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Modeling harvest and biomass removal effects on the forest carbon balance of the Midwest, USA

Scott D. Peckham [a,1,*], Stith T. Gower [a], Charles H. Perry [b], Barry T. Wilson [b], Kirk M. Stueve [b,2]

[a] Department of Forest and Wildlife Ecology, University of Wisconsin, 1630 Linden Drive, Madison, WI 53706, USA
[b] Northern Research Station, USDA Forest Service, 1992 Folwell Avenue, St. Paul, MN 55108, USA

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ABSTRACT

The objective of this study was to use an ecosystem process model, Biome-BGC, to explore the effects of different harvest scenarios on major components of the carbon budget of 205,000 km^2 of temperate forest in the Upper Midwest region of the U.S. We simulated seven harvest scenarios varying the (i) amount of harvest residue retained, (ii) total harvest area, and (iii) harvest type (clear-cut and selective) to assess the potential impacts on net biome production (NBP), net primary production (NPP), and total vegetation carbon. NBP was positive (C sink) in year 1 (2004) and generally decreased over the 50-year simulation period. More intensive management scenarios, those with a high percentage of clear-cut or a doubling of harvest area, decreased average NBP by a maximum of 58% and vegetation C by a maximum of 29% compared to the current harvest regime (base scenario), while less intensive harvest scenarios (low clear-cut or low area harvested) increased NBP. Yearly mean NPP changed less than 3% under the different scenarios. Vegetation carbon increased in all scenarios by at least 12%, except the two most intensive harvest scenarios, where vegetation carbon decreased by more than 8%. Varying the amount of harvest residue retention had a more profound effect on NBP than on vegetation C. Removing additional residue resulted in greater NBP over the 50-year period compared to the base simulation. Results from the seven model simulations suggest that managing for carbon storage and carbon sequestration are not mutually exclusive in Midwest forests.

1. Introduction

The forests of the Midwest region of the United States are both an important source of fiber for wood and paper products and a carbon sink for atmospheric carbon dioxide (Goodale et al., 2002; Crevoisier et al., 2010; Ryan et al., 2010). Minnesota, Wisconsin, and Michigan, contain the majority of the forests in the Midwest, with forests covering approximately 50% of each of these states (Smith et al., 2004). The Midwest forests produce more than 20 Mm^3 of pulpwood annually, or 14% of pulp for the paper industry in the U.S. (USDA, 2001), and they produce >250 Mm^3 of wood, or >50% of the supply for the nation's composite wood products. These same forests also provide numerous other ecosystem services in addition to wood production, such as carbon sequestration, habitat for game and non-game species, and soil and water protection. The forests of the Midwest region (see Section 2 for description) cover more than 20 million hectares, include both public and private ownership, exist in tracts from small

* Corresponding author. Tel.: +1 608 265 5628; fax: +1 608 262 9922.
E-mail addresses: sdpeckha@wisc.edu, sdpeckha@carbonmodel.org (S.D. Peckham).

[1] Present address: Department of Botany, University of Wyoming, 1000 E. University Avenue, Laramie, WY 82071, USA.
[2] Present address: Department of Geosciences, North Dakota State University, Stevens Hall 218, Fargo, ND 58108, USA.

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farm woodlots to the expansive wilderness of northern Minnesota, and have been utilized by humans in most areas since the 1800s. The forests' tree species composition is diverse ranging from central hardwoods in the south, to cold-temperate northern hardwoods and conifer forests, including transitional boreal forests in the far north. In summary, the past and current use(s) of Midwest forests are diverse and sometimes competing.

These same forests are also a potential source for feedstock for bioenergy as the U.S. attempts to develop sustainable bioenergy systems that will reduce national dependence on foreign fossil fuel (Perlack et al., 2005). In anticipation of greater demand for woody biomass, forest managers and policy makers are developing harvest guidelines to ensure sustainable forest management practices. Options to increase woody biomass harvest include increased removal of residue (i.e. cull trees, tops of trees etc.) normally left in the forests, increased harvest frequency, and increased harvested area. However, there are extremely few long-term field studies that can be used to guide management and policy decisions. It is unclear how greater biomass utilization of the forest resource will affect the long-term soil carbon storage, nutrient availability, and productivity (i.e. carbon sequestration) of future forests. It is imperative to quantify the effects of harvest regimes on carbon pools with fast to moderate residence times (e.g. vegetation) and especially carbon pools with slow residence times (e.g. mineral soil). Recent studies have shown that forest disturbance is an important driver of ecosystem C balance (Euskirchen et al., 2002; Thornton et al., 2002; Law et al., 2004; Bond-Lamberty et al., 2007b; Amiro et al., 2010; Peckham et al., 2012).

Ecosystem process models allow scientists to simulate effects of different management practices on forest sustainability, growth, and carbon dynamics at scales ranging from stand to region. Unlike empirical growth and yield models, process-based ecosystem models simulate water, nitrogen, and carbon cycles, and their interactions, and they account for soil and detritus carbon dynamics (Peckham and Gower, 2011). Modeling the C balance of a heterogeneous forestscape, such as the Upper Midwest, is challenging because the spatially and temporally explicit disturbance history is not well documented. Hence, most modeling studies covering this region do not account for disturbance history in C balance or net ecosystem production (NEP) (e.g. Lu and Zhuang, 2010; Wang et al., 2011). However, previous modeling studies have shown that management regime is the most important determinant of forest C balance (Euskirchen et al., 2002), for individual forest stands (Peckham and Gower, 2011), and at the regional level (Peckham et al., 2012). Landscape-level effects of management choices on the future forest C balance over the Midwest are poorly understood.

The objective of this study was to use the ecosystem process model Biome-BGC to simulate the carbon balance of the Midwest deciduous and coniferous forests subjected to different harvest scenarios. We used historic (1800s to early 1900s) to near present-day (2004) harvest and management records to simulate initial harvests and estimate forest vegetation carbon (vegC), net primary production (NPP), net biome production (NBP, defined as NEP integrated over space and time (Chapin et al., 2006), and to examine historic patterns and spin the model up to present-day conditions. Then, we simulated 50-year future management scenarios that varied the total harvest area, the clear-cut and selective harvest proportions (0.0–1.0), and three harvest residue retention rates (15, 25, and 35%). Due to the large number of simulations and the temporal and spatial scale, we could not do a complete factorial set of simulations. Instead we selected seven simulations that span the range of conditions and hypothesized responses. Also, the seven scenarios were selected to provide a range of scenarios to elucidate the trade-offs between two competing forest carbon management objectives: carbon storage (i.e. total vegC) versus carbon sequestration (i.e. NBP). To assess potential management effects on forest ecosystem C dynamics, the model output of stand age structure, vegC, NPP and NBP were compared to a base scenario that continued the current harvest regime. We hypothesized that increased biomass removal would increase NBP but decrease C storage in vegetation and that increased removal of harvest residues would decrease NPP. It is important to note that we only consider the fluxes of C in the forest ecosystem explicitly simulated by Biome-BGC. Carbon emission and storage resulting from the use of harvested biomass has important consequences on total carbon sequestration and is the subject of a companion study (Peckham and Gower, accepted).

2. Methods

2.1. Study area

The simulations were run for the forested areas within the boundary of the Mid-continent intensive (MCI) study area of the North American Carbon Program (http://www.nacarbon.org/nacp/mci.html). This area includes the states of Minnesota, Wisconsin, Iowa, Illinois, and portions of North Dakota, South Dakota, Nebraska, Kansas, Missouri, Indiana, and Michigan (Fig. 1). The MCI region encompasses 125 Mha of forest, agriculture, and urban landscapes, of which forests comprise 18% of the region. The dominant forest types are deciduous broad-leaf (hardwoods) and evergreen needle-leaf forests (conifers) in both uplands and lowlands. The largest forest regions occur in the northern Michigan, Wisconsin, and Minnesota, while smaller regions but exist in northern Missouri and southern Illinois. The topography is generally low relief (Potter et al., 2007), with some rolling hills and deep river valleys. Climate ranges from long, cold winters and a short growing season (<120 days) in the northern region to mild winters and long (>180 days) growing season in the southern region. Based on the climate data used to drive the model (1955–2004), air temperatures averaged −2.9 and 28.3 °C in January and July, respectively. Precipitation is primarily rain from May to October and averages 803 mm/yr. Fig. 1 summarizes annual air temperature and precipitation for the region.

2.2. Biome-BGC

We used Biome-BGC, an ecosystem process model that simulates carbon (C), nitrogen (N), and water cycles, and their