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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ARTICLE INFO

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

ABSTRACT

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