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Modeling soil organic carbon dynamics in temperate forests using Yasso07

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Abstract. Facing global changes, modeling and predicting the dynamics of soil carbon stock of forest ecosystems is vital but challenging work. Yasso07 is considered as one of the most promising models for such a purpose. We aim at examining the prediction accuracy of Yasso07 on soil carbon dynamics over the whole French metropolitan territory at a decennial time scale.

We used the dataset from 101 RENECOFOR sites network, which encompass most of the French temperate forests. The data include (i) measured yearly litter quantity from aboveground organs part from 1994 to 2008, and soil carbon stocks twice at an interval of c.a. 15 years (early 1990s versus around 2010). Using Yasso07, we simulated the stock changes (tC ha^{-1} yr^{-1}) per site and compared them with the measured ones. We carried out meta-analyses to reveal the variability in litter biochemistry between different tree organs for conifers and broadleaves. We also performed sensitivity analyses to explore Yasso07's sensitivity to inputs, including litter carbon quality and initial carbon stocks.

At the national level, the simulated annual carbon stock changes (ACC, +0.45 ± 0.09 tC ha^{-1} year^{-1}, mean ± standard error) stayed in the same order of magnitude with the observed ones (+0.34 ± 0.06 tC ha^{-1} year^{-1}). The correlation between predicted and measured ACC remained weak (R^2 <0.1). There was significant overestimation for broadleaves sites and underestimation for conifers sites. Sensitivity analyses showed that the final carbon stock was weakly affected by litter carbon quality, but a strongly affected by simulation length to investigate and initial soil carbon quality.

We revealed both interest and challenges of applying Yasso07 for temperate forests, which reflected the whole state-of-the-art of soil carbon modelling due to lacking knowledge or data on soil and litter carbon quality and fine root litter quantity, rendering high uncertainties for model inputs.

Nomenclature and abbreviations

Name	Meaning
carbon stock	Quantity of soil organic carbon stock (in tC ha^{-1})
carbon stock change	Increment (positive value) or decrement (negative value) of soil organic carbon stock from the year t1 to the year t2 (in tC ha^{-1})
annual carbon stock change (ACC)	carbon stock change standardized by duration (in tC ha^{-1} year^{-1})
carbon pools	The Yasso07 model contains a series of organic compounds differing in solubility in solvents and mean residence time in decomposition processes: water soluble compounds (W), acid-hydrolysable compounds (A); non-polar solvent, ethanol or dichloromethane compounds (E), non-soluble and non-hydrolyzable compounds (N). For soil, there is an extra recalcitrant pool named “humus” (H)
coarse woody litter	Litter yield from either coarse aboveground residues due to either harvests or storms (including coarse branches, defined as branched of >4 cm in diameter and miscellaneous) and coarse roots (defined as those of >5 mm in diameter)
fine non-woody litter	Litter yield from either natural above-ground litterfall (leaves, small branches) or fine roots activities
litter carbon quality	Composition of litter carbon belonging to A, W, E and N carbon pools (in %)
litter quantity	Annual litter input (in tC ha^{-1} year^{-1})
soil carbon quality	Composition of soil carbon belonging to A, W, E, N and H carbon pools (in %)

1 Introduction

The carbon stock in global soils, including litter and peatlands is 1500 to 2400 GtC, greatly exceeding that in vegetation (350 à 550 GtC, mainly in forests) and in the atmosphere (829 GtC in 2011, IPCC, 2014). Soils share a common interface with all the other spheres and play a key role in driving the global carbon cycle. Soil carbon stock dynamics are directly related to the greenhouse gas emissions (notably carbon dioxide (CO_2)) that are leading to the global warming effect (IPCC, 2014). An accurate estimation of soil carbon stock dynamics allows us to better understand the turnover rate and fate of soil carbon flux at both local and global geographical scales. Facing global changes, this task is essential for the evaluation of the climate change mitigation potentials of forests and the support of environmental policy decisions.

Significant challenges exist for accurate estimation of soil carbon stock changes. Current soil monitoring networks are generally not able to detect changes on timescales of less than 10 years (Saby et al. 2008). To obtain soil C stock change estimates at shorter intervals such as for the annual reporting to the United Nations Framework Convention on Climate Change and the Kyoto Protocol, the use of models is encouraged (IPCC, 2011). Numerous models have been elaborated for evaluating soil carbon dynamics (Manzoni and Porporato, 2009). The vast majority of terrestrial soil carbon models developed at the global or at the plot scales, e.g., CENTURY (Parton et al**.**, 1987), RothC (Coleman and Jenkinson, 1996) and ORCHIDEE (Krinner et al., 2005), assume that decomposition is the first order decay process accounting for the size of soil carbon pools. The dynamics of carbon pools depend on the quantity and quality of litter inputs and on temperature, soil moisture and other soil parameters, e.g. texture, structure, chemical richness, pH etc. (Todd-Brown et al., 2012). Incorporating explicit mechanisms such as microbial activities or carbon protection by the soil matrix into soil carbon models has repeatedly been suggested in the last years (Schmidt et al., 2011; Lehmann and Kleber, 2015). However, for forest ecosystems, such refined mechanistic input data remain often limited. Accordingly, the typical time-step for litter input demanded by most of soil carbon models for forests is year, not month (but see RothC, Coleman and Jenkinson, 1996) or day (but see Romul, Chertov et al., 2001) (Didion et al., 2016). At this yearly-timescale, it is common to consider microbial communities and processes as a relatively stable factor (Todd-brown et al, 2012), and the assumption of carbon dynamics governed by first order decay may therefore be reasonable.

This is the choice made by the group who built the Yasso model (Liski et al., 2005) and Yasso07 model (Tuomi et al., 2009; 2011a and 2011b), i.e. an improved version of Yasso with more refined carbon pooling and abundant data for calibration. The intention of the models' developers is to let their models be suitable for general forestry applications by taking into account the low availability of forest soil and litter data (Liski et al., 2005). Yasso07 explicitly defines several chemical pools of chemical compounds in litter carbon (Tuomi et al., 2011b) and possesses well-defined, biological meaningful and measurable parameters. Due to these qualities, Yasso and Yasso07 were applied in more than 70 case studies (URL: http://www.syke.fi/en-US/Research__Development/Research_and_development_projects/Projects/Soil_carbon_model_Yasso/) in forest ecosystems in the northern hemisphere with generally high satisfaction levels in comparison with measured carbon values (e.g. Karhu et al., 2011 ; Rantakari et al., 2012; Ortiz et al., 2013 ; Didion et al., 2014; Lu et al., 2015; Wu et al., 2015). Yet, so far most of these applications have been limited to local case studies, especially those on cold forests with limited tree species diversity (e.g. boreal or montane forests). Rarely have previous studies validated Yasso07 based on data (i) of long-term observations (here defined as data of >10 years), (ii) from temperate forests with a much higher diversity of tree species or (iii) on carbon stock changes (in tC ha^{-1} year^{-1}). This is partially due to the lack of extensive long term soil carbon monitoring in forest ecosystems which differ in climatic and soil conditions and species, stretch over a large territorial scale. Nevertheless, Yasso07 has been considered as one of potential models appropriate for evaluating national and continental inventories of forest carbon balance in Europe (Hernández et al. 2017). It is therefore of high interest to assess the ability of Yasso07 to reflect the carbon balance in different European forest ecosystems at large spatial-temporal scales. Moreover, as a carbon pool based model, Yasso07 shares certain similar principles to other prevailing soil carbon models in the same genre (e.g., RothC, CENTURY etc.). Via Yasso07 as an example, we may also learn from this application case for future carbon modelling for temperate forests

The measured data of carbon stock and litter quantity dynamics from the RENECOFOR network (URL: http://www.onf.fr/renecofor/@@index.html), National Forest Management Agency (ONF), France, offered us a valuable opportunity for model validation. The used 101 forest sites belonging to the network are located all over the French metropolitan territory covering the most common forest types and tree species. For each site, annual observations of litterfall were available in addition to two inventories of soil organic carbon stock with an average interval of 15 years (minimum 12 years and maximum 20 years). These data allowed us to use site-specific observed soil carbon stock and above-ground litterfall dynamics as model input estimates, thus reducing the uncertainties of the model input, which were identified as a major source of uncertainties for model estimates of soil carbon stock changes (Ortiz et al. 2013). By minimizing this source of uncertainty, we were able to focus on the inherent model structure. To our best knowledge, this might be the unique dataset available for the fit of the model.

Consistent with our objective to contribute to the further development of soil carbon modeling, we aim at (i) testing and characterizing the ability of Yasso07 to model soil carbon stock dynamics for temperate forests (ii) identifying limitations and providing suggestions for a better adaptation of the model for C dynamics in both deciduous and evergreen temperate forests and (iii) discussing the perspectives based on the current state-of-the-art of soil carbon modelling. Associated with the above aims, our null hypotheses are as follows: (i) Yasso07 predicts accurate and unbiased carbon stock changes at the national scale and (ii) the model's fit residuals (predicted data minus observed data) have null relationships with site characteristics (e.g. location, climate, forest type, soil type and initial carbon stock).

2 Materials and methods

2.1 The model Yasso07

The dynamic soil carbon model Yasso07 is based on the general assumption that the soil carbon stock is driven by decomposition of different litter types, which may differ in quantity and quality, and by climatic conditions. Litter carbon quality is represented by four chemical compound groups which have different decomposition rates (Tuomi et al., 2009). Soil organic carbon is divided into these four relatively labile carbon pools and one recalcitrant pool named "humus" (H) (Figure 1). The five pools differ in specific mass loss rates and mass flows among them. Some mass flows correspond to CO_2 release (microbial respiration). The mean residence time of carbon in these pools varies from several months (i.e., water soluble compounds, W), a few years (i.e., acid-hydrolysable compounds, A; non-polar solvent, ethanol or dichloromethane compounds, E), several decades (i.e., non-soluble and non-hydrolyzable compounds, N), or even several centuries (i.e., H).

Mathematically, the kernel equation of Yasso07 can be written as follows:

$$\dot{\boldsymbol{X}}(t) = \boldsymbol{A_p}\boldsymbol{K}(c)\boldsymbol{X}(t) + \boldsymbol{I}(t) \qquad \text{(Eq. 1a)}$$

where, symbols in capital letters in bold denote either vectors or matrices whilst those in small letters in parentheses denote scalars**;** $\boldsymbol{X}(t)$ and $\boldsymbol{X}(\dot{t})$ are vectors describing the masses of the five carbon pools (A, W, E, N, H) and carbon mass changes in soil at time (t), respectively; $\boldsymbol{A_p}$ is mass flow matrix describing carbon allocation among pools; ***K(c)*** is decomposition matrix describing the decomposition rates as a function of climatic conditions (c); ***I(t)*** is litter input to the soil, with the last element equal to 0, as "H" does not exist in litters. (Eq. 1a) can be expressed in a more detailed form:

$$\begin{pmatrix} \partial x_A/\partial t \\ \partial x_W/\partial t \\ \partial x_E/\partial t \\ \partial x_N/\partial t \\ \partial x_H/\partial t \end{pmatrix} = \begin{pmatrix} -1 & p_{W\to A} & p_{E\to A} & p_{N\to A} & 0 \\ p_{A\to W} & -1 & p_{E\to W} & p_{N\to W} & 0 \\ p_{A\to E} & p_{W\to E} & -1 & p_{N\to E} & 0 \\ p_{A\to N} & p_{W\to N} & p_{E\to N} & -1 & 0 \\ p_{A\to H} & p_{W\to H} & p_{E\to H} & p_{N\to H} & -1 \end{pmatrix} \begin{pmatrix} k_A & 0 & 0 & 0 & 0 \\ 0 & k_W & 0 & 0 & 0 \\ 0 & 0 & k_E & 0 & 0 \\ 0 & 0 & 0 & k_N & 0 \\ 0 & 0 & 0 & 0 & k_H \end{pmatrix} \begin{pmatrix} x_A \\ x_W \\ x_E \\ x_N \\ x_H \end{pmatrix} + \begin{pmatrix} I_A \\ I_W \\ I_E \\ I_N \\ 0 \end{pmatrix} \qquad \text{(Eq. 1b)}$$

where, $p_{F\to T}$ is the relative mass flow parameters between two pools (from F to T; F and T can be any two pools in A, W, E, N and H) in the soil (dimensionless, $p_{F\to T} \in [0, 1]$).

Temperature and precipitation are supposed not to affect the mass flows p, but influence the mass loss rates k_i (i = A, W, E, N or H) according to:

$$k_i(c) = \alpha_i \exp(\beta_1 T + \beta_2 T^2)[1 - \exp(\gamma P_a)] \qquad \text{(Eq. 2)}$$

where, α_i is the mass loss rate parameter of the chemical pool *i*; β_1, β_2 and γ are parameters related to temperature (*T*, in °C) and precipitation (P_a, in mm).

To consider the effect of litter size on the decomposition rate of litters, k_i was multiplied by a litter size factor (h_s), which allows making the distinction between different types of litters, e.g. foliage, coarse woody, stem etc., which differ in diameter (*d*, in mm):

$$h_s(d) = \min\{(1 + \varphi_1 d + \varphi_2 d^2)^r, 1\} \qquad \text{(Eq. 3)}$$

where, φ_1, φ_1 and *r* are parameters related to litter size.

Yasso07 has 44 parameters calibrated using the Markov chain Monte Carlo (MCMC) method with the Metropolis-Hastings algorithm (Tuomi et al., 2011a). Currently, several calibrated parameter sets for Yasso07 are available, including the two most recent sets published by Tuomi et al. (2011) and Rantakari et al. (2012). In this present study, the Tuomi 2011 set was chosen to fit the RENECOFOR dataset containing various forest species, as it had been calibrated using a wider range of observed foliage and root decomposition data. The Tuomi 2011 set was calibrated using a combination of three sources of dataset: (i) a global dataset (*n* >9000) of litterbags for mass loss of non-woody litters from approximately 100 sites in Europe, Northern and Central America. These sites covered a wide range of climate and soil conditions, forest types and tree species; (ii) a dataset (*n* > 2000) of mass loss of decomposing woody litter measured in Northern Europe; (iii) measured accumulation rate of soil carbon pools of forest sites along a 5300 year soil chronosequence in southern Finland, for determining the residence time of the H carbon pool. The Tuomi 2011 parameter set contains 10000 parameter vectors (each vector contains the values of all the 44 Yasso07 parameters), which are randomly generated to take into account stochastic effect.

2.2 RENECOFOR network

The RENECOFOR network is part of the Level II network of the International Cooperative Program on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forest). The used 101 sites (Fig. 2) cover almost all the most common types of forest ecosystems in France, including even-aged forests in plain area, pine plantations and uneven-aged mountain forests. They also cover the majority of tree species in France and central Europe, including *Quercus robur*. *Quercus petraea*, *Pseudotsuga Menziesii*, *Picea abies*, *Fagus sylvatica*, *Pinus pinaster*, *Pinus sylvestris* and *Abies alba*. At each site, annual forest woody and non-woody litter quantities have been either directly measured or estimated based on the existing dendrometric data.

2.2.1 Soil carbon data

At each site, soil carbon stocks were measured twice with an interval of approximately 15 years (1993 – 95 for the first assessment and 2007 – 12 for the second one). The temporal evolution of soil carbon stocks was analyzed by Jonard et al. (2017). At each site and for each assessment, soils were sampled from five points selected in each of the five subplots and divided into layers until a depth of 0.4 m, including both organic layer and mineral soil layers; composite samples were produced for each layer and subplot, and analyzed for mass, bulk density and soil organic carbon. Table 2 provides a synthesis of the data source for each of the 101 sites of the RENECOFOR network (URL: http://www.onf.fr/renecofor/sommaire/renecofor/reseau/20090119-130815-828957/@@index.html). More detailed information about each site and soil sampling procedure is available in Supplementary Material I (Table S1) and Jonard et al. (2017).

2.2.2 Climate data

Necessary climate data required by Yasso07 includes annual mean precipitation (mm) and annual maximum, mean and minimum temperature (°C). These measured data were obtained from the nearest national meteorological stations of Météo-France (http://www.meteofrance.com) for each RENECOFOR site.

2.3 Litter quantity

Litter input (in tC ha^{-1} yr^{-1}) comes from several sources (Table 2) as follows. The conversion factor between biomass (dry matter) and carbon was assumed to be 0.5 (Thomas and Martin, 2012).

Aboveground litter input from living trees, including leaves for broadleaves and needles for conifers, small branches, fruits and miscellaneous (e.g., flower, bud etc.). Aboveground litterfall mass was annually measured between 1994 and 2008. For sites where litter quantity data from 1992 – 1993 and 2009 – 2012 were lacking, we used mean litter quantity of all the other years of the same site. The observed branch size in this category is below 2 cm (fine branches). Branches and stems bigger than 2 cm due to natural mortality should be rare (as some of them can be salvaged) and thus were not included.

Woody residues due to harvest or storms were estimated on the basis of repeated stand inventory data and species specific height-girth and biomass. Coarse woody litter inputs from harvesting residues or storms were estimated from full inventories performed by ONF since 1991. Missing years of litter input of this category are gap-filled using the average over the period. On average 3 years are missing per site but there are high differences amongst sites. The mode is one year, and 6 sites have 10-11 missing years. These residuals are assumed to be coarse branches (> 4 cm in diameter, confirmed with ONF) as a function of aboveground tree characteristics. Litter input from stems were set to 0, since in most cases stemwood was removed from the site after storm damage. Litter input from coarse woody roots is considered to be equal to total root biomass, which could be estimated using meta-analysis based allometric equations proposed by Cairns et al. (1997). More detailed information about forest inventories and storm events occurring at each site is available in Supplementary Material I (Table S1). Litter input from fine roots (here defined as roots of ≤ 5 mm in diameter), especially those finest ones with diameter ≤2 mm, can significantly contribute to carbon sequestration in soils (Brunner et al., 2013; Kögel-Knabner et al., 2002; Berg and McClaugherty, 2008). Fine root litter was supposed to be proportional to that of foliage, which was measured on the RENECOFOR sites. Jonard et al. (2017) suggested using the generic equation published by Raich and Nadelhoffer (1989) and, simultaneously, adopting the hypothesis that fine root litter production represents about one third of the carbon allocated to roots (Nadelhoffer and Raich, 1992):

$$I_{fine\ root} = 0.333 \times \left(1.92 \times \left(100 \times I_{foliage}\right) + 130\right) \times 0.01 \qquad \text{(Eq. 4)}$$

Where, $I_{fine\ root}$ and $I_{foliage}$ are litter input of fine root and foliage, respectively (in tC ha^{-1} year^{-1}).

However, the relationship between fine root and foliage litter inputs can be highly variable as a function of tree species, stand characteristics and climate (Raich and Nadelhoffer, 2007) and such variability may not be represented in the generic equation. Therefore, here we estimated litter input for Yasso07 simulations using fine root:foliage ratios ranging from 0.1 to 4.0. Based on a sensitivity an analysis on the effect of fine root:foliage ratio, we found that ratios of 0.1 for broadleaves and 1.9 for conifers achieved the best fit between simulated and observed soil C stock changes (Fig. S1). We decided to fix such ratio at 1.0 for all the modelling and simulation work, because the use of 1.0 (i) achieved a slightly worst, but comparable model fit for both broadleaved and coniferous sites (Fig. S1); (ii) coincidentally corresponded to the median (1.0) and mean (1.0 – 1.1) ratios calculated using Raich and Nadelhoffer (1989)'s equation (Eq. (4)) over all the RENECOFOR sites (Fig. S2) and (iii) facilitate computation and comparisons between sites differing in dominant tree functional types.

2.4 Litter carbon quality

There are no measured data of litter carbon quality, defined as composition of litter carbon belonging to different carbon pools (A, W, E and N) in the RENECOFOR network. Therefore, we carried out a meta-analysis on the data collected in literature where authors measured litter carbon quality via chemical fractioning procedures or near-infrared spectroscopy (NIRS) techniques. This data collection was restricted to non-tropical areas. Chemical data on litters of tree coarse organs (e.g. stems, coarse branches) are relatively scanty, so we used tree stemwood data compiled in Pettersen (1984), Rowell et al., (2005) and Rowell (2012). Assembly of these works covers a wide range of temperate tree species from North America, Japan and Russia, but no data are available for Europe. Data on foliage and root litter carbon quality were manually searched from either networks, e.g. CIDET (Trofymow et al., 1998) and LIDET (http://andrewsforest.oregonstate.edu/research/intersite/lidet.htm) or independent studies in northern hemisphere, including Europe. The database for the meta-analysis is available in Supplementary Material II. Root diameter or branching order can play a significant role in modifying the composition of the chemical compounds (Fahay et al., 1988; Tingey et al., 2003; Guo et al., 2004). All the measurements included in the meta-analysis on roots refer to fine roots (diameter < 5.0 mm), although in several studies, e.g. Aber et al. (1990), Aulen et al. (2011) and Stump and Binkley (1993), root size was not clearly indicated. Yet, we still included the data from these above studies, as available root data are less abundant than foliage. The collected coarse roots data in literature were too few for a meaningful meta-analysis and thus values for stemwood were used instead.

We then used the litter carbon quality database to assign the quality of litter input of each site of our study. Partitioning of litter inputs in biochemical classes respects the following order of priority: (i) values for the target species, when available in the database (ii) mean values of the species from the same genus, if data for the target species are absent, and (iii) mean values of the species from the same tree functional type (conifers versus broadleaves), if data are available at neither species nor genus level for a target species (see Table 1).

2.5 Initialization of soil carbon quality

To calculate steady-state carbon stock, we used an analytical approach on the basis of (Eq. 1a). At steady-state carbon stock ($t = t_s$), carbon gain is equal to carbon loss. Setting $\dot{\boldsymbol{X}}(t_s) = 0$, (Eq. 1a) becomes:

$$\boldsymbol{A_p}\boldsymbol{K}(c)\boldsymbol{X}(t_s) + \boldsymbol{I}(t_s) = 0 \qquad \text{(Eq. 5)}$$

Solving (Eq. 5), we obtained steady-state carbon stock at time t_s: $\boldsymbol{X}(t_s)$:

$$\boldsymbol{X}(t_s) = -(\boldsymbol{A_P}\boldsymbol{K}(c))^{-1}\boldsymbol{I}(t_s) \qquad \text{(Eq. 6)}$$

Where $\boldsymbol{I}(t_s)$ is a constant vector.

This steady-state carbon stock (tC ha^{-1}) was only used to calculate the soil carbon quality distribution, here defined as the composition of soil carbon pools (A, W, E, N and H). Such calculation was performed for each site and for each randomly chosen Yasso07 parameter vector (see Sect. 2.7). Regarding the initial soil carbon quantity, we used the measured one during the first period of assessment of the RENECOFOR network. Measurement uncertainties of soil carbon quantity were not considered as a source of stochastic effect when Yasso07 was fed, as we were more interested in the output uncertainties related to the model per se (i.e., the choice of model parameter set) and that of root:foliage ratios, on which huge knowledge gaps in ecology still exist.

2.6 Sensitivity analyses of litter and soil carbon pool composition

To assess the effects of initial litter and soil carbon quality on model outputs, we conducted two modules of sensitivity analyses differing (see below).

2.6.1 Module I - Effect of litter carbon quality on steady-state carbon stock

First, we investigated the effect of all the theoretical possibilities of litter carbon quality on steady-state carbon quality. For this, we permuted the carbon percentage in each pool with the following constraint: the minimal and maximum percentages are 5 and 85%, respectively (In permutations, the unitary increment or decrement of each pool is ± 5 %).

Second, we investigated the impact of tree functional type on the steady state of soil carbon quality. For this, we used the mean and standard deviation of broadleaved and coniferous litter carbon quality calculated from the meta-analysis in Sect. 2.4. To only focus on the effect of litter carbon quality, the litter quantity was the same for broadleaves and conifers. Outcomes were calculated using the matrix method stated in Sect. 2.5 and the Tuomi-2011 parameter set. Possible correlations between A, W, E and N were not considered in simulations.

2.6.2 Module II - Effect of initial soil carbon quality and simulation length on final soil carbon stock

With a fixed initial soil carbon stock, we carried out simulations on both the effect of initial soil carbon quality and that of simulation length on final soil carbon quantity and quality. For this, we permuted the initial percentage of chemical pools with the following constraint: the minimal and maximum percentages are 5% and 80%, respectively. For the effect of simulation length, we used 1 to 10000 years for each combination of soil carbon quality distribution. We created a virtual site where the climatic condition and litter input were constant and equal to the average value of all the 101 sites. For carbon dynamics analysis, the initial carbon stock was fixed to 100 tC ha^{-1} and this quantity is in the same order of magnitude of all the measured carbon stocks. Regarding the setting of litter input during the simulation length, the following two scenarios were tested:

S1: mean broadleaved litter carbon quality (obtained from the meta-analysis, idem for the other scenarios) and mean litter input quantity of all the broadleaves dominated sites (of the RENECOFOR network, idem for the other scenarios);

S2: mean coniferous litter carbon quality and mean litter input quantity of all the conifers dominated sites.

In the present paper, only the results of S1 are presented, as results between conifers and broadleaves did not change much, especially in long term.

2.7 Running Yasso07 and statistical analyses

We used the same FORTRAN code of the Yasso07 version 1.0.1 used in Didion et al. (2014) for all the model simulations. For each analyses (both RENECOFOR site specific and sensitivity analyses), we conducted 10 simulations. In each simulation, one parameter vector was randomly chosen from the 10 000 parameter vectors.

For each site, we calculated annual carbon stock changes (ACC, in tC ha^{-1} year^{-1}), i.e., the difference of carbon stock between the two national inventories standardized by the temporal interval (t_2 - t_1) as follows:

$$\begin{cases} ACC_{obs} = (CS_{obs,t2} - CS_{obs,t1})/(t_2 - t_1) \\ ACC_{sim} = (CS_{sim,t2} - CS_{obs,t1})/(t_2 - t_1) \end{cases} \tag{Eq. 7}$$

Where, $CS_{sim,t2}$, $CS_{obs,t2}$ and $CS_{obs,t1}$ are the simulated carbon stock at the year t_2, observed carbon stock at the year t_2 and t_1, which are around the year of 1994 and 2010 depending on each site, respectively. In simulations, while observed soil carbon stock at t_1 was used as input, soil carbon quality at steady state achieved by the analytical matrix transformation approach (see Sect. 2.5) was used.

Two reasons account for our preference of comparing ACC_{sim} with ACC_{obs} over comparing $CS_{sim,t2}$ with $CS_{obs,t2}$. First, the parameter sets of Yasso07 were calibrated for a maximum soil depth of 1.0 m, while carbon stocks at the RENECOFOR sites were only estimated down to 0.4 m. It is thus reasonable to speculate that the observed carbon stock data are not

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comparable with Yasso07 estimates. However, focusing on carbon changes instead of carbon stocks may largely erase this bias, because previous studies have evidenced that carbon dynamics are much less active at deep soil layers than at superficial layers (Balesdent et al., submitted). Second, ACC indicates if a site is gaining or losing soil carbon and this information is sometimes more important than the site's carbon stock value. Using a standardized metric (by year) such as ACC can also facilitate result comparison for future studies. The only exception came to the sensitivity analysis on the effect of initial soil carbon quality (Sect. 2.6.2), in which we showed $CS_{sim,t2}$ instead of ACC_{sim}, as the initial soil carbon stock was fixed at 100 tC ha^{-1}.

In order to test the performance of Yasso07 in estimating soil carbon changes at the RENECOFOR sites, we analyzed the residuals of carbon changes, i.e. difference between the simulated and observed values, using analysis of variance (ANOVA). The following environmental and biological factors were tested: site geographical location (latitude, longitude, and altitude), climatic conditions (temperature and precipitation), soil types, tree functional type and tree species. Before each ANOVA, we tested the normality of data using a Shapiro – Wilk test. For the sensitivity analyses, we performed loess regressions (Fox and Weisberg, 2011) to characterize the variation of soil carbon stock as a function of initial soil carbon stock settings and simulation length (1 – 10000 years). Statistical analyses were performed using R 2.13.0 (R Core Team, 2013).

3 Results

3.1 Litter carbon quality of northern temperate tree species

Our meta-analysis (Fig. 3) showed that the litter carbon quality, i.e., carbon composition, of northern temperate tree species significantly differed between tree organs. For woody litters (only using stem data) the percentage of A carbon pool attained up to 80% of the total carbon pool; the sum of A and N carbon pools took at least > 75% and, in most cases, >90%, rendering small percentages of W and E (Fig. 3a). Nevertheless, this dominance of A and N over W and E was much less pronounced in foliage and root litters (Figs. 3b and 3c). Generally, the different tree organs can be ranked according to the sum of the proportions of A and N as follows: wood (>90%) > roots (70 – 80%) > foliage (60 – 70%, Fig. 3d).

The effect of tree functional type on litter carbon quality strongly interacted with that of tree organs. For wood, broadleaves and conifers had clearly shifted point clouds for the relationship between A and N carbon pools: greater proportion of A, but lower proportion of N in broadleaves compared to those in conifers. In foliage and root litter, the effect of tree functional type on proportions of A and W was less pronounced than in wood. The main difference between broadleaves and conifers occurred in N rather than in A (Fig. 3d). Broadleaves litter had lower proportion of N than conifers litter regardless of tree organ (Fig. 3d). The proportions of A and N relative to those of E and W were quite stable between broadleaves and conifers regardless of tree organs (Fig. 3d).

3.2 Simulated versus observed data of carbon changes

The choice of fine root:foliage ratio significantly influenced Yasso07's performance in predicting soil C changes (Fig. S1). Based on the criteria of minimum root mean square error (RMSE), the ideal ratio for conifers appeared between 1.8 and 2.2, while the ideal ratio for broadleaves was the smallest ratio tested (0.1).

When simulated annual carbon stock changes were plotted against observed ones, the point clouds were distributed around the 1:1 diagonal line despite fairly high dispersion (Fig. 4). The correlation between predicted and measured ACC remained weak ($R^2 < 0.1$). The mean observed and simulated annual carbon stock changes (ACC) of all sites are +0.34 ± 0.06 tC ha^{-1} $year^{-1}$ (+0.20 ± 0.06 tC ha^{-1} $year^{-1}$ for broadleaves dominated sites and +0.48 ± 0.10 tC ha^{-1} $year^{-1}$ for conifers dominated sites) and +0.45± 0.09 tC ha^{-1} $year^{-1}$ (+0.96 ± 0.10 tC ha^{-1} $year^{-1}$ for broadleaves dominated sites and -0.05 ± 0.10 tC ha^{-1} $year^{-1}$ for conifers dominated sites), respectively. 48% of broadleaves dominant sites and 39% of conifers dominant sites showed significant differences between observed and simulated ACC (Fig. 4a). In only c.a. 25% of the sites, ACC were significantly different from 0 for both simulated and observed results (i.e. the case 3 in Fig. 4b). There is a significant effect of the tree functional type on the observed and simulated values. The model tended to overestimate the carbon stock changes at broadleaves dominated sites but to underestimate the carbon stock changes at conifers dominated sites. The quantity of sites in which estimates and observed carbon stock changes share the same tendency (i.e. data points in the zone I, IV, III and VI, Fig. 4) was approximately two thirds of the total sites. c.a. one third of sites are in the remaining zones (II, and V) where the predicted tendency was contrary to the observed tendency.

The simulated carbon stock changes exhibited a negative linear relationship with the initial soil carbon stock (Fig. 5b), whereas this tendency was not observed for the observed carbon stock changes (Fig. 5a). Storm damage and soil type could not provide clear tendencies in explaining the residuals. Only for conifer dominant sites, residuals showed significantly differences among the three major types of soil (*n* of sites >5): cambisol > luvisol > podzol (Fig. S3). Tree ages in conifers dominant sites tend to be smaller than those in broadleaves. When considering both tree functional types and tree ages, neither the latter nor their interaction had a significant effect on residuals. With all sites together, residuals become higher with increasing latitude, indicating that simulated ACC was more overestimated in northern zones (ANCOVA, F = 14.9, $P<0.001$). This pattern was particularly strong for broadleaves dominated sites, with the exception of several ones in Pyrenees Mountains (Fig. S4a). Yet, this tendency was not clear for conifers dominant sites (Fig. S4e). Identical residual sign is generally present in clusters in all of the main species (Fig. S4b, S4c, S4d, S4f, S4g and S4h). Broadleaves and conifers dominated sites differed in their responses to environmental factors: for conifers, both temperature and precipitation had no effect on residuals (Fig. S5a), whilst for broadleaves, precipitation was negatively correlated with residuals (ANCOVA, F = 7.17, $P<0.001$, Fig. S5b).

3.3 Effect of litter carbon quality on model prediction (Sensitivity analyses 2.6.1)

Variation of litter carbon quality (without distinction of original organ) altered the steady-state distribution of soil carbon pools (Fig. 6). The carbon belonging to soil A, W and E carbon pools remained below 15%, whatever the biochemistry of litter inputs. The percentages of soil N and H were more susceptible to the variation of litter carbon quality. The size of soil N and H always varied between 25% and 65% of, whenever the pools in litter varied from 5% to 80% (Fig. 6).

The strong sensitivity of the carbon steady state distribution to litter carbon quality was *de facto* greatly discounted in reality, because the variation in chemical composition of tree species was very limited (Fig. 3). Using average compositions of broadleaves and conifers species, we found that, at the steady state, the H pool contains 30 – 40% of soil carbon, the N pool 45 to 55 %, the A pool <5% and W and E pools <2% (Fig. 7). Broadleaves dominated sites differed from conifers dominated sites with a slightly lower percentage N-carbon in the steady-state soil carbon stock, but a higher percentage of H-carbon (Fig. 7).

3.4 Impact of initial condition of soil carbon stock on model prediction (Sensitivity analyses 2.6.2)

Fig. 8 obtained from the sensitivity analysis visualized all the theoretically possible final carbon stocks by varying initial carbon stocks and simulation length (from 1 to 10 000 years). The initial soil carbon quality had a pronounced impact on the final soil organic carbon stocks (including both total stock and stocks in each chemical pools) at annual and decennial scales. For example, when the initial proportion of A pool increased from 0 to 80%, the final proportion of A could increase by +30 to +40 tC ha^{-1} (Fig. 8a) and the final total carbon stock could decrease by c.a. -20 to -30 tC ha^{-1}(Fig. 8u) at annual (i.e., axis log(Year) = 0) and decennial (i.e., axis log(Year) = 1) scales. When simulations were performed over millennium timescale, the initial soil carbon quality did not impact the final soil carbon quality anymore. In other words, the same final soil carbon quality was obtained regardless what the initial soil quality was (Fig. 8). The final stocks of A and the sum of W and E were generally much less sensitive to the variations of initial soil carbon quality than did the final stocks of N and H (Fig. 8, the 1st and 2nd rows versus the 3rd and 4th rows).

4 Discussion

4.1 Agreement between simulated and observed annual soil carbon stock changes

Testing widely popularized soil carbon models using large dataset is highly meaningful work that enables not only assessing the model's ability over various climatic and ecosystem types, but also providing lessons and implications for future modelling work. Here, based on the on average 15 year interval between the measurements of two soil carbon stock change at the RENECOFOR site, the simulated annual carbon stock changes (ACC) using Yasso07 were significantly biased for more than one third of the French RENECOFOR sites. Particularly, Yasso07 generally overestimated the ACC at the broadleaves dominated sites located in the north of France (Fig. 6a-d) and the overestimation can be exacerbated with lower precipitation. We would expect slightly better performance of Yasso07 at conifers dominated sites than at the broadleaves dominated ones, since the model's estimates have shown good correspondence to measurements (of stocks and/or changes) in coniferous forests, especially the Nordic boreal ones (e.g., Karhu et al., 2011; Ortiz et al., 2013). Yet, Yasso07 tended to underestimate the ACC at conifers dominant sites. Except for tree functional type and geographical location (e.g. latitude), ecological variables that are assumed as key factors influencing carbon sequestration processes, e.g. soil type (except for conifers dominated sites), storm damage and stand age, did not show clear tendencies in explaining residuals. Note that those factors were not fully crossed in the 101 sites, rendering testing each signer factor difficult. The simulated ACC showed strongly negative correlation with the initial soil carbon stock which was served as input in Yasso07 (Fig. 5). Such phenomenon can be logically explained by the model mechanism: with increasing initial carbon stock, there is also an increase in the quantity of those easily decomposable compounds, i.e. A, W and E, in soil, which triggers a more substantial mass loss in the following years. However, the observed data on carbon stock changes did not support this trend, suggesting that initial soil carbon pool size is not a controlling factor for soil carbon accumulation at these sites.

Despite Yasso07's significant prediction bias at a number of sites, it is unreasonable to simply attribute the bias to the model *per se*, as multiple uncertainties affecting the quality of the model's input data can be identified (see Sects. 4.2 – 4.4). These uncertainties can occur not only with Yasso07, but also with other prevailing models one may choose, highlighting large knowledge gaps in ecology and soil carbon modelling.

4.2 Soil carbon quality: a recurrent challenge in soil carbon modelling

A great uncertainty is associated with the model initialization of soil carbon quality, as it was not measured, but obtained by matrix inversion with the assumption that the litter input has been the same for decades. Compared to total soil carbon stock, measuring soil carbon quality is much labour intensive and time-consuming. Moreover, data of soil carbon quality from different sources are sometimes incompatible or incomparable due to the use of different chemical pools or protocols of fractionation (Blair et al., 1995). Therefore, measured data of soil carbon quality are generally lacking at worldwide scale. Such lack of information is a recurrent issue for soil carbon dynamics modeling (see Elliot et al. (1996), who has discussed the issue of "Measuring the modelable"). Nearly all the existing soil carbon models require setting carbon quality besides carbon quantity, e.g., Romul (Chertov et al., 2001), RothC (Coleman and Jenkinson, 1996), CENTURY versions Parton et al., 1987; Metherell et al., 1993, CBM-CFS3 (Kurz et al., 2009). Inappropriate setting of carbon quality in models may greatly change carbon stock predicts (Wutzler and Reichstein, 2007; Carvalhais et al., 2008; 2010).

In the present study, soil carbon quality data were unavailable at the French RENECOFOR sites. As a result, we used the simulated carbon quality at steady-state to feed Yasso07. This is a strong, but widely adopted hypothesis in soil carbon modelling work (Foereid et al., 2012). In order to know Yasso07's sensitivity to initial soil carbon quality, we conducted a sensitivity analysis that computed the final soil carbon stocks using all the possible combinations of the composition of chemical pools. This sensitivity analysis confirmed the high influence of initial soil carbon quality on soil carbon stock estimates (Fig. 8), notably at short temporal scales (i.e., yearly and decennial). This result is in line with the previous carbon stock modelling studies (Parton et al., 1993; Kelly et al., 1997; Smith et al., 2009; Foereid et al., 2012), confirming that it is a general problem for all of the chemical pool based carbon models. Besides this consensus, our sensitivity analysis further showed that such effect of initial composition carbon stocks will gradually vanish with increasing length of simulation and especially when the length is up to several centuries or millenniums. Our analysis provides new insights on the sensitivity of model estimated carbon stocks to the method and assumptions used in model initialization. Such analysis can be transplanted to the other carbon models to test their theoretical performance and robustness of each model at different temporal scales and also, to compare models. It is also worthwhile to mention that Yasso07's particular model configuration, i.e. the use of measurable chemical pools, may open the possibility of using measured data of soil carbon quality for model initialization instead of simulated steady-state ones. Future measurements on soil carbon quality of the RENECOFOR sites may offer an ideal opportunity to compare the impact of the two sources of soil carbon quality on Yasso07's predictions.

4.3 A precise estimation of root litter quantity may greatly improve Yasso07 prediction

An important source of uncertainty in the estimates of litter quantity at the RENECOFOR sites was the fine root litter input. Many studies have revealed that fine roots act as a major source contributing to total litter quantity due to their fast turnover rates (Brunner et al., 2013; Kögel-Knabner et al., 2002; Berg and McClaugherty, 2008). In some forest ecosystems, the proportion of fine root litter is even comparable to that of foliage (Freschet et al., 2013; Xia et al. 2015). However, estimating fine root litter inputs is, again, a time-consuming and challenging task. Due to this reason, so far rarely have national wide forest inventory projects ever incorporated direct measurement of the dynamics of fine root litter input (i.e. the case of RENECOFOR network). Fine root turn-overs of forest species are variable depending on climate, tree species and management scenarios (Kögel-Knabner et al., 2002; Litton et al., 2003; Mokany et al., 2006), rending the choice of model input values highly subjective and difficult. By testing variable fine root:foliage ratios of litter input, we observed a significant shift in the predicted carbon stock changes by Yasso07 (Fig. S1). This finding not only highlights the importance of precisely quantification of fine root litter input, but also suggests that broadleaves and conifers may have separated quantification of fine root litter input with regard to that of foliage, although here we chose the same ratio for both broadleaves and conifers dominant sites. We also noted that using one ratio per tree functional type (conifers versus broadleaves) could only change the overall prediction baseline, but cannot reduce the data dispersion. Consequently, it is of great interest to estimate root litter input quantity at species level on the basis of direct measurement and then couple specific data with Yasso07.

Another potentially important litter inputs may come from the understory shrubby and herbaceous species, which were not taken into account in this study due to data unavailability. Herb and shrub layer are typically not estimated in forest inventories but they can contribute significantly to the annual litter production in forests (eg. de Wit et al. 2006, Gilliam 2007, Lehtonen et al. 2016). Muukkonen and Mäkipää (2006) estimated that the carbon inputs from herb and shrub vegetation in Finnish forests were in the range of 0.50 to 0.66 tC ha^{-1} year^{-1}. Such value is apparently high, as it attains 12% - 23% of the mean total tree litter inputs of all the RENECOFOR sites (Table 1). This is in line with the preliminary data from Etzold et al. (2014), who suggested that understory vegetation contributed c.a. 12% (0.1 to 36.8%) to the total observed annual C turnover at six sites of the Long-term Forest Ecosystem Research Programme LWF (ICP-Level II plots).

Also, Yasso07's parameter set was calibrated using one of the richest litterbag datasets in the world in terms of number of observation. The state-of-the-art of soil carbon modeling is based on the litter input and decomposition processes as the driving forces in soil carbon accumulation where measured mass loss of litter is used to fit model parameters. Our knowledge on the importance of other sources of biological carbon input, e.g. soil fauna and rhizodepostion, as well as how to take them into account in modelling processes still remains poor. Accordingly, whether and to which extent the bias of Yasso07 is related to these alternative sources of biological carbon input is unknown.

4.4 Limited but potentially strong effect of litter carbon quality on Yasso07 prediction

Litter carbon quality, especially the content of litter carbon in the N carbon pool, controls the bulk litter decomposition rate and this has been well-known (De Deyn et al., 2008). Indeed, the meta-analysis (Fig. 3) confirmed the significant disparity of carbon allocation between broadleaves and conifers litter in all the investigated organs. However, little has been known about how this disparity of litter carbon quality between broadleaves and conifers dominated sites will be projected into the long-term prediction of soil carbon stock. Our sensitivity analysis Module I (Sect. 2.6.1) with Yasso07 showed a generally limited impact of such disparity on the soil carbon quality of steady-state (Fig. 6) and this impact only occurred in N and H pools (Fig. 7). Litter carbon quality seems to be a less important factor determining the model predictions via affecting soil stock initialization. This is especially true for the three more labile carbon pools (i.e. A, W and E) and their mean residence time has quite low disparity between themselves (Fig. 1). This seems to more or less weaken the meaningfulness of splitting litter and soil labile carbon compounds into the three carbon pools (A, W and E) in Yasso07.

4.5 Suggestions for model improvement in the future

First of all, we found the model structure and algorithm good, clear and simple to operate and this goes along well with the positive remarks toward Yasso and Yasso07 in literature (Rantakari et al., 2012; Didion et al., 2014; Lu et al., 2015; Wu et al., 2015). Fig. 1 only showed the mass flows that are statistically significant for the case of using the Tuomi 2011 parameter set. Yasso07 keeps all the theoretical mass flow possibilities in the $\boldsymbol{A_p}$ matrix in (Eq. 1b). However, a mass flow parameter with a statistical significance does not signify that it is biologically meaningful. For this we can quote the flow N → A of the model (Fig. 1), for which the modeler had assigned an astonishingly high percentage: $p_{N \to A} = 83\%$. This quantity is disputable in the angle of soil biochemistry, because as lignin, i.e. the major component constituting the N carbon pool, likely does not turn into the A pool, but would condense with other nearby phenol, peptides or saccharides (Burns et al., 2013).

As a model aiming at predicting soil carbon dynamics, Yasso07 is still highly simple in the description of soil variables that are known to impact decomposition processes in soil, For example, the effect of soil mineralogy or aggregation have not been considered in Yasso07 yet. Indeed, the model was often applied on soils fairly rich in organic matter (e.g., Karhu et al., 2011), where the consideration of soil mineral properties was not particularly relevant, and where the authors' assumption that litter quantity is a good proxy for soil properties was reasonable. In addition, when Yasso, i.e., Yasso07's prototype, came up in 2005 (Liski et al., 2005), information on mineral soil properties in the various forest soil horizons was not commonly available, but nowadays it is easier to obtain it, although there is still a lack of such detailed data for consistent application across large regions or at the national scale (Didion et al., 2016).

In spite of the lack of explicit description of soil variables, the framework of Yasso07, based on a chemical partitioning of soil organic carbon inputs and pools, holds two advantages: (i) it enables the measurement of the model pools, and (ii) it offers a clear structure based on litter and soil chemistry. These advantages make the model appropriate for future improvement by incorporating the most recent findings with regard to the mechanisms on soil organic carbon dynamics. Indeed, the chemistry of organic substrates rules the interaction level with mineral surfaces, and thus the level of protection from degradation. It also regulates the interactions with extracellular enzymes, and thus the soil organic carbon degradation rates.

5 Conclusions

We tested the performance of the soil carbon model Yasso07 using the decennial scale French national wide forest data thank to the RENECOFOR network, as well as a meta-analysis database for litter carbon quality and sensitivity analyses to characterize the effect of inputs of initial litter and soil carbon quality on the model's predicts. We showed that while the model's predicts of the annual soil organic carbon changes (ACC) stay within the same order of magnitude with the observed ones, correlation between the observed and simulated ACC remained weak. There was a bias of model prediction for the carbon change tendency at more than one third of the French sites. The performance of Yasso07, as well as the other soil carbon models, should be examined before their application for management guidelines and policy-making for forest ecosystems at any study scales.

Such bias can be attributed to multiple reasons concerning model input, such as (i) large uncertainty in the measured soil carbon stock and changes; (ii) lack of information on initial soil carbon quality at the site level and (iii) lack of information on below ground litter production. For the latter two aspects, their importance was explicitly confirmed by our sensitivity analyses. These reasons are valid for the whole state-of-the-art of soil carbon modelling, regardless of the model that one uses. Some of the model's parameters governing the transfer among soil pools are statistically derived but not directly measured, and thus may poorly represent the real biochemical processes of decomposition.

These findings allow us to provide a series of suggestions to modelers, users and policy makers:

- To Yasso07 modelers, we suggest keeping the current model structure, algorithm and parameter natures, but incorporating more refined some biochemical processes, including (i) revising certain mass flows to achieve both statistically and biologically meaningful process (especially the N→ A flow) and (ii) refining decomposition process (i.e., the residence times between the A, W and E soil carbon pools).
- To Yasso07 users, we suggest working in conjunction with modelers in order to better reduce the uncertainties in both model initialization of soil carbon stock. We also suggest using measurement based forest litter input quality and quantity, especially the belowground fine root litter data.
- To policy makers, we suggest keeping prudent toward diagnosis from based on a single carbon model, especially when long term trend is predicted. Predictions from multiple models served as a cross-validation procedure are preconized for both global and local scales areas.

Our decennial observation sites spreading at a large spatial scale that covers different ecosystems can facilitate and provide good opportunities for future calibration, improvement, and re-evaluation of the model. Finally, taking Yasso07 as an example, this work highlighted both the interest and methodologies of testing the other soil carbon models using sensitivity analyses, which enable us to better understand the limits of the model and of data input for future improvements in soil organic carbon modelling.

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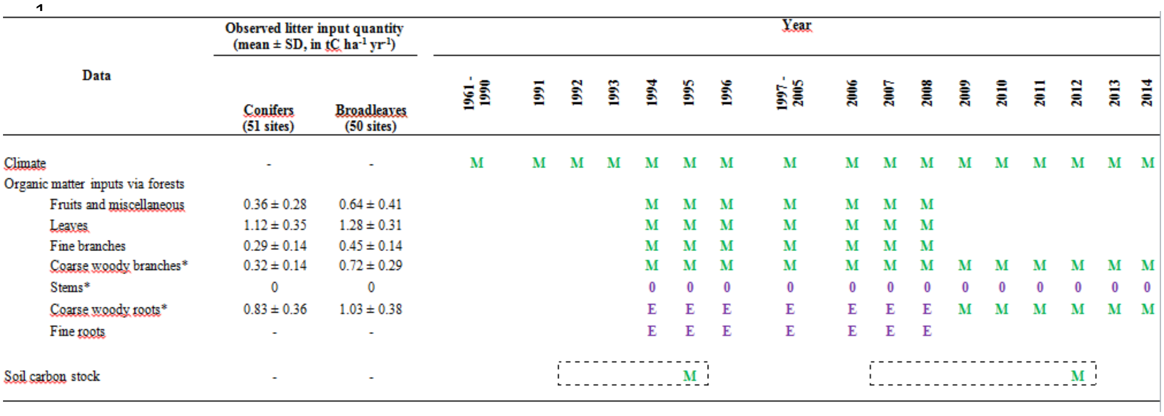
Tables

Functional type	Species	Organ	Case	No. of obs.				Mean (%)				SD (%)			
				A	W	E	N	A	W	E	N	A	W	E	N
Broadleaves	*Fagus sylvatica* L.	wood	4	4	4	4	4	74.5	2.8	1.2	21.5	1.4	1	0.5	1.4
		leaf	2	2	1	1	2	39.6	22.1	12.5	25.8	3.5	NA	NA	1.7
		root	3	1	9	9	1	31.5	8.8	18.6	41.1	NA	1.2	1.2	NA
	Quercus petraea (Matt.) Liebl.	wood	4	19	19	19	19	67.5	6.1	3.5	22.9	4.9	2.3	1.7	2.6
		leaf	4	12	12	12	12	40.8	16.3	14.2	28.7	3.5	4.7	9.3	7.1
		root	5	15	9	9	15	34.9	7.6	16.2	41.3	8.0	1.1	1.1	10.4
	Quercus robur L.	wood	4	19	19	19	19	67.5	6.1	3.5	22.9	4.9	2.3	1.7	2.6
		leaf	2	1	12	12	1	37.7	21.6	17.3	23.4	NA	7.3	7.3	NA
		root	3	1	9	9	1	28.6	11.1	23.4	36.9	NA	1.5	1.5	NA
Conifers	*Abies alba* Mill.	wood	4	14	14	14	14	66.7	2.7	2.4	28.2	1.9	1.3	0.8	1.3
		leaf	2	1	6	6	1	32.4	26.4	10.7	30.5	NA	1.4	1.4	NA
		root	3	1	13	13	1	25.3	19.1	21.5	34.1	NA	6.2	6.2	NA
	Larix deciduas Mill.	wood	4	6	6	6	6	65.3	5.9	1.9	26.9	3.2	2.4	0.9	1.5
		leaf	2	2	4	4	2	33.3	30.2	10.1	26.4	2.5	1.6	1.6	7.7
		root	3	1	13	13	1	32.5	16.2	18.2	33.1	NA	5.2	5.2	NA
	Picea abies (L.) H. Karst	wood	1	1	1	1	1	69.5	1.9	1.0	27.6	NA	NA	NA	NA
		leaf	2	1	6	6	1	37.0	29.5	12.0	21.5	NA	2.2	2.2	NA
		root	3	3	13	13	3	36.6	14.8	16.6	32.0	7.8	4.8	4.8	2
	Pseudotsuga menziesii (Mirb.) Franco	wood	1	1	1	1	1	65.3	4.0	4.0	26.7	NA	NA	NA	NA
		leaf	1	6	6	6	6	36.4	25.1	10.9	27.6	6.8	13.1	1.2	6.3
		root	1	2	2	2	2	41.7	16.9	8.4	33.0	2.4	5.5	0.3	3.3
	Pinus nigra var. corsicana (J.W. Loudon) Hyl.	wood	4	22	22	22	22	66.6	3.3	4.0	26.1	2.9	1.5	2.4	1.3
		leaf	2	1	27	27	1	47.1	15.2	13.8	23.9	NA	6.3	6.3	NA
		root	4	10	10	10	10	36.0	9.2	11.9	42.9	4.9	4.4	3.1	7.3
	Pinus pinaster Aiton	wood	4	22	22	22	22	66.6	3.3	4.0	26.1	2.9	1.5	2.4	1.3
		leaf	2	1	27	27	1	43.2	18.2	16.5	22.1	NA	7.5	7.5	NA
		root	4	10	10	10	10	36.0	9.2	11.9	42.9	4.9	4.4	3.1	7.3
	Pinus sylvestris L.	wood	1	1	1	1	1	71.7	0.9	1.0	26.4	NA	NA	NA	NA
		leaf	1	3	3	3	3	40.7	17.0	16.0	26.3	3.8	7.5	6.5	2.4
		root	2	4	10	10	4	51.2	4.4	6.0	38.4	3.7	1.4	1.4	4.5

Table 1 Litter carbon quality of the species present in the French RENCOFOR network estimated based on literature. In the column "Case," each number corresponds to one case of data availability in literature: 1- at least one dataset of complete chemical composition (i.e. for AWEN) exists at species level; 2 - at least one dataset of incomplete chemical composition (only for A, N and the sum of W and E) exists at species level; in this case, the mean proportion of W and E at genus level is used; 3 – no data are available at species level, but at least one complete dataset of chemical composition exists at genus level; 4 - no data are available at species level, but at least one dataset of chemical composition exists at genus level; in this case, the mean proportion of W and E at tree functional type level is used; 5 – no data are available at neither species nor genus level, in this case, the mean AWEN composition at tree functional type level is used. From Case 1 to 5 is in descending order of priority.



Data	Observed litter input quantity (mean ± SD, in tC ha^{-1} yr^{-1})		Year																
	Conifers (51 sites)	Broadleaves (50 sites)	1961 - 1990	1991	1992	1993	1994	1995	1996	1997 - 2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Climate	-	-	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
Organic matter inputs via forests																			
Fruits and miscellaneous	0.36 ± 0.28	0.64 ± 0.41					M	M	M	M	M	M	M						
Leaves	1.12 ± 0.35	1.28 ± 0.31					M	M	M	M	M	M	M						
Fine branches	0.29 ± 0.14	0.45 ± 0.14					M	M	M	M	M	M	M						
Coarse woody branches*	0.32 ± 0.14	0.72 ± 0.29					M	M	M	M	M	M	M	M	M	M	M	M	M
Stems*	0	0					0	0	0	0	0	0	0	0	0	0	0	0	0
Coarse woody roots*	0.83 ± 0.36	1.03 ± 0.38					E	E	E	E	E	E	E	M	M	M	M	M	M
Fine roots	-	-					E	E	E	E	E	E	E						
Soil carbon stock	-	-						M									M		

Table 2 A summary of the data used for Yasso07 simulations in the present study. In the "Year" columns: M - measured data; E - estimated data according to the measured ones; 0 – noted, but the contribution to litter is ignorable. For soil carbon stock measurement, dashed line zones denote the inventory duration. For each year, each symbol (M and E) only account for the general case and hence it is possible that measurement was occasionally omitted at some sites. * - litter input caused by harvest or storms were included (once they occurred); SD - standard deviation; litter inputs are dry matters. Diameters used for defining each litter type: ≤2 cm for fine branches, >4 cm for coarse woody branches, > 5 mm for coarse woody roots and ≤ 5 mm for fine roots.

Figures

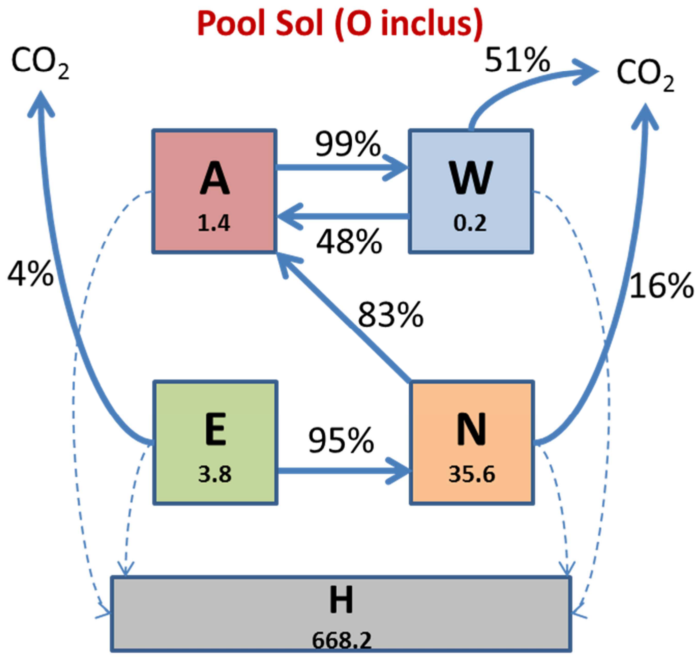


Figure 1 Partitioning of soil carbon pools in Yasso07 (after Tuomi et al., (2011b)) Letters: A: hydrolysable in Acid; W: soluble in Water; E: soluble Ethanol; N: Non-soluble; H: recalcitrant Humus. Solid arrows represented the carbon flows that are statistically significant from zero. Dashed arrows refer to the carbon flows toward H. Values in each pool is an example inverse of mean residence time (*1/k*, in year) estimated using Yasso07 parameters.

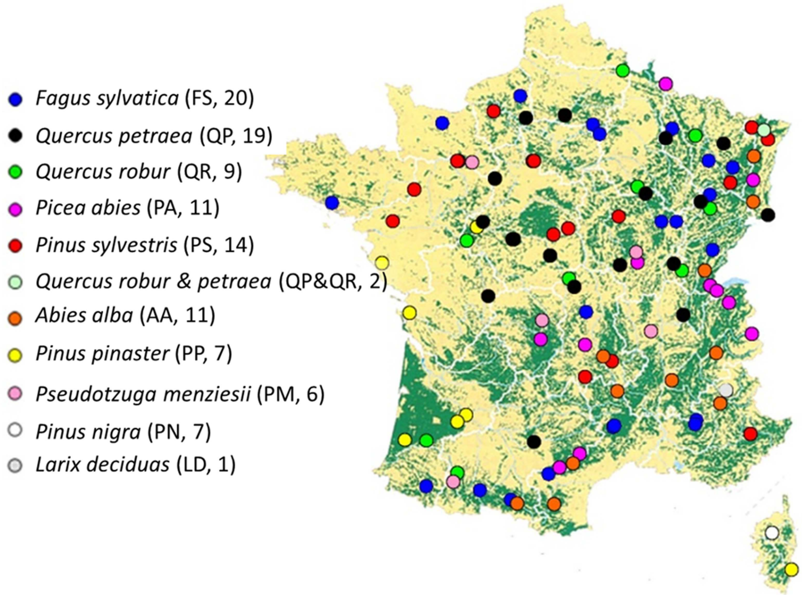


Figure 2 Geographical distribution of the sites of RENECOFOR network used for testing the performance of Yasso07 (see also Jonard et al., 2017). Forested areas are represented in green. Each circle represents one site; the color represents the dominant tree species of the plot. In each pair of parentheses, the species abbreviation and number of sites by species are indicated.

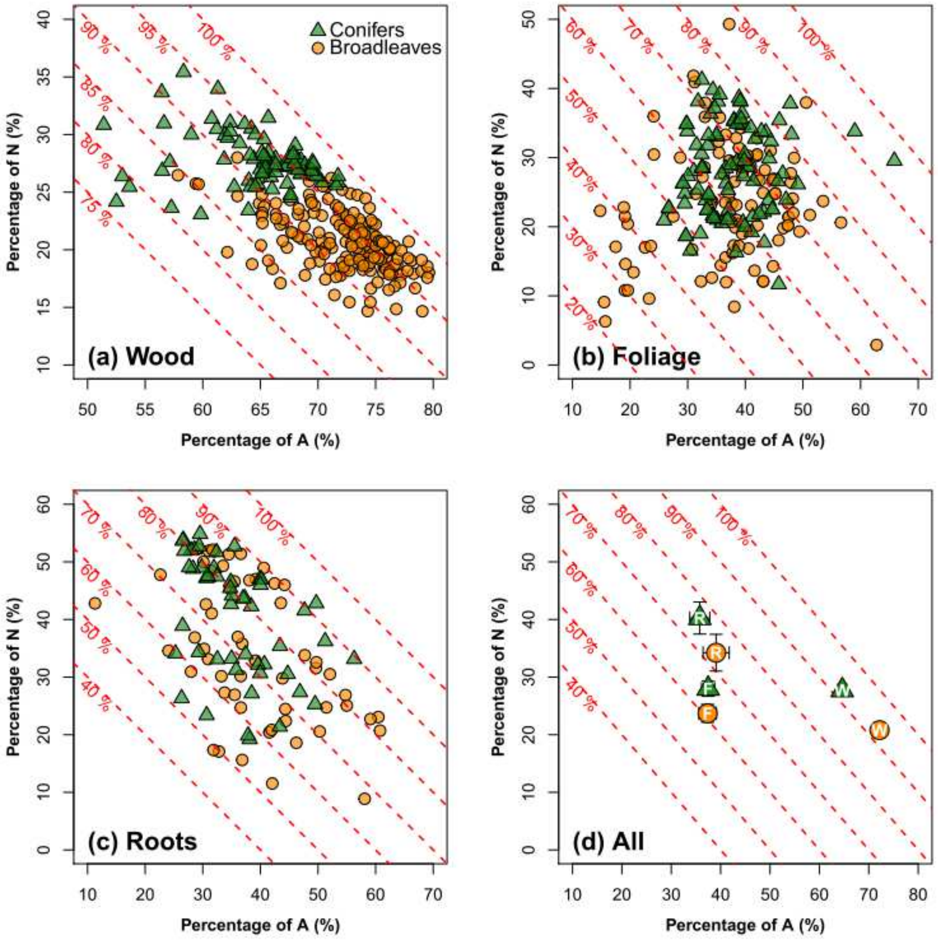


Figure 3 A meta-analysis of the carbon composition for northern temperate tree species: *x*-axis represents the percentage of acid-hydrolysable compounds (e.g. cellulose, noted by A, in %) and *y*-axis represent the percentage of non-soluble and non-hydrolyzable compround (e.g. lignin, noted by N, in %). The oblique dashed red lines notify the sum of A and N, the values of which are shown here. The remaining percentage, i.e. 100 - A - N, refers to the portion of compounds like non-polar extractives, ethanol ordichloromethane (E), or in water (W). (a) Analysis conducted for wood (106 data points for broadleaves; 79 for conifers), (b) for foliage litter (b, 106 data points for broadleaves; 83 for conifers) and (c) for root litter (58 data points for broadleaves; 49 for conifers); (d) is a statistical synthesis (symbols – means and error bars – 1.96 * standard error) of wood (W), foliage (F) and roots (R) in a common coordinates system. Attention to the use of different axis graduations in each plot. See Supplementary Material II for the data sources. Note the different y-axis scales.

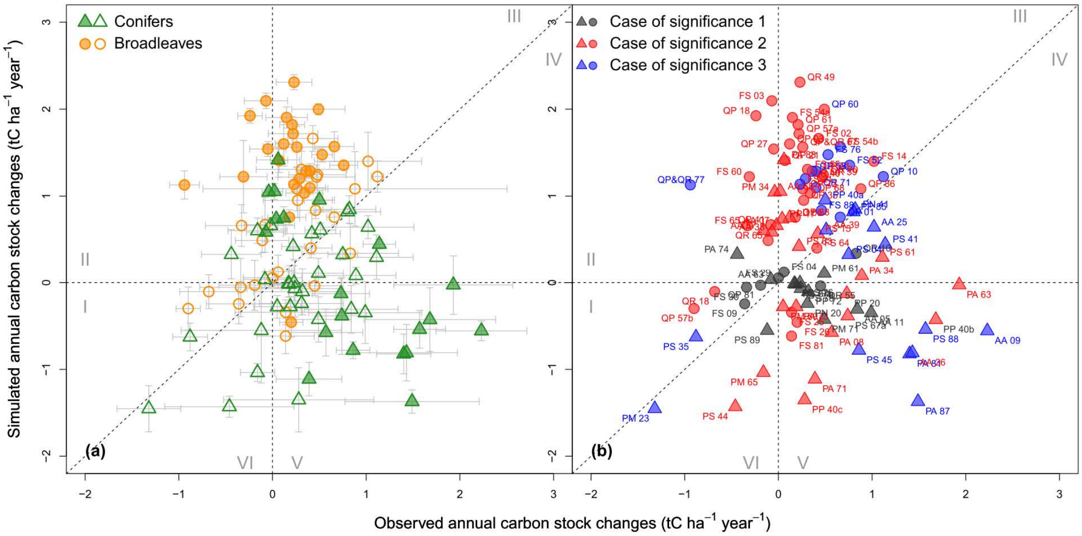


Figure 4 Comparison between simulated and observed annual carbon stock changes (ACC, in t ha^{-1} year^{-1}). Round and triangle symbols represent broadleaves and conifers dominated sites, respectively. The chosen fine root:foliage ratio for broadleaves and conifers is 1.0. To facilitate discussions, we set Roman numbers (I-VI) denoting the six zones in which data points are distributed. In (a), error bars represent standard errors; hollow and filled points represents non-significant and significant differences between simulated and observed ACC according to t-test (at 95% confidence level). In (b), case of significance: 1 – no significant difference from 0 for neither observed nor simulated ACC; 2 - a significant difference from 0 for either observed or simulated ACC and 3: - a significant difference from 0 for both observed and simulated ACC.

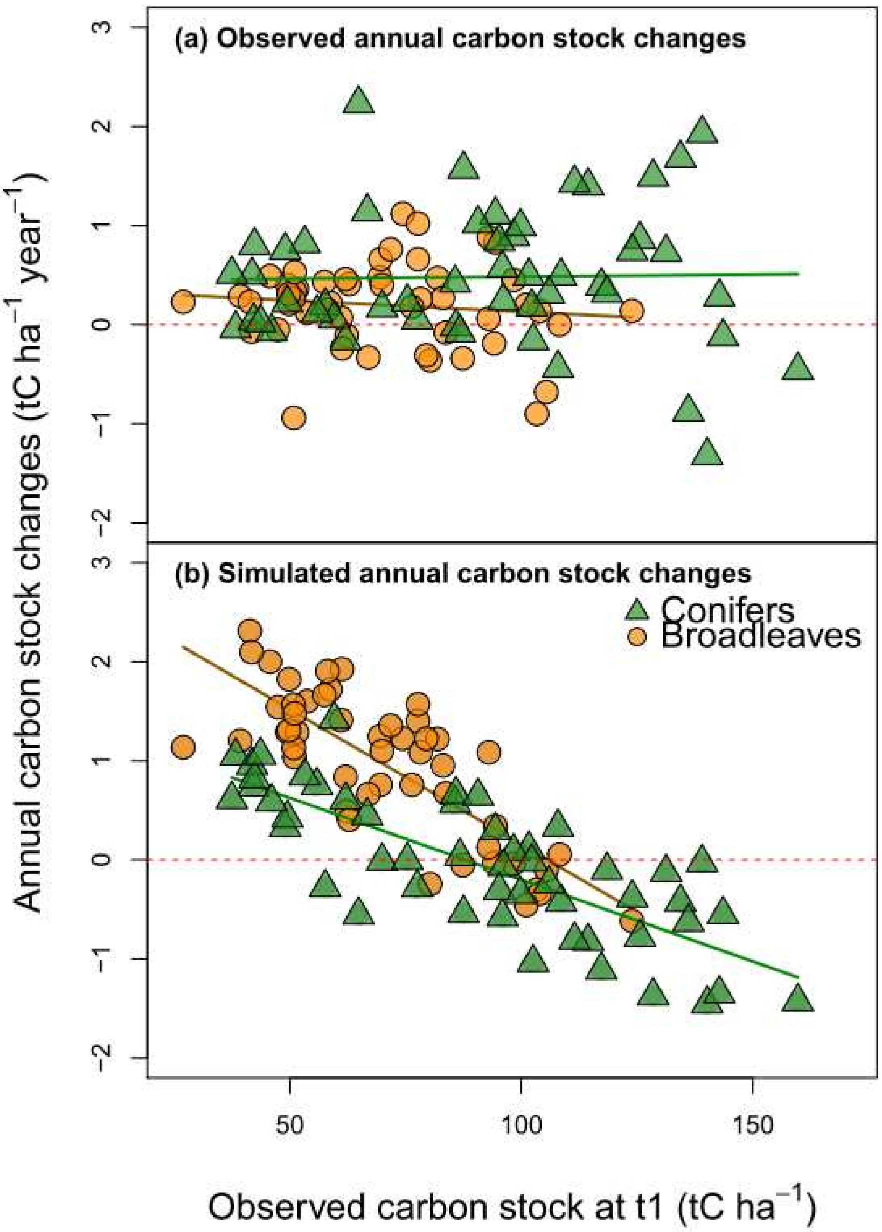


Figure 5 Observed (y-axis, a) and simulated annual change changes (y-axis, b) plotted against the observed carbon stock (x-axis) during the first soil carbon stock inventory. Regressions: $y = -0.002x + 0.360$ ($R^2 = 0.00$) for observed values of broadleaves dominated sites; $y = 0.0004x + 0.440$ ($R^2 = -0.02$) for observed values of conifers dominated sites; $y = -0.027x + 2.881$ ($R^2 = 0.62$) for simulated values of broadleaves dominated sites; $y = -0.016x + 1.449$ ($R^2 = 0.60$) for simulated values of conifers dominated sites;

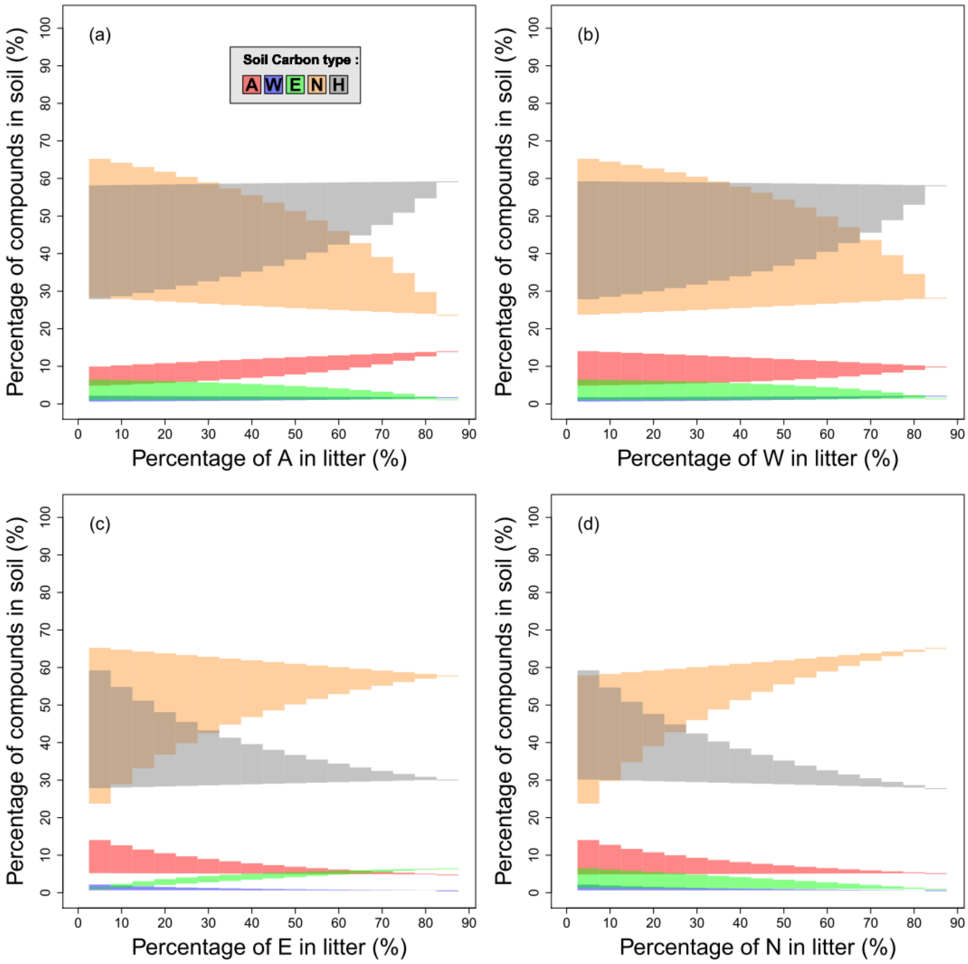


Figure 6 Variation of soil carbon quality at steady-state (y-axis) in response to fully theoretical permutation of carbon pool composition in litter. From (a) to (d) – permutations of proportion of litter A, W, E and N carbon pools, respectively. Outcomes were calculated using the matrix method. For each permutation, litter input quantity was fixed to a constant.

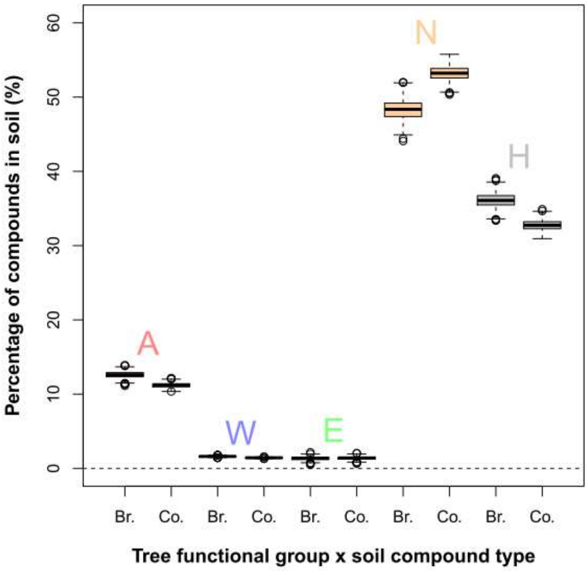


Figure 7 Sensitivity analysis of the impact of litter source (broadleaves and conifers differing in litter carbon pool compositions) on soil carbon quality at the theoretical steady state. 1000 permutations were performed based on the mean and standard deviation of the percentage of each pool. For each boxplot, the lower and top edge of the box corresponds to the 25th and 75th percentile data points; lower and top bars the line within the box represents the median and the hollow points indicate outliers.

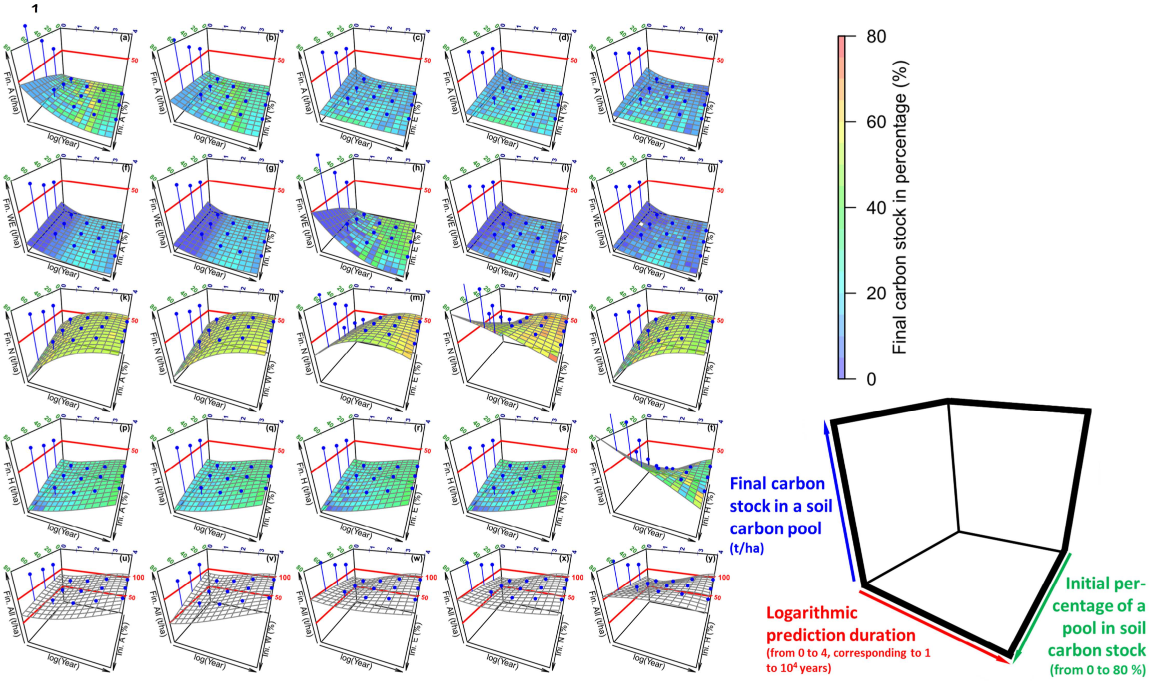


Figure 8 Sensitivity analysis of the impact of carbon pool composition of initial soil C stock (*x*-axis (↙), in %) and simulation length (*y*-axis (→), in logarithmic years) on final soil carbon stock (*z*-axis (↑), in tC ha^{-1}). Here, the results are generated using the mean broadleaves litter input quantity and quality of the RENECOFOR sites. Initial soil carbon stock was fixed to 100 tC ha^{-1}. Subplots in each row show the final stock evolution of one type of soil carbon pools (i.e. A, W, E, N and H). Particularly, in the 2nd row W and E were combined due to their weak quantities in most of cases. Subplots in each column show the effect of one type of soil chemical groups on the final stocks of the five soil carbon pools (each of them for the first four and the last one is the total stock). In each subplot, a membrane (with grids for three-dimensional effect) represents the loess fit (polynomial equation) to *z* (in tC ha^{-1}) as a function of *x* and *y*; the color of the membrane represent the relative value of *z* (in %), i.e. the proportion of one soil carbon pool within the total soil carbon stock. No color is assigned to the membranes in the last row, because the relative value is 100 %. Blue lollipops denote the standard deviations of the simulated mean z (on the membrane surface) given each (x, y) locations, which follow a systematic distribution.

Supplementary Materials

Supplementary Materials I: Supplementary tables and figures.

Supplementary Materials II: Database for the meta-analysis of wood and litter chemical composition.