amount is very close to scenario (A) "constant growing stock" in 2026.

In FOEN (2011), the pathway of reaching the target value was not defined. In the technical correction in 2015, an exponential pathway has been used for calculation of Switzerland's FMRL (FOEN 2015). This reflects the fact 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 effect at the end of the commitment period. Applying this exponential pathway has the following advantages:

- Using a BAU-scenario with an exponential pathway for calculating the FMRL results in a more conservative accounting of Forest management than a linear pathway. In case of a linear pathway, harvesting values would be higher on average because of higher losses in living biomass.
- The exponential pathway better reflects reality than the linear pathway, especially since harvesting rates have declined starting in 2009 due to the worldwide, unforeseen financial crisis.

From this, it is concluded that Switzerland's BAU harvesting scenario is not changed, neither are the policy assumptions. The increase in harvest of to 8.2 million m^3 merchantable timber in 2020 remains as defined in FOEN (2011). To reach this target, the increase in harvest follows an exponential pathway.

Assigning merchantable timber to sawn-wood, industrial wood and energy wood

In Switzerland's Wood Ressource Policy 2020 (FOEN, 2008, p. 62) the targeted annual harvesting amount of 8.2 million m^3 merchantable timber was defined as “sales measurement of forestry statistics plus statistically unrecorded quantities such as cut imputations (Zumass), bark, and non-recorded minimum quantities in private forests“. In the NFI and in the model Massimo merchantable timber corresponds closely to “merchantable timber including stem and branches >= 7 cm” (cmcomm). However, Switzerland's Wood Ressource Policy 2020 (FOEN, 2008) does not further specify the division of merchantable timber into further use of wood. As a consequence, for the Swiss BAU-scenario it remains unclear, how the total amount of 8.2 million m^3 merchantable timber should be distinctly assigned to sawn-wood, industrial wood and energy wood. For reporting to the UNFCCC and the Kyoto Protocol, the Federal Office for the Environment (FOEN) applies mean distributions from the harvesting statistics 2005-2009 (FOEN, 2019a, b) to assign total harvesting amounts from NFI and the model Massimo to the assortments sawn-wood, industrial wood and energy wood.

2.2 Living Biomass: Massimo

2.2.1 Model description

Massimo is an empirical, stochastic and dynamic individual-tree simulator that was developed to run on the common grid of sample plots within the productive forest (no shrubs) of two consecutive Swiss NFIs (Stadelmann et al., 2019; Stadelmann 2020). In the current version of Massimo, the initialized grid encompasses measures of the second (NFI2: 1993-1995; Brassel et al., 1999) and the third NFI (NFI3: 2004-2006; Brändli et al., 2010) resulting in a common grid of 5086 sample plots in the productive forests. After loading tree- and plot-level data from the NFI data base the program reads the files containing specific settings for simulation scenarios (e.g. harvest restrictions, regulation of species mixture, harvesting targets etc.; for more details cf. Stadelmann et al. (2019). Sub-models of Massimo are distance-independent and demographic processes (growth, mortality and ingrowth) were empirically fitted with data from the Swiss NFI. Massimo was originally implemented in SAS® and has recently been migrated to Java SE 8 (© Oracle, Redwood Shores, CA, USA).

We used the Java implementation of Massimo to simulate the corrected BAU scenario. Main advantages of the new software are, (i) better replicability of the program codes, (ii) full reproducibility by archiving program code together with scenario settings and simulation results, and (iii) higher performance of Massimo, which allows to simulate more replicates of a scenario. Besides technical optimizations of Massimo, we are further developing demographic processes (growth, mortality and regeneration) in a climate sensitive manner, but only the improved version of regeneration was applied for the simulation of the corrected BAU scenario.

We replaced the former mortality model by a more plausible formulation with mortality depending from tree species, basal area and diameter at breast height (dbh) as a quadratic term (for details cf. Stadelmann et al., *in review*). The current mortality model accounts for density dependent (i.e. increasing basal area results in increasing mortality) and age dependent mortality (i.e. the U-shaped dependence on dbh shows both, large mortality in the self-thinning phase as well as for old trees). Further, the mortality model performed well with the simulated mortality being close to the historically measured mortality rate of 16.39%.

The former simulation of regeneration was based on observed regeneration subplots that were assumed to be constant over time. This, however, lead to strongly varying ingrowth rates over time (Temperli et al., 2017) and conifer proportions in the regeneration were overestimated. By not simulating regeneration pools but directly simulating ingrowth (i.e., trees growing over the 12 cm caliper threshold of the Swiss NFI), we now simulate the number, diameter and main tree species based on stand, site and environmental characteristics (Zell et al., 2019).

2.2.2 Model evaluation

To test the accuracy and the consistency of Massimo, we compared model predictions against independent forest development data. The forest model, driven by empirical measurements, should be able to reproduce gains and losses, when targeting current measured values for growing stock. To this end, we initialized Massimo with measured NFI data and targeted observed growing stocks after a model run over ten years. Predicted gains and losses were then compared to observed measures of the fourth Swiss NFI. Slight differences may occur because the simulation of forest management and disturbances will not harvest and kill, respectively, the identical trees as observed in reality. Further, forest management and disturbances do not remain exactly constant over the years.

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

The Swiss BAU aims at (i) reaching the given harvesting target in 2020, and (ii) an exponential increase of harvesting possibly being realized in all regions of Switzerland. Total harvesting amount was assumed to increase exponentially from 2007 to the level of 8.2 million m^3 merchantable timber in the year 2020. After 2020, harvesting amount was assumed to remain constant (Figure 2).

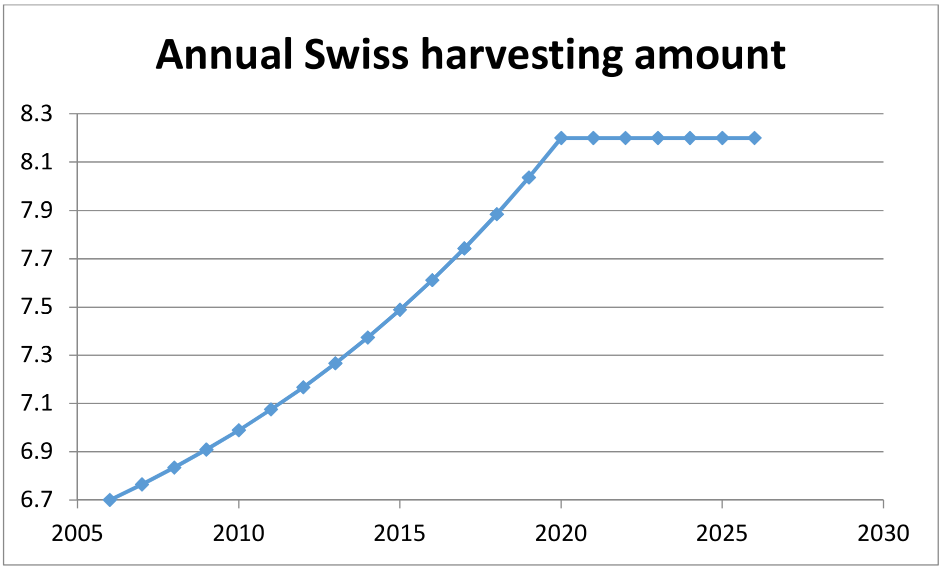

Figure 2 BAU scenario of annual harvesting amount in Mio m^3 merchantable timber.

The value 6.7 million m^3 merchantable timber was assumed as the initial harvesting value for the year 2006. This value is derived from NFI data (Abegg et al., 2014). Between 1996 and 2006, 6.1 million m^3 merchantable timber was harvested per year on the common, accessible forest area of NFI 2 and 3. Between NFI 2 and 3, the mortality due to the storm Lothar made up 22% of total cut and mortality. For future forecasts, this extreme mortality was normalized to the empirical values of 14% mortality by correcting the initial harvesting.

6.1 Mio m^3 merchantable timber /(100-22)*(100-14) = 6.7 Mio m^3 merchantable timber

As Massimo runs with a time step of 10 years, the annual increase in harvesting amounts had to be converted to time steps of 10 years each. Given the initial values of 6.7 Mio m^3 merchantable timer, this results in an increase of 7% of harvesting of merchantable timber in the first decade from 2007 to 2016, and 21% in the second decade from 2017 to 2026.

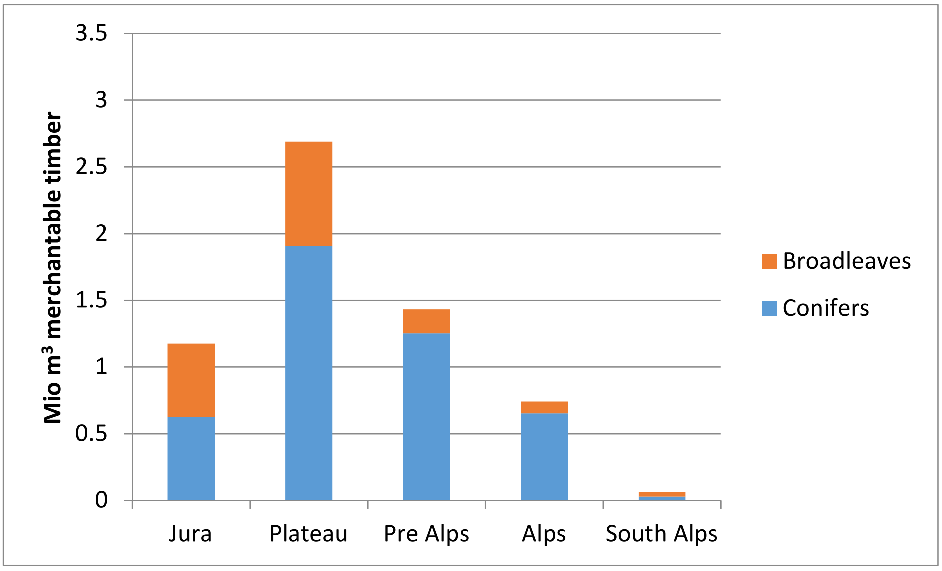

Figure 3 Annual harvesting amount from the common accessible forest area between NFI 2 and 3 (Abegg et al. 2014).

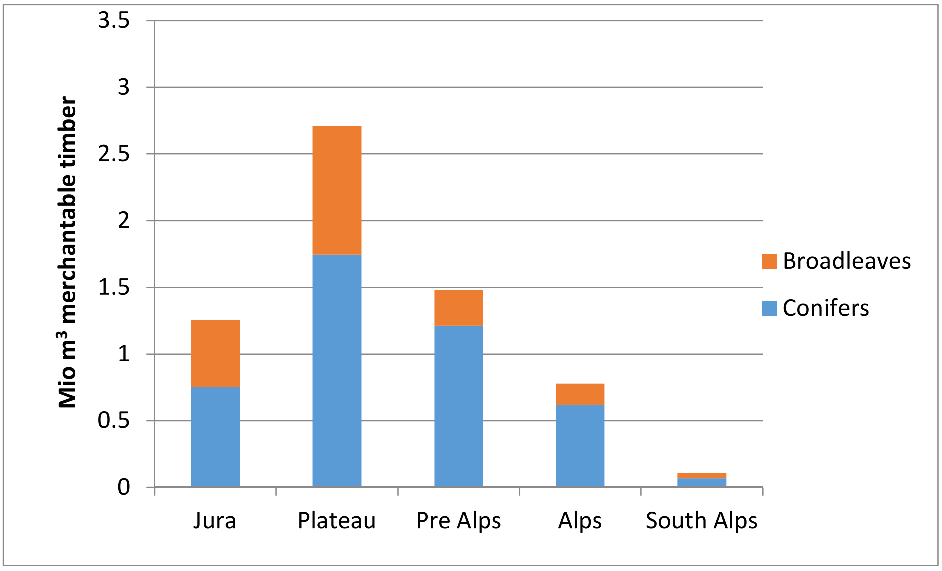

Figure 4 Annual harvesting amount from the common accessible forest area between NFI 3 and 4 (2009-2017, Brändli et al. 2020).

In the model simulations, these increases in harvesting of merchantable timber could not be implemented equally in all regions as the initial situation set by NFI 3 in 2006 set limits to the availability of coniferous wood in the different regions. The simulated model results for the years 2007 to 20016 can be evaluated with the independent empirical data of NFI4. NFI 4 data show that in the Plateau, the empirical harvesting amount of conifers already decreased in the last decade (Figure 3 and Figure 4). This is in parallel with a decreasing growing stock of conifers in the Plateau because harvesting of conifers already exceeds its increment (Rigling, 2015, page 33 and 60). While the Plateau remains the largest provider of coniferous timber (Figure 4), an additional increase would pose a serious threat to sustainability of forest development.

Thus, simulated harvesting in the Plateau could only be intensified by markedly increasing the harvesting amount of broadleaves leading to a remarkable increase of broadleaf proportion in the total amount of harvested timber. This increase was especially pronounced by the fact, that merchantable timber of broadleaves contains a notable amount of branch-wood. This percentage increases with increasing dbh resulting in 15% to 60% branch-wood for trees larger than 50 cm dbh (Figure 5).

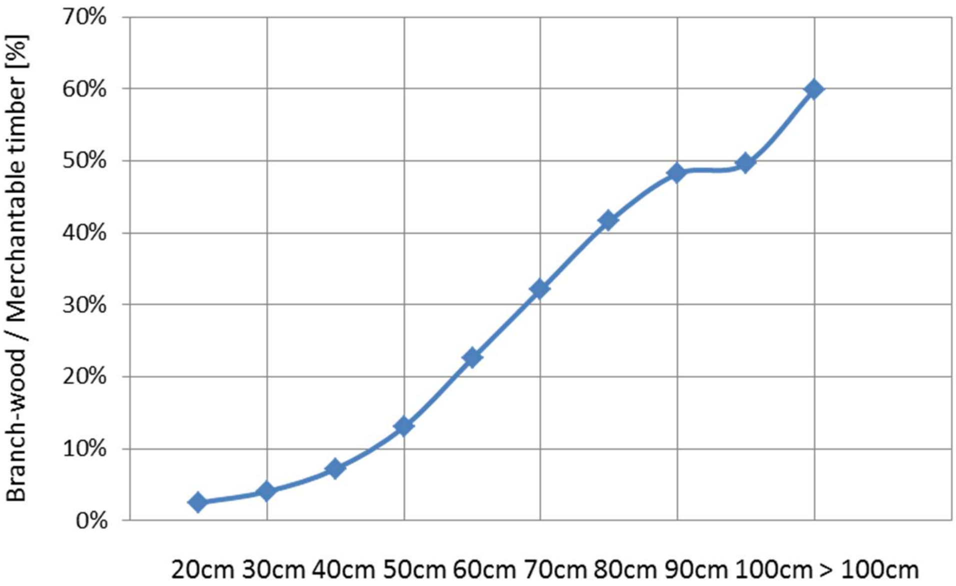

Figure 5 Percentage of branch-wood for growing stock of broadleaves, stratified for dbh classes. Data from NFI4 (2009-2017)(Brändli et al., 2020).

A huge percentage of growing stock is stored in trees thicker than 52 cm dbh (Figure 6). As Massimo aims at harvesting thickest trees first, increased harvesting on the Plateau leads to an increased harvesting amount of large broadleaves. This leads to a drastic increase in both the proportion of broadleaves in the merchantable timber and consequently also the proportion of branch-wood. A proportion of 50% broadleaved timber however does not correspond to recent harvesting statistics with a percentage of broadleaved timber of approximately 33% (Rigling, 2015, p. 63).

In practice, it can be assumed that not all harvested branches are removed from the forest but remain in the forest as dead wood. However, the exact amount of branches that are removed from the forest is highly variable. We therefore simulated three different scenarios of branch-wood removal. 1) all branches left in the forest (0% removed; -0.08 Mt CO_2), 2) 35% of branches were assumed to be removed and sold on the market (0.73 Mt CO_2), 3) all branches of harvested trees were removed (100% of branches removed from the forest; -1.13 Mt CO_2). Approximated by recent harvesting statistics (FOEN, 2019b) it was assumed that 35% of all branches of deciduous trees are removed from the forest.

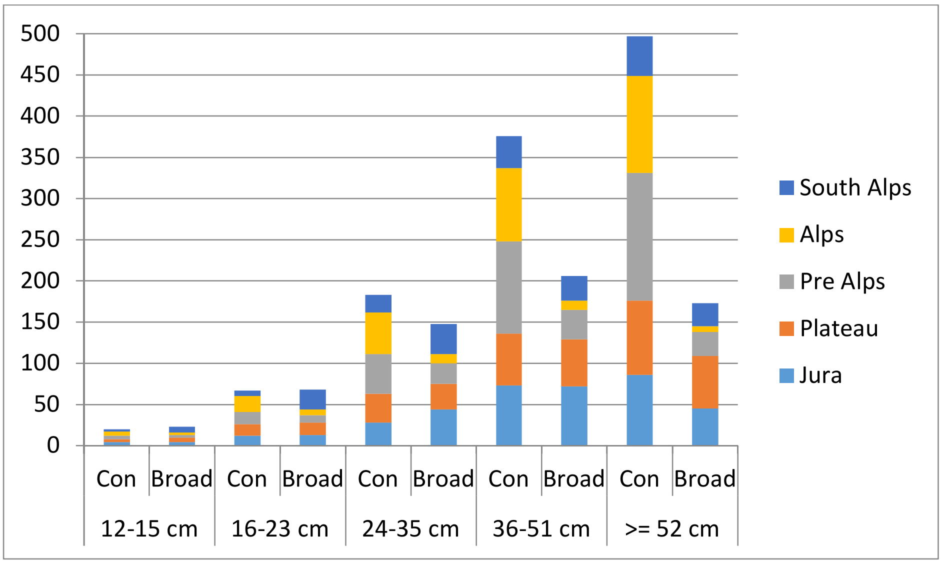

Figure 6 Growing stock in m^3 stem-wood over bark per ha, stratified for production region and dbh classes. Data from NFI4 (2009-2017)(Brändli et al., 2020).

To follow the assumptions met in the BAU scenario, the increase of harvesting amount to 8.2 million m^3 merchantable timber can only be realized by further intensifying harvesting in other regions than the Plateau.

For all three scenarios, mortality was adjusted to 16.34% of the merchantable timber lost per year. This corresponds to the so-called "background level for natural disturbances".

The new implementation of Massimo does not yet distinguish forest reserves. However, according to GeoPartner (2008[1], p. 18) this affects 15'509 ha or approximately 1.2% of the forest area.

2.3 Dead wood, litter and soil: Yasso07

The C decomposition model Yasso07 (Tuomi et al., 2011; Tuomi et al., 2009) was used for deriving estimates of carbon stock change in dead wood (incl. stems, stumps, branches and roots), litter and in mineral soils on productive forest lands following the methodology applied in the current Swiss greenhouse gas inventory (Didion 2020a).

2.3.1 Model description

Yasso07 (Tuomi et al., 2011; Tuomi et al., 2009) is a model of C cycling in mineral soil, litter and dead wood. The model was developed for general application with low parameter and input requirements. For estimating stocks of organic C in mineral soil up to a depth of ca. 100 cm and the temporal dynamics of the C stocks, Yasso07 requires annual litter and dead-wood information. This includes C inputs from dead organic matter components (i.e., non-woody inputs, incl. foliage and fine roots, and woody inputs, incl. standing and lying dead wood and dead roots) and climate (temperature, temperature amplitude and precipitation). Decomposition of the different components of C inputs is modeled based on their chemical composition, size of woody parts and climate (Tuomi et al., 2011; Tuomi et al., 2009). Decomposition rates of insoluble (N), soluble in ethanol (E), in water (W) or in acid (A), flow rates of C between these four compartments, flow rates to a more stable humus compartment (H) and out of the soil (Tuomi et al., 2011 Fig. 1) were derived from a global data set (Tuomi et al., 2011; Tuomi et al., 2009). Parameters defining C decomposition rates and C cycling between carbon compartments of Figure 7 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.

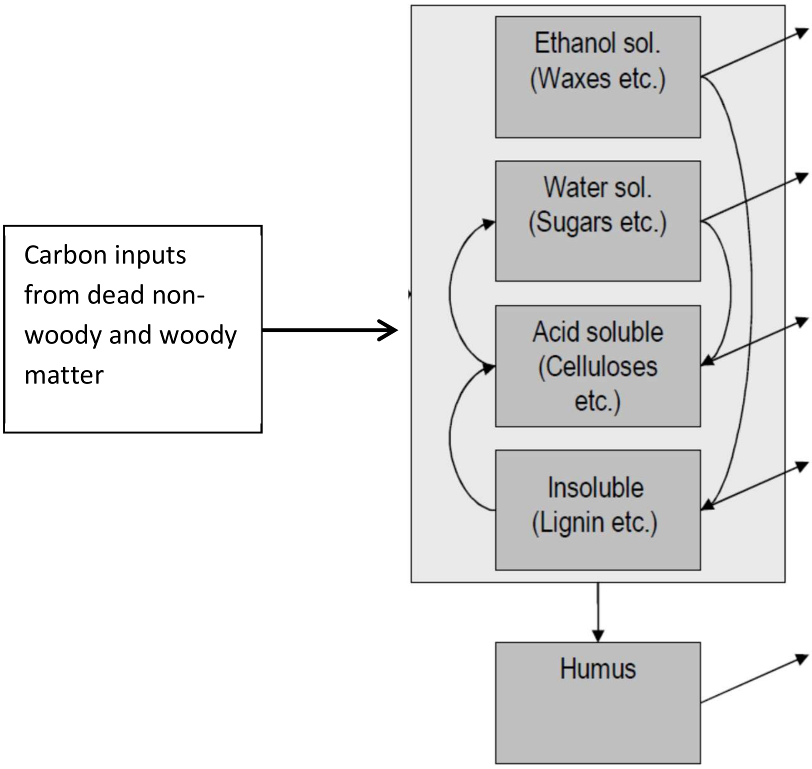

Figure 7 Flow chart of Yasso07 soil carbon model. The boxes represent soil carbon compartments, the arrows carbon flows; only those carbon flows are shown that deviate significantly from zero, adapted from Liski et al. (2009).

2.3.2 Continuous model development for application in Switzerland

In Switzerland, the Yasso07 model was first applied to estimate C stocks and C stock changes for the Swiss GHG inventory 2013 (FOEN, 2013) and its implementation on lands with productive forests in Switzerland was described in detail in Didion et al. (Didion et al., 2014). The model and its application in the context of the Swiss GHG inventory has been continuously improved since the first application (Didion 2020a, ch. 2.4).

Compared to the model version used in the technical correction of Switzerland's FMRL submitted in 2019 (FOEN, 2019c), no changes relevant for the FMRL simulation were made.

2.3.3 Model evaluation

The model was evaluated for conditions in Switzerland by Didion et al. (2014) who found that Yasso07 reproduced observed C losses in dead wood and litter very accurately. Considering that simulated and measured C stocks are not fully comparable (e.g. regarding the contribution of understory vegetation to litter production), simulated stocks are plausible (Didion 2020a).

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

For the purpose of estimating C stock changes in dead wood, litter and soil for constructing the Swiss FMRL, Yasso07 was applied following the same methodology as used in Switzerland's Greenhouse Gas Inventory 1990–2019 (FOEN, 2021). Because data on litter production from 2007 onward are obtained from the Massimo model, data from only 5096 plots of the Swiss national forest inventory (NFI) could be considered for the FMRL compared to 5866 plots considered for the Swiss GHG inventory (Didion 2020a, Tab.1). Since the plots that could not be considered for the FMRL consist primarily of degraded forests with little biomass such as found in forest aisles and embankments, dead wood and litter on these plots is negligible.

Apart from the difference in the NFI plots, the resulting time series from 1990 to 2006 for C stocks and C stock changes in dead wood, litter and soil is the same for the FMRL and the GHG inventory. The methodology is explained in detail in chapter 2.3 in Didion (2020a) and considers plot-specific historic forest cover changes since 1880 and climate since 1961. Dead wood and litter production on individual plots is estimated based on NFI data for the period 1986 to 2006. Starting 2007 the simulations were continued with projected C inputs obtained from Massimo.

The model parameters identified by Didion et al. (2014) 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 10 randomly sampled C input time series and 10 randomly sampled parameter vectors, i.e. a total of 100 replicate simulations.

The Yasso07 release 1.0.1 was used in this report. More information and the source code are available on https://code.google.com/archive/p/yasso07ui/source/default/source. The Yasso07 Fortran source code was compiled for the Windows10 operating system. The statistical software R (R Core Team, 2018) version 3.5.1 (64 bit) was used for administrating the Yasso07 simulations.

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, 2016a, b).

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

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

For simulating the C balance in dead wood, litter and soil based on C inputs for the Swiss FMRL until 2026, observed climate data were used until the end of 2019. For the years 2020 to 2026, constant temperature and precipitation corresponding to the mean over the norm=period 1981-2010 were assumed.

2.3.4.2 C inputs

Estimates of C inputs for the simulations with Yasso07 were derived from observed (until 2006) and simulated (2007 onwards) data on NFI sample plots. Dead wood and litter production was estimated separately for coniferous and broadleaved tree species. On plots with forest cover, C inputs included

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

On temporarily unstocked plots occurring in the period 1880-2006 (i.e. before dead wood and litter production was estimated based on Massimo data), annual above-ground C inputs were estimated based on data from Didion et al. (2020b) and described in chapter 2.3.2 in Didion (2020a).

On forested plots, the annually accumulating mass in these DOM components was derived through allometric relationships to the volume of living standing and removed (harvest and mortality) trees (Thürig et al., 2015) and specific lifespans of tree tissues (Thürig et al., 2005). 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, 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 six DOM components: 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.

The plausibility of estimates of dead wood and litter production obtained from Massimo simulations was evaluated for the period 2007-2016 based on data compiled for the Swiss GHG inventory 1990-2017 (Didion 2020a; FOEN, 2021), derived from observations on NFI sample plots between NFIs 3 and 4 and 5, respectively (cf. ch. 2.3.1 in Didion 2020a). Compared to estimates based on observations, Massimo-based predictions differed for the non-woody litter and dead wood pools (Figure 8). These deviations are reasonable because harvesting intensity expected for the FMRL and simulated with Massimo is higher than observed intensity (see section 2.2.3); higher harvesting rates result in fewer trees that produce non-woody litter (foliage and fine roots) and increase amounts of residuals, stumps, and coarse roots of harvested trees to decay.

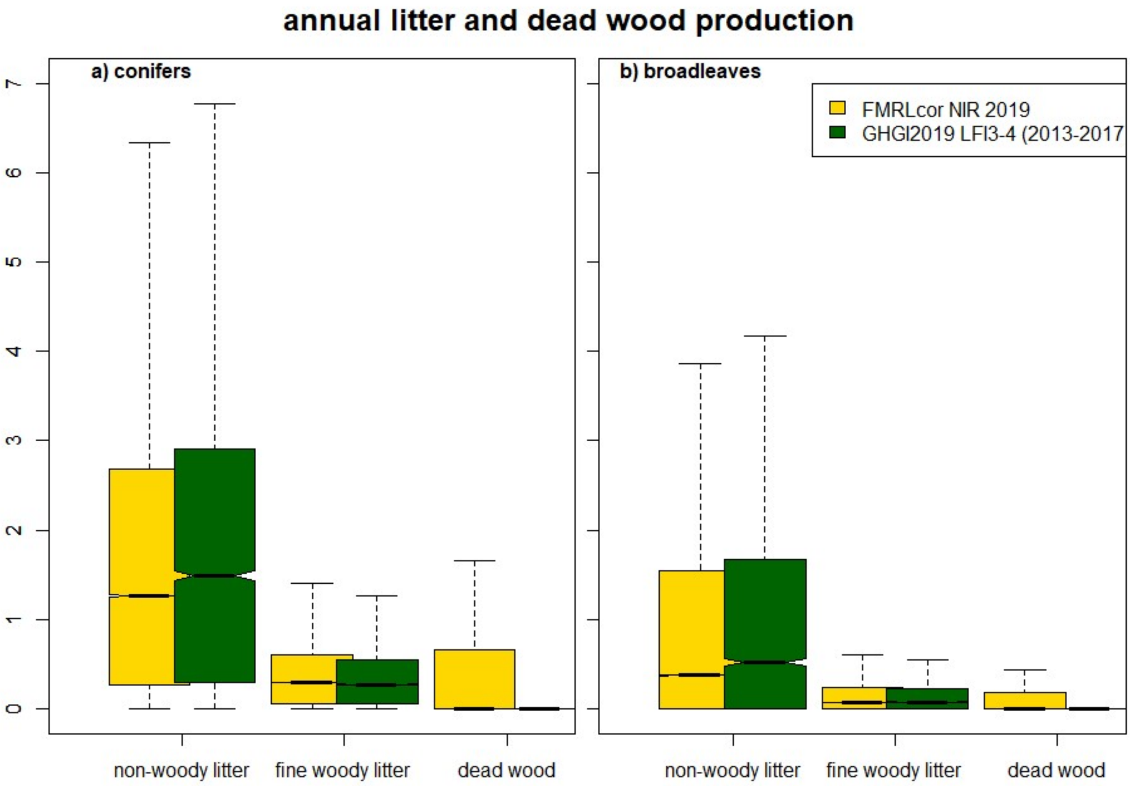

Figure 8 Annual litter and dead wood production of coniferous and broadleaved trees estimated for the period 2007-2016 based on Massimo simulations of forest development (FMRLcor NIR 2021) and as estimated for the Swiss GHGI inventory reported in the NIR2021 (GHGI NIR 2021 LFI3-4/5 (2015-2019). Data for non-woody and fine woody litter, and for dead wood for Massimo are based on data from 5086 NFI sample plots and for the GHGI NIR 2021 LFI3-4/5 (2015-2019) on 3221 sample plots (Didion 2020a, ch. 2.3.1).

3 Results

3.1 Evaluation of the Massimo model version for the FMRL with historical data

The new implementation of Massimo was validated by comparing the simulated results to historically observed data for growth rates (gross growth including ingrowth, GGI) and losses (harvest and mortality). To this end, we ran a simulation starting from NFI3 (2004-2006) that targeted to reach observed growing stocks of NFI4c (2014-2017) after one simulation timestep of 10 years. At national scale (Switzerland), we found no significant differences neither in gains (GGI) nor in total losses (Figure 9). At the regional scale, we found no significant differences in gains, neither. However, losses differed in two economic regions, namely Central Alps and Southern Alps. In general, Massimo tended to underestimate GGI, while overestimating the total losses. Nevertheless, since predictions at the national scale did not differ significantly from historical data, the Massimo suits to model the FMRL scenario and to simulate plausible values for gains and losses on a Swiss scale. As NFI4c (2014-2017) data were not used for model calibration, this is an independent model validation. The validation showed that the model Massimo is assessed as a valuable tool to simulate short-term development of Swiss forests based on predefined management scenarios.

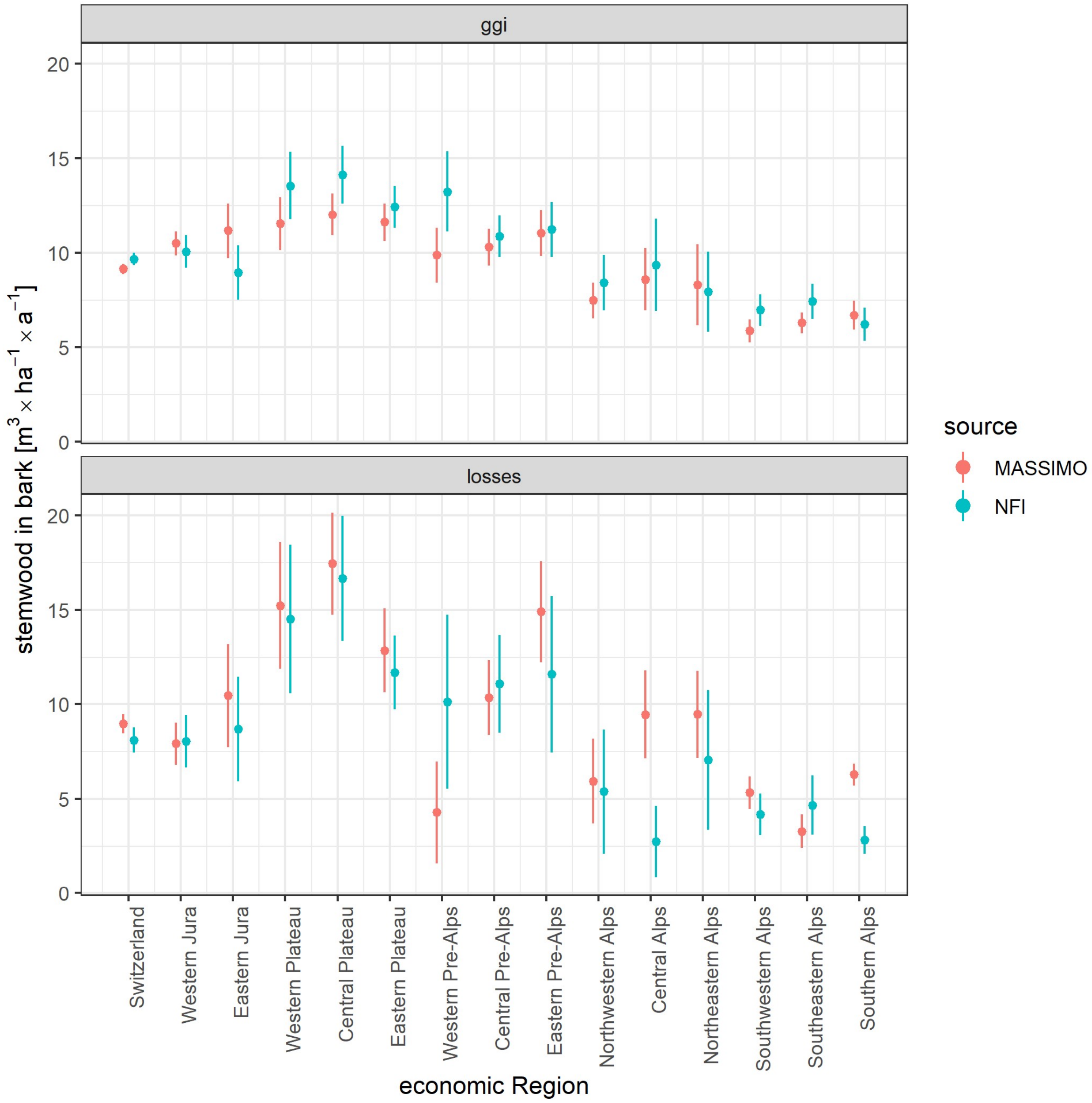

Figure 9 Validation of simulation results per economic region of Switzerland. The point and interval plots indicate mean ± 1.96×SE (Standard Error) of simulation Results (red) and NFI observations (blue). Not overlapping intervals indicate significant differences between simulation and observation.

3.2 FMRL scenario on the national scale

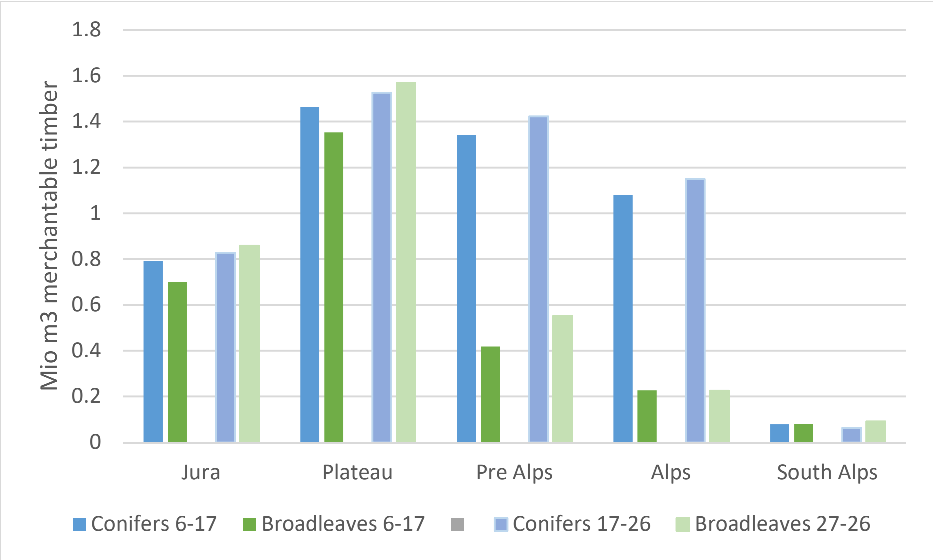

Figure 10 Total harvested amount per year in merchantable timber 2007-2016 (dark colors) and 2017-2026 (light colors) simulated with Massimo and the scenario 8.2 exponential in 2020. Total over Switzerland for 2007 to 2016 is 7.6 Mio m3 merchantable timber per year and 8.3 merchantable timber per year for the years 2017-2026.

The assumptions of the scenarios were followed well. The simulated harvesting amount increased from the empirically measured 6.7 Mio m3 merchantable timber in the year 2006 to 7.6 Mio m3 merchantable timber between 2007 and 2016 and were further simulated to increase to 8.3 for the years 2017 to 2026. The empirically observed shift of the harvesting amount towards cutting more broadleaved trees continued in the simulated scenario. Therefore, the percentage of harvested broadleaved trees in the Jura and the Plateau increased. In the Pre-Alps and Alps, the amount of both the coniferous and the broadleaved trees harvested could be slightly increased. However, a further increase would cause significantly larger harvesting costs due to a lower accessibility.

3.3 FMRL emission factors for living biomass

Table 1 shows the emission factors of growing stock, gains and losses applied in FOEN (2021). The increasing harvesting amount led to an increase in total losses from 11.1±0.24 Tons CO_2 per ha and year between 2007 to 2016 to 12.0±0.32 Tons CO_2 per ha and year simulated for the years 2017-2026.

Table 1 Emission factors simulated with Massimo and the BAU scenario 8.2 exponential in 2020 (WSL data delivery from October 2020 to FOEN. All values are given in Tons CO2eq per ha. Gains and losses are reported per year.

Simulated time period	**Growing stock Tons CO2 / ha**	**Gains Tons CO2 / ha and year**	**Losses Tons CO2 / ha and year**
2007-2016	458±4.5	12.4±0.1	11.1±0.24
2017-2026	452±4.8	11.4±0.1	12.0±0.32

3.4 Dead wood, litter and soil

The complete set of result tables of C stock and CSC in the pools dead wood, litter, and mineral soil that were prepared for this technical correction of Switzerland’s Forest Management Reference Level can be found in Appendix I. Compared with the technical correction of Switzerland's FMRL submitted in 2019 (FMRLcor 2019; FOEN, 2019c), the current technical correction (FMRLcor 2021) results initially after 2006 in higher total removals and lower or similar removals after 2017 (Figure 11). Table 2 shows the mean emission factors for the three pools and their total estimated for the two technical corrections for the second commitment period as well as for the years 2013 to 2019 based on the GHGI data reported in the NIR 2021 (FOEN 2021).

	FMRLcor 2019		FMRLcor 2021		GHGI NIR2021	
Pool	mean	2 SE	mean	2 SE	mean	2 SE
	Mg CO_2 eq ha^{-1} a^{-1}	%	Mg CO_2 eq ha^{-1} a^{-1}	%	Mg CO_2 eq ha^{-1} a^{-1}	
Soil	-0.010	8.8	-0.010	9.2	-0.010	14.9
Litter	0.021	280.6	0.019	307.6	0.040	94.5
Dead wood	-0.774	23.8	-0.759	26.9	-0.152	31.2
Total	-0.764	23.7	-0.751	28.1	-0.121	50.7

Table 2. Mean (Mg CO_2 eq ha^{-1} a^{-1} ± 2SE) emission factors (pos. value indicate a source, neg. values a sink) for dead wood, litter, and mineral soil pools and their total over the 2nd commitment period 2013-2020 of the Kyoto Protocol for the technical correction of Switzerland's FMRL submitted in 2019 (FMRLcor 2019; FOEN 2019c) and this technical correction (FMRLcor 2021; FOEN 2021) in addition to the estimates based on measured data for the GHGI 1990-2019 reported in the NIR 2021 (FOEN 2021).

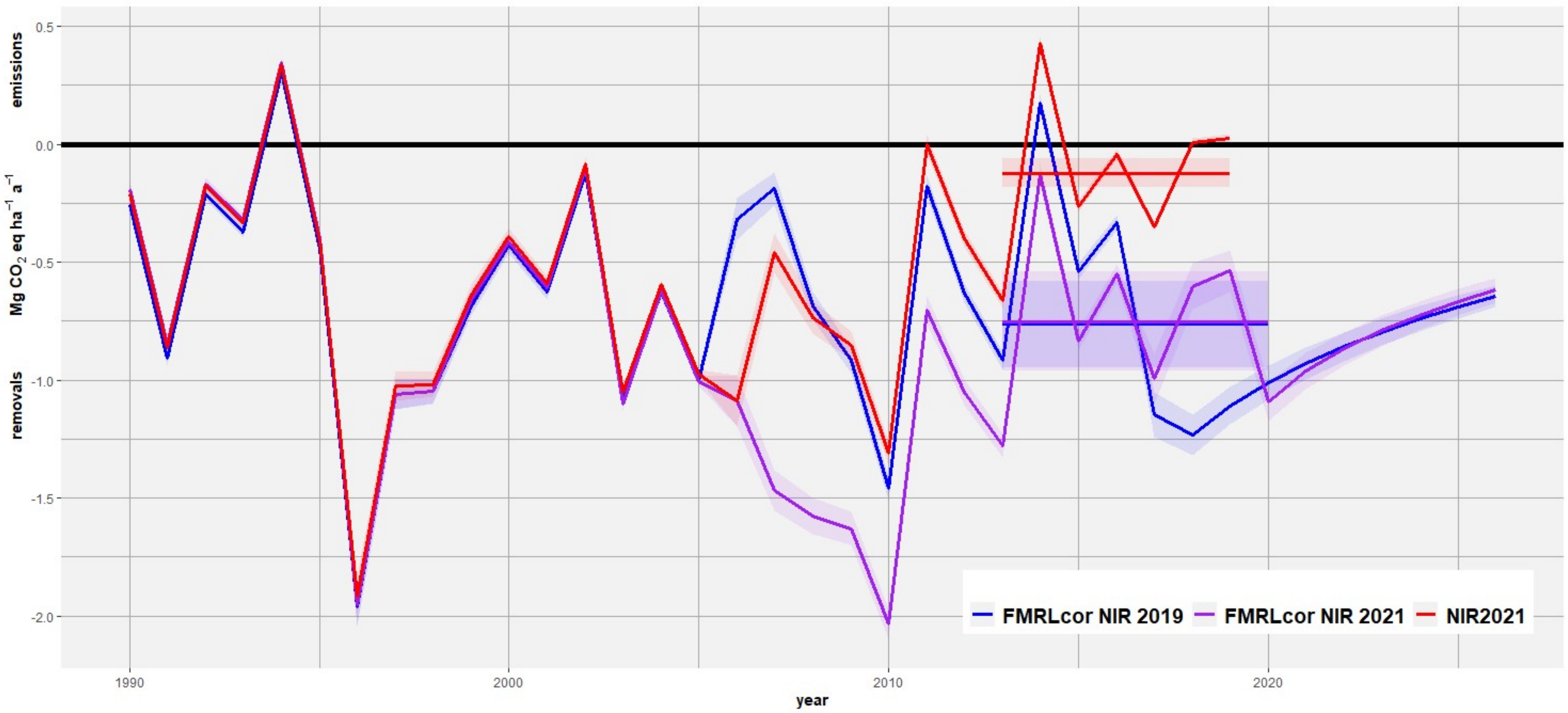

Figure 11 Mean (Mg CO_2 eq ha^{-1} a^{-1} ± 2SE) annual total emissions (pos. value) and removals (neg. values) from dead wood, litter, and mineral soil pools in productive forests between 1990 and 2026 and mean emissions/removals for the 2nd commitment period 2013-2020 of the Kyoto Protocol for the technical correction of Switzerland's FMRL submitted in 2019 (FMRLcor 2019; FOEN 2019c) and this technical correction (FMRLcor 2021; FOEN 2021) in addition to the estimates based on measured data for the GHGI 1990-2019 reported in the NIR 2021 (FOEN 2021)

4 Implications

The model-based approach to construct the Swiss FMRL relies on two well-documented models, i.e. Massimo (Stadelmann et al., 2019) and Yasso07 (Didion et al., 2014; Ortiz et al., 2013; Rantakari et al., 2012). The application of Yasso07 in GHGI reporting is well documented (Didion 2020a). 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 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, except for the HWP-pool or other sources like emissions from organic soils or fires which are not covered in this report. 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 to 10-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.

Our analysis showed that the calculated carbon budget of the Swiss forest reacts sensitively to the proportion of broadleaves of the harvested merchantable timber. However, the amount of branches that are removed from the forest is on the one hand highly variable. On the other hand, harvesting statistics and the NFI data indicate that the total amount of broadleaved timber does change over time. Therefore, either the percentage of harvested broadleaved timber should be fixed based on harvesting statistics or the amount of branches removed from the forest should be determined in more detail.

4.2 Planned improvements

The models Massimo and Yasso07 are continuously further developed. For the Massimo model, it is planned to further improve the algorithms and assumptions. The major aspects of the revision, which will be implemented in Massimo over the coming years, include:

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

- Fix the proportion of broadleaved merchantable timber in the total harvesting amount, either by fixing it to values from most recent harvesting statistics, or by a better estimation of branches that are removed from the forest.
- Forest reserves will be distinguished and forest management will be reduced or even stopped.
- The implementation of mortality will be further improved by fitting empirical models to NFI data.

Verification of allometries will also result in more accurate estimates of C inputs for Yasso07. In addition, planned improvements for Yasso07 include:

- Improving the completeness of the litter inputs by accounting for the contribution of litter from the trees <12 cm dbh and from the herb- and shrub layer. This extends on the study by (Didion 2020b) which provided a consistent methodology to obtain estimates of above-ground biomass of plants in the herb- and dwarf shrub layer on NFI sites. These activities will improve the accuracy of the simulated estimates (planned for the first submission (GHGI 2023) under the Paris agreement).
- Review of the litter production estimates, including turnover rates (planned for the first submission (GHGI 2023) under the Paris agreement).
- Improving the uncertainty estimates for litter production by revising allometries and by estimating tree compartments using a Monte-Carlo approach. This is expected to improve the accuracy of the estimates of C stocks and C stock changes (planned for the first submission (GHGI 2023) under the Paris agreement).

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Appendix I: Data on dead wood, litter, and mineral soil prepared the technical correction of Switzerland's Forest Management Reference Level 2021

Table A-1. List of result tables that were included in the data delivery from 14.10.2020. The associated Excel file presents the relevant data based on averaged annual stocks and stock changes.

Table	Content	Unit
CWDha_csc	Mean CSC in coarse woody debris	Annual C stock change [Mg C $ha^{-1}a^{-1}$]
LFHha_csc	Mean CSC in LFH layers ('organische Auflage')	
SOCha_csc	Mean CSC in soil	
ALLha_csc	Mean CSC over ALL pools	
CWDha_csc_SE	Standard error CSC in coarse woody debris	
LFHha_csc_SE	Standard error CSC in LFH layers ('organische Auflage')	
SOCha_csc_SE	Standard error CSC in soil	
ALLha_csc_SE	Standard error CSC over ALL pools	
CWDha_stocks	Mean C stock in coarse woody debris	Annual C stock [Mg C ha^{-1}]
CWDha_stocks_SE	Standard error C stock in coarse woody debris	

NOTE:
1) The following strata were combined due to a low number of sites in NFI3-4; for time series consistency the strata were combined for the complete time series: a) elevation classes 601-1200m and >1200m in production region 2 'Central Plateau'; b) elevation classes <601m and 601-1200m in production region 3 'Pre-Alps; and c) elevation classes <601m and 601-1200m in production region 4 'Alps (cf. NIR ch. 6.4.2.2).
2) Table values were rounded to 6 decimal places.
3) Negative values for CSC indicate a C sink, positive values a C source.

Data on soil carbon stock change, carbon stock and stock change in surface litter and in coarse dead wood based on the technical correction of the Swiss FMRL

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Supplement to the report 'Estimating carbon stock changes in living and dead biomass and soil for the technical correction of Switzerland's forest management reference level for the Swiss NIR 2021 (1990–2019) – modeling methodology and results' (Thürig et al. 2021)

This document contains supplementary information to the estimation of soil carbon stock change, and carbon stock and stock change in surface litter and in coarse dead wood for Switzerland's FMRL following the technical correction reported in Thürig et al. (2021). The estimates for the three pools were prepared with the C decomposition model Yasso07 (Tuomi et al. 2009, Tuomi et al. 2011) as described in chapter 2.3 in Thürig et al. (2021). Following good practice (IPCC 2014) and consistency with actual FM emissions reported in Switzerland's NIR2022, the Yasso07 simulations were updated with the measurement-based temperature and precipitation data for 2020, which were not available for the estimation in Thürig et al. (2021); cf. chapter 2.3.4.1. There were no other changes methodology and data inputs for the modeling, including the dead wood and litter production estimates derived from the simulations with the forest scenario model Massimo (cf. chapter 2.3.4.2 in Tuomi et al. 2009, Tuomi et al. 2011). Yasso07 produces a time series of C stock in dead wood, incl. stems, branches and roots, non-woody litter and in mineral soils on productive forest lands (CC12; see ch. 6.4.1 in FOEN 2021).

Time series of C stocks in dead wood, litter

The time series of stocks in the three pools dead wood, litter and mineral soil is based on GHGI data from Switzerland's NIR 2020 and 2021 (FOEN 2020, 2021) up to and including 2006. These simulations were based on dead wood and litter production estimates derived from measured trees in Switzerland's National Forest Inventory (NIR; Didion 2020)Because the FMRL simulations are based on only a portion of the NFI sampling plots of the used for GHGI, the mean values of the 15 strata used are not directly comparable.

The stocks of the two pools are used to calculate the stock changes in land use changes for the dead wood and litter pools (Table 1) between productive and unproductive forest (i.e., CC12 to CC13 and CC13 to CC12; FOEN 2021). C stock changes in mineral soils in case of land use changes are based on Nussbaum and Burgos (2021).

Time series of C stocks changes in dead wood, litter and in mineral soils

The calculated stock changes of the three Yasso pools are used for the productive forest (CC12). Table 2 shows the mean of the stock changes in the three pools for the period 2013-2020, as well as the total for the recalculated estimates and as a comparison with the 2020 data.

Table 1. Mean C stock of dead wood and litter for the period 2013-2020 based on dead wood and litter inputs derived from simulated forest development with Massimo for the technical correction of the Swiss FMRL (Thürig et al. 2021).

pool	stratum	updated estimate (this document)	Thürig et al. (2021)
		mean C stock 2013-2020 [tC ha^{-1}]	
dead wood	Switzerland	9.608	9.614
litter	Switzerland	13.251	13.273

Table 2. Mean C stock changes in the pools dead wood, litter, and mineral soil for the period 2013-2020 based on dead wood and litter inputs derived from simulated forest development with Massimo for the technical correction of the Swiss FMRL (Thürig et al. 2021). Negative values indicate sinks, positive values sources.

pool	stratum	updated estimate (this document)	Thürig et al. (2021)
		mean C stock change 2013-2020 [tC $ha^{-1}yr^{-1}$]	
dead wood	Switzerland	-0.201	-0.207
litter	Switzerland	0.026	0.005
soil	Switzerland	-0.003	-0.003
all	Switzerland	-0.177	-0.205

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