Journal of Environmental Management 181 (2016) 498–514

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Ecosystem services of boreal forests – Carbon budget mapping at high resolution

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A R T I C L E I N F O

Article history:
Received 2 December 2015
Received in revised form
24 June 2016
Accepted 28 June 2016

Keywords:
Carbon stock
Mapping
Ecosystem services
Spatial variation
Forest management

A B S T R A C T

The carbon (C) cycle of forests produces ecosystem services (ES) such as climate regulation and timber production. Mapping these ES using simple land cover -based proxies might add remarkable inaccuracy to the estimates. A framework to map the current status of the C budget of boreal forested landscapes was developed. The C stocks of biomass and soil and the annual change in these stocks were quantified in a 20 × 20 m resolution at the regional level on mineral soils in southern Finland. The fine-scale variation of the estimates was analyzed geo-statistically. The reliability of the estimates was evaluated by comparing them to measurements from the national multi-source forest inventory. The C stocks of forests increased slightly from the south coast to inland whereas the changes in these stocks were more uniform. The spatial patches of C stocks were larger than those of C stock changes. The patch size of the C stocks reflected the spatial variation in the environmental conditions, and that of the C stock changes the typical area of forest management compartments. The simulated estimates agreed well with the measurements indicating a good mapping framework performance. The mapping framework is the basis for evaluating the effects of forest management alternatives on C budget at high resolution across large spatial scales. It will be coupled with the assessment of other ES and biodiversity to study their relationships. The framework integrated a wide suite of simulation models and extensive inventory data. It provided reliable estimates of the human influence on C cycle in forested landscapes.

1. Introduction

Mapping the goods and services of ecosystems has become an important aspect of implementing the concept of ecosystem services (ES) in sustainable environmental management (Balmford et al., 2011). The carbon (C) cycle of forests produces many ES such as regulating atmospheric greenhouse gas concentrations and maintaining the stability of global climate (Bonan, 2008; Janzen, 2004). An example of provisioning services is that a fair portion, about 15–20%, of the C sequestered annually in the net primary production of forests is consumed by society as wood products and bioenergy (Saikku et al., 2015; Smith et al., 2008; Liski et al., 2006). In the future, climate warming, exploitative use of natural resources and the loss of biodiversity will threaten the availability of many ES (Foley et al., 2005; Schröter et al., 2005). To manage ecosystems sustainably, there is a growing need for spatially explicit, landscape-level information on the effects of human activity on the state and trend of ES (Maes et al., 2012; Nelson et al., 2009). Mapping can be used to identify the trade-offs and synergies between climate change mitigation, timber production and biodiversity of forested landscapes (Duncker et al., 2012; Koschke et al., 2012; Schwenk et al., 2012). In addition, maps serve as a communication tool to visualize locations where valuable ES are produced and to facilitate discussions with stakeholders (Nemec and Raudsepp-Hearne, 2013).

The methods of ES mapping have been studied extensively recently (Maes et al., 2012; Nelson and Daily, 2010; Seppelt et al., 2011). Mapping ES based on actual sampling and surface modeling has been relatively rare (Eigenbrod et al., 2010). It has been applied in quantifying the C stocks and flows at national (Liski and Westman, 1997; Milne and Brown, 1997) and global (McGuire et al., 2001) scales. According to Eigenbrod et al. (2010), regulating services have often been mapped using land cover and land

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http://dx.doi.org/10.1016/j.jenvman.2016.06.066
0301-4797/

use based proxies (e.g. Chan et al., 2006; Maes et al., 2012; Naidoo et al., 2008; Turner et al., 2007). For example the widely used InVEST tool simplifies the spatial characteristics of some ES and assumes constant and linearly increasing C stocks for land cover classes (Kareiva et al., 2011; Nelson et al., 2009). These overly simplistic assumptions may add remarkable inaccuracy to estimates (Eigenbrod et al., 2010). Coupling dynamic modeling of the C cycle with comprehensive information on land cover could produce potentially more reliable estimates (Morales et al., 2005; Schröter et al., 2005).

Accurate information about the effects of human activities on the state and trends of ES is urgently needed to promote sustainable land use planning. In a pilot application of a virtual laboratory for ES, the current status of the C budget of a boreal landscape was quantified using mass-balance equations with statistics of land use and harvests (Holmberg et al., 2015). In addition, the future trends of forest C budget in relation to bioenergy production were estimated based on regional forest resource scenarios and simulation models (Forsius et al., 2016). However, these previously applied methods could still be improved by using spatially explicit information on forest characteristics and simulating the effects of forest management at stand-scale. Maps of C budget could serve, for example, as a tool for municipalities and other private land owners to evaluate the climate impacts of alternative forest management scenarios.

Regional estimates of ES can be improved significantly and cost-efficiently by connecting dynamic modeling of ecosystem functions to open, high-quality GIS datasets. The Finnish Multisource National Forest Inventory (MS-NFI) produces comprehensive and high-resolution spatial data on forest resources applicable for ES assessment (Katila and Tomppo, 2001; Tomppo et al., 2008, 2014). The MS-NFI is based on extensive field measurements and high-resolution satellite images. It has been operative since the late 1980s. Forest characteristics such as volume, biomass and stand age are estimated between the sample plots using the k Nearest Neighbors estimation. The MS-NFI enables exploring the forest characteristics at varying spatial scales, from individual 20 × 20 m grid cells up to the national level.

The objectives of this study were, first, to develop a method for mapping the C stocks and changes of forest biomass and soil; second, to analyze the fine-scale variation of these estimates; and finally, to evaluate their reliability in the light of more detailed measurements. Simulated C budget estimates were validated using spatially explicit information on forest resources from the MS-NFI 2011.

2. Materials and methods

2.1. Study region

The study region (22–26°E; 59–61°N) in Finland is located in the southern boreal zone (Fig. 1). It is divided into 48 municipalities. The annual mean temperature was 4.2 °C and the annual precipitation 637 mm during 1970–2012. The total area is 89000 km^2 and coniferous forests dominate the landscape. Mineral soils cover nearly 90% and peatlands 10% of the forestry land according to the national forest inventory. About two thirds of the forests are managed by private land owners. A majority of the forests, around 95%, is used for timber production and managed by planting or natural regeneration, regular thinning and clear-cutting (Finnish Statistical Yearbook of Forestry, 2012).

2.2. Framework

A framework to map the C budget of biomass and soil in boreal forests was developed in this study. In the framework, simulated time-series of biomass and soil C stocks were connected to spatially explicit information of forest age. The basic idea and methods of the framework are based on a carbon balance review conducted for five Finnish municipalities a few years ago (Rasinmäki and Känkänen, 2014). Two models were employed in the framework: the MOTTI v. 3.3 simulator (http://www.metla.fi/metinfo/motti/index-en.htm) to simulate the development of forest stands, and the Yasso15 soil C model to estimate the corresponding soil C stocks and changes in these stocks (http://www.syke.fi/projects/yasso). The biomass and soil C stocks and changes were estimated separately for each forest site type and main tree species present in the study region.

The spatially explicit information on forest characteristics, namely site type, tree biomass and stand age, were derived from the Multi-Source National Forest Inventory 20 × 20 m grid dataset dating back to 2011 (hereafter MS-NFI 2011) (Tomppo et al., 2014). The MS-NFI 2011 forest resource maps have been compiled based on the NFI field plot data, satellite images and digital maps using a non-parametric k Nearest Neighbors estimation (Katila and Tomppo, 2001; Tomppo et al., 2008). Peatlands were excluded from this study because the Yasso15 soil C model is applicable only on mineral soils.

Grid layers of forest site type, tree biomass and stand age were downloaded from the public data service (http://kartta.luke.fi/). The data were processed using the Esri® ArcMap™ v. 10.2.2 software. The main tree species was defined pixel by pixel as the species having the maximum total biomass among the biomass layers of Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) and deciduous trees. The latter consists mainly of Silver birch (*Betula pendula*) and Downy birch (*Betula pubescens*). The proportion of forest land dominated by other deciduous species than birch varied between 0.4 and 1.2% in southern Finland in the early 2000s according to the NFI (Tomppo et al., 2008). In the model simulations, the class of deciduous trees was treated as birch because the proportion of other deciduous species in forest land is very small and the growth models are only available for birch.

Each grid cell of the stand age layer was classified according to forest site type (Cajander's (1949) classification) and main tree species deduced from the tree biomass layer. Forest site types present in the study region are shown in Appendix 1. The simulated estimates of the C stocks of biomass and soil, and the mean annual change in these stocks in 2011 per each site type and main tree species, were then joined to this classified stand age layer using look-up tables.

2.3. Model simulations

2.3.1. Biomass carbon stocks

To estimate the C stock of biomass, the development of forest stands was simulated over one rotation for each main tree species and site type −combination present in the study region using the MOTTI v.3.3 simulator (Hynynen et al., 2014; Salminen et al., 2005). A total of 18 simulations representing these combinations were generalized for the whole study region. Because the time-step of the MOTTI v. 3.3 simulator is 5 years, the intermediate annual values were generated by linear interpolation. Stand regeneration method (natural or planting) and timing and intensity of thinning were assumed according to national recommendations of forest management (Tapio, 2006). The recommendations are based on scientific knowledge about optimal forest stand development in each site type. By following the recommendations the forest owners can maximize their economic revenue without risking the long-term productivity of forest (Tapio, 2006). The rotation lengths were extended to cover the wide distribution of stand age in the MS-NFI 2011 data. As a result, only fully-stocked stands were

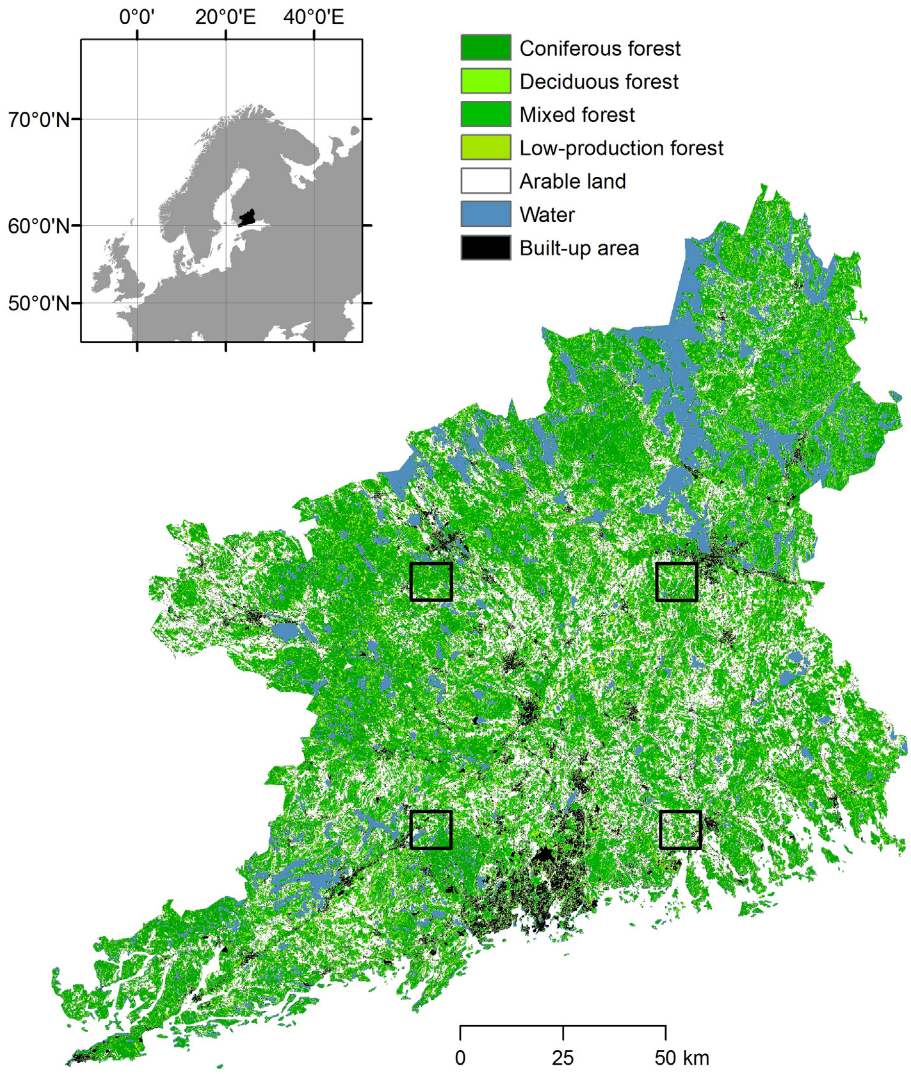


Fig. 1. The location of the study region and its main land cover types according to the CORINE Land Cover 2012 classification (© Finnish Environment Institute). Squares indicate the location of four case study areas for geospatial analysis.

regenerated. The extended rotation lengths mimic the current behavior of forest owners who often delay final harvesting.

The MOTTI v.3.3 simulator is based on forest growth and yield models that enable detailed description of forest structure, growth and management at stand level (Hynynen et al., 2002). These models cover the most typical site types and tree species in Finland. They have been evaluated nationally based on long time-series of forest inventories and field experiments (Matala et al., 2003). The annual change of biomass C stock was calculated over the forest rotation as the difference between the C stocks of subsequent years. A positive value of the stock change indicates that the forest is a net sink of C and a negative value that it is a source.

The calculation scheme for estimating the C stocks of biomass and soil is shown in Fig. 2. The C input to soil was estimated using the same method as is used in the national greenhouse gas inventory of Finland (NIR, 2012; Ortiz et al., 2013; Sievänen et al., 2014). The C input to soil consists of 1) natural mortality, 2) forest harvest residues and 3) annual litter production of living trees and ground vegetation. The simulated estimates of annual volumes of growing stock and natural mortality were transformed to biomass using allometric biomass equations (Repola, 2008, 2009). Tree biomass consists of stems, branches, foliage, stumps, coarse roots and fine roots. The C content of biomass was assumed to be 50%. The annual litter production of the living trees was estimated over a forest rotation based on the simulated estimates of standing biomass. The litter production was calculated by multiplying the biomass compartments (stems, branches, foliage, stumps, coarse roots and fine roots) with compartment-specific turnover rates, separately for coniferous and deciduous trees (Liski et al., 2006). For the litter production of ground vegetation, the values used in the national greenhouse gas inventory of Finland were applied (Muukkonen and Mäkipää, 2006).

2.3.2. Soil carbon stocks

The C stock of soil was estimated over the forest rotation using the Yasso15 litter and soil C model (Järvenpää et al., manuscript in preparation), an improved version of the Yasso07 model (Tuomi et al., 2011a; 2011b; 2009). The annual change of soil C stock was calculated over the forest rotation as the difference between the C stocks of subsequent years. Yasso07 has been applied and its validity has been tested at the global (Goll et al., 2015; Thum et al., 2011), regional (Lehtonen and Heikkinen, 2015; Wu et al., 2015) and site (Karhu et al., 2011; Lu et al., 2013) scales. According to these tests, the Yasso15 model is suitable for this study and the study region. Yasso15 is a dynamic model. It has five state variables representing chemical compound groups of soil organic C. The decomposition rate of each group depends on temperature and precipitation. The decomposition of woody litter depends additionally on its diameter (Tuomi et al., 2011a).

The chemical quality of litter was derived from earlier studies (Ortiz et al., 2013; Sievänen et al., 2014; Appendix 2). A diameter of 2 cm was assumed for branches and roots and 10 cm for stems and stumps. The initial soil C stock was estimated by running the model to a steady state with the mean litter production over forest rotation and average climate (Appendices 1 and 2). The average values of precipitation, mean annual temperature and temperature amplitude (the difference between the average temperatures of the warmest and the coldest month) were derived from the weather station data of the Finnish Meteorological Institute. The dataset was based on daily observations from years 1970–2012 from the Lammi weather station located in the study region.

2.4. Spatial autocorrelation

To study the fine-scale spatial variation in the simulated C budget estimates, a semivariogram analysis was conducted. The size of spatially autocorrelated patches was characterized by computing empirical semivariograms for four 10 × 10 km^2 case study areas inside the study region. The distance between each case study was 50 km. These four areas were considered sufficient for the analysis because the fine-scale variation of the C stock estimates appeared fairly uniform across the study region.

The lag interval used was 20 m, equal to the pixel size. By common convention, half the dimension of the study area (5 km) was analyzed. Exponential models were fitted to the semivariances of the C stocks and spherical to those of the C stock changes, except for one area where an exponential model was used (Biswas and Si, 2013). The semivariance at a lag distance equal to h $\gamma(h)$ is half the variance between the paired data values v_i, i = 1, …, k at locations x_i, …, x_k (Eq. (1)) (Isaaks and Srivastava, 1989).

$$\gamma(h) = \frac{1}{2N(h)} \sum_{(i,j)|h_{ij}=h} (v_i - v_j)^2 \quad (1)$$

where N(h) denotes the set of pairs of observations i, j such that $|x_i - x_j| = h$, and N(h) is the number of pairs in the set.

2.5. Model performance

To evaluate the reliability of the mapping framework approach, the simulated and measurement-based estimates of biomass and soil C stock were compared to each other. The measurement-based estimates of biomass were derived from the MS-NFI 2011 dataset and converted to C stock by multiplying with 0.50. The simulated estimates of biomass C stock were compared to measurement-based means per grid cell, stand age and municipality. The measurements of soil C stocks were derived from earlier studies from the same region (Liski and Westman, 1995; Rantakari et al., 2012). The simulated and measured means were compared by forest site type because measurements of the soil C stocks were not available per stand age or in each municipality.

Harvests reduce the biomass C stock and increase the soil C stock temporarily (Fig. 4). The C stock changes were evaluated by comparing the estimated and measured mean harvests in 2011 per municipality. Harvests were estimated by subtracting the harvest residues entering the soil from the total harvest removal pixel by pixel. The volume of harvest removals and residues was derived from the MOTTI v. 3.3 stand simulator output. Harvest statistics were supplied by the Natural Resources Institute Finland.

The model performance was analyzed using a regression analysis of the measured mean vs. model predicted mean values. The measures estimated were regression coefficient R^2 and root mean square error (RMSE) (Eq. (2)) (Janssen and Heuberger, 1995). RMSE was weighted with the area of observation groups. RMSE is a measure of the mean error between model predictions (P) and observations (O). RMSE of 0 implies a perfect model fit. All statistical analyses were conducted using R version 3.1.3 (R Core Team, 2015).

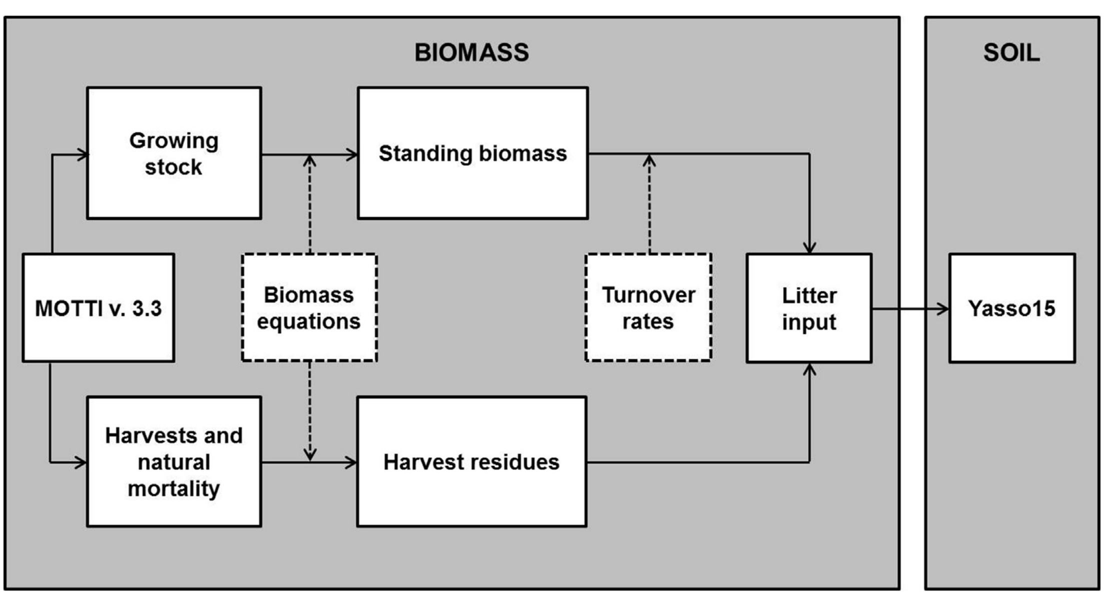


Fig. 2. The calculation scheme for estimating the C stocks of biomass and soil. The figure was modified after Repo et al. (2015).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \quad (2)$$

3. Results

3.1. Carbon stocks and changes

The mean C stock of tree biomass across the study region in 2011 was 6.6 kg m^{-2}, ranging from 0–14.1 kg m^{-2}, according to the model simulations (Table 1). The C stock of biomass was slightly lower in the south coast compared to the inland (Fig. 3a). It was spatially autocorrelated up to about 400–500 m among the case study areas according to the visual interpretation of the maps and the semivariograms (Fig. 3a and Appendix 4). The simulated estimate of the mean C stock of soil was 7.9 kg m^{-2}, ranging from 3.4–14.9 kg m^{-2} (Table 1). The soil C stock showed a similar regional trend to the C stock of biomass (Fig. 3b). It was spatially autocorrelated up to about 300–600 m (Appendix 5).

The C stocks of biomass and soil increased in the study region in 2011 according to the simulated estimates indicating that the forests were a sink of C (Table 1). The mean change in the C stock of biomass was 0.032 kg m^{-2} a^{-1}, ranging from −11.9–1.02 kg m^{-2} a^{-1} (Table 1). The change in the C stock of biomass showed no trend across a climatic gradient from south to north (Fig. 3c). It was spatially autocorrelated up to about 60–100 m (Fig. 3c and Appendix 6). The mean change in the C stock of soil was 0.022 kg m^{-2} a^{-1}, ranging from −0.388–5.40 kg m^{-2} a^{-1} (Table 1). The change in the C stock of soil showed no regional trend either. It was spatially autocorrelated up to 100–300 m (Fig. 3d and Appendix 7).

3.2. Mapping framework performance

The simulated time-series of the C stock of biomass followed the measurement-based means over the stand age (Fig. 4). The simulated estimates were, however, generally higher than the measurement-based ones. The simulated and the measurement-based means of the biomass C stock were clearly correlated ($R^2 = 0.75$) per municipality across the study region (Fig. 5a). The correlation was even higher at the level of individual grid cells ($R^2 = 0.77$, data not shown). The simulated means showed a tendency for overestimation compared to the measurement-based means being on average 1.4 kg m^{-2} higher at grid cell level and 1.6 kg m^{-2} higher at the municipality level (Fig. 5a).

The simulated means of the C stock of soil were highly correlated with the measured means per forest site type ($R^2 = 0.93$) across the study region after removing one obvious outlier (Fig. 5b). The measured mean of the soil C stock equal to 3.58 kg m^{-2} for the fertile, *Oxalis-Maianthemum* type (OMaT) forest was regarded as a measurement error. The simulated means showed a slight tendency for overestimation compared to the measured means being on average 1.1 kg m^{-2} higher (Fig. 5b). The simulated estimates of harvests in the municipalities of the study region in 2011 were highly correlated ($R^2 = 0.88$) with the reported harvests (Fig. 5c). The $RMSE_{weighted}$ of the simulated vs. measured harvests was 44 300 m^3.

Table 1
Mean estimates of the simulated biomass and soil C stocks and the changes in these stocks across the study region in 2011. Minimum and maximum represent the total range of the estimates among all grid cells.

	Mean	Minimum	Maximum
C stock (kg m^{-2})			
Biomass	6.57	0.00	14.1
Soil	7.91	3.38	14.9
Total	14.5	3.90	23.9
C stock change (kg m^{-2} a^{-1})			
Biomass	0.032	−11.9	1.02
Soil	0.022	−0.39	5.38
Total	0.055	−8.56	1.61

4. Discussion

A framework to map the current status and spatial variation of the C budget of boreal forested landscapes was developed in this study. The C stocks of biomass and soil and the annual change in these stocks were quantified at the level of individual grid cells and the results were scaled up to the regional level. The C stocks increased from south coast to inland whereas the changes in these stocks were more uniform. The spatial patches of C stocks were larger than those of C stock changes. The simulated estimates were very similar to measurement-based estimates indicating a good mapping framework performance.

4.1. Spatial variation of C budget

The spatial variation in the C budget maps was a result of connecting the simulated estimates of C stocks and changes to detailed, spatially explicit information about forest characteristics. The spatial variation reflected the variation in site type, main tree species and age of the forest, and the management actions related to age. The visual overview of the maps showed that the C stocks of biomass and soil were slightly lower in the south coast compared to the inland. A similar regional trend has been observed in previous research (Liski and Westman, 1997). It is likely explained by the soil properties reflected in the site type. The south coast is mostly covered by dry heath (*Calluna* site type (CT) according to Cajander's (1949) classification) which has lower forest growth and litter production rates compared to more fertile sites in the inland. The changes in the C stocks had no regional trends.

The spatial interpretation of the simulated estimates revealed that the C stocks of biomass and soil were spatially autocorrelated up to 400–600 m. This is probably explained by the fine-scale variation in the site type and tree species composition controlling the biomass and litter production estimates (Liski et al., 2006; Lu et al., 2013). The decomposition rate of the litter of deciduous and coniferous trees differs causing variability in the soil C stock (Tupek et al., 2015). The estimates of C stock changes were spatially autocorrelated on average up to 100–200 m. The C stock changes thus had a smaller and also more heterogeneous spatial pattern compared to the C stocks. The variation in the changes of C stocks is likely explained by the stand age and the management actions related to age (Sievänen et al., 2014). The average area of forest management compartments in southern Finland is 1.5–2 ha (Kangas and Maltamo, 2006) which supports this suggestion.

4.2. Evaluation of the mapping framework

The reliability of the simulated estimates is an important prerequisite for using the method in real-world applications. The simulated estimates of the C stock of biomass were highly correlated with the measurement-based estimates from the MS-NFI 2011. The correlation was equal at 20 × 20 m^2 grid cell and municipality -levels which indicates a high spatial accuracy of the mapping framework. The high correlations were expected because both datasets are based on extensive, though partly different field

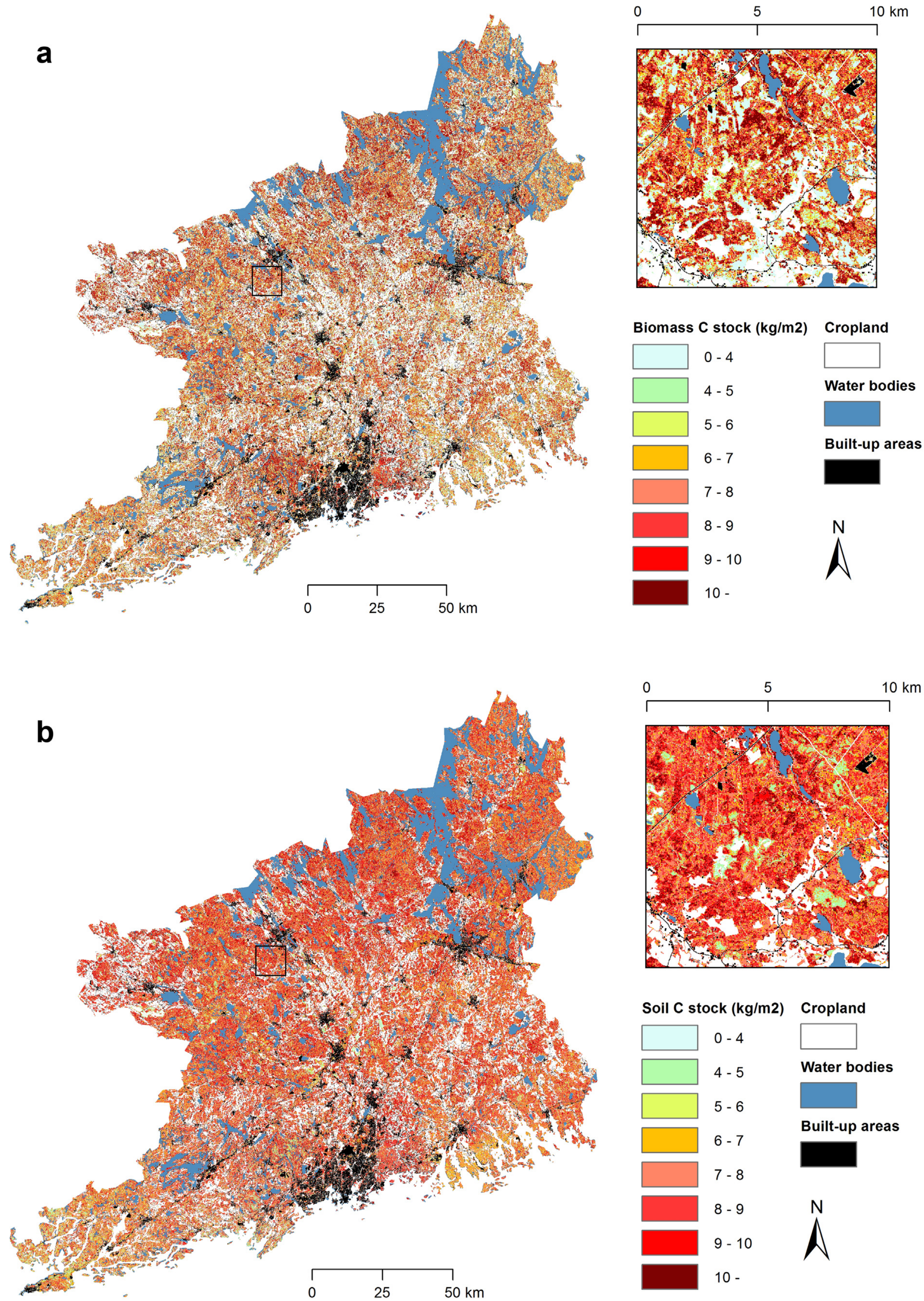


Fig. 3. The simulated biomass (a) and soil (b) C stock and the change in these stocks (c and d respectively) in the study region in 2011. Positive values indicate a net sink and negative values a net source of C. The 10 × 10 km^2 square illustrates the fine-scale variation of the simulated estimates in one of four case study areas.

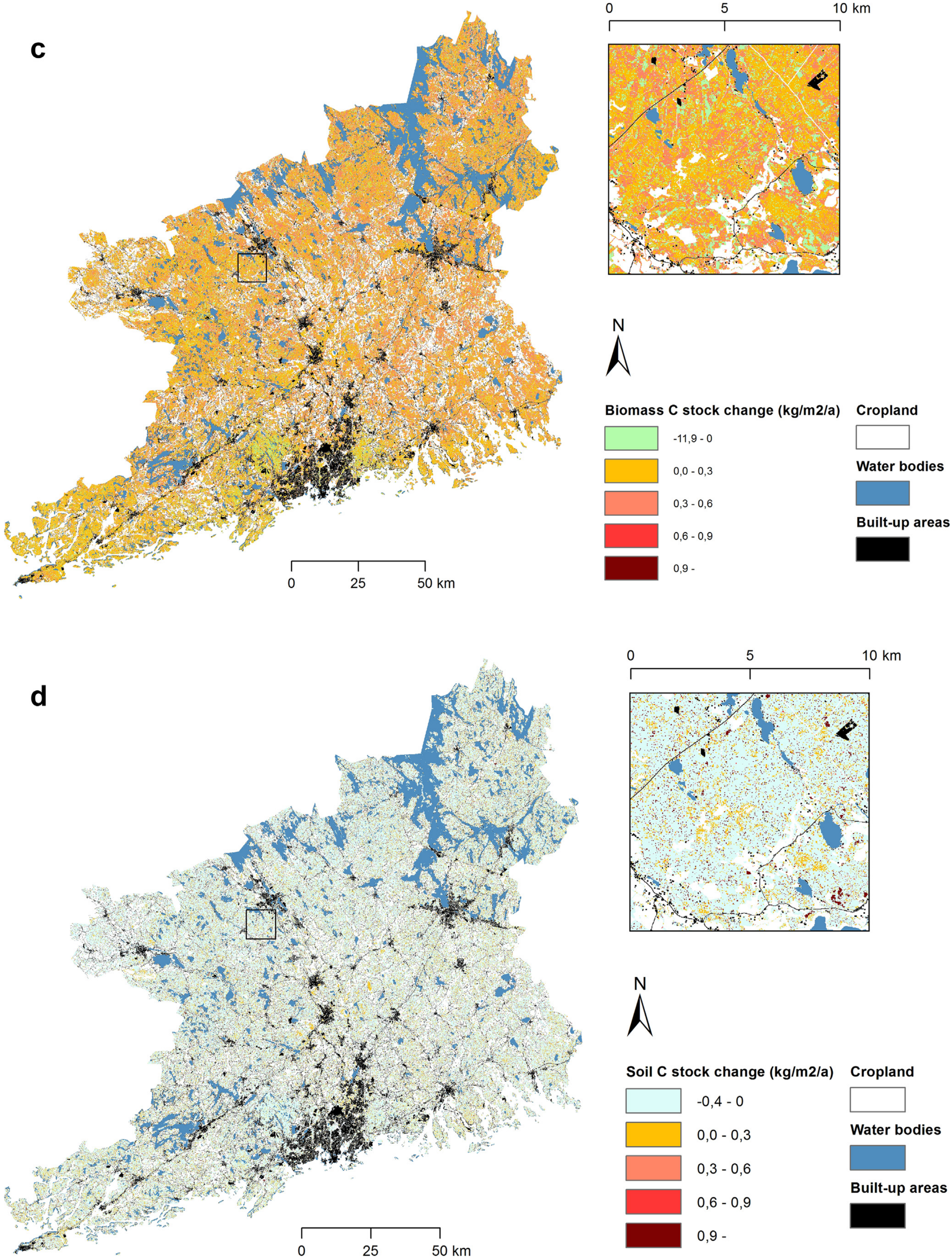


Fig. 3. (*continued*).

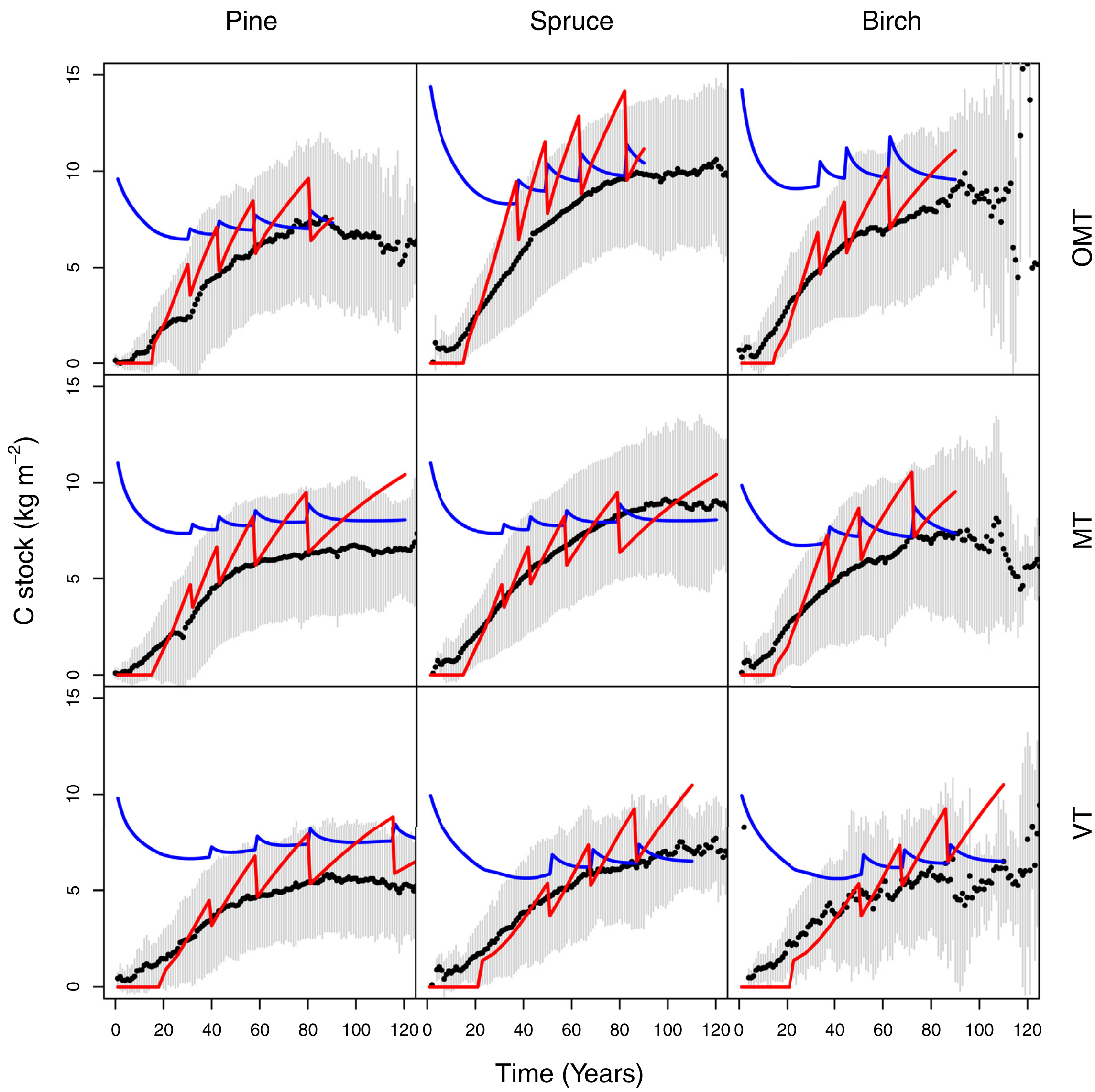


Fig. 4. The simulated estimates of biomass (red line) and soil (blue line) C stock and the measurement-based estimates of biomass C stock (black dots) for pine, spruce and birch -dominated forest stands over stand age. Error bars stand for 95% of the variation in the measurement-based estimates. OMT stands for *Oxalis-Myrtillus* Type, MT for *Myrtillus* Type and VT for *Vaccinium* Type according to Cajander (1949). Data for other site types are shown in Appendix 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

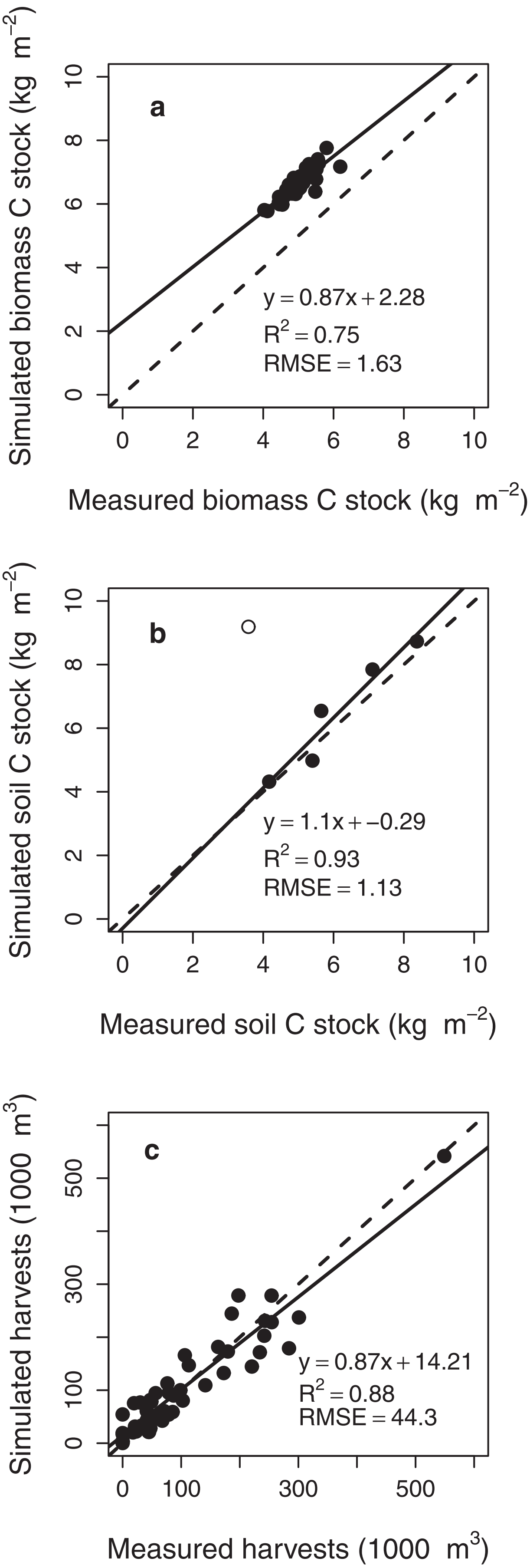


Fig. 5. The simulated vs. the measurement-based estimates of a) biomass C stock, b) soil C stock and c) harvests, and the 1:1 line. The mean estimates of the biomass C stock and the harvests were estimated for the municipalities of the study region (N = 48). The mean estimates of the soil C stock were estimated for the forest site types in the study region (N = 6, excluding one obvious outlier).

measurements from Finnish forests. The C stock of biomass was, however, somewhat overestimated because in the simulations it was assumed that forest management actions followed the national recommendations strictly; thinning was assumed to occur always on optimal time, only fully-stocked stands were regenerated and natural disturbances were absent. The measurement-based estimates represent actual forests that do not follow the recommendations exactly and are exposed to various disturbances.

The deviations between the simulated and measurement-based estimates do not indicate an error in the models used as such. Rather they indicate that the recommendations are not strictly followed in practical forestry and the assumptions applied in the simulations were overly optimistic. The discrepancy with the measurement-based estimates was the highest in mature stands. Nevertheless, the simulated estimates were mostly within 95% of the variation in the measurements. It is also noteworthy that the measurement-based estimates derived from the MS-NFI 2011 dataset (Katila and Tomppo, 2001; Tomppo et al., 2008, 2014) might be inaccurate due to measurement and model errors in site type classification and age estimation.

The C stock of soil in 2011 was well in line with the measurements taken from the same region in the 1990s (Liski and Westman, 1995) and in 2006 (Rantakari et al., 2012). The soil C stock showed, however, a slight tendency for overestimation. This was expected because the simulated estimates of the soil C stock include also dead wood unlike the field measurements. The good model fit implies that the mapping framework produces reliable estimates of the mean soil C stock per forest site type in boreal forested landscapes. The validity of the Yasso soil C model used in this framework has been tested before in boreal (Ortiz et al., 2013; Rantakari et al., 2012) and temperate conditions (Lu et al., 2013; Wu et al., 2015). These tests have also suggested that the model is suitable for estimating the effects of forest management on the soil C stock from site-level up to regional and global levels.

The similarity of the estimated and reported harvests as well as the simulated and the measurement-based time-series of biomass C stock imply that the C stock changes were estimated reliably. They were also comparable with earlier estimates (Liski et al., 2006; Rantakari et al., 2012). All forest stands of the same site type and main tree species −combination were assumed to follow an identical simulated development which is naturally unrealistic. The method approximates the total amount of harvests in the region based on the applied thinning regime, rotation length and the forest age distribution. Thus it involves uncertainties about the precise location and timing of harvests. However, it produced mainly reliable estimates of the amount of harvests at the municipality-level. The exclusion of peatlands added also some uncertainty to the harvest estimates. This uncertainty was, though, considered minor because most peatland forests are young and located on unproductive forestry land (Finnish Statistical Yearbook of Forestry, 2012). The importance of drained peatlands for timber production will increase in the future when the stands reach maturity (Kojola et al., 2012).

To conclude, the model performance was surprisingly good in spite of possible uncertainties related to model inputs, parameter values and the forest management scenario applied (see Lehtonen and Heikkinen, 2015). Therefore, it is argued that the mapping framework developed in this study can be applied to illustrate the present status of the C stocks and changes of boreal forests.

4.3. Implications for environmental management

The C budget estimates of this study were more accurate and reliable than simple land cover -based proxies for three reasons. Firstly, the C stocks of biomass and soil were simulated using models of forest development and soil C cycle, applicable in the study region based on several validity tests (Karhu et al., 2011; Matala et al., 2003; Ortiz et al., 2013; Rantakari et al., 2012). Secondly, the model system described the connection of forest growth to biomass and soil C cycles correctly. As a result, the effects of forest management on the C budget were estimated convincingly although the simulated forest management was more intensive than in practice. Thirdly, the maps had a high spatial resolution because the simulated C stocks and changes were connected to detailed inventory data on forest characteristics. Simple land cover-based proxies have been shown to fit poorly to primary data on C stocks and are therefore more suitable for mapping broad-scale trends of ES (Eigenbrod et al., 2010; Van der Biest et al., 2015).

The mapping framework developed in this study connected simulated forest biomass and soil C stocks to Finnish multisource national forest inventory data. Availability of suitable forest models and spatial data is a prerequisite for transferring the framework to other countries. The C stocks can be simulated also using other models than presented here to better respond to regional information needs. Forest characteristics have been mapped also elsewhere using the k Nearest Neighbors technique (Chirici et al., 2016). In Sweden, national maps of tree volume, height and age were produced by combining NFI, satellite and digital map data (Reese et al., 2005). In Canada, various forest variables were mapped by combining observations from NFI photo plots and geospatial data (Beaudoin et al., 2014). In the United States of America, similar methods have been applied to map tree basal area and C stocks (Wilson et al., 2012, 2013). Discrepancies between the simulated and actual forests might be a challenge for applying the framework successfully, as shown in this study. For example growth models for uneven-aged forests should be further improved to capture the large variation of forest management systems in boreal regions (see e.g. Pukkala et al., 2013).

Climate warming, increased use of biomass for bioenergy and urbanization will change forest management and land use patterns driving the supply of ES (Haase et al., 2012; Lu et al., 2014; Makkonen et al., 2015; Smith et al., 2013). The mapping framework developed can be applied to estimate the carbon budget of boreal forests at varying spatial scales, such as municipalities, catchments or regions. Future development of the framework includes analysis of alternative forest management scenarios on climate regulation as well as other ES, such as water regulation and recreation. A potential application of the framework is quantifying the effects of forest bioenergy production on the development of carbon stocks and sinks at the landscape scale. Integrated modeling can produce new information on the trade-offs and synergies between ES in the changing environment (Aherne et al., 2012; Forsius et al., 2016; Granell et al., 2013). Maps can also serve as input to optimization between alternative forest management scenarios (e.g. Muys et al., 2010; Mönkkönen et al., 2014) and valuation of the natural capital (Daily and Matson, 2008; Kareiva et al., 2011; Nelson et al., 2009).

The C budget maps will be presented for a wider public using a virtual research environment for ES (Holmberg et al., 2015). Web-based services based on open data can enhance the utilization of research results because they require less expertize than conducting model simulations independently. Maps of multiple ES could, for example, serve as a planning tool for municipalities and private land owners (Albert et al., 2014; Hauck et al., 2013). They could also facilitate discussions about sustainable environmental management and climate policy with decision-makers (Koschke et al., 2012; Swetnam et al., 2011). In regard to the above mentioned applications, the advantages of this framework are open and regularly updated data and models, a broad spatial cover and a high resolution. In addition, the framework enables verifying the environmental impacts of alternative forest management and land use scenarios at a regional level.

The mapping framework is the basis for evaluating the effects of environmental management alternatives on C budget at high resolution across large spatial scales. It will be coupled with the assessment of other ES and biodiversity to study their relationships. The framework integrated a wide suite of simulation models and multi-source forest inventory data. It provided reliable estimates of the human influence on C cycle in boreal forested landscapes.

Acknowledgements

This study was funded by Maj and Tor Nessling Foundation (Grant no. 201500289) and LIFE+ financial instrument of the European Union (LIFE12 ENV/FI/000409, MONIMET). The authors are solely responsible of the simulations and the application of the MOTTI model in this study. The authors wish to thank Miska Luoto (University of Helsinki), Maria Holmberg (Finnish Environment Institute) and Saija Huuskonen, Hannu Salminen and Jari Hynynen (Natural Resources Institute Finland) for commenting and pre-reviewing this manuscript thoroughly.

Appendix

Appendix 1

Mean annual input of C to the soil in the forest site types according to Cajander (1949). OMaT = *Oxalis-Maianthemum*, OMT = *Oxalis-Myrtillus*, MT = *Myrtillus*, VT = *Vaccinium*, CT = *Calluna* and ClT = *Cladina* Type (respectively).

Main tree species	Site type					
	OMaT	OMT	MT	VT	CT	ClT
	Input of C, kg m^{-2} a^{-1}					
Scots pine	0.19	0.21	0.22	0.20	0.15	0.15
Norway spruce	0.32	0.32	0.24	0.19	0.16	0.14
Silver birch	0.27	0.29	0.23	0.15[a]	0.24	0.21

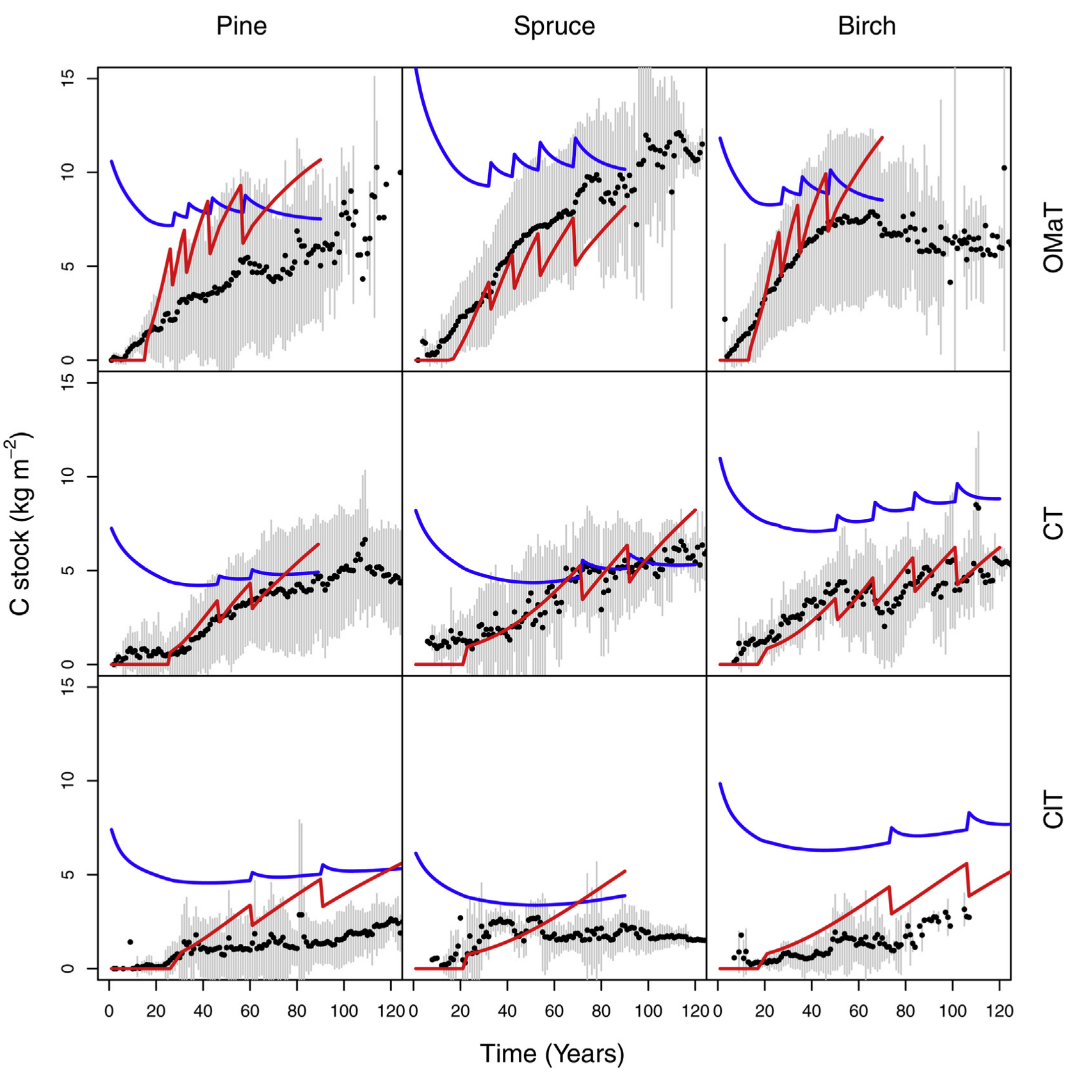
[a] Calculated using the litter production estimates of VT Scots pine stands.

Appendix 2

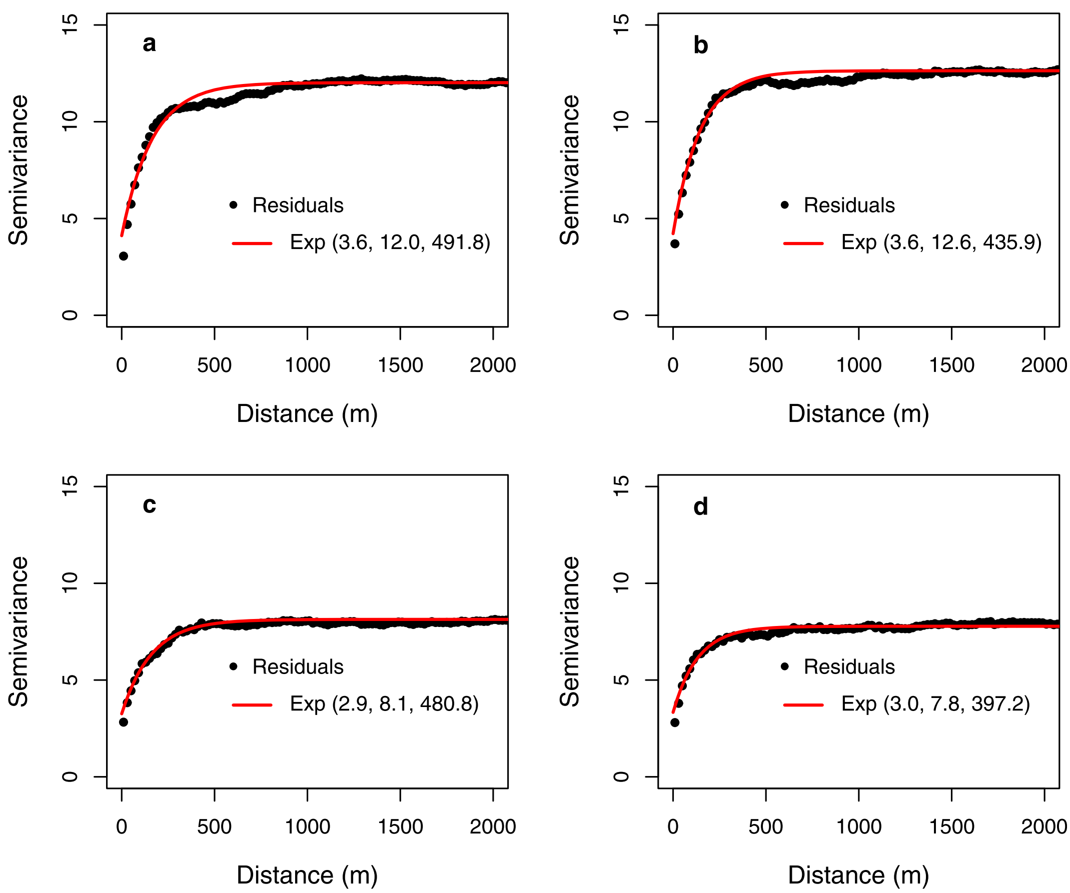
The chemical composition of litter and climate applied in the soil C stock simulations.

Plant litter component	Proportions of acid hydrolysable (A), water soluble (W), ethanol soluble (E) and non-soluble (N) fractions of litter			
	A	W	E	N
Scots pine				
Stems, stumps	0.68	0.02	0.01	0.27
Needles, fine roots	0.51	0.13	0.10	0.25
Branches, coarse roots	0.68	0.02	0.01	0.27
Norway spruce				
Stems, stumps	0.68	0.01	0.01	0.30
Needles, fine roots	0.50	0.09	0.05	0.35
Branches, coarse roots	0.68	0.01	0.01	0.30
Birch				
Stems, stumps	0.76	0.01	0.00	0.24
Foliage, fine roots	0.39	0.09	0.05	0.35
Branches, coarse roots	0.76	0.01	0.00	0.24
Ground vegetation	0.56	0.23	0.09	0.13

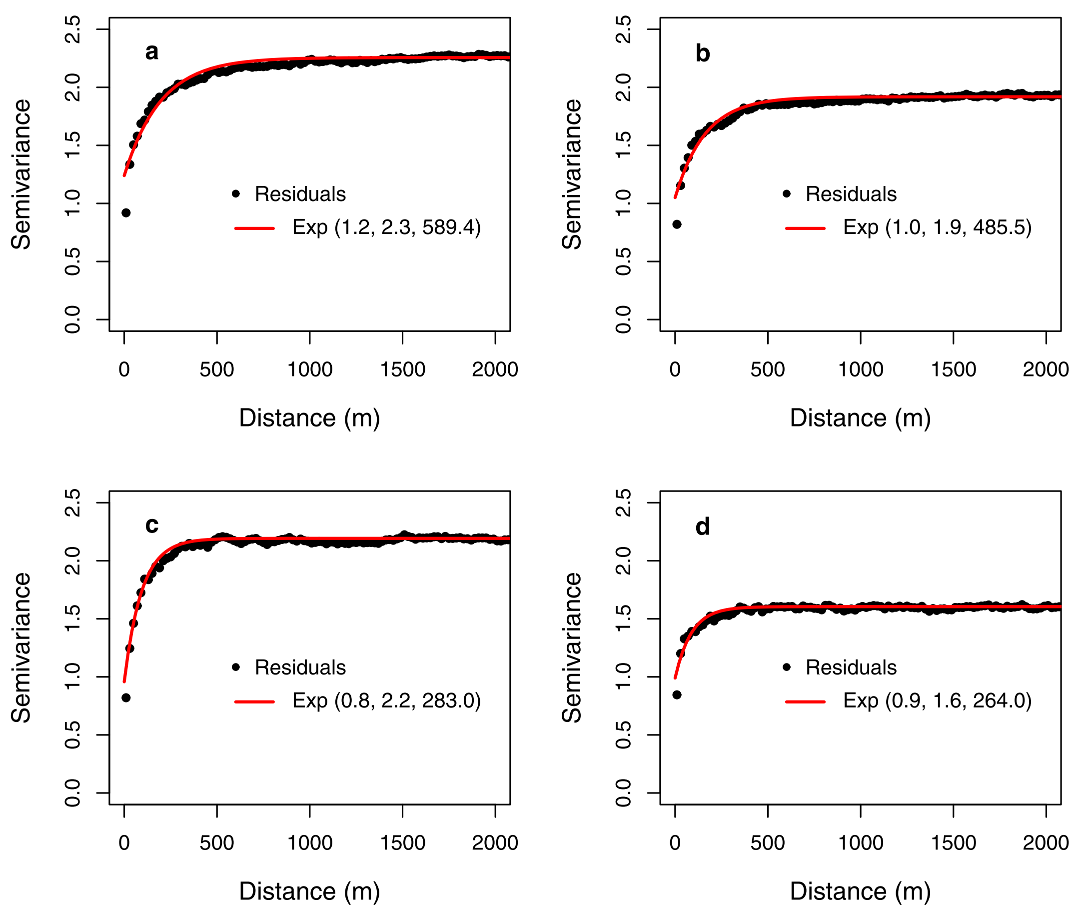
Climate Annual precipitation (mm)	Mean annual temperature (°C)	Amplitude (°C)
637	4.2	12.7



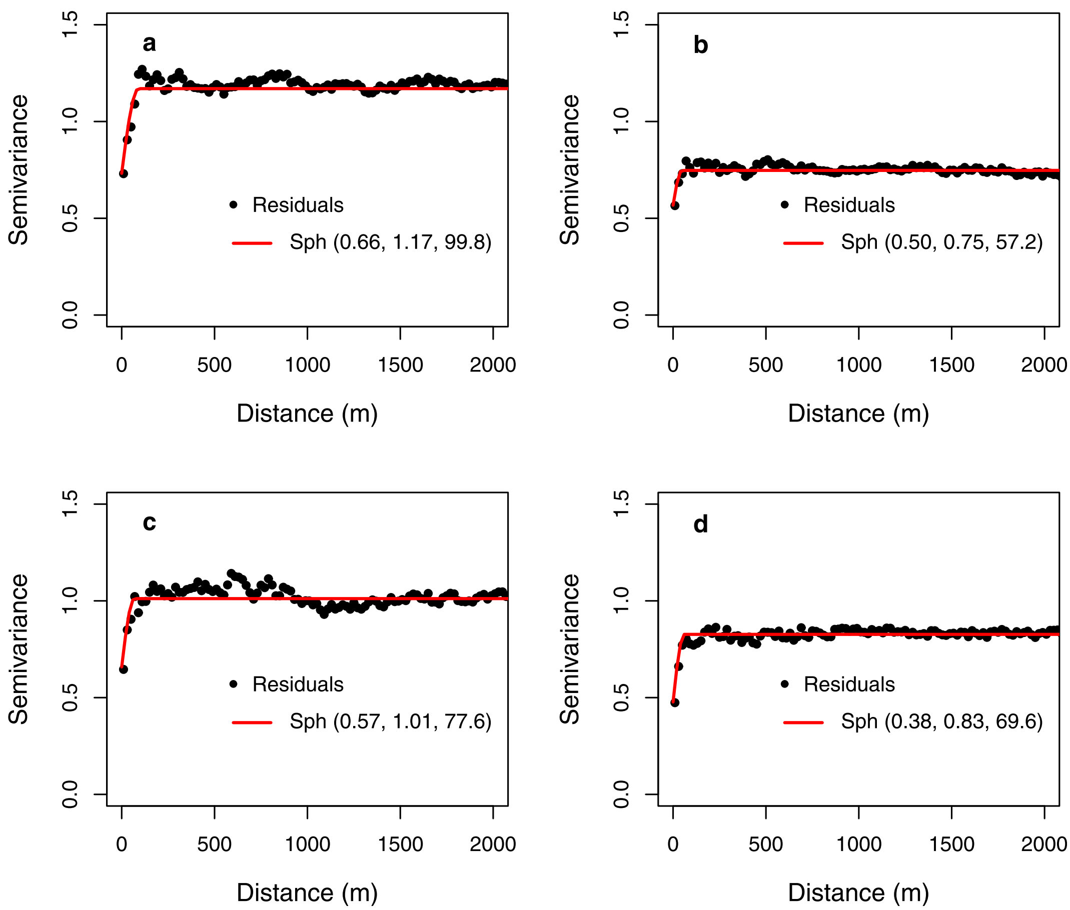
Appendix 3. The simulated estimates of biomass (red line) and soil (blue line) C stock and the measurement-based estimates of biomass C stock (black dots) for pine, spruce and birch -dominated forest stands over stand age. Error bars stand for 95% of the variation in the measurement-based estimates. OMaT stands for *Oxalis-Maianthemum* Type, CT for *Calluna* Type and CIT for *Cladina* Type according to Cajander (1949). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



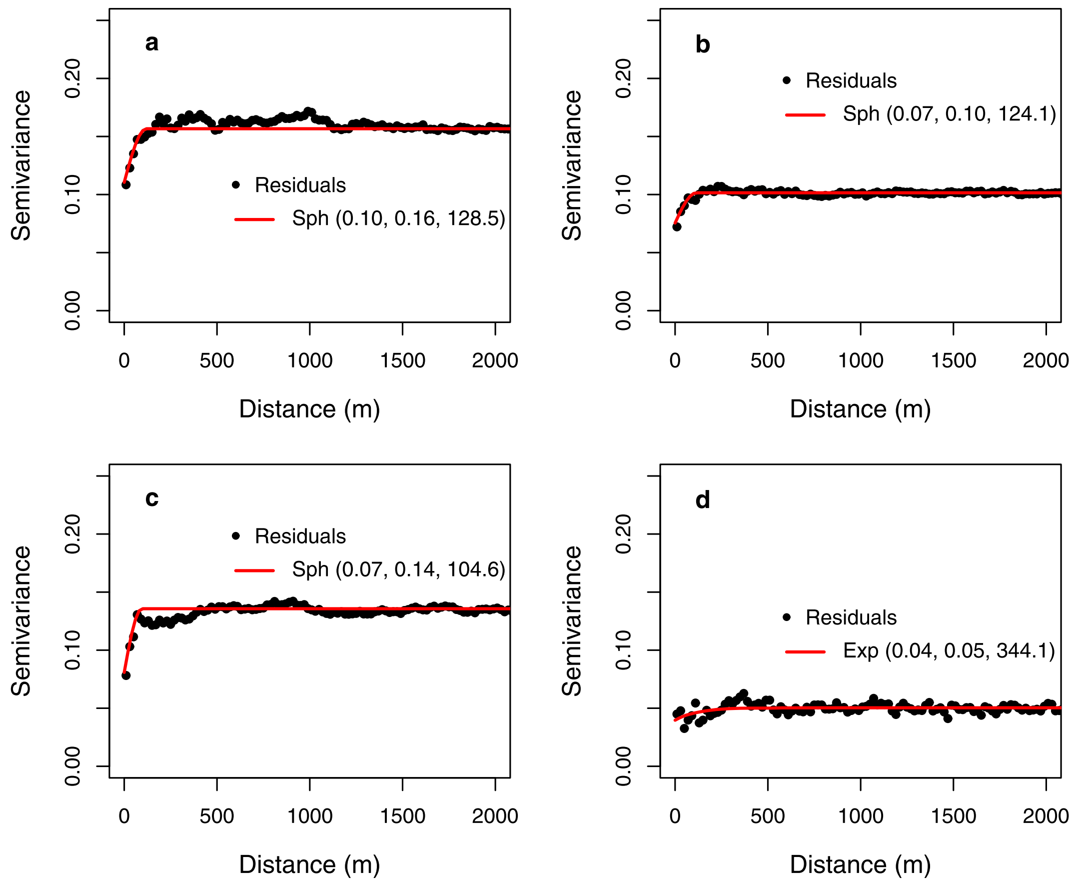
Appendix 4. Semivariograms for the simulated biomass C stock in four 10 × 10 km^2 case study areas (a to d) in the study region in 2011. Exp stands for exponential and Sph stands for spherical. The numbers in parenthesis correspond to the nugget, sill and range parameters of the model equations (Biswas and Si, 2013).



Appendix 5. Semivariograms for the simulated soil C stock in four 10 × 10 km^2 case study areas (a to d) in the study region in 2011. Exp stands for exponential and Sph stands for spherical. The numbers in parenthesis correspond to the nugget, sill and range parameters of the model equations (Biswas and Si, 2013).



Appendix 6. Semivariograms for the simulated biomass C stock change in four 10 × 10 km^2 case study areas (a to d) in the study region in 2011. Exp stands for exponential and Sph stands for spherical. The numbers in parenthesis correspond to the nugget, sill and range parameters of the model equations (Biswas and Si, 2013).



Appendix 7. Semivariograms for the simulated soil C stock change in four 10 × 10 km2 case study areas (a to d) in the study region in 2011. Exp stands for exponential and Sph stands for spherical. The numbers in parenthesis correspond to the nugget, sill and range parameters of the model equations (Biswas and Si, 2013).

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