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Comparing net ecosystem exchange of carbon dioxide between an old-growth and mature forest in the upper Midwest, USA

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Abstract

Old-growth forests are often assumed to exhibit no net carbon assimilation over time periods of several years. This generalization has not been typically supported by the few whole-ecosystem, stand-scale eddy-covariance measurements of carbon dioxide exchange in old-growth forests. An eddy-flux tower installed in a >300-year-old hemlock–hardwood forest near the Sylvania Wilderness, Ottawa National Forest, MI, USA, observed a small annual carbon sink of CO_2 of -72 ± 36 g C m^{-2} year^{-1} in 2002 and -147 ± 42 g C m^{-2} year^{-1} in 2003. This carbon sink was much smaller than carbon sinks of -438 ± 49 g C m^{-2} year^{-1} in 2002 and -490 ± 48 g C m^{-2} year^{-1} in 2003 observed by a nearby flux tower in a 70-year-old mature hardwood forest (Willow Creek, WI). The mature forest had vegetation similar to the old-growth site prior to European settlement. Both sites had slightly larger carbon sinks in 2003, which was a drier and cooler year than 2002. However, the difference in sink strength between the two years was smaller than the uncertainty in the results arising from missing and screened data. Both sites also had significant systematic errors due to non-representative fluxes during certain micrometeorological conditions, which required careful screening. The difference in sink strength between the two sites was driven mainly by greater ER at the old-growth site (965 ± 35 g C m^{-2} year^{-1} in 2002 and 883 ± 69 g C m^{-2} year^{-1} in 2003) compared to the mature site (668 ± 21 g C m^{-2} year^{-1} in 2002 and 703 ± 17 g C m^{-2} year^{-1} in 2003). GEP was lower at the old-growth site (1037 ± 47 g C m^{-2} year^{-1} in 2002 and 1030 ± 41 g C m^{-2} year^{-1} in 2003) compared to the mature site (1106 ± 47 g C m^{-2} year^{-1} in 2002 and 1192 ± 51 g C m^{-2} year^{-1} in 2003), especially in 2003. Observations also suggested that growing season ER had greater interannual variability at the old-growth site. These results imply that old-growth forests in the region may be carbon sinks, though these sinks are smaller than mature forests, mostly likely due to greater ER.

Keywords: Carbon balance; Old-growth forest; Sylvania Wilderness; Eddy covariance; ChEAS

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1. Introduction

Old-growth forests are traditionally viewed to be in equilibrium with respect to net ecosystem exchange (NEE) of carbon (Caspersen and Pacala, 2001; Kira and Shidei, 1967). Forests typically start out as net carbon sources during stand initiation after disturbance and become large carbon sinks as they mature due to rapidly increasing production and slowly increasing respiration (Law et al., 2003). As forests move from stand reinitiation to old growth, carbon sink strength is expected to decline in magnitude and may reach neutrality as growth slows down and decomposition increases.

This decline is hypothesized to be attributable to increased respiration and decreased photosynthesis in an old-growth forest compared to a mature forest. Ecosystem respiration (ER) is expected to increase steadily with stand age due to increased decomposition (i.e., from greater amounts of coarse woody debris (CWD) arising from mortality) and sapwood maintenance respiration. Gross ecosystem production (GEP) typically peaks in mature forests and declines as stands age due to decreased stomatal conductance, decreased hydraulic conductivity from increased tree height, decreased nutrient availability, and increased tree and branch mortality (Gower et al., 1996; Murty et al., 1996).

Because many forest productivity models assume that net primary production (NPP) declines steadily after stem exclusion and approaches zero for old-growth stands, the ability of old-growth forests to act as carbon sinks may actually be underestimated (Carey et al., 2001). Continuous recruitment of various tree species of all ages in a natural old-growth forest could lead to positive net primary productivity (NPP), as opposed to carbon equilibrium expected in monospecific even-aged old stands or carbon uptake decline expected with individual old trees. In addition, the contribution of sapwood respiration to ER may not increase over the course of stand development (Carey et al., 1997; Ryan and Waring, 1992).

The objective of this study was to examine net ecosystem carbon exchange in an old-growth eastern hemlock (*Tsuga canadensis*)–northern hardwood forest located in the Ottawa National Forest, Michigan, USA, and compare it to a mature northern hardwood forest located in the nearby Chequamegon-Nicolet National Forest, Wisconsin, USA. The old-growth stand is representative of the forest type found in the mature forest stand and much of northern Michigan and Wisconsin prior to European settlement in North America (Frelich, 1995; Manies and Mladenoff, 2000; Schulte et al., 2002). Prior to European settlement, hemlock–hardwood forests occupied almost half of the forested land area in Minnesota, Wisconsin, and Michigan (Frelich, 1995; Woods, 2000b). Harvesting from the late 1800s through mid 1900s resulted in the conversion of these forests to secondary forests of aspen (*Populus tremuloides*), yellow birch (*Betula alleghaniensis*), and sugar maple (*Acer saccharum*) that characterize the region today.

Carbon exchange seen at the old-growth site may be representative of carbon exchange at the mature site had it not been logged in the late 19th and early 20th centuries. Although only ∼1% of primary forest and ∼5% of old-growth forest that existed prior to European settlement remain in upper Great Lakes states (Minnesota, Wisconsin, Michigan), the decline of logging in the area during the 20th century has led to a resurgence of older forest that continues to expand in space and age (Caspersen et al., 2000; Frelich, 1995; Houghton et al., 1999). Thus, the undisturbed old-growth forest may also represent the potential for future carbon storage by late successional stands in the region (Woods, 2000b).

We measured the fluxes of carbon dioxide between the forest and atmosphere at the old-growth and mature forest stand over two years using the eddy covariance technique. Since the early 1990s, over 200 eddy covariance flux towers have been built in numerous ecosystems across the world. Few, however, are located in old-growth forests, and only one other is in an old-growth hemlock–northern hardwood forest (Hadley and Schedlbauer, 2002).

Most flux measurements from old-growth forests have shown small to moderate carbon sinks, contrary to the previously assumed carbon balance (e.g., Griffis et al., 2003; Hollinger et al., 1994; Knohl et al., 2003; Law et al., 2001). Based on these results and theories of forest succession, we tested the following hypotheses to better quantify stand age effects in models of forest carbon exchange and improve regional-scale estimates of NEE: