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Validating tree litter decomposition in the Yasso07 carbon model

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ABSTRACT

Up-to-date and accurate information of ecosystem state and functioning becomes ever more critical for decision-making and policy. For complex ecosystems such as forests, these demands can in some cases not be met by field observations only, especially at larger scales. Additionally, methodological requirements include comparability and transparency. To satisfy these needs, models can provide an important supplement or alternative.

We examined the validity of the litter decomposition and soil carbon model Yasso07 in Swiss forests based on data on observed decomposition of (i) foliage and fine root litter from sites along a climatic and altitudinal gradient and (ii) of 588 dead trees from 394 plots of the Swiss National Forest Inventory. Our objectives were to (i) examine the effect of the application of three different published Yasso07 parameter sets on simulated decay rate; (ii) analyze the accuracy of Yasso07 for reproducing observed decomposition of litter and dead wood in Swiss forests; and (iii) evaluate the suitability of Yasso07 for regional and national scale applications in Swiss forests.

From the three examined parameter sets, the set was identified which resulted in the best agreement between Yasso07 results and observed decomposition. No significant differences were found between simulated and observed remaining C in foliage and fine root litter after 10 years and in lying dead trees after 14–21 years. The model overestimated the decomposition of standing dead trees. We concluded that Yasso07 can provide accurate information on temporal changes in C stocks in litter and deadwood in Swiss forests in a transparent manner that is valid for, e.g., reporting purposes under the UNFCCC and the Kyoto Protocol.

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1. Introduction

Global climate change has been recognized as a major threat for the future development in the United Nations Framework Convention on Climate Change (UNFCCC) in 1992. A key driver of climate change is the increasing emission of greenhouse gases (GHG; IPCC, 2007). An important greenhouse gas is carbon dioxide (CO_2), which can be removed from the atmosphere by plants through photosynthesis and stored as carbon (C) in living and dead biomass and in the soils of terrestrial ecosystems.

Forests and forest soils are major C stores and a change in these stocks may have significant effects on atmospheric CO_2 concentrations (Pan et al., 2011). A primary driver of the soil C budget is C from decomposing dead organic matter (DOM[1]; Amundson, 2001), which is continously fed by the production of non-woody and woody litter from living trees. Litterfall dynamics are highly variable over time and are driven mainly by climate and disturbance events (Portillo-Estrada et al., 2013) such as storms and harvesting. Because of the role of DOM for the carbon balance of forests, valid and accurate methods for accounting for the changes in this C pool are required.

C stock changes (CSC) can be derived by calculating the difference between observed stocks from repeated measurements, for example, from national forest inventories (NFI). This so-called 'stock change method' is suitable particularly for CSC in living biomass, where forest inventories provide sufficient and accurate

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[1] As defined in IPCC (2003); includes deadwood (non-living woody biomass above a defined size either standing, lying on the ground, or in the soil) and litter (non-living biomass below a defined size lying dead, in various states of decomposition above the mineral or organic soil).

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data (Mäkipää et al., 2008; Thürig and Schmid, 2008). Estimates of CSC in soil and DOM can be reliably derived only when repeated measurements of these pools are included in forest inventories, which is rarely done (Woodall et al., 2009). Where observations for soil and DOM are not available, models can be used (Liski et al., 2006).

Dead organic matter in forests is highly diverse (Pyle and Brown, 1999) and includes dead wood of different sizes, dead roots as well as fallen leaves and needles (Freedman et al., 1996) with different decomposition characteristics depending particularly on their size (e.g., Harmon et al., 1986; Abbott and Crossley, 1982), and chemical composition including lignin content (e.g., Freschet et al., 2012). For estimating soil C dynamics on forest lands, a model should therefore be able to accurately reproduce C decay in DOM.

The Yasso model was developed specifically for application on forest lands (Liski et al., 2005). The improved version Yasso07 (Tuomi et al., 2011a) also accounts for the size of logs, resulting in more accurate estimates of deadwood decomposition. One of the strengths of Yasso07 is the ability to model temporal C dynamics in soil, litter and deadwood based on readily available data on C inputs from dead organic matter and on climate. For forest lands, such C input data can be derived from forest inventories which are carried out by many countries. Yasso07 has been applied in research to assess the contribution of the soil and dead organic matter C pools to regional and global carbon balances (Johnson et al., 2010; Thum et al., 2011) and has been used by several European countries for greenhouse gas reporting under the Kyoto protocol (FOEN, 2013; Statistics Finland, 2013; Umweltbundesamt, 2013; Norwegian Climate and Pollution Agency, 2013).

Rantakari et al. (2012) showed the validity of the model for boreal forests in Scandinavia by comparing simulated results with observed soil C stocks. The rate of C decay in litter and deadwood simulated by the model has however not yet been validated with independent data on litter decomposition over time. In this study, we used time series data on DOM decomposition to compare simulated and observed decay rates. Our specific objectives were to (i) examine the effect of the application of three different published model parameter sets from Tuomi et al. (2009, 2011a) and Rantakari et al. (2012) on simulated C stock changes; (ii) analyze the ability of Yasso07 for reproducing observed decomposition in litter and deadwood in Swiss forests; and (iii) evaluate the suitability of Yasso07 for regional and national scale applications in forests in Switzerland. We used published parameter sets which were independently derived and evaluated based on the rationale to apply the Y07 in a transparent manner that is also applicable to other regions.

2. Methods

2.1. Yasso07

Yasso07 (Tuomi et al., 2011a, 2009) is a litter decomposition model to calculate C stocks and stock changes in mineral soil, litter and deadwood. For estimating stocks of organic C in these pools and their temporal dynamics, Yasso07 (Y07) requires information on C inputs from dead organic matter (e.g., foliage and woody material) and climate (temperature, temperature amplitude and precipitation). DOM decomposition is modelled based on the chemical composition of the C input, size of woody parts and climate (Tuomi et al., 2011a,b, 2009). In Y07 it is assumed that DOM consists of four compound groups with specific mass loss rates. The mass flows between compounds that are either insoluble (N), soluble in ethanol (E), in water (W) or in acid (A) and to a more stable humus compartment (H), as well as the flux out of the five pools (Fig. 1, Table A.1; Liski et al., 2009) are described by a range of parameters (Tuomi et al., 2011a, 2009).

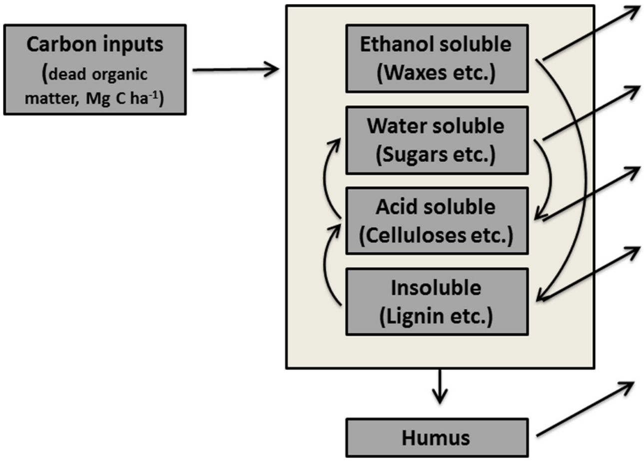

Fig. 1. Flow chart of Yasso07 soil carbon model. The boxes represent soil carbon compartments, the arrows carbon flows; only those carbon flows are shown that deviate significantly from zero.
Adapted from Liski et al. (2009).

Parameter values for Y07 are obtained probabilistically using Markov Chain Monte Carlo sampling and are fitted based on measurements related to organic C accumulation in mineral soils, foliage and fine root litterdecomposition (Tuomi et al., 2009) and woody litter decomposition (Tuomi et al., 2011a). The probabilistic approach allows the calculation of the maximum a posteriori point estimate and confidence set for the model parameter vector which consists of a unique combination of 24 correlated parameters (Table A.1). This information can be used to derive uncertainty estimates for simulated C stocks. At the time of this study, three parameter sets have been developed and published: (1) Tuomi et al., 2009 (henceforth P09), (2) Tuomi et al., 2011a (henceforth P11) and (3) Rantakari et al., 2012 (henceforth P12). The P09 parameter set was developed based on a global data set of litter mass loss measurements (Table 1 in Tuomi et al., 2009) with additional data on SOC accumulation from a soil chronosequence in southern Finland (Liski et al., 2005). Tuomi et al. (2011a) extended Y07 to also describe decomposition of deadwood which resulted in parameter set P11. In addition to the litter and soil data that were used for P09, Tuomi et al. (2011a) employed data on mass loss of decomposing woody litter from locations in Northern Europe. For the development of P12, Rantakari et al. (2012) obtained a subset of the previously used data which was restricted to European sites.

The source code of Yasso07 and a user interface software (Tuomi et al., 2011b) are avilable from the project homepage.[2] At the time of this study, the Yasso07-UI has ben distributed with the parameter set P11.

2.2. Observed data

Simulated DOM decomposition by the carbon model Yasso07 was validated with observed data on decomposition of two litter types (dead fine roots and foliage litter) and in deadwood.

2.2.1. Fine root and foliage litter

The decomposition of below- and aboveground litter was studied over 10 years on five forest sites in Switzerland, which are part of a national forest monitoring network within the framework of

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[2] http://www.syke.fi/en-US/Research__Development/Research_and_development_projects/Projects/Soil_carbon_model_Yasso.

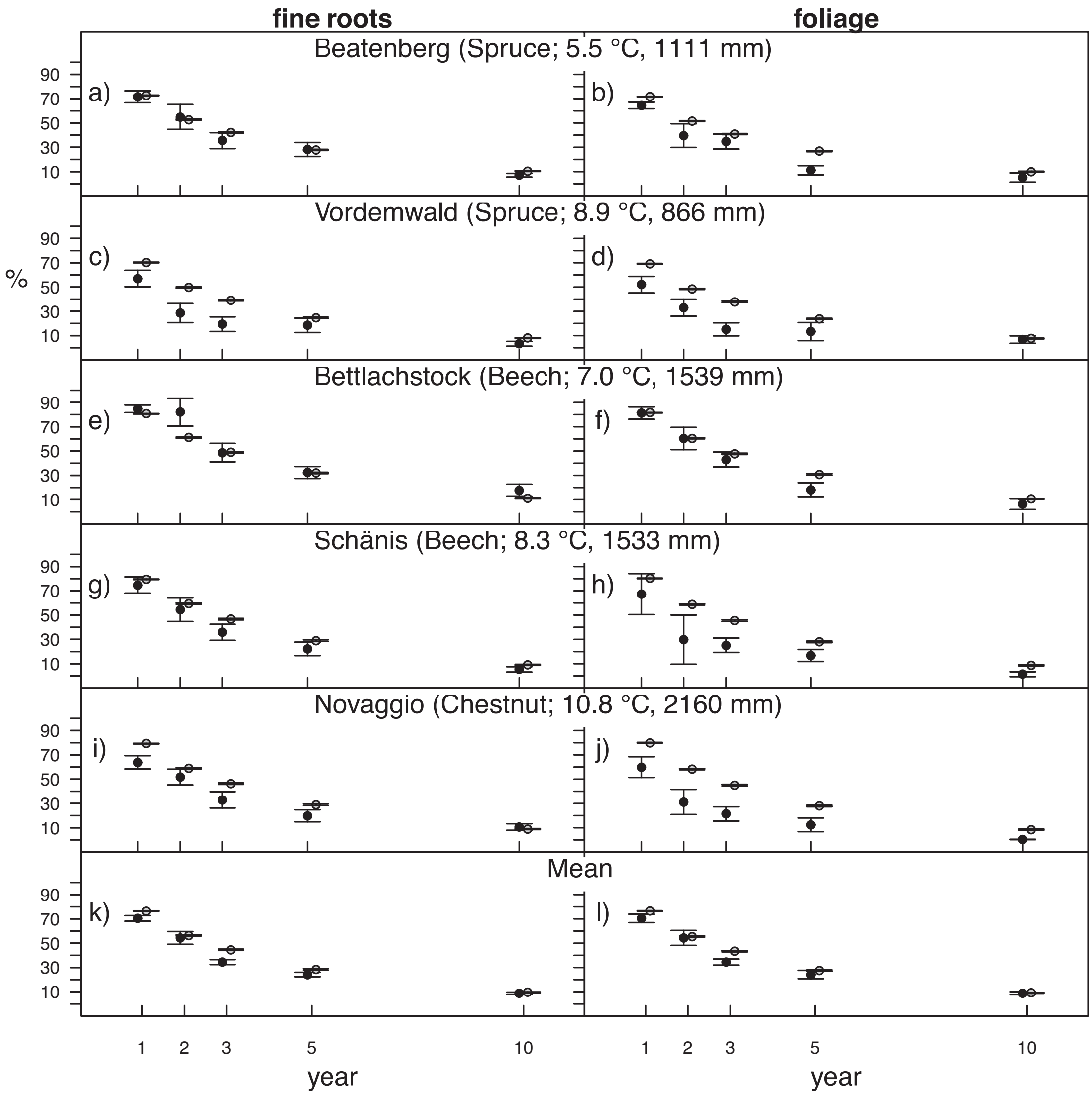

Fig. 2. Mean and standard deviation for remaining mass of C [%] in fine root and foliage litter at five LWF-sites and the mean over all sites. Measured data were based on 20 replicate samples (filled circles). Simulated data were the result of 500 replicate simulations for parameter values of parameter set P12 (open circles). Note that the annual data points are slightly offset for better comparison. For each site the dominant species, annual mean soil temperature measured at 5 cm depth and annual mean throughfall precipitation are given.

the Swiss Long-term Forest Ecosystem Research project LWF (Graf Pannatier et al., 2012). The sites (Fig. 2; Heim and Frey, 2004) included different forest types dominated by Norway Spruce (*Picea abies*), European Beech (*Fagus sylvatica*) and Sweet Chestnut (*Castanea sativa*). The spruce and beech sites represent a climatic and altitudinal gradient from cool and moist to warm and dry. The site dominated by chestnut is located in southern Switzerland and is characterized by insubrian climate, i.e., high annual precipitation of uneven distribution including heavy rainfall events interrupted by extended periods of drought in spring and summer.

In 2000 at each site, several samples of local litter were packed in litterbags that were placed in the forest for later harvest. Heim and Frey (2004) reported the results of the first two years of the study. Additional samples were harvested after 3, 5 and 10 years. From this study, we obtained data on the observed mass loss of C in fine root and foliage litter (Fig. 2) for comparison with simulated data.

2.2.2. *Deadwood*

In the Swiss National Forest Inventory (NFI; incl. NFI2: 1993–1995, NFI3: 2004–2006, NFI4: 2009–2013) data is collected that allows estimating the volume of deadwood with diameter >12 cm that is either standing (henceforth snags) or lying (henceforth logs). Since the NFI3, for each snag and log, the state of decay is recorded using five classes of progressing decay (1: raw wood, 2: solid dead wood, 3: rotten wood, 4: mould wood, 5: duff wood; Keller, 2011). Applying measured, decay-class-specific wood densities (Table 1), the biomass of snags and logs can be estimated (cf.

Table 1
Wood density of deadwood in five NFI decay classes. Data for raw wood (i.e., recently dead wood) were taken from fresh wood as used in the Swiss GHGI and based on Assmann (1961). Data for decay classes 2–5 were obtained from measurements of 1150 dead logs from 40 sites across Switzerland (Table 1 in Dobbertin and Jüngling, 2009).

	Conifers Density (±1 SD) (g cm^{-3})	Broadleaves Density (±1 SD) (g cm^{-3})
1. Raw wood	0.390	0.560
2. Solid dead wood	0.394 (±0.101)	0.521 (±0.124)
3. Rotten wood	0.333 (±0.094)	0.319 (±0.091)
4. Mould wood	0.274 (±0.075)	0.241 (±0.052)
5. Duff wood	0.247 (±0.043)	0.233 (±0.076)

Table 2
Number (N), mean diameter at breast height (DBH), mean stemwood volume over bark (ob) and mean C stock including standard deviations for dead trees that were measured consecutively in 3 National Forest Inventories (NFI) and that were either standing or lying at NFI2. For the NFI2 a high and a low estimate (based on the estimates of the decay class, cf. section 'Methods') for C stock was calculated.

	NFI2 (1993–1995)		NFI3 (2004–2006)		NFI4 (2009–2013)	
	Standing at NFI2	Lying at NFI2	Standing at NFI2	Lying at NFI2	Standing at NFI2	Lying at NFI2
N	379	209	316	272	262	326
Mean DBH (cm)	26.7 (±15.3)	32.8 (±15.2)	26.3 (±15.0)	31.9 (±15.0)	25.9 (±14.8)	30.6 (±14.2)
Stemwood volume (ob) (m^3)	0.74 (±1.03)	1.03 (±1.09)	0.71 (±0.98)	0.95 (±1.01)	0.68 (±0.94)	0.86 (±0.91)
Mean C stock (kg)	Low: 141.7 (±186.7) High: 146.2 (±191.9)	Low: 191.7 (±203.8) High: 200.0 (±210.1)	126.0 (±171.4)	154.2 (±166.9)	110.7 (±151.7)	128.9 (±140.3)

chapter 2.5 in Brändli, 2010). The amount of C that is contained in a snag or log is calculated from its biomass and a C concentration of 49.3% for conifers and 47.6% for broadleaves (Dobbertin and Jüngling, 2009).

The NFI reports the deadwood C stock at the time of a particular NFI. To compare the decomposition of deadwood over time with simulated decomposition, we extracted data from the NFI database for snags and logs >1.30 m in length which were measured in three consecutive NFIs. We thus obtained data for a total of 588 snags and logs from 394 inventory plots across Switzerland (Table 2). Since in the NFI2, no decay class of coarse deadwood was recorded, we derived two estimates for the decay class using the following assumptions:

- Trees that were alive in NFI1 and dead in NFI2 ($n = 439$) were placed in decay class 1 (fast decay estimate) or decay class 2 (slow decay estimate);
- Trees that were not recorded in NFI1 and were dead in the NFI2 but had a diameter smaller than the measurement threshold (i.e., 12 and 36 cm, respectively) plus 3 cm ($n = 52$) were placed in decay class 1 (fast decay estimate) or decay class 2 (slow decay estimate); this was based on the assumption that these trees were alive at the NFI1 but were still below the measurement threshold, grew in size greater than the measurement threshold and died before the time of the NFI2;
- All remaining 107 trees were assigned to one decay class less than observed (e.g., class 2 instead of class 3) in the NFI3 (fast decay estimate) or the same decay class as observed in the NFI3 (slow decay estimate).

Thus, the fast decay estimate, henceforth FDE, assumes deadwood decomposed more rapidly between NFIs 2 and 3 than the slow decay estimate, henceforth SDE.

The assumptions for deriving a decay class for snags and logs at the time of the NFI2 were based on observed transition times between NFIs 3 and 4, deadwood composition data from the Long-term Forest Ecosystem Research project LWF, and relevant literature (e.g., Harmon et al., 1986; Holeksa et al., 2008; Mäkinen et al., 2006; Næsset, 1999). We were thus confident that the FDE and the SDE represented the most probable decay state of snags and logs at the time of NFI2.

The two estimates for decay class of snags and logs in the NFI2 yielded corresponding approximations of the C stored in individual deadwood pieces: the FDE to a high C store due to the higher wood density (cf. Table 1) and the reverse for the SDE. The resulting estimates for C stored in snags and logs (Table 2) did not differ significantly. Hence, we used the mean of the two estimates as initial value for the simulations of individual snags and logs with Y07 (see section 'Simulations of DOM decomposition with Yasso07').

The estimates of C stored in individual snags and logs were obtained for observed stemwood volume over bark. Stemwood volume can be accurately modelled using tariff-functions and is more accurate than biomass of the full tree (i.e., incl. roots, branches and foliage) that relies on expansion factors introducing additional uncertainties in the estimates (cf. Zianis et al., 2005). Besides the C stock of snags and logs (Table 2), additional attributes were available for the simulation of the decomposition with Y07 including diameter and recording year within each NFI period. The maximum time span of 20 years (1993–2013) between the observations during the NFI2 and NFI4 applied to 21 snags and logs, the minimum of 14 years (1995–2009) applied to 32 snags and logs. For the majority of snags and logs 17 years lay between the two observations. Of the 588 deadwood records, at the time of the NFI2 379 were snags and 209 were logs (Table 2). The majority of the snags were still standing upright at the time of the NFI4 ($n = 262$, Table 2).

2.3. Simulations of DOM decomposition with Yasso07

For this study, we used the Yasso07 release 1.0.1 (cf. project homepage). The Yasso07 Fortran source code was compiled for the Windows7 operating system. The statistical software R (R Core Team, 2013) version 3.0.1 (64 bit) was used for administrating the Yasso07 simulations.

The decomposition of DOM was simulated with Y07 using the parameter sets P09, P11 and P12 with the purpose of identifying a parameter set that is applicable to conditions in Switzerland. In the simulations we used the value of the maximum a posteriori point estimate (cf. Tuomi et al., 2009) derived from the distribution of parameter values for each set (Table A.1). The simulations were initialized with the C mass contained in (a) one litterbag at the start of the litterbag experiment for foliage and fine root litter (Heim and Frey, 2004) and (b) individual deadwood pieces at the time of the NFI2 for deadwood. The respective mass of C was separated into the four compound groups used by Y07. The simulations were run for the time span of the observed data. The result of the simulation was an annual estimate of the remaining fraction of the initial mass, which could then be compared with observed data.

To investigate the accuracy of the simulated DOM decomposition and to examine the uncertainty related to model parameters, additional simulations were carried out for the parameter set that performed best for conditions in Switzerland. We used a Monte Carlo approach and repeated the simulations with 500 randomly sampled parameter vectors (cf. Rantakari et al., 2012).

2.3.1. Fine root and foliage litter

For each of the two litter types simulations were carried out based on annual temperature and precipitation data that were recorded at the five sites over the duration of the experiment from 2000 to 2010. The chemical analysis of the initial mass of C in one litterbag was used to derive mean proportions of C in the four compound groups for coniferous and broadleaved litter (Table 3) used in Y07. For consistency with our aim to apply Y07 in a manner that is valid for regional and national scale application, we used mean proportions over all sites rather than site-specific values.

Table 3
Initial ratios of the four compound groups in Yasso07, i.e., C that is either insoluble (N), soluble in ethanol (E), in water (W) or in acid (A) for three different types of dead organic matter (DOM), foliage and fine root litter and deadwood, and two tree species types.

DOM type	Tree species	N	E	W	A
Foliage litter	Conifers	0.235	0.065	0.2935	0.4065
	Broadleaves	0.33	0.055	0.1315	0.4815
Fine roots litter	Conifers	0.245	0.025	0.28	0.449
	Broadleaves	0.39	0.015	0.1595	0.433
Deadwood	Conifers	0.305	0.0025	0.0175	0.675
	Broadleaves	0.27	0	0.015	0.715

2.3.2. Deadwood

The decomposition of deadwood was simulated on an annual time step separately for each of the 588 snags and logs. The simulation of an individual snag or log was started using the estimated C store at the time of the observation in the NFI2 and it was continued until the year of observation in the NFI4. The initial C store was portioned into the four compound groups used by Y07 following experimentally derived fractions (Table 3; cf. Liski et al., 2009). We used the same proportions for all snags and logs irrespective of their decay class because (a) relevant data do not exist and (b) the values for deadwood provided by Liski et al. (2009) were derived from dead branches and stems in different decay stages (e.g., Vávřová et al., 2009). Based on the location of the inventory plot of a snag or log, annual mean temperature, temperature amplitude and precipitation sum were obtained for the respective simulation period from spatially gridded data with a 2.2 km resolution prepared by the Federal Office of Meteorology and Climatology MeteoSwiss (MeteoSwiss, 2012a,b).

2.4. Comparison of simulated and observed decomposition

Following the representation of decomposition dynamics in Y07 (Fig. 1), we derived the simulated C store from the N, E, W and A compound groups. Insoluble C in the N compartment is associated with lignin (Fig. 1; cf. Liski et al., 2009) and is degraded over time into soluble compounds (e.g., Berg et al., 1982). Soluble C is rapidly assimilated and <1% is found in the soil (Batlle-Aguilar et al., 2011). Hence, we reasoned that the fraction of C in the simulated N, E, W, and A compound groups is still associated with the respective input pool (i.e., litter and dead wood). Following from there, we considered C that had moved to the more stable H compartment becomes incorporated into the mineral soil and is thus not part of the litter or deadwood pool any longer (cf. Kahl et al., 2012). The simulated annual C store consisting of the NEWA fractions was compared with observed data.

Simulated and observed data were compared either graphically or by descriptive statistics, including mean absolute error (MAE) and Mann–Whitney *U* to test for a statistical difference between simulated and observed data. Specifically, we tested for differences in the C store over time which remained of the initial value; for the litterbag data this corresponded to the C store in each litterbag and for the deadwood data to the C store in each snag and log. The analyses were completed with the statistical software R (R Core Team, 2013) using the library *hydroGOF* (Zambrano-Bigiarini, 2014) for calculating the MAE, i.e., the mean of the absolute errors of each pair of predicted and true values.

3. Results

Following the objectives of this study, first the results on the effect of different parameter sets P09, P11 and P12 are presented. These are followed by detailed outcomes of the simulations with the P12 parameters, which produced the best agreement between simulated and observed data.

3.1. Selection of a Yasso07 parameter sets

The effect of the parameter set on simulated decomposition differed by litter type, i.e., non-woody foliage and fine root litter, and coarse-woody deadwood.

3.1.1. Fine root and foliage litter

The observed decomposition varied significantly between sites (standard deviations in Table 4). Observed foliage litter decomposed significantly faster than fine root litter. This trend was not well reproduced in the Y07 simulations by any of the parameter

Table 4
Observed and simulated remaining mass of C [%] in (a) fine root and (b) foliage litter from five sites. The results of the simulations were obtained using three different parameter sets P09 (Tuomi et al., 2009), P11 (Tuomi et al., 2011a) and P12 (Rantakari et al., 2012).

(a) Fine root litter

Year	Observed [%]	Simulated [%]					
		Parameter set P09		Parameter set P11		Parameter set P12	
	Mean (±SD)	Mean (±1 SD)	MAE[1]	Mean (±1 SD)	MAE	Mean (±1 SD)	MAE
1	70.60 (±10.69)	70.40 (±5.77)	7.77	78.56 (±4.98)	8.36	76.71 (±5.64)	7.94
2	54.40 (±18.80)	42.03 (±7.49)	15.67	56.83 (±7.58)	11.96	56.87 (±6.57)	11.95
3	34.40 (±10.67)	28.60 (±6.93)	8.17	46.16 (±8.06)	11.76	45.16 (±5.98)	10.76
5	24.00 (±5.83)	14.57 (±4.72)	9.43	35.35 (±7.46)	12.21	29.17 (±4.76)	6.85
10	9.60 (±5.18)	3.04 (±1.64)	6.56	24.97 (±6.05)	15.37	9.97 (±2.45)	2.20
(b) Foliage litter							
1	64.80 (±10.66)	70.95 (±5.73)	7.65	79.00 (±5.13)	14.20	76.79 (±6.68)	11.99
2	38.80 (±12.48)	42.72 (±6.59)	9.42	57.10 (±6.67)	18.30	56.03 (±6.94)	17.23
3	27.80 (±11.19)	29.39 (±5.93)	9.08	46.32 (±6.61)	18.52	43.99 (±6.00)	16.19
5	14.20 (±3.11)	15.35 (±4.08)	2.77	35.42 (±5.59)	21.22	28.07 (±4.61)	13.87
10	3.00 (±2.55)	3.33 (±1.60)	1.79	24.99 (±4.39)	21.99	9.52 (±2.34)	6.52

[1] MAE: mean absolute error between observed and simulated data with three Yasso07 parameter sets.

Table 5

Fraction of C in the stable humus compartment (H) of Yasso07 as percentage of total C, i.e., sum of C in all five compartments (labile compartments of C that is either insoluble, soluble in ethanol, in water or in acid, and the stable humus compartment; cf. Fig. 1).

Parameter set	Year 1	Year 2	Year 3	Year 5	Year 10
			% (±SD)		
P09	2.72 (±0.63)	8.83 (±2.02)	15.22 (±3.64)	29.98 (±6.73)	69.78 (±9.91)
P11	0.40 (±0.10)	1.21 (±0.30)	1.90 (±0.50)	3.01 (±0.77)	4.90 (±1.18)
P12	0.10 (±0.02)	0.31 (±0.05)	0.53 (±0.08)	1.14 (±0.16)	4.39 (±0.79)

sets. Generally, the rate of decomposition was underestimated in the simulations with the P11 and P12 parameter set and overestimated with P09, particularly for fine root litter (Table 4). The best match between observed and simulated data was obtained with P12 for fine roots (MAE between ca. 2% and 12%) and with P09 for leaves and needles (MAE between ca. 2% and 9%). Overall, for both litter types Y07 reproduced observed data similarly successful with P09 and P12. The high underestimation of decomposition with P11 suggested that this parameter set is less suitable for reproducing C dynamics in foliage and fine roots.

The fraction of C that had moved to the more stable humus compartment in Y07 differed between parameter sets and the variability between sites was greater than between fine root and foliage litter (data not shown). After the first year of the simulation the fraction varied between 2% and 4% for P09 and <1% for P11 and P12 (Table 5). Over the simulation period of 10 years, the accumulation rate of C in the humus compartment increased, particularly for P09. For P09, after 10 years more stable C had accumulated than C remaining in the labile NEWA compartments. For P11 and P12, after 10 years stable C comprised ca. 3–6% of the total C store (Table 5).

3.1.2. *Deadwood*

Several authors could already show that snags decompose slower than logs (Boulanger and Sirois, 2006; Fraver et al., 2013; Holeksa et al., 2008). This finding was also confirmed by the Swiss NFI-Data: from NFI2 to NFI4 snags lost 18–21% of the initial C and logs 30–35% (Table 6). This observation could however not be reproduced by Y07 simulations: the model overestimated observed decomposition rates regardless of the parameter set. The degree of underestimation of remaining C was similar in simulations with P11 and P12 and was even higher with P09 (Table 6).

Remaining C was highly variable between trees in the observed data and was clearly higher than in the simulated data (Table 6). The MAE between observed and simulated remaining C was high compared to the mean values. Both findings could be related to the fact that 43% (253 out of the total of 588) measured deadwood pieces increased in volume after the first observation in NFI2. After conversion to C mass based on observed decay class in NFIs 3 and 4, the increase in volume resulted in a consequent increase in C store (192 out of 588 deadwood pieces).

The flow of C to the stable humus compartment in Y07 was small with <1% annually (data not shown). Although at a low level, the accumulation rates differed between parameter sets with P09 > P11 > P12.

3.2. *Accuracy of simulated decomposition*

The parameter set P12, which produced the best results among the three examined sets, was selected for further investigation of the accuracy of the simulated decomposition of litter (foliage and fine roots) and deadwood. The effect of uncertainty of the individual parameter values on the simulation results was examined.

3.2.1. *Fine root and foliage litter*

The mean remaining C over all five sites in foliage and fine root litter was reproduced accurately (Fig. 2). The means over all five sites for simulated and measured remaining C (Fig. 2) were not significantly different. The MAE after 10 years for mean remaining C over all five sites was 2.20% for roots and 6.52% for foliage, respectively. This varied between years from 2% to 12% for fine roots and 6–17% for foliage litter (P12 in Table 4). MAE also varied by site: after 10 years MAE ranged for fine root litter from <1% at the two beech-dominated sites to 4.6% at Novaggio dominated by Sweet chestnut, and for foliage litter from 2.2% at the beech-dominated site Schänis to 10.9% at the beech-dominated site Bettlachstock.

At the site level, the model tended to underestimate the rate of decomposition for foliage litter (Vordemwald, Schänis and Novaggio; Fig. 2). Until the second year of the experiment simulated remaining C did not agree very well with observed data but the agreement improved subsequently and no differences were found in year 10 with the exception of foliage litter in Novaggio. The data in Fig. 2 indicated a nonlinear rate of decomposition. This was confirmed by calculating the percentage of annual C loss for the different time intervals, which returned (a) for roots 28.4% (observed data) and 27.2% (simulated data) lost C during the first year compared to 4.2% and 3.5% between years 5 and 10 of the experiment, and (b) for leaves 35.6% and 28.3% lost C during the first year compared to 1.2% and 3.4% between years 5 and 10 of the experiment. The average annual percent C loss over the complete 10-year period of the experiment ranged (a) for the observed data from 8.2% (Bettlachstock) to 9.7% (Vordemwald) for roots and 9.3%

Table 6

Observed and simulated remaining mass of C [%] in dead trees NFI3 (2004–2006) and NFI4 (2009–2013) relative to NFI2 (1993–1995). The dataset consists of (a) standing ($n = 379$) and (b) lying ($n = 209$) dead trees at the time of the NFI2.

Year	Observed [%]	Simulated – P09 [%]		Simulated – P11 [%]		Simulated – P12 [%]	
	Mean (±1 SD)	Mean (±1 SD)	MAE[1]	Mean (±1 SD)	MAE	Mean (±1 SD)	MAE
(a) Standing dead (snags)							
NFI3	88.56 (±31.76)	43.42 (±12.97)	45.87	59.21 (±11.27)	32.05	60.44 (±9.24)	30.93
NFI4	79.99 (±33.44)	30.50 (±12.67)	49.99	48.29 (±11.48)	34.37	47.94 (±10.35)	34.64
(b) Lying dead (logs)							
NFI3	78.46 (±32.93)	51.02 (±11.75)	30.5	65.91 (±10.08)	22.74	65.30 (±8.20)	22.67
NFI4	67.5 (±31.99)	38.52 (±11.83)	31.26	55.65 (±10.63)	22.09	54.04 (±9.06)	22.32

[1] MAE: mean absolute error between observed and simulated data with three Yasso07 parameter sets.

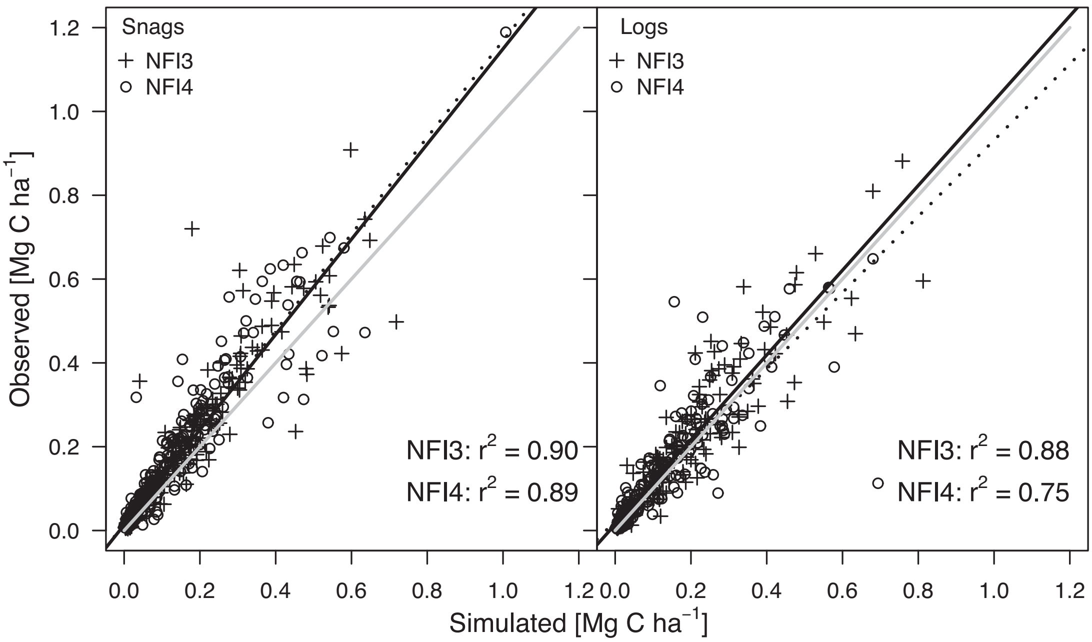

Fig. 3. Observed and simulated C stores at NFIs 3 and 4 in dead trees that were (a) standing ($n = 379$), i.e., snags and (b) lying ($n = 209$), i.e., logs at the time of the NFI2 (1993–1995). The solid black line shows the fit at NFI3 and the dashed black line at NFI4. The solid grey line indicates a perfect fit. Reported is the adjusted r^2. Regressions are significant with p-values < 0.01. The 95% confidence intervals for the slope of the regression line were (a) for snags at NFI3 1.098–1.174 and at NFI4 1.113–1.193, and (b) for logs at NFI3 0.960–1.063 and at NFI4 0.838–0.980.

(Vordemwald)–10.0% (Novaggio) for leaves and (b) for the simulated data from 8.9% (Bettlachstock) to 9.2% (Vordemwald) for roots and 8.9% (Bettlachstock)–9.2% (Vordemwald) for leaves.

Generally, the differences between sites (i.e., mainly driven by the dominance of either coniferous or broadleaved tree species) were apparent only at the start of the experiment (Fig. 2). After 5 and 10 years, the differences between sites were minimal in the observed and in the simulated data. Also, decomposition of foliage and fine root litter differed noticeably for the first two years especially in the observed data. Remaining C after 10 years was still different for the two litter types, albeit not statistically significant. The model reproduced the observed trend that root litter C typically decomposes slower than foliage litter C (Fig. 2).

The uncertainty in the parameter values introduced only minor variability in the results. Based on 500 simulations with randomly sampled parameter vectors the effect was <1% on the estimates of remaining C.

3.2.2. Deadwood

Fig. 3 presents the relationship between simulated and observed amount of C stored in individual snags and logs at the time of NFIs 3 and 4. For snags, there was an overestimation of decomposition by the model. Decomposition of logs was reproduced better by Y07 with no difference between observed and simulated data at NFI3 and a small underestimation at NFI4 (cf. confidence intervals for the slope of the regression line in Fig. 3).

The percentage loss in C was calculated based on the time between the NFI2 and NFI4 (i.e., 14–20 years). The mean loss for all observed deadwood was 2.7% (±5.1%) compared to 3.9% (±4.1%) for all simulated deadwood. The reduction in observed logs (3.9 ± 6.4%) was significantly higher ($p < 0.001$; Wilcoxon rank sum test) than the corresponding data for observed snags (2.0 ± 4.1%). No significant difference was found for simulated logs and snags. Fig. 4 shows the relationship between percentage C change and climate variables. The C decrease in snags was not affected by climate and significant correlations were found only for observed logs and precipitation ($p < 0.1$), simulated logs and temperature ($p < 0.05$) and simulated logs and precipitation ($p < 0.05$).

Uncertainty of estimated remaining C for individual snags and logs that derives from parameter uncertainty was small ranging from 0.35% to 1.71% at NFI3 and from 0.54% to 2.55% at NFI4.

4. Discussion

4.1. Selection of a Yasso07 parameter set

The studies by Tuomi et al. (2011a, 2009) and Rantakari et al. (2012) yielded different parameter sets (P09, P11 and P12). We used published parameter sets that were developed based on global (P09 and P11) or continental (P12) data to be able to apply Y07 in a transparent manner which can be easily replicated in other regions. Alternatively, the model could be parameterized using local data. Besides the required effort, this would limit the transparency and comparability between model application in other locations.

Based on the results of the comparison of observed and simulated decomposition of foliage, fine root and coarse deadwood, the parameter set P12 produced the best overall agreement with observed data (Tables 4 and 6). The results for remaining C in foliage and fine roots suggested that decay rates were initially underestimated (cf. results for years 1–3, Table 4) and followed by an overestimation (cf. results for years 5 and 10, Table 4). This may be due to inconsistencies in the flow rates between the C compound groups in Yasso07 (cf. Section 2). In the model and in reality, fresh foliage and fine root litter annually enters the existing organic layer pool to further decompose. Hence, it can be expected that possible inconsistencies in the flow rates between the compound groups in the model balance out over time.

Although the P09 parameter set resulted in an equally good agreement between observed and simulated percentage remaining C for foliage and fine roots as P12, the simulated data showed that observed decay rates were overestimated, albeit not initially for foliage litter where decomposition progressed faster than observed only after year 3 (Table 4). The overestimation of observed decay

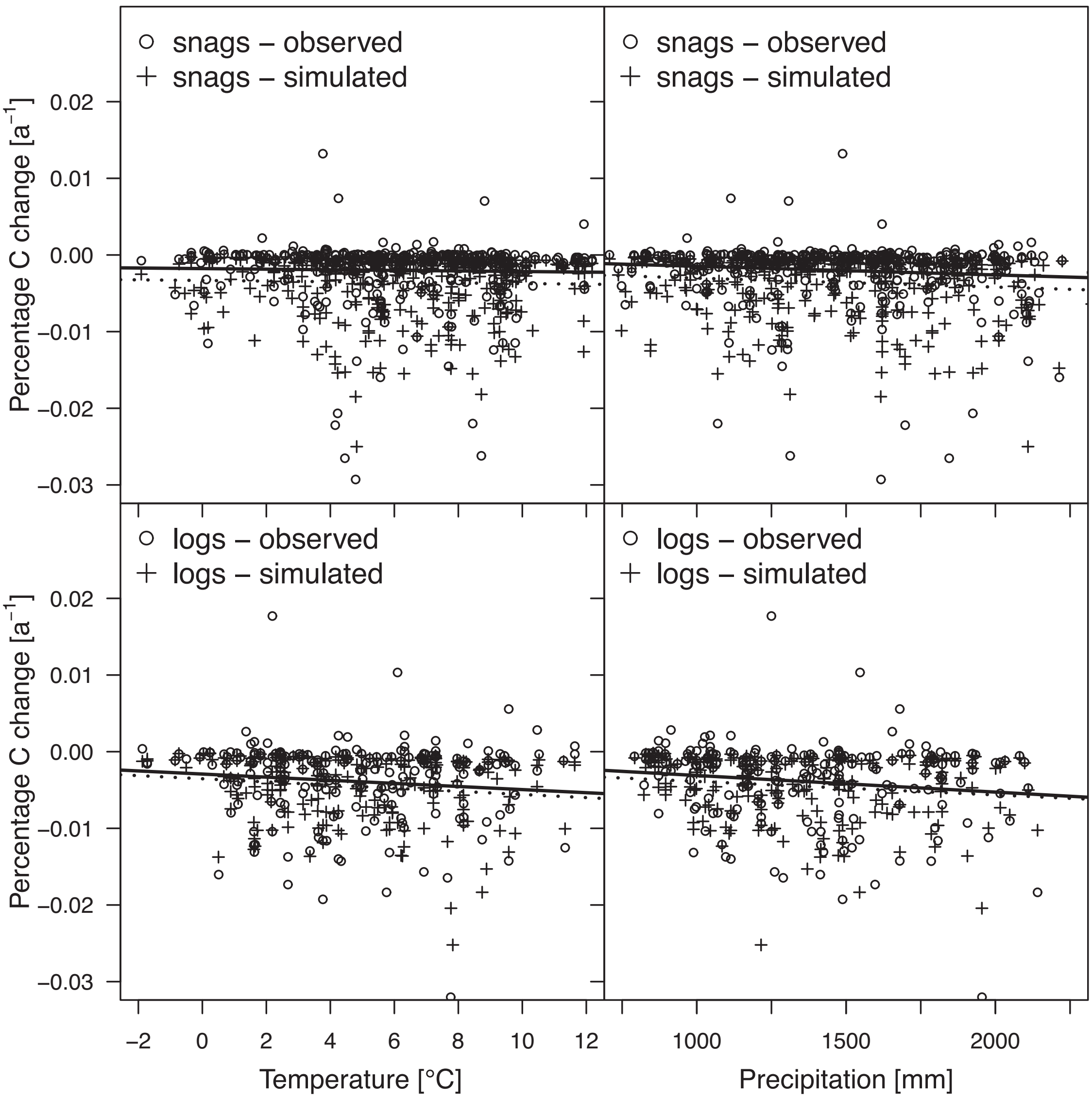

Fig. 4. Percentage change in C mass calculated over the period NFI2 to NFI4 based on observed and simulated decomposition of snags ($n = 379$) and logs ($n = 209$) at the time of the 2nd NFI (1993–1995) against long-term annual mean temperature and annual precipitation sum. Regression lines for C change based on observed data (solid line) and based on simulated data (dashed line) are shown. Note that the positive values for observed data, which indicate a gain in C over time were due to measurement errors in the field.

with P09 was even stronger for coarse deadwood (Table 6). The stronger overestimation of deadwood decay compared to P11 and P12 was likely due to the fact that P09 was optimized for non-woody litter (cf. Tuomi et al., 2009). Furthermore, the flow rates of C to the more stable humus compartment in Y07 were probably overestimated in P09 compared to the more recent P11 and P12 parameter sets that represent different parameterizations to also describe deadwood decomposition (cf. Rantakari et al., 2012). Since P12 resulted in a significantly better agreement with observed decomposition of foliage and fine roots compared to P11, we selected P12 for further investigations.

4.2. Accuracy of simulated decomposition

For decomposition of foliage and fine root litter, no statistical difference was found between the mean measured and simulated estimates of remaining C from five sites (Fig. 2). Although in the model the two litter types are distinguished based only on the initial proportions of the four compound groups (see Section 2), the observed difference in their decomposition were reproduced (Fig. 2). The expected negative exponential decay rate in litter (cf. Vesterdal et al., 2012) was apparent in the observed and simulated data.

The agreement between simulated and observed dynamics of C decay was better for foliage and fine root litter than for deadwood. This can mainly be attributed to the difference in properties of the observed data that were used as starting values for the simulations and for comparisons over time. The litterbag data originated from a controlled experiment with a well-defined initial C store contained in one litterbag and accurate follow-up measurements of remaining C at defined intervals. The source of the deadwood was the National Forest Inventory where the C store of deadwood is estimated based on diameter measurements and assessments of decay class in the field and further conversion to volume, biomass and C mass.

The measurement of deadwood attributes in the field is challenging (Rondeux et al., 2012) and measurement errors as well as uncertainties in the conversion resulted in a high variance in the data on C stored in deadwood (Table 2). This was attributed to the fact that 43% of all snags and logs increased in diameter and consequently also in C mass after death resulting in implausible gains in C mass over time (Fig. 3). While an initial increase in wood density following the death of a tree is sometimes observed, volume decreases (e.g., Fraver et al., 2013). The known effect of volume depletion after death is implicitly accounted for in the model. This may explain to some degree the difference between observed and simulated data (Figs. 3 and 4).

The agreement between observed and simulated remaining C in deadwood was better for logs than for snags (Fig. 3). This may be due to the difference in the sizes of the observed deadwood pieces. Size is a model input and affects the simulated decomposition (Tuomi et al., 2011a). This difference between simulated and observed data was expected because the model does not distinguish between snags and logs.

Considering larger-scale effects, the results demonstrated the strength of Yasso07 for general application over a range of different environmental conditions. The measurements of foliage and fine root litter decomposition showed a clear trend related to climate (cf. also Heim and Frey, 2004) that was reproduced with the model (Fig. 2). Observed decay rates increased from moist and cool climate in Bettlachstock (i.e., 7.0 °C, 1539 mm precipitation) to dry and warm climate in Vordemwald (i.e., 8.9 °C and 866 mm; Table 1 in Heim and Frey, 2004). Compared to the generally good agreement between simulated and observed decomposition at the four beech and spruce dominated sites, the agreement was poor at the site Novaggio in southern Switzerland. This can be related to the insubrian climate in this region with extended summer droughts and short-term, heavy rainfall events throughout the year. The results for Novaggio suggest a possible limitation of a Y07 application with the examined three parameter sets on sites with large annual precipitation sums, i.e., >180–200 cm. This may be due to the fact that the data that have been used to obtain parameter values for the three sets P09, P11 and P12 did not include sites with very high precipitation and sites with extended periods of droughts.

Climate effects would also be expected for deadwood decay (e.g., Kueppers et al., 2004). However, the weak correlations found between measured decay of snags and logs may be due to several reasons, including (a) too small temperature and precipitation gradient for the observed NFI sites, (b) too short observation period, (c) limitations in the observed deadwood data as discussed above and (d) other site variables. Despite the fact that deadwood decomposition in the model depends on temperature and precipitation only, besides the size of snags and logs, Y07 did not exaggerate the observed trends of weak positive effects of increasing temperature and precipitation on decay rate (Fig. 4). The trend was consistent with results from subalpine forest in North-America (Kueppers et al., 2004). On the other hand, Mäkinen et al. (2006) found no effect of temperature and precipitation on decay rates in boreal forests of Finland.

The uncertainty in the estimates of remaining C that results from model parameter uncertainty was small compared to the uncertainty originating from other sources including measurement errors. This was particularly true for deadwood where the conversion of diameter to volume and further to biomass and C mass results in large uncertainties (e.g., Monni et al., 2007; Wutzler and Mund, 2007).

4.3. Suitability for national scale carbon stock change estimates

Yasso07 was able to reproduce observed dynamics accurately. The good agreement between mean observed and simulated results over all sites confirmed the ability of Y07 to be applied in a generalist manner using mean rather than local data for the proportions of the four compound groups This was an important finding to demonstrate the suitability of Y07 for an application at regional and national scales in Swiss forests and elsewhere. Compared to the simulations in this study, a typical application of the model is based on annual data on litter production. Generally, such data are estimated for forest inventory plots based on, for example growing stock, mortality and harvesting statistics.

The model not only produces accurate results, but can be used in a transparent manner and results are reproducible and comparable. These criteria also apply to model parameters and the associated uncertainty, which are published, and reliable estimates of the effect of parameter uncertainty on simulated C stocks can be derived. Meeting the principles of transparency, consistency and comparability, the model can be used for regional and national applications such as estimating carbon stock changes for greenhouse gas inventories under the UNFCCC and the Kyoto protocol.

4.4. Implications and further research needs

This study showed the limitations of observed deadwood data. Inaccuracies with regard to estimates of C stored in decaying wood are inherent to the measurements because diameter measurements on deadwood become more difficult over time due to disintegration of the wood or moss mats and because the degree of decay may vary along the length of a deadwood piece. Hence the stock change method would be associated with an unknown degree of uncertainty as an observed change may be due to measurement errors, inconsistencies in the decay stage along a piece of deadwood. Further research on deadwood decomposition including the variability of decay along and across a piece of deadwood, e.g., heart rot, could improve estimates of deadwood biomass and C stocks in forests.

The accuracy of the model results depends on the quality of the estimates of the annual DOM production. Few studies (e.g., Monni et al., 2007; Wutzler and Mund, 2007) have analyzed the uncertainty of e.g., biomass expansion and foliage turn over that is associated with the application of allometric relationships. Additional studies on litter production and variability of deadwood (e.g., different sizes and amounts of fine- and coarse-woody material) and particularly dead roots could improve the reliability of the estimates.

In this study we assumed that the fraction of C that remains in the litter consists of the AWEN compound groups and does not include C that moved to the more stable humus compartment (see Section 2). This separation of C deriving from decomposing litter and deadwood into distinct above- and below-ground pools has been suggested by studies on C flows from dead organic matter to the soil (e.g., Kahl et al., 2012; Mund, 2004). Since observed remaining C was accurately reproduced, this assumption was justified. It may thus be possible to separate C into the respective dead organic matter pools and C that leached to the soil. This could be investigated further by comparing simulated C fluxes in different pools including the soil C pool with observed data or in a comparison with similar models.

5. Conclusion

The simulation of DOM decomposition based on site-specific data for foliage and fine root litter and on data for individual snags and logs demonstrated the strength of Y07 for general application over a range of environmental conditions and the limitations regarding local accuracy. Based on the parameterization of the model in this study, we deem the Y07 is valid for a wide gradient with limitations in dry regions with extended droughts and in regions with high annual precipitation sums. The model was suited to work with readily available data from the Swiss forest inventory. Since Y07 requires few input data that are easily obtained, it can applied at a large number of sites to produce results that are representative at regional and national scales.

The approach to examine the validity of the model using published parameter sets rather than relying on locally derived parameters was successful and a suitable parameter set was identified. The application of openly available parameters provides transparency and the possibility to reproduce the results. This would also allow a comparison with estimates obtained with Y07 in other regions or countries. The transparent and comparably simple structure of the model makes it possible to identify possible differences in results obtained with other models in a joint application, which would further improve the credibility of Y07. The results for the comparison between observed data and model estimates obtained with the identified parameter set provided confidence for applying Y07 to estimate C stocks and C stock changes in dead organic matter in forests in Switzerland. Yasso07 presents thus a valid tool to provide current and accurate information on carbon balances in Swiss forests in a transparent manner, which can be used for reporting purposes under the UNFCCC and the Kyoto Protocol.

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Appendix A.

Table A.1
Values of the maximum a posteriori point estimate for three Yasso07 parameter sets P09 (Tuomi et al., 2009), P11 (Tuomi et al., 2011a,b) and P12 (Rantakari et al., 2012). Standard errors in brackets.

Parameter	Parameter set			Unit	Interpretation
	P09	*P11*	*P12*		
αA	0.66 (±0.11)	0.72 (±0.09)	0.517 (±0.0004)	a^{-1}	Decomposition rate of A
αW	$4.3^{+1.6}_{-1.0}$	5.9 (±0.8)	3.552 (±0.003)	a^{-1}	Decomposition rate of W
αE	0.35 (±0.08)	$0.28^{+0.07}_{-0.04}$	0.346 (±0.0005)	a^{-1}	Decomposition rate of E
αN	0.22 (±0.06)	$0.031^{+0.011}_{-0.004}$	0.266 (±0.0002)	a^{-1}	Decomposition rate of N
$\rho 1$	0.32 (±0.08)	0.48 (±0.06)	0.0449 (±0.0001)		Relative mass flow, W → A
$\rho 2$	$0.01^{+0.14}_{-0.01}$	$0.01^{+0.15}_{-0.01}$	0.0029 (±0.00009)		Relative mass flow, E → A
$\rho 3$	$0.93^{+0.03}_{-0.11}$	$0.83^{+0.16}_{-0.23}$	0.978 (±0.00006)		Relative mass flow, N → A
$\rho 4$	$0.34^{+0.18}_{-0.15}$	$0.99^{+0.01}_{-0.05}$	0.637 (±0.0001)		Relative mass flow, A → W
$\rho 5$	$0.00^{+0.07}_{-0.00}$	$0.00^{+0.08}_{-0.00}$	0.312 (±0.0002)		Relative mass flow, E → W
$\rho 6$	$0.00^{+0.07}_{-0.00}$	$0.01^{+0.2}_{-0.01}$	0.0187 (±0.00003)		Relative mass flow, N → W
$\rho 7$	$0.00^{+0.01}_{-0.00}$	$0.00^{+0.01}_{-0.00}$	0.0225 (±0.00002)		Relative mass flow, A → E
$\rho 8$	$0.00^{+0.01}_{-0.00}$	$0.00^{+0.01}_{-0.00}$	0.0117 (±0.00006)		Relative mass flow, W → E
$\rho 9$	$0.00^{+0.07}_{-0.01}$	$0.02^{+0.23}_{-0.02}$	0.001 (±0.00005)		Relative mass flow, N → E
$\rho 10$	$0.00^{+0.01}_{-0.00}$	$0.00^{+0.01}_{-0.00}$	0.336 (±0.0002)		Relative mass flow, A → N
$\rho 11$	$0.00^{+0.06}_{-0.00}$	0.015 (±0.015)	0.042 (±0.00005)		Relative mass flow, W → N
$\rho 12$	$0.92^{+0.04}_{-0.15}$	$0.95^{+0.05}_{-0.16}$	0.0899 (±0.0001)		Relative mass flow, E → N
$\beta 1$	7.6 (±2.0)	9.5 (±2.0)	0.0895 (±0.00009)	$10^{-2}\,°C^{-1}$	Temperature dependence
$\beta 2$	−8.9 (±6.5)	$-1.4^{+0.6}_{-0.9}$	−0.0023 (±0.000005)	$10^{-4}\,°C^{-2}$	Temperature dependence
γ	−1.27 (±0.2)	−1.21 (±0.14)	−2.94 (±0.001)	m^{-1}	Precipitation dependence
αH	$3.3^{+0.6}_{-0.7}$	$1.6^{+0.3}_{-0.2}$	0.24 (±0.001)	$10^{-3}\,a^{-1}$	Humus decomposition rate
ρH	4 (±0.9)	0.45 (±0.08)	0.15 (±0.0002)	10^{-2}	Mass flow to humus
$\varphi 1$	NA	−1.71 (±0.16)	−0.539 (±0.0003)	cm^{-1}	First order size dependence
$\varphi 2$	NA	0.86 (±0.1)	1.186 (±0.0005)	cm^{-2}	Second order size dependence
r	NA	−0.306 (±0.013)	−0.263 (±0.000002)		Size dependence power

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