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A coupled modeling framework for predicting ecosystem carbon dynamics in boreal forests

Chao Huang [a, b], Hong S. He [c, d, *], Todd J. Hawbaker [e], Yu Liang [a], Peng Gong [f], Zhiwei Wu [a], Zhiliang Zhu [g]

[a] CAS Key Laboratory of Forest Ecology and Management, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] School of Natural Resources, University of Missouri, Columbia, MO, USA
[d] School of Geographical Sciences, Northeast Normal University, Changchun 130024, China
[e] U.S. Geological Survey, Geosciences and Environmental Change Science Center, Denver, CO 80225, USA
[f] Ministry of Education Key Laboratory for Earth System Modeling, Center for Earth System Science, Tsinghua University, Beijing 100084, China
[g] U.S. Geological Survey, Reston, VA 20192, USA

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ABSTRACT

Carbon stocks in boreal forests play an important role in global carbon balance but are sensitive to climate change and disturbances. Ecological models offer valuable insights into the effects of climate change and disturbances on boreal forests carbon stocks. However, the current pixel-based model coupling approaches are challenging to apply over large spatial extents because high computational loads and model parameterizations. Therefore, we developed a new framework for coupling a forest ecosystem and a landscape model to predict aboveground and soil organic carbon stocks at the ecoregion level. Our results indicated that the new model-coupling framework has some advantages on computation efficiency and model validation. The model results showed that carbon stocks and its spatial distribution were significantly influenced by fire, harvest, and their interactions. Simulation results showed that boreal forests carbon stocks are vulnerable to loss because of future potential disturbances, complicating efforts to offset greenhouse gas emissions through forest management.

Software availability

Name of software: LANDIS PRO
Developer: Prof. Hong S. He (heh@missouri.edu)
Program language: C++
Download: http://landis.missouri.edu/
Name of software: LINKAGES v2.2
Developer: Dr. Stan D. Wullschleger (wullschlegsd@ornl.gov)
Program language: FORTRAN and C++
Download: http://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1166

1. Introduction

Boreal forests cover about one third of the global forest area, contain 32% of global forest carbon stocks (Pan et al., 2011), and play an important role in the global carbon balance (Bradshaw and Warkentin, 2015; Dixon et al., 1994). Field and model-based studies have shown that carbon stocks of boreal forests are highly sensitive to climate change and disturbances (Harden et al., 2000; Lutz et al., 2013; McGuire et al., 2009). Changes in boreal forest carbon stocks may significantly alter terrestrial ecosystem carbon balance and may lead to a positive feedback between climate change and carbon cycling (Goodale et al., 2002; Jones et al., 2005). Therefore, future changes of boreal forest carbon stocks and reasons for those changes have emerged as an important research topic (Bond-Lamberty et al., 2007).

Modeling provides a unique approach for projecting forest ecosystem carbon dynamics. Forest ecosystem models have a tight coupling between physical and biological processes such as photosynthesis, growth, mortality, and decomposition while simulating aboveground carbon dynamics. They also include biogeochemical processes while simulating belowground carbon dynamics (Lu and Cheng, 2009). Several forest ecosystem models

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[*] Corresponding author. School of Natural Resources, University of Missouri, Columbia, MO, USA.
E-mail address: heh@missouri.edu (H.S. He).

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were developed to predict boreal forests carbon stocks, including the Boreal Forests Carbon Dynamics Model (Nalder and Wein, 2006), the Carbon Budget Model of the Canadian Forest Sector (Cameron et al., 2015; Chen et al., 2000; Kurz et al., 2009), the Individual based Spatially Explicit Simulation Model of Forest Ecosystem (Chertov et al., 2009), the Individual based forest ecosystem model LINKAGES (Post and Pastor, 1996) and the Terrestrial Ecosystem Model (Zhuang et al., 2002). These models offer valuable insights into the effects of climate change and disturbances on future potential changes in carbon dynamics. However, they typically have no, or simple treatment of forest landscape processes (typically disturbances and management) as well as stand-scale processes such as establishment and competition. Forest ecosystem carbon stocks are the result of interactions between forest growth, climate, soil, and forest landscape processes (Chen and Shrestha, 2012; McGuire et al., 2009; Smith et al., 2000; Ter-Mikaelian et al., 2013). These interactive processes control forest net primary production and litter decomposition, which in turn affect carbon stocks (Bonan and Cleve, 1992; Pregitzer and Euskirchen, 2004). For instance, fire and harvest may release carbon directly into the atmosphere and transfer a large amount of carbon from live biomass into detritus, soils, or forest products (Jandl et al., 2007; Kashian et al., 2006; Nave et al., 2010). Besides, repeated disturbances, such as fires and harvest may result in a large proportion of forest in young age classes which contain less carbon than mature stands (Pregitzer and Euskirchen, 2004; Yang et al., 2011). Moreover, timber harvesting after fire reduces the forest canopy and net primary production, which affects litter decomposition, carbon sequestration capacity, and nutrient cycling (Brais et al., 2000; Marañón-Jiménez and Castro, 2012; Serrano-Ortiz et al., 2011). Therefore, without considering these interactive processes, predictions made by forest ecosystem models may have high uncertainties.

Forest landscape models are designed to simulate landscape-level processes of seed dispersal, disturbance, management and their interactive effects on forest composition and biomass (He et al., 2005; Scheller and Mladenoff, 2005). Forest landscape models provide insight into the relationship between disturbances and aboveground biomass at landscape level. However, most forest landscape models do not simulate forest ecosystem processes (especially biogeochemical processes) and thus, are limited in their ability to predict belowground carbon dynamics. Thus, coupling forest landscape and forest ecosystem models may provide viable alternatives to this problem. Loudermilk et al. (2013) and Lucash et al. (2014) coupled a forest landscape model (LANDIS-II) with an ecosystem process model (CENTURY) to integrate forest stand dynamics with belowground carbon and nitrogen processes. The coupled modeling approaches offer advantages over either model alone, such as disturbance-caused changes in species composition can affect soil nutrient dynamics (Scheller et al., 2011). However, the current model coupling approach creates challenges because of the overwhelming computational resources needed to process large landscapes. This is because the current framework of model coupling is at the pixel level and having to processes millions of pixels makes the simulation intractable (Fig. 1). In addition, most parameters related to biogeochemical cycling (soil water and nutrients) do not often exist at the pixel level, rendering model parameterization and validation difficult.

Most soil and hydrological data are usually available and follow natural boundaries such as landform, landtype, or ecoregion. Therefore, coupling forest ecosystem and landscape models at landform or ecoregion levels may not only improve parameter realism but also improve simulation efficiency since one landform or ecoregion unit may contain numerous pixels. In this paper, we propose a framework of coupling different ecological models at the ecoregion level, which may provide an alternative to current pixel

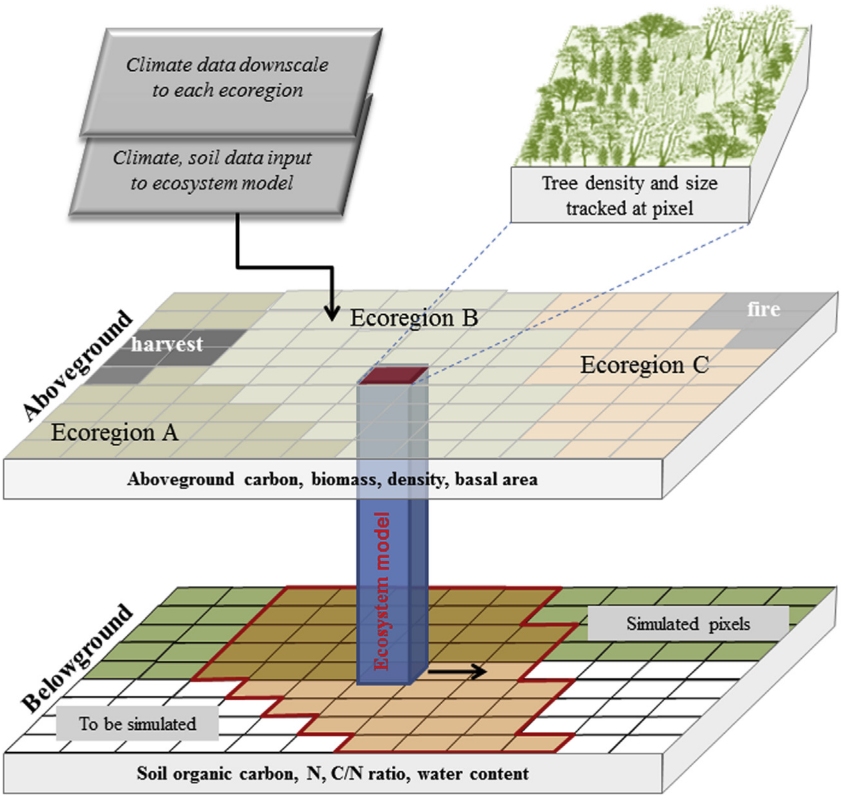

Fig. 1. The current framework for coupling forest ecosystem and landscape model to predict forest ecosystem carbon stocks.