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Conclusions and caveats from studies of managed forest carbon budgets

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A B S T R A C T

Forests are a critical component of the global carbon (C) budget, whether in their natural state or actively managed. While deforestation is a primary driver affecting forest C sources and sinks, the role of actively managed forests has gained appreciation and study by scientists and policymakers in recent decades. Implementation of active management regimes typically results in initial C losses, depending on the baseline used for comparison. There is strong evidence to support the long-term C benefits of actively managed forests compared to their unmanaged counterparts, however, when harvested biomass is efficiently used for wood products and to replace fossil fuels. Temporal, spatial, management, and land use factors, as well as the conceptual scope of assessments, all influence conclusions drawn regarding forest C budgets. Individual stand dynamics are sometimes used to assess C implications of management regimes, for example, even though forested landscapes buffer such dynamics and offer a more accurate, long-term picture. Managers must confront tradeoffs among C benefits and other environmental and economic values, but it is important to recognize that forested landscapes, even those with a high proportion of actively managed forest, most often contain substantial areas set aside and protected or managed with low intensity due to logistic, economic, and environmental considerations or certification and best management practice requirements. Emissions associated with management practices, harvesting, biomass transport, and product manufacturing should be accounted for in C budget assessments even though evidence suggests they comprise a small percentage of C sequestered in actively managed stands. Harvesting and other practices can reduce C stored in forest floors and soil but studies worldwide show responses too inconsistent to form the basis of default assumptions. Often overlooked are C benefits resulting from the role of active management in reducing susceptibility to wildfire, pests, and disease and in providing economic incentives that can deter forest conversion to urban development and other land uses that have substantial and permanent impacts on C storage and emissions.

1. Introduction

Forests play a critical role in mitigating greenhouse gas emissions through carbon (C) sequestration and other processes. Factors contributing to forest C budgets include sequestration and other inputs as well as emissions and other outputs. Established forests are estimated to offset about 30 percent of global fossil fuel emissions (Birdsey and Pan, 2015). In the U.S., C stored in forests and forest products are estimated to offset 10–20 percent of emissions, and offsets could be substantially increased by expanding forest area, managing C in existing forests, and using wood for products and biomass energy (McKinley et al., 2011). Managed forest C budgets are unique in that their reach extends beyond the forest itself to the type, use, and fate of harvested biomass that continue to store C or reduce emissions when used to replace fossil fuels.

The scope of forest C budget assessments greatly influences conclusions drawn about effects of forest management regimes and practices on sequestration and emissions. In particular, recommendations for reducing management and harvesting intensity to maximize C benefits and assessments of tradeoffs between C and other ecosystem services sometimes focus on the forest only without considering post-harvest fossil fuel replacement or product C storage (Krug et al., 2012; Butarbutar et al., 2016; Wang et al., 2016; Carpentier et al., 2017; Spies et al., 2017; Triviño et al., 2017; Watson et al., 2018). Although the atmosphere does not distinguish particular sources or sinks of carbon, some assessments set priorities as a means of enhancing other environmental values such as the preservation of intact or "natural" forests over those more actively managed (Watson et al., 2018). The purpose of this summary is to highlight major findings from studies of managed forest C budgets published over the last decade.

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2. Carbon implications of forest management regimes depend on time and space

Due to funding limitations and other factors, short-term field studies form the basis of many C assessments, which can result in misleading conclusions about longer-term consequences. The most common example is C budgets of unmanaged or preserved forests compared to those of actively managed stands; while the former typically store more C, the latter generally have the potential for greater long-term C benefits (Gustavsson et al., 2017). One global forest C model-based analysis found greater C benefits from actively harvested stands compared to preservation over 100 years, during which time C stored in preserved forests reached a maximum (Ni et al., 2016). Such temporal dynamics form the concept of C debt, which refers to the amount of C lost and associated emissions due to a change in land use or management relative to the initial forest condition (Miner et al., 2014; Butarbutar et al., 2016; Bentsen, 2017). The significance of C debt is related to both the size of the initial forest C stock and its payback time, based on the C sequestration rate of the regenerating forest (Bentsen, 2017). Carbon emitted from establishing forest plantations on sites previously occupied by naturally regenerated forest may contribute to C debt (Van Minnen et al., 2008). The baseline of comparison for C debt, such as the age of the counterfactual, as well as the timing of harvests, bioenergy use, and harvest residue decay are critical factors affecting the conclusions drawn (Keith et al., 2014; Kalies et al., 2016; Pingoud et al., 2016). The worst-case scenario for C is likely the conversion of old growth forests to forests where "management" consists of logging only without practices designed to increase productivity and when fossil fuel savings from biomass energy and the substitution of wood products for alternatives is not accounted for (Keith et al., 2014). Because tree growth rate is the primary factor affecting sequestration rate of the regenerating forest, the payback time for biomes contrasting in climate and tree species, such as boreal vs. tropical forests, would be expected to vary accordingly. Carbon debt definitions and assumptions vary widely, limiting the utility of the concept for developing forest policy (Bentsen, 2017).

Spatial considerations are also important in forest C budget assessments. Assessments that focus on individual stands can lead to incomplete or biased results because they fail to consider the full impact of practices across landscapes or regions (Eliasson et al., 2013; Gabrielle et al., 2013). While stand-level aboveground biomass and associated C may take years or decades to return to pre-harvest levels following harvesting (i.e., C debt), managed forest landscapes often contain multiple ownerships, landowner objectives, management regimes, and ages that buffer individual stand C dynamics (Loehle et al., 2009; Creutzburg et al., 2016). One study of European forests, for example, showed that large-scale increases in harvesting would not increase C debt, unlike conclusions from studies carried out on a small scale (e.g., 1 ha) (Nabuurs et al., 2017). It's also important to note that even intensively managed forest landscapes may include 25–35 percent of their area set aside or managed under lower intensity due to certification or best management practice requirements (e.g., streamside management zones), their environmental sensitivity, or because they are technically or economically inappropriate for intensive management regimes (Loehle et al., 2009; Vance et al., 2014; Siry et al., 2015). It should be noted that the beneficial buffering effects of managed forest landscapes does not absolve the responsibility of landowners to manage individual stands in a way that sustains C and other environmental values as much as possible and that is consistent with best management practice and certification protocols.

3. Implications beyond the forest

Active forest management and the use of biomass in place of fossil fuels and alternative products most often have greater long-term C benefits than maintaining or increasing forest stocks alone (Pingoud et al., 2010; Gonzalez-Benecke et al., 2011; Malmsheimer et al., 2011; Krug et al., 2012; Peckham et al., 2012; Poudel et al., 2012; Chen et al., 2014; Miner et al., 2014; Kilpeläinen et al., 2016; Kurz et al., 2016; AiXin et al., 2017; Taeroe et al., 2017). For example, in a study of the U.S. Upper Great Lakes region, investigators found that increasing forest management intensity over 100 years enhanced the forest C sink and that optimizing system management could increase C sequestration and wood production by 20–30 percent (Peckham et al., 2012). An assessment of Canada's forest sector from 1901 to 2010 found its managed forest and harvested wood product C sinks (7510 Tg and 849 Tg, respectively) exceeded Canada's fossil fuel emissions (Chen et al., 2014); it was concluded, however, that future forest C stocks were highly uncertain and most future emission mitigation would likely come from product C storage and fossil fuel emission substitution. Investigators studying Swedish forests concluded that maximum C benefits were derived from a combination of high forest productivity, residue recovery, and efficient use of harvested biomass (Gustavsson et al., 2017). In contrast to more comprehensive forest C assessments, those that do not include post-harvest utilization of biomass for products and energy tend to conclude that the greatest C benefits come from forest preservation, reducing management intensity, and extending harvest rotation lengths (Stoy et al., 2008; Raymer et al., 2011; Creutzburg et al., 2016).

Forests used as sources of biomass that replace fossil fuels have long-term C benefits when they are sustainably managed (Zanchi et al., 2012; Hektor et al., 2016). Fossil fuel conversion efficiencies and alternatives to which forest-based products are compared also influence net C benefits (Butarbutar et al., 2016; Pingoud et al., 2016; AiXin et al., 2017; Taeroe et al., 2017). Although emissions of CO_2 and other greenhouse gases resulting from harvesting and management practices, manufacturing, and transportation should be factored in to forest C budgets, these contributions are relatively small in most cases. An Australian forest greenhouse gas inventory showed that emissions associated with wood production, transport, and harvest comprised only about 3 percent of C stored in an average plantation log; the largest emission contributions in the study were from log transport (England et al., 2013). In a southeastern U.S. loblolly pine plantation, investigators found emissions from management and harvesting activities accounted for only 1.6 percent of gross C stock and that thinning had a positive effect on net C balance by increasing product C storage (Gonzalez-Benecke et al., 2011). Fossil fuels are also required for manufacturing and transport of fertilizer but emissions from these sources were found to comprise less than 5 percent of the additional C sequestered from fertilizer-induced increases in loblolly pine growth (Albaugh et al., 2012). Even long-distance transport may not negate the C benefits of substituting fossil fuels with biomass; forest-derived biomass pellets transported from the southern U.S. for electricity generation in the U.K. were still found to reduce net greenhouse gas emissions by up to 68 percent compared to local fossil fuels (Dwivedi et al., 2014). Investigators found emissions associated with pellet transport were less than 3 percent of the total. In what may be close to a worst-case scenario for transport, pellets exported from British Columbia to The Netherlands showed an "energy penalty" of 33% compared with 21% for domestically used pellets, with marine transportation comprising 35% of energy consumed (Pa et al., 2012). The authors noted that emissions avoided from the use of pellets in Europe were still substantially larger than those from the production and transport of the pellets. Another assessment of pellet transport from British Columbia to The Netherlands showed that whether wood or natural gas was the energy source used for feedstock drying had a much greater impact on emissions than marine transportation (Sikkema et al., 2010).

4. Benefits from intensive practices that increase productivity

Site factors, tree species, and management practices all influence productivity and associated C sequestration of forest stands. While