Uncertainty of upland soil carbon sink estimate for Finland

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Abstract

Changes in the soil carbon stock of Finnish upland soils were quantified using forest inventory data, forest statistics, biomass models, litter turnover rates and the Yasso07 soil model. Uncertainty in the estimated stock changes was assessed by combining model and sampling errors associated with the various data sources into variance-covariance matrices that allowed computationally efficient error propagation in the context of Yasso07 simulations.

In sensitivity analysis we found that the uncertainty increased drastically as a result of adding random year-to-year variation to the litter input. Such variation is smoothed out, when using periodic inventory data with constant biomass models and turnover rates. Model errors (biomass, litter, understorey vegetation) and the systematic error of total drain had a marginal effect on the uncertainty regarding soil carbon stock change. Most of the uncertainty appears to be related to uncaptured annual variation in litter amounts. This is due to fact that variation in the slopes of litter input trends dictates the uncertainty of soil carbon stock change. If we assume that only foliage and fine root litter of trees vary year-to-year, being less than 10% we can claim that Finnish upland forest soils have accumulated carbon during first Kyoto period (2008 - 2012).

Keywords: Yasso07, Bayesian, GHG inventory, soil modelling

Introduction

Carbon stocks of trees in European forests are increasing (Nabuurs et al. 2013). This means that simultaneously litter input to soils also increases, assuming that litter production is proportional to biomass. At the same time there are studies that report soil carbon losses for upland forest soils (e.g. Bellamy et al. 2005) and studies that report increases in carbon stocks (e.g. Grüneberg et al. 2014, Ortiz et al. 2013). These differences in reported soil carbon stock change estimates between countries may have originated for various reasons, but a common feature is that soil carbon inventories are sensitive to systematic errors (Smith et al. 2007) and the necessary sample size for carbon stock change detection requires substantial resources (Mäkipää et al. 2008). Currently, very few European countries are able to statistically demonstrate whether their upland forest soils accumulate or lose carbon. Similarly, soil carbon models show both sinks and sources for carbon stock changes at a national level (Ortiz et al. 2013). Future soil carbon stock changes predictions are urgently needed, but earth system models (ESM) face challenges when predicting soil carbon stock change feedback in the future climate. For example, Todd-Brown et al. (2014) reports that boreal forests may lose 28 Pg of carbon or accumulate 62 Pg of carbon during this century, depending on the ESM model applied. Evidently, there is urgent need for uncertainty estimates for soil carbon stock change.

In order to provide tools for climate change mitigation, countries are obliged under the Kyoto protocol to report the carbon stock changes of tree biomass, dead wood, litter and soil organic carbon. Reporting follows the guidelines provided by the IPCC (2003). National greenhouse gas (GHG) inventory of Finland reports soil carbon stock changes based on a chain of forest inventory data and models of living tree biomass and soil processes. National Forest Inventory (NFI) data is used to estimate the time series of litter input due to both litterfall from living trees and natural mortality. Forests statistics are used to quantify harvesting residues that are left in the forest to decay. Coverage measurements of understorey vegetation have been converted to biomass and then to litter input using specific turnover rates. The estimated litter input from these sources is given as an input to theYasso07 soil carbon model (Tuomi et al. 2011), which has been simulated with weather and litter data as input to quantify soil carbon stock changes. This methodology builds on the work by Perruchoud et al. (1999) and Liski et al. (2006). A similar method has also been applied to soil carbon stock change with the GHG inventories of other countries, such as Norway and Switzerland.

The Yasso07 model estimates of soil carbon stock change have been tested against repeated soil carbon inventories. Ortiz et al. (2013) tested the performance of the Yasso07 model against Swedish soil carbon inventory data and found that model estimates did not differ significantly from the measured values, while noting that the uncertainties of both model estimates and measurements were substantial. Rantakari et al. (2012) also tested Yasso07 against Biosoil soil data from Southern Finland, where Yasso07 performed reasonably well and produced soil carbon stock change estimates of the same magnitude as those based on measurements from the organic layer.

The uncertainties in tree biomass and soil carbon accumulation for Finnish forests have been studied by Peltoniemi et al. (2006). The study was based on Monte Carlo simulations with biomass, litter, and soil carbon estimates from NFI data combined with the Yasso model (Liski et al. 2005). According to Peltoniemi et al. (2006), the most uncertain part of the carbon stock change of Finnish forests was related to the Yasso soil model and its initial carbon pool values. Peltoniemi et al. (2006) also highlighted the importance of the quantification of uncertainty in the litter input, particularly the input originating from foliage and fine roots. From previous studies we know that the mass and turnover rates of fine roots are challenging to measure and that their estimates are often inherently biased (Brunner et al. 2013). In the US, Ogle et al. (2010) studied the error budgets of CENTURY model for croplands. They found that most of the uncertainty was attributed to model structure, and the role of model input uncertainty was marginal (i.e. manure and tillage practice). In both of these earlier studies, the error budget was incomplete: Peltoniemi et al. (2006) did not include uncertainties and correlations in model parameters and Ogle et al. (2010) excluded the uncertainty of the quantity of vegetation litter input.

The Yasso07 model builds on the Yasso model (Liski et al. 2005). In contrast to earlier versions, more data was included and the Markov Chain Monte Carlo (MCMC) methods (Tuomi et al. 2011) were applied both to determine the model structure and to estimate its parameters. The advantage of MCMC methods is that the end-user can run Yasso07 accounting for the uncertainty in model parameters. The tree-level biomass models of Repola (2008, 2009) provided an update for biomass estimation methodology in Finland. Ståhl et al. (2014) presented a method for assessing the total uncertainty of NFI-based tree biomass estimates, accounting for both NFI sampling errors and uncertainty, and correlations in the estimates of biomass model parameters.

In summary, the necessary elements are now available for taking into account all major uncertainties in model-based estimation of soil carbon stock change driven by litter input and weather. But to the best of our knowledge, a coherent method for implementing this analysis in the context of operational GHG inventory is still lacking. The main objectives of this research were (i) to develop such a method, (ii) to apply it in the context of Finnish GHG inventory, quantifying the uncertainties in estimated soil carbon changes in the upland soils, and (iii) to determine whether we can say, in a transparent and verifiable way, that these soils are a carbon sink. We also tested how the addition of inter-annual variation to litter production alters our conclusions, and evaluated the contributions of individual error components to the total uncertainty of soil carbon stock change.

Material and methods

Annual changes in the carbon stock of litter, dead wood and the soil organic matter pool of forest land upland soils were estimated with the Yasso07 soil carbon model for the years 1990-2013 separately in southern and northern Finland, similarly to the Finnish GHG-inventory (Statistics Finland 2014). The Yasso07 model simulates soil carbon for upland forests and is based on mass flows according to organic matter quality. Data used in calibration originates from litter bags, deadwood measurements and from soil carbon stock measurements and their fractionation according to solubility. Given the initial stock and the time series of litter input and weather data, it provides estimates of carbon stocks and changes of litter, dead wood and soil organic matter down to a depth of one meter. In this work, we used the parameterization of Yasso07 based on Rantakari et al. (2012) and the estimated litter input from living trees, understorey vegetation, natural mortality and logging, as in the Finnish GHG-inventory (Statistics Finland 2014).

Litter input from living trees

Annual litter production from living trees was estimated as the product of annual estimates of living tree biomass according to different components (foliage, branches, stem+bark, stump and roots) and component-specific litter turnover rates. The biomass estimates were derived using tree-level measurements from four NFIs and Repola’s (2008, 2009) biomass models (Tables A1.1 and A1.2). Uncertainty due to sampling was evaluated with standard NFI methods (e.g. Tomppo et al. 2011sec. 3.5), and sampling correlations between different biomass components, originating from the use of same tree measurements, were similarly evaluated based on empirical correlations of biomass estimates at the level of NFI sample plot clusters (Table A1.3). Uncertainty and correlations stemming from the estimation of biomass model parameters (Table A1.4) were assessed following the approach of Ståhl et al. (2014). The amounts of fine roots were estimated as products of leaf mass based on the models of Marklund (1988) and the leaf mass-to-fine root ratios of Helmisaari et al. (2007). The uncertainty in those leaf mass-to-fine root ratios was not included in our analyses.

The uncertainties of litter turnover rates for each biomass component were mostly based on the work by Peltoniemi et al. (2006). The rates of the different components were assumed to be mutually independent (Table A1.5).

Litter input from understorey vegetation

Litter production from ground vegetation was assessed based on NFI measurements of vegetation coverage measurements conducted during 1995. Litter was estimated with cover-to-biomass models and with turnover rates. The litter input of the ground vegetation groups, such as shrubs, herbs and grasses, lichen and mosses, of both southern and northern Finland were estimated with data from 3000 permanent sample plots, described in more detail by Mäkipää and Heikkinen (2003). Biomass models (Muukkonen and Mäkipää 2006, Muukkonen et al. 2006) and the litter turnover rates from Liski et al. (2006) were used to estimate litter (see Table A1.5). The uncertainties of the parameter estimates of the understorey biomass model were included by utilizing parameter uncertainties and variance-covariance matrices (Muukkonen et al. 2006). It was assumed that the coefficient of variation for the litter turnover rate was 10% for each vegetation group (bryophytes, lichens, dwarf shrubs and herbs & grasses). We thus obtained the mean litter input and its uncertainty for southern and northern Finland (Table A1.1).

Litter input from logging and natural mortality

The amounts of litter input from harvesting residues and natural mortality were estimated based on forest statistics (Finnish Forest Research Institute 2014). For logging, we used annual estimates of harvested stem volume (Statistics Finland 2014, table 7.2-2) and waste wood ratios based on NFI, in order to estimate the residues from stem wood. The volumes from both logging and natural mortality (Table A1.6) were converted to biomass using expansion and conversion factors estimated from trees that were felled or died, between two measurements of permanent NFI9 and NFI10 sample plots (Tables A1.2, A1.3, and A1.4). Uncertainties and correlations of the expansion factors, as well as of the volume of natural mortality were obtained from these measurements in the same way as for living biomass. For the time series of logging volumes, a 5% relative standard error with systematic over- or under-estimation over the years was assumed. This was based on comparisons between drains observed in permanent NFI plots and those derived from forest statistics (H. M. Henttonen 2015, pers. comm.). The estimated amount of harvesting residue that was used as energy wood instead of being left on the site was subtracted from the litter input of harvesting residue.

Total litter input and its uncertainty

An annual time series of total litter input (Fig. 1) was obtained by totalling the time series of litter input from:

(1) living trees, interpolated linearly between the mid-years of NFI rotations,

(2) harvesting residues excluding energy wood use, based on annual statistics,

(3) natural mortality, based on estimated amounts at four time points: 1990, 1998, 2003, and 2008, and

(4) understorey vegetation, based on 1995 coverage measurements and assumed as constant over the years.

For the Yasso07 input, these totals were finally divided by annual estimates of the area of forest land (Statistics Finland 2014, Tables 7.1-3 and 7.2-1). The Monte Carlo approach was adopted to propagate the uncertainties in estimated input from these different sources in a form that could be further combined with the uncertainty in the Yasso07 model parameters. In other words, our aim was to simulate a distribution of litter input series, where variability and correlations within and across the simulated series reflect the uncertainty and correlations between the corresponding estimates.

To describe the principles of our estimation and simulation procedure in a bit more detail, let $L_{\mathrm{lb},T,c}$ denote the estimate of litter input from biomass component c of living trees based on T'th NFI rotation, $L_{\mathrm{logg},t,c}$ the estimated input from year t's logging, and $L_{\mathrm{nm},Y,c}$ the input from natural mortality based on its estimated volume at time point Y. Our estimator, L_t, of total litter input for year t can then be expressed as

$$(1)\;\; L_t = L_{\mathrm{und}} + \sum_c \left[a_t L_{\mathrm{lb},T^-(t),c} + b_t L_{\mathrm{lb},T^+(t),c} + L_{\mathrm{logg},t,c} + L_{\mathrm{nm},Y(t),c}\right],$$

where L_{und} is the estimated annual litter from understorey vegetation, $T^-(t)$ and $T^+(t)$ are the nearest previous and following NFI rotations to year t, a_t and b_t their weights in the linear interpolation for year t, and $Y(t)$ the time of the most recent estimate of natural mortality. Each tree litter estimate $L_{s,\tau,c}$, in turn, can be expressed in general form

$$L_{s,\tau,c} = V_{s,\tau} B_{s,\tau,c} P_{s,c}$$

where $V_{s,\tau}$ is the stem volume estimate in litter source category s (living biomass, logging, natural mortality) for time (or NFI rotation) τ, $B_{s,\tau,c}$ is the corresponding biomass conversion and expansion factor (BEF) to biomass component c (estimated for living biomass separately from the measurements of each NFI rotation; for logging and natural mortality, the factors are the same for all τ), and $P_{s,c}$ is the litter production rate from component c of source s ($P_{\mathrm{nm},c} \equiv 1$, $P_{\mathrm{logg},c}$ is the waste wood ratio for c = stem+bark and =1 for other components). Note that BEF is a ratio between biomass component c and stem volume.

To simulate one litter series from the distribution describing the uncertainty in litter estimates, we (i) simulated one realization from a multivariate normal distribution with expected values equal to the estimated values of $L_{\mathrm{lb},T,c}$, $L_{\mathrm{nm},Y,c}$, and $W_{\mathrm{logg},c}= B_{\mathrm{logg},c}\ P_{\mathrm{logg},c}$ and a covariance matrix built from the sampling and model covariances of the estimators (see Supplementary data for details <footnote: Supplementary data are available with the article through the journal Web site at… : suppla.pdf provides further details and an example that can be reproduced using the R code and data provided in supplb.zip>),

(ii) simulated a systematic relative error $e_{\mathrm{logg},t} = e_{\mathrm{logg}} V_{\mathrm{logg,t}}$ to the time series of logging volumes, with e_{logg} ~N(0,0.05^2) reflecting the assumption of 5% relative standard error (variation coefficient, CV), and a random error e_{und} ~ N(0,0.10^2) to L_{und} with assumed CV=10%, and

(iii) interpolated a simulated litter series by applying formula (1) to the values obtained in steps (i) and (ii).

In practice, we worked with separate litter estimates for the main tree species groups (pine, spruce, and broadleaf), because they have different BEFs and turnover rates, however, all litter estimates are independent across species, and those for living biomass and natural mortality were aggregated over species before simulation. Similar aggregation was done over biomass components in the same size class (non-woody, fine woody, and coarse woody litter). The dimension of our multivariate normal was thus 3(size classes) × [4(NFI rotations)+4(time points for natural mortality)+3(W_{logg}-value per size class, one per species)] = 33, and the resulting simulated litter series contained 24(years) × 3(size-classes) = 72 values.

Yasso07 is a stand-alone soil decomposition model and its structure is based on organic material solubility. Model has a structure of five boxes, those being acid-, water-, ethanol-, non-soluble and humus boxes. Each of these boxes has individual decomposition rate driven by weather and there also exists material flows between these boxes. Slower decomposition of larger woody material compared to smaller woody material has been taken into account with the parameterisation of the Yasso07. In this study litter input quantities and types originate from forest inventory data, forest statistics and from understorey biomass modelling as described above. Yasso07 needs litter input divided into acid-, water-, ethanol- and non-soluble compounds, varying between biomass components and tree species, and those proportions were here same as used in the Finnish GHG inventory (Statistics Finland 2014). Uncertainty in these proportions was not included in our analyses. The whole exercise was repeated independently for southern and northern Finland. If we reported the uncertainty in the combined results for whole country, then the between-region correlations of litter estimates, due to common biomass models, should be accounted for. These correlations could either be included in the analysis in the same way as other correlations between litter estimates, or we could work with stem volumes and biomass factors computed for the whole country.

Yasso07 simulations

The parameters of the Yasso07 model have been estimated in the Bayesian framework applying MCMC methods (Tuomi et al. 2011). The 24 parameters define decomposition rates of acid-, water-, ethanol- and non-soluble compounds, as well as transfer rates between different compounds, sensitivity of decomposition to temperature and precipitation, humus decomposition and the impact of size on decomposition of woody material (Appendix 2). The MCMC method produced a sample of parameter combinations, and variation within that sample reflects the uncertainty and correlations of the estimates.

We simulated 500 realizations of Yasso07 parameter values from the MCMC sample, combined them with 500 simulated litter series from 1990 to 2013, and ran 500 Yasso07 simulations with these parameter and input values in order to obtain 500 series of annual carbon stock changes, whose variability reflects the total uncertainty. The weather conditions (mean temperature, precipitation and temperature amplitude) were fixed to constant values, the mean from 1971 to 2013, over the whole simulation. The initial soil carbon stocks were obtained as in the Finnish GHG-inventory for south and northern Finland for 1972 and 1975, respectively. Litter input series for the period 1972/1975 to 1990 was partially based on NFIs from the 1970s, for which uncertainty assessments similar to those for the later NFIs could not be obtained. For that period, the litter series used in the GHG inventory (Statistics Finland 2014) was re-scaled for each simulated 1990-2013 series so that the 1990 values agreed.

Sensitivity to annual variation and components of uncertainty

From previous literature we know that the litter production of trees varies substantially between years (Tupek et al. 2015, Yanai et al. 2012, Lehtonen et al. 2008). We therefore tested the sensitivity of our analysis to added uncorrelated year-to-year variation in the simulated litter series of needles, leaves and fine roots from living trees. This allowed us to evaluate the impact of the often ignored inter-annual variation of biomass components with high turnover rates, into soil carbon stock change uncertainty results.

We also studied the contributions of different components of uncertainty. We evaluated the impact of omission for the following components: NFI sampling uncertainty for the volume of living trees and natural mortality, the assumed systematic error in logging volumes, NFI sampling uncertainty in BEFs, uncertainty in BEFs due to errors in the parameter estimates of biomass models, uncertainty of litter turnover rates, and uncertainty in the amount of litter from understorey vegetation.

Results

In the last 25 years, litter input to the soil has increased steadily in both southern and northern Finland (Fig. 2, top row). The effect of annual changes in logging was more pronounced in southern Finland. Different realizations of the simulated litterfall series had similar slopes due to high autocorrelation originating from uncertainties that affect the whole series: the same biomass models with the same errors in parameters are used throughout the series, static turnover rates are applied, and so on.

According to our main analysis, soils have been a carbon sink each year over the whole period, with the possible exception being the soils of southern Finland in 2009 (Fig. 2, bottom row). Although the confidence intervals of the litter series were little affected by the addition of year-to-year variation with a 5% relative standard deviation to the non-woody litter from living trees (Fig. 3, top row), the effect on the uncertainty of soil carbon changes was dramatic (Fig. 3, bottom row).

According to our sensitivity analysis, the soils of southern Finland could reliably be claimed to have been a carbon sink during the first Kyoto protocol period (2008-2012), if we accept that the uncaptured year-to-year variation in foliage and fine root litter from living trees is less than 10% of the estimated amount; for northern Finland this limit is as high as 20% (Table 1). In northern Finland, uncertainty about the volumes of living trees due to sampling error in NFI was clearly more influential than the other components of uncertainty: without it, the relative uncertainty was reduced from 31.5% to 11%. In southern Finland, the contributions of the different components were more even. The effects of uncertainty in logging volumes, biomass models, litter rates, and understorey litter were relatively small.

Discussion

We have presented a simulation-based approach to the assessment of total uncertainty in the estimates of soil carbon stock changes, applicable to a GHG inventory, where these estimates are derived using a chain of NFI data and models of living tree biomass and soil processes. Our approach takes into account, in a coherent way, the uncertainties resulting from NFI sampling and from estimation errors in model parameters, litter production rates, logging volume statistics, and litter from understorey vegetation. We did not include the residual variation around estimated biomass models, since according to Breidenbach et al. (2014), it is negligible when models are applied to a large inventory data.

Our sensitivity analysis conducted by adding uncorrelated year-to-year variation to the simulated litter series also serves the purpose of illustrating the importance of taking into account the correlations between estimators: As a result of adding noise, temporal correlations were reduced and the consequences were found dramatic (Fig. 3). Strong temporal correlations in biomass estimates are caused by the use of the same biomass models throughout the series: The errors in parameters introduce systematic error to the whole series. As another example, estimates of biomass are also correlated between tree components, because the same stem measurements of the same NFI trees are utilized to construct them.

We found that upland forest soils were probably accumulating carbon during the first period of commitment to the Kyoto protocol. This result was obtained under assumptions of a modest annual variation in leaf and fine root litter, and by applying Yasso07 with a constant climate. The exclusion of annually varying weather was justified by the synchrony between this study and the Finnish GHG-inventory.

According to our sensitivity analyses, the uncertainty about the soil carbon stock change gets severely underestimated, if inter-annual variation of litter input is ignored, as was reported by Peltoniemi et al. (2006). This is due to the fact that annual variations of error components have an effect on trend slopes of litter input, strongly affecting the variation of soil carbon stock change. From the literature we know that biomass productivity varies annually at a large scale (Keenan et al. 2012) and litter production on monitoring plots varies substantially between years (e.g. Tupek et al. 2015, Lehtonen et al. 2008). If such variation in litter input holds at regional level where soil models have usually been applied then it implies that estimates of uncertainty about soil carbon stock change have generally been too optimistic. Our assumption of annual variation is supported by Hashimoto et al. (2015), where soil respiration database was used to develop a simple model, which reports substantial inter-annual variation of soil respiration at biome scale. We can assume that this variation is partly due to greater annual litter input and faster decomposition of that litter during favourable years, and vice versa. We can thus agree with Ogle et al. (2010) on the importance of uncertainty about model structure; here the structural uncertainty results from the lack of appropriate drivers for inter-annual variation of litter input.

In our simulations, the effect of uncertainty of Yasso07 parameters was marginal. However, we were not able to assess the effect of applying Yasso07 in a scale that differs greatly from that used in the estimation of its parameters. Furthermore, discrepancies between Yasso07 parameterizations between Tuomi et al. (2011) and Rantakari et al. (2012) indicate that optimal solutions for parameters obtained from decomposition data vary greatly, and that the parameter values of unmeasurable flows between boxes are arbitrary and depend strongly on other parameters.

The fact that the uncertainty of soil carbon stock change is dominated by the uncertainties which affect litter input trends underlines room for improvement. For reliable quantification of the uncertainty of carbon stock change estimates, we should be able to assess the annual variation in litter input. The majority of the litter input originates from living trees, and in our approach the estimation of that litter has been based on consecutive forest inventories. In the Finnish case most of the sample plots of forest inventories have been independent. A larger proportion of permanent sample plots would reduce the uncertainty about soil carbon stock changes by increasing the correlation between sampling errors and thus decreasing the variance of change estimates. However, this would only solve a part of the problem. To assess all sources of inter-annual variation in the litter input, it is also essential to maintain long-term monitoring sites with litter production measurements.

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Table 1. Change in soil C [Mg C per ha] during the first Kyoto period 2008-2012, and its uncertainty (presented according to IPCC guidelines as 2 x standard error of the estimate), uncertainty after omitting each component of uncertainty in turn (the 'drop' rows), and the uncertainty after adding uncorrelated year-to-year variation to the simulated series of non-woody litter from living trees (the 'add' rows) with standard deviation of this variation proportional to the estimated litter amount and the proportion given as row title.

	southern Finland		northern Finland	
		%		%
estimate	0.508		0.797	
uncertainty, U	0.131	25.8	0.251	31.5
drop				
U in lb & nm vol.	0.103	20.3	0.087	11.0
U in logg vol.	0.120	23.6	0.250	31.4
sampling U in BEFs	0.108	21.2	0.239	30.1
model U in BEFs	0.113	22.2	0.235	29.5
U in litter rates	0.124	24.4	0.238	29.9
U in und. litter	0.130	25.6	0.247	31.0
add noise to nwl of lb				
5%	0.309	60.9	0.323	40.6
10%	0.550	108.1	0.445	55.9
20%	1.114	219.3	0.845	106.0

Figure captions

Fig 1. Estimated tree litter in northern Finland by source category a) living trees, b) natural mortality, and c) harvesting residues, and the total litter d).

Fig 2. Some simulated time series (thin lines) and 95% confidence intervals computed from 500 simulated series for total litter input (top) and soil carbon stock changes (bottom) in a), c) southern and b), d) northern Finland.

Fig 3. As Fig. 2, but with random year-to-year variation with a 5% relative standard deviation added to the non-woody litter from living trees.

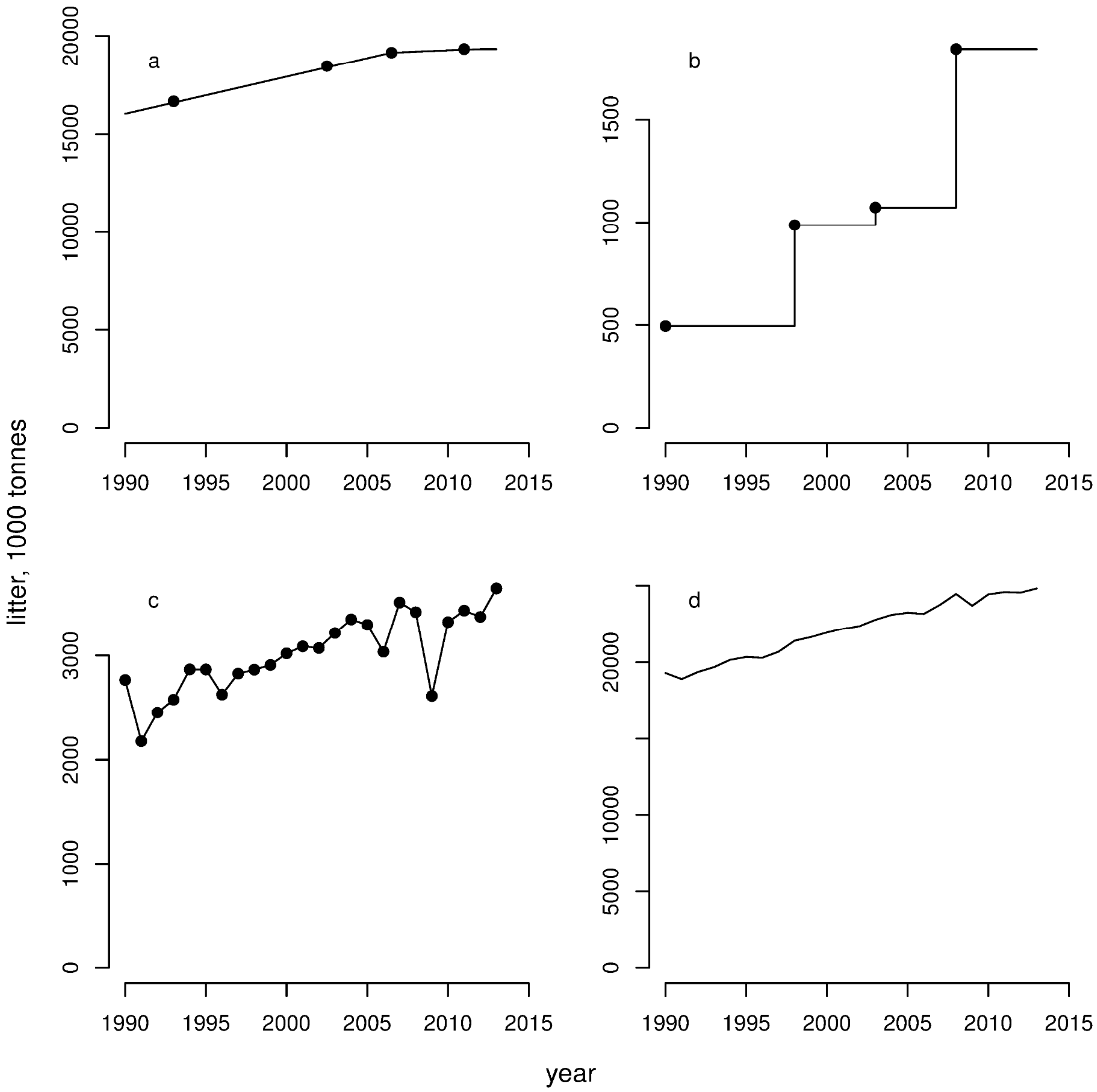
a
b
c
d
litter, 1000 tonnes
year
0
5000
10000
15000
20000
500
1000
1500
2000
3000
1990
1995
2000
2005
2010
2015

Figure 1.

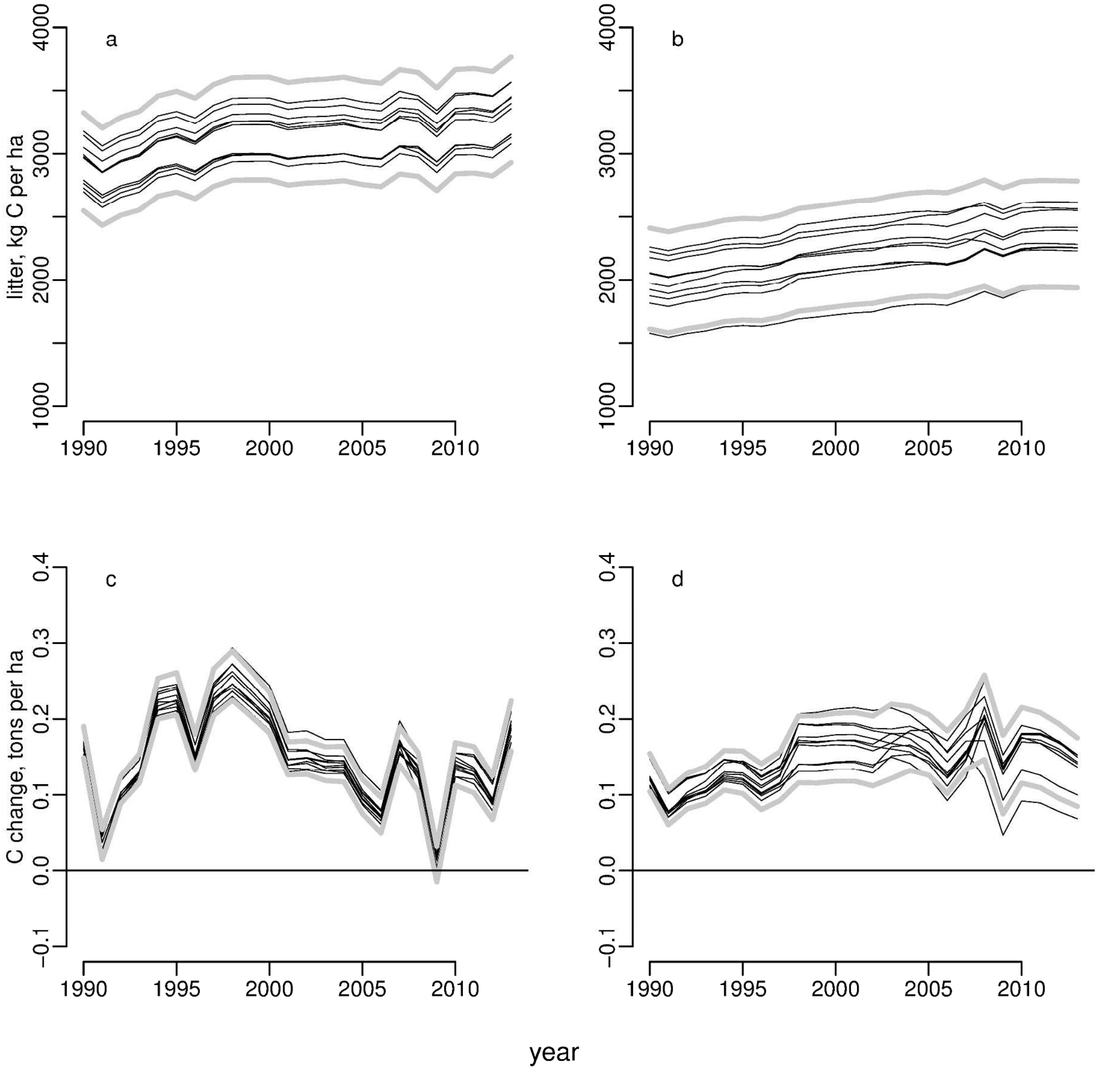
a
b
c
d
litter, kg C per ha
C change, tons per ha
1000
2000
3000
4000
−0.1
0.0
0.1
0.2
0.3
0.4
1990
1995
2000
2005
2010
year

Figure 2.

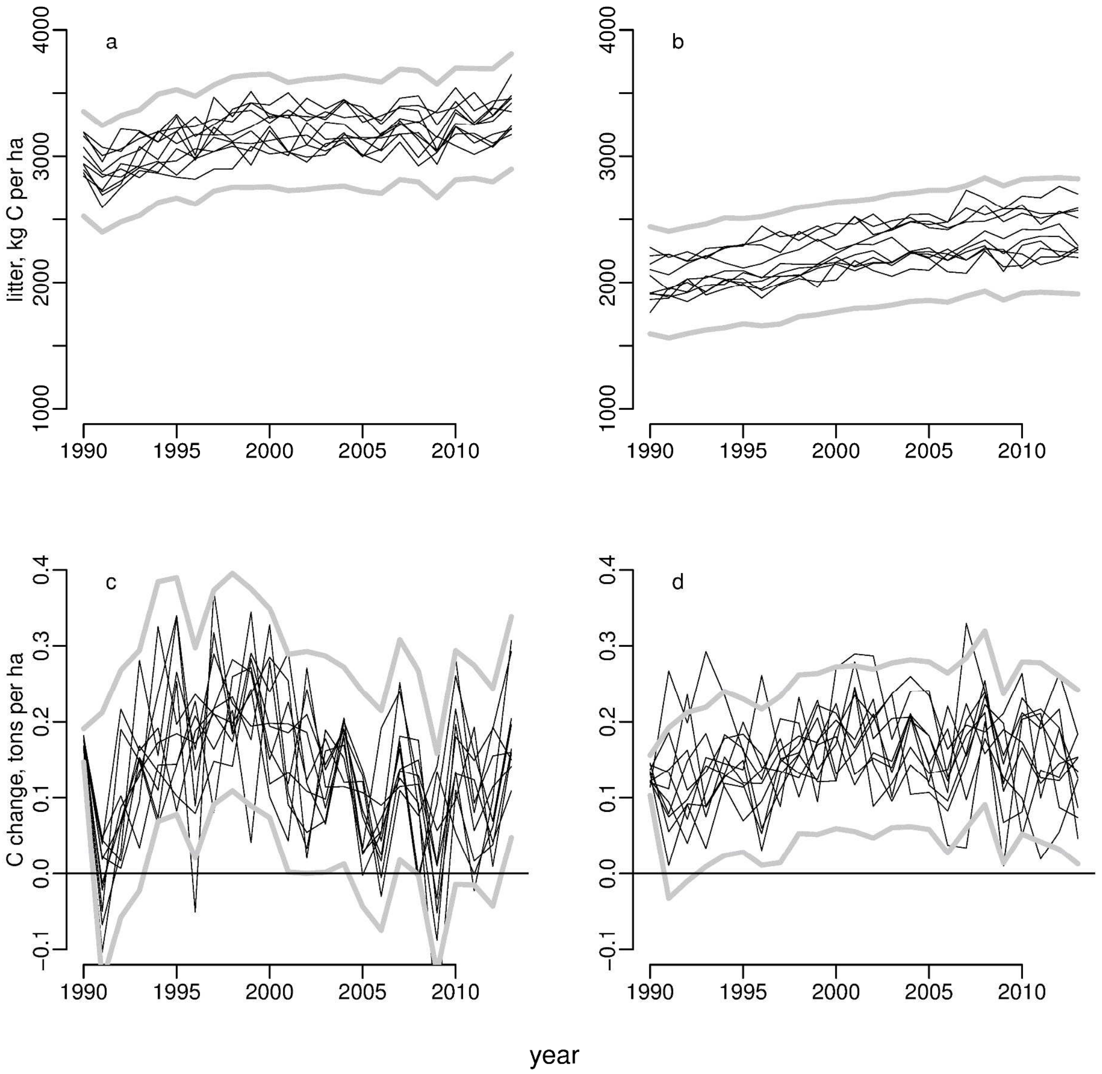
a
b
c
d
litter, kg C per ha
C change, tons per ha
1000
2000
3000
4000
−0.1
0.0
0.1
0.2
0.3
0.4
1990
1995
2000
2005
2010
year

Figure 3.

Appendix 1. Input data for estimating the time series of litter amounts and their uncertainty.

Table A1.1. Stem volumes and relative sampling errors (rse) of the estimates of living trees on upland soils of FAO forest land according to four NFIs.

Region	Species group	NFI	Volume mill. m^3	rse %
southern Finland	pine	8	408.4	1.2
		9	450.0	1.0
		10	493.8	1.1
		11	528.2	0.9
	spruce	8	486.9	1.2
		9	473.9	1.1
		10	449.5	1.3
		11	471.1	1.2
	broadleaves	8	164.6	1.5
		9	196.2	1.3
		10	225.4	1.3
		11	249.0	1.2
northern Finland	pine	8	279.3	2.2
		9	311.5	1.7
		10	334.7	1.7
		11	351.8	1.6
	spruce	8	101.9	2.8
		9	101.0	3.1
		10	103.9	3.0
		11	112.9	3.4
	broadleaves	8	68.1	2.5
		9	77.1	2.4
		10	80.4	2.4
		11	87.1	2.5

Table A1.2 NFI-based estimates of biomass conversion and expansion factors (kg/m^3 of stemwood) for living trees (lb), harvested trees (logg), and natural mortality (nm) on upland soils of southern (SF) and northern Finland (NF), uncertainties (relative standard error, %) due to sampling (rse, s) and due to uncertainty of biomass model parameters (rse, m).

Biomass	Region	Litter	NFI	Pine			Spruce			Broadleaves		
component		source		BEF	rse, s	rse, m	BEF	rse, s	rse, m	BEF	rse, s	rse, m
foliage	SF	lb	8	30	1.1	4.9	66	0.9	4.8	29	1.5	16.7
			9	28	0.7	4.8	63	0.6	4.8	28	0.9	17.7
			10	27	0.7	4.9	64	0.7	4.8	28	0.9	16.4
			11	25	0.6	4.9	65	0.7	4.8	26	0.9	15.2
		logg	-	22	1.8	5.0	59	1.2	4.8	23	2.1	7.4
		nm	-	33	7.3	4.9	67	7.2	4.8	26	6.6	13.7
	NF	lb	8	34	1.4	4.9	86	1.3	4.9	41	1.9	21.0
			9	34	1.3	4.9	80	1.3	4.9	44	1.4	23.7
			10	35	1.3	4.9	82	1.5	4.9	43	1.6	21.0
			11	33	1.1	4.9	80	1.3	4.9	40	1.5	20.7
		logg	-	26	3.3	4.9	75	4.4	4.8	34	8.5	12.4
		nm	-	20	9.4	4.8	64	10.7	6.1	30	7.2	12.0
branches	SF	lb	8	73	0.7	3.2	106	0.5	3.6	90	0.8	4.5
			9	71	0.5	3.2	100	0.4	3.6	89	0.7	4.5
			10	68	0.4	3.2	97	0.4	3.5	88	0.6	4.3
			11	64	0.4	3.3	97	0.4	3.5	87	0.6	4.3
		logg	-	61	1.2	3.4	91	1.0	3.7	87	7.6	4.7
		nm	-	67	5.9	3.0	90	5.6	3.4	90	7.1	6.1
	NF	lb	8	91	1.0	3.3	132	0.8	4.0	125	1.5	7.6
			9	90	1.0	3.4	148	0.9	4.1	124	1.5	7.9
			10	89	0.9	3.2	146	1.0	4.0	120	1.3	6.8
			11	87	0.8	3.3	143	0.9	4.0	115	2.0	7.3
		logg	-	71	2.6	3.3	110	3.2	3.6	104	8.3	6.7
		nm	-	51	8.3	3.3	126	11.5	5.5	103	9.7	7.2
stump	SF	lb	8	32	0.4	6.1	34	0.3	12.7	47	1.3	5.9
			9	32	0.2	6.0	34	0.3	12.6	49	1.7	6.1
			10	31	0.2	6.0	34	0.3	12.7	47	1.2	5.9
			11	31	0.2	6.1	34	0.3	12.7	45	1.1	5.8
		logg	-	30	0.8	6.2	34	0.8	13.5	54	15.0	6.9
		nm	-	32	4.3	4.9	36	5.3	10.6	65	8.4	8.6
	NF	lb	8	36	0.4	5.7	43	0.7	11.8	64	3.0	6.8
			9	37	0.4	5.7	44	0.7	12.0	65	2.5	7.7
			10	36	0.4	5.7	43	0.8	11.8	62	2.1	7.0
			11	36	0.3	5.8	43	0.7	12.3	62	6.7	7.5
		logg	-	33	1.8	6.0	38	2.1	12.3	63	17.1	9.5
		nm	-	33	4.1	5.5	49	10.5	15.0	65	14.8	8.5
roots	SF	lb	8	98	0.3	6.2	132	0.4	16.1	152	1.1	8.3
			9	97	0.2	6.1	132	0.3	15.9	156	1.0	8.6
			10	94	0.2	6.1	130	0.3	16.0	154	0.8	8.0
			11	93	0.2	6.2	130	0.4	15.9	150	0.8	7.8
		logg	-	92	0.9	6.4	126	1.0	17.0	168	8.1	9.3
		nm	-	87	3.9	4.8	151	7.3	13.5	218	8.5	12.6
	NF	lb	8	107	0.4	5.8	170	0.7	14.9	171	2.1	12.8

			9	108	0.5	5.8	173	0.7	15.1	178	1.9	14.1
			10	106	0.4	5.7	172	0.9	14.8	176	1.6	11.8
			11	105	0.4	5.9	168	0.7	15.4	172	3.6	13.1
		logg	-	97	1.9	6.1	149	2.7	15.5	197	13.5	13.4
		nm	-	106	8.5	5.8	177	8.6	19.1	181	12.5	14.1
stem+bark	SF	lb	8	391	0.1	1.0	377	0.1	1.6	496	0.1	1.1
			9	390	0.0	1.0	375	0.1	1.6	495	0.1	1.1
			10	388	0.0	1.0	374	0.1	1.6	494	0.0	1.1
			11	388	0.0	1.0	373	0.1	1.6	494	0.0	1.1
		logg	-	391	0.5	1.0	375	0.5	1.7	495	1.0	1.1
		nm	-	397	3.9	0.9	387	2.3	1.6	487	1.4	1.4
	NF	lb	8	389	0.1	0.9	397	0.1	1.8	499	0.1	1.7
			9	387	0.1	1.0	395	0.1	1.8	496	0.1	1.9
			10	386	0.1	0.9	394	0.1	1.7	497	0.1	1.6
			11	384	0.1	1.0	391	0.1	1.7	497	0.1	1.7
		logg	-	388	1.3	1.0	392	2.0	1.6	491	1.7	1.5
		nm	-	398	6.6	0.8	390	3.8	2.0	497	2.5	1.6
fineroots	SF	lb	8	19	1.1	4.9	18	0.7	4.8	15	1.5	16.7
			9	19	0.7	4.8	18	0.6	4.8	14	0.9	17.7
			10	18	0.6	4.9	18	0.6	4.8	14	0.9	16.4
			11	16	0.6	4.9	17	0.6	4.8	13	0.9	15.2
		logg	-	19	1.8	5.0	20	1.2	4.8	8	2.1	7.4
		nm	-	19	7.3	4.9	20	7.2	4.8	8	6.6	13.7
	NF	lb	8	27	1.2	5.0	28	1.2	5.0	20	1.9	21,0
			9	27	1.1	5.0	28	1.1	5.0	22	1.4	23.7
			10	26	1.1	4.9	27	1.3	5.0	22	1.6	21.0
			11	25	1.0	4.9	25	1.1	4.9	20	1.5	20.7
		logg	-	25	3.3	4.9	28	4.4	4.8	11	8.5	12.4
		nm	-	25	9.4	4.8	28	10.7	6.1	11	7.2	12.0

Table A1.3 Typical (median) sampling correlations between biomass conversion and expansion factors estimated for different biomass components but same litter source, NFI rotation, region and species (across the latter categories, sampling errors are uncorrelated).

Species	Component	branches	stump	roots	stem+bark	fineroots
Pine	foliage	0.83	0.68	0.15	-0.53	0.91
	branches		0.86	0.60	-0.48	0.77
	stump			0.75	-0.28	0.80
	roots				-0.11	0.30
	stem+bark					-0.36
Spruce	foliage	0.81	0.49	0.78	0.22	0.88
	branches		0.80	0.82	0.03	0.76
	stump			0.89	-0.16	0.58
	roots				0.19	0.89
	stem+bark					0.39
Broadleaves	foliage	0.29	0.03	0.11	-0.46	1.00
	branches		0.55	0.30	0.02	0.29
	stump			0.90	-0.37	0.03
	roots				-0.60	0.11
	stem+bark					-0.46

Table A1.4. Some correlations between biomass conversion and expansion factors due to correlations between parameter estimates of biomass models and due to applying the same models for different litter sources and NFI rotations. This submatrix corresponds to factors for pine in southern Finland; for living biomass, only two NFIs were included to save space. Correlations between above- and below-ground components were not available because their models were estimated separately.

Component	Source	NFI	foliage				branches				stem+bark				fineroots				stump				roots		
			lb8	lb11	logg	nm	lb8	lb11	logg	nm	lb8	lb11	logg	nm	lb8	lb11	logg	nm	lb8	lb11	logg	nm	lb8	lb11	logg
foliage	lb	11	1.0																						
	logg	-	1.0	1.0																					
	nm	-	0.9	0.9	0.9																				
	lb	8	0.6	0.6	0.6	0.6																			
branches		11	0.6	0.6	0.6	0.5	1.0																		
	logg	-	0.6	0.6	0.6	0.5	1.0	1.0																	
	nm	-	0.7	0.7	0.6	0.7	0.9	0.8	0.8																
stem+bark	lb	8	-0.1	-0.1	-0.1	-0.1	0.0	0.0	0.0	-0.1															
		11	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.0	-0.1	1.0														
	logg	-	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.0	-0.1	1.0	1.0													
	nm	-	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	0.6	0.7	0.7												
fineroots	lb	8	1.0	1.0	1.0	0.9	0.6	0.6	0.6	0.7	-0.1	-0.1	-0.1	-0.2											
		11	1.0	1.0	1.0	0.9	0.6	0.6	0.6	0.7	-0.1	-0.1	-0.1	-0.2	1.0										
	logg	-	1.0	1.0	1.0	0.9	0.6	0.6	0.6	0.6	-0.1	-0.1	-0.1	-0.2	1.0	1.0									
	nm	-	0.9	0.9	0.9	1.0	0.6	0.5	0.5	0.7	-0.1	-0.1	-0.1	-0.1	0.9	0.9	0.9								
stump	lb	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0							
		11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0						
	logg	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0	1.0					
	nm	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0.8	0.8				
roots	lb	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.6	-0.6	-0.6	-0.4			

lb	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.6	-0.6	-0.6	-0.4	1.0		
logg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.6	-0.6	-0.6	-0.4	1.0	1.0	
nm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.5	-0.5	-0.5	-0.6	0.8	0.8	0.8

Table A1.5. Litter turnover rates for tree biomass by component and species, and their uncertainty. For conifers there are separate turnover rates for southern and northern Finland. For understorey litter, biomass estimates and their coefficient of variation.

Biomass component	Species / compartment	Value [%]	Coefficient of variation [%]	Reference (Value)	Reference (Uncertainty)
Foliage	Pine	24.5% / 15.4%	11%	(Muukkonen 2005)	(Peltoniemi et al. 2006)
Foliage	Spruce	10% / 5%	11%	(Muukkonen and Lehtonen 2004)	(Peltoniemi et al. 2006)
Foliage	Broadleaved	79%	11%	(Tupek et al. 2015)	(Peltoniemi et al. 2006)
Branches	Pine	2%	20%	(Lehtonen et al. 2004)	(Peltoniemi et al. 2006)
Branches	Spruce	1.25%	20%	(Muukkonen and Lehtonen 2004)	(Peltoniemi et al. 2006)
Branches	Broadleaved	1.35%	20%	(Lehtonen et al. 2004)	(Peltoniemi et al. 2006)
Stump + Bark	Pine	0.3%	15%	(Viro 1956, Mälkönen 1977)	(Peltoniemi et al. 2006)
Stump + Bark	Spruce	-	-	(Viro 1956, Mälkönen 1977)	(Peltoniemi et al. 2006)
Stump + Bark	Broadleaved	0.01%	15%	(Viro 1956, Mälkönen 1977)	(Peltoniemi et al. 2006)
Stem + Bark	Pine	0.5%	15%	(Viro 1956, Mälkönen 1977)	(Peltoniemi et al. 2006)
Stem + Bark	Spruce	0.3%	15%	(Viro 1956, Mälkönen 1977)	(Peltoniemi et al. 2006)
Stem + Bark	Broadleaved	0.3%	15%	(Viro 1956, Mälkönen 1977)	(Peltoniemi et al. 2006)
Coarse roots	Pine	2%	20%	(Viro 1956, Mälkönen 1977)	(Peltoniemi et al. 2006)
Coarse roots	Spruce	1.25%	20%	(Muukkonen and Lehtonen 2004)	(Peltoniemi et al. 2006)
Coarse roots	Broadleaved	1.35%	20%	(Lehtonen et al. 2004)	(Peltoniemi et al. 2006)
Fine roots	Pine	85%	15%	(Kleja et al. 2008)	(Peltoniemi et al. 2006)
Fine roots	Spruce	85%	15%	(Kleja et al. 2008)	(Peltoniemi et al. 2006)

Fine roots	Broadleaved	85%	15%	(Kleja et al. 2008)	(Peltoniemi et al. 2006)
	Region	**Biomass [kg C**	**CV [%]**	**Reference (Value)**	**Reference (Uncertainty)**
Understorey	Southern	506	26%	(Muukkonen and Mäkipää 2006)	(Muukkonen and Mäkipää 2006)
Understorey	Northern	666	26%	(Muukkonen and Mäkipää 2006)	(Muukkonen and Mäkipää 2006)

Table A1.6 Stem volumes and relative sampling errors (rse) of the estimates of natural mortality on upland soils of FAO forest land.

Region	Species group	Year	Volume mill. m^3	rse %
southern Finland	pine	1990	0.1	16.6
		1998	0.2	16.6
		2003	0.2	16.6
		2008	0.4	16.6
	spruce	1990	0.1	16.1
		1998	0.2	16.1
		2003	0.2	16.1
		2008	0.4	16.1
	broadleaves	1990	0.1	14.7
		1998	0.3	14.7
		2003	0.3	14.7
		2008	0.5	14.7
northern Finland	pine	1990	0.2	35.1
		1998	0.4	35.1
		2003	0.4	35.1
		2008	0.8	35.1
	spruce	1990	0.2	32.6
		1998	0.4	32.6
		2003	0.4	32.6
		2008	0.8	32.6
	broadleaves	1990	0.2	29.3
		1998	0.4	29.3
		2003	0.5	29.3
		2008	0.8	29.3

Appendix 2. Yasso07 model, parameter uncertainties and their correlations

Parameter	Parameter function
alfaA	decomposition rate of A
alfaW	decomposition rate of W
alfaE	decomposition rate of E
alfaN	decomposition rate of N
p1	relative mass flow, W to A
p2	relative mass flow, E to A
p3	relative mass flow, N to A
p4	relative mass flow, A to W
p5	relative mass flow, E to W
p6	relative mass flow, N to W
p7	relative mass flow, A to E
p8	relative mass flow, W to E
p9	relative mass flow, N to E
p10	relative mass flow, A to N
p11	relative mass flow, W to N
p12	relative mass flow, E to N
beta1	temperature dependence
beta2	temperature dependence
gamma	precipitation dependence
omega1	precipitation induced leaching
alfaH	humus decomposition rate
PH	mass flow to humus
phi1	first order size dependence
phi2	second order size dependence
r	size dependence power

Table A2.1 Yasso07 parameters and their function in the model.

Figure A2.1. Yasso07 parameter distributions based on Rantakari et al. (2012) and density function of normal distribution fitted to them.

	alfaA	alfaW	alfaE	alfaN	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10	p11	p12	beta1	beta2	gamma	omega1	alfaH	PH	phi1
alfaA																							
alfaW	**0.71**																						
alfaE	0.17	0.34																					
alfaN	**0.92**	**0.7**	0.26																				
p1	-0.09	-0.21	**0.54**	0.01																			
p2	-0.32	-0.3	-0.01	-0.3	0.15																		
p3	0.47	0.33	-0.01	0.38	-0.19	-0.26																	
p4	0.26	0.29	-0.27	0.27	-0.41	-0.21	-0.06																
p5	-0.48	**-0.58**	0.15	-0.45	0.23	0.1	**-0.62**	-0.04															
p6	-0.41	-0.25	0.05	-0.34	0.01	0.08	**-0.9**	0.24	**0.71**														
p7	0.17	0.12	-0.16	0.22	-0.29	0.1	0.32	-0.25	-0.4	-0.38													
p8	-0.05	-0.3	-0.21	-0.1	0.24	0.14	-0.01	0.14	0.11	-0.06	-0.43												
p9	-0.21	0.02	-0.27	-0.18	-0.48	-0.03	-0.09	0.12	-0.03	0.02	-0.03	-0.12											
p10	-0.37	-0.43	0.32	-0.43	**0.59**	0.17	-0.13	**-0.78**	0.31	-0.01	-0.32	0.13	-0.13										
p11	**-0.59**	**-0.55**	**-0.6**	**-0.71**	-0.45	0.13	0.01	-0.01	0.17	0.1	0.06	0.07	0.28	0.06									
p12	-0.17	-0.07	-0.49	-0.26	**-0.82**	0.06	0.17	0.41	-0.07	0.04	0.28	-0.23	0.33	**-0.51**	**0.66**								
beta1	0.4	0.47	**0.54**	0.47	0.32	-0.31	0.23	0.01	-0.09	-0.21	0.09	-0.1	-0.28	-0.11	**-0.67**	-0.46							
beta2	-0.26	-0.38	-0.49	-0.35	-0.28	0.26	-0.22	0.03	0.1	0.21	-0.09	0.06	0.22	0.06	**0.57**	0.37	**-0.89**						
gamma	**-0.51**	-0.32	-0.06	-0.41	-0.19	0.07	**-0.63**	0.1	**0.53**	**0.66**	-0.04	-0.29	0.22	-0.13	0.15	0.19	-0.01	0.02					
omega1	0.35	0.33	-0.05	0.38	0.03	-0.2	0.19	0.15	-0.19	-0.19	0.15	0.01	-0.21	-0.36	-0.37	-0.27	**0.54**	-0.36	-0.08				
alfaH	0.12	0.11	0.11	0.14	-0.03	-0.01	0.21	-0.12	-0.05	-0.17	0.17	-0.16	-0.03	-0.03	-0.06	-0.05	0.15	-0.08	-0.05	0.22			
PH	0.09	0.11	0	0.08	0.07	-0.09	-0.1	0.2	-0.08	0.06	-0.13	0.15	-0.04	-0.08	-0.16	-0.05	0.08	-0.11	-0.07	-0.05	**-0.93**		
phi1	-0.1	0.05	0.3	-0.01	-0.07	0.05	-0.44	0.26	0.46	**0.54**	0	-0.47	0	-0.25	-0.2	0.25	0.15	-0.13	**0.58**	-0.14	0	0	
phi2	-0.22	-0.29	0.37	-0.08	**0.74**	-0.03	-0.29	-0.39	0.33	0.12	-0.37	0.28	-0.22	**0.54**	-0.38	**-0.77**	0.3	-0.27	0.14	0.13	-0.01	0.01	-0.09
r	-0.02	-0.24	0.21	0.03	0.43	0	-0.39	-0.13	0.3	0.32	-0.41	0.16	-0.08	0.44	-0.16	-0.37	-0.24	0.17	0.04	**-0.51**	-0.33	0.26	0.06

Table A2.2 Pearson correlations of Yasso07 parameters based on Rantakari et al. (2012). Correlations higher than 0.5 with bold.

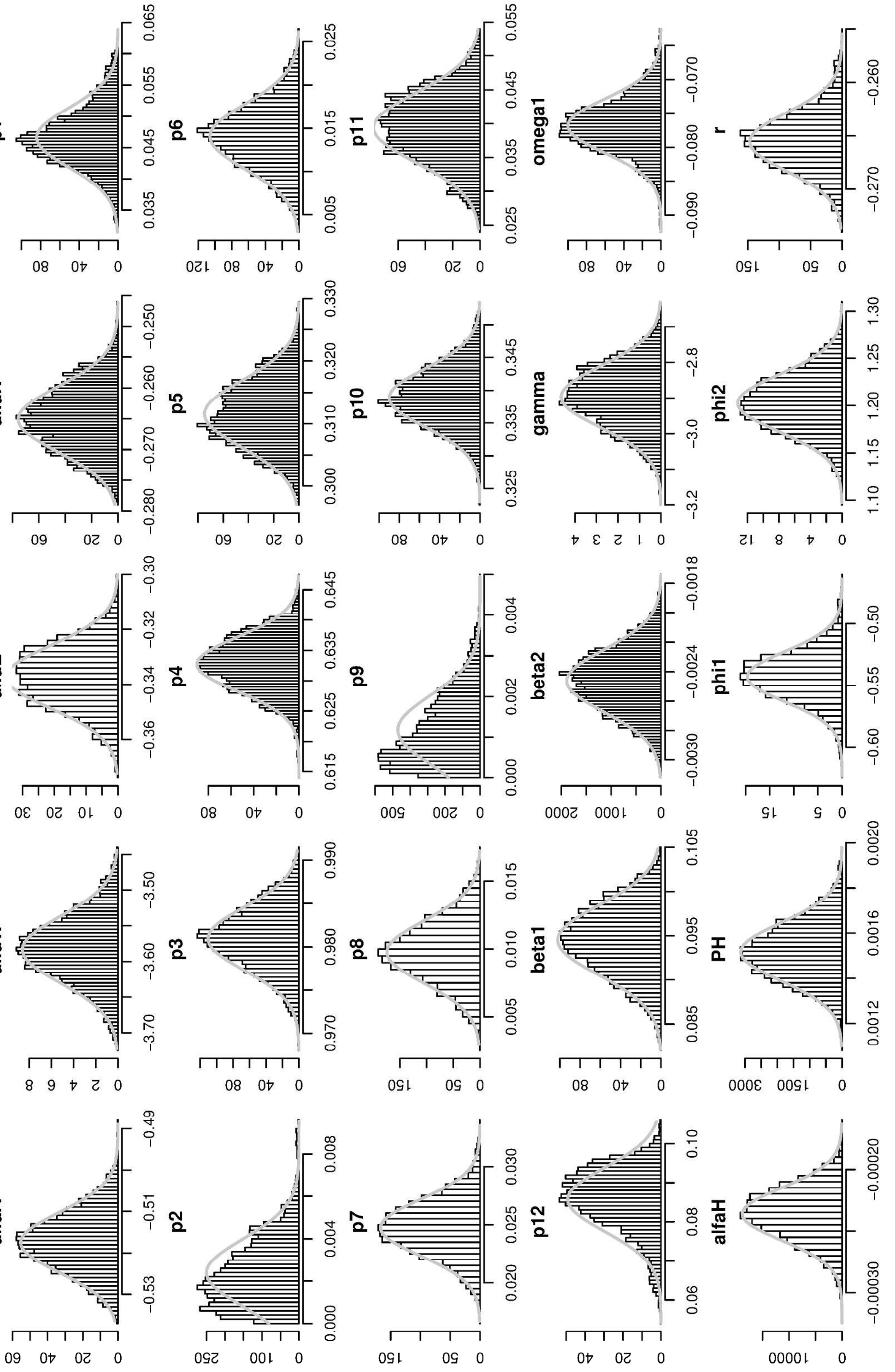
alfaA
−0.53 −0.51 −0.49
0 20 40 60
alfaW
−3.70 −3.60 −3.50
0 2 4 6 8
alfaE
−0.36 −0.34 −0.32 −0.30
0 10 20 30
alfaN
−0.280 −0.270 −0.260 −0.250
0 20 60
p1
0.035 0.045 0.055 0.065
0 40 80
p2
0.000 0.004 0.008
0 100 250
p3
0.970 0.980 0.990
0 40 80
p4
0.615 0.625 0.635 0.645
0 40 80
p5
0.300 0.310 0.320 0.330
0 20 60
p6
0.005 0.015 0.025
0 40 80 120
p7
0.020 0.025 0.030
0 50 150
p8
0.005 0.010 0.015
0 50 150
p9
0.000 0.002 0.004
0 200 500
p10
0.325 0.335 0.345
0 40 80
p11
0.025 0.035 0.045 0.055
0 20 60
p12
0.06 0.08 0.10
0 20 40
beta1
0.085 0.095 0.105
0 40 80
beta2
−0.0030 −0.0024 −0.0018
0 1000 2000
gamma
−3.2 −3.0 −2.8
0 1 2 3 4
omega1
−0.090 −0.080 −0.070
0 40 80
alfaH
−0.00030 −0.00020
0 10000
PH
0.0012 0.0016 0.0020
0 1500 3000
phi1
−0.60 −0.55 −0.50
0 5 15
phi2
1.10 1.15 1.20 1.25 1.30
0 4 8 12
r
−0.270 −0.260
0 50 150

Figure A2.1

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