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Influence of stand age on the magnitude and seasonality of carbon fluxes in Canadian forests

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ABSTRACT

Proper management and accounting of forest carbon requires good knowledge of how disturbances and climate affect the carbon dynamics of different stand types. We have investigated such relationships by measuring, over a 5-year period (2003–2007), the net ecosystem productivity (NEP), gross ecosystem productivity (GEP) and ecosystem respiration (ER) of 26 forest sites in Canada using the eddy covariance technique. The study included black spruce, jack pine, Douglas-fir, aspen, boreal mixedwood and white pine forest ecosystems ranging in age from 1- to 153-years. The dataset included six chronosequences (one afforested plantation, three harvested and two burned).

Following planting, the afforested white pine stands quickly became carbon sinks and offset initial carbon losses after 4 years. Depending on forest type, the other forest stands were carbon sources for 10–18 years following a disturbance, offset initial carbon losses after 19–47 years, and showed net total gains ranging from 38 to 86 Mg C ha^{-1} at 80 years. Peak NEP ranged from 0.9 to 2.9 Mg C ha^{-1} year^{-1} at ages of 35–55 years except for the afforested white pine where it was 6.9 Mg C ha^{-1} year^{-1} at 15–20 years. Stepwise regression and Pearson correlation analyses indicated that the GEP and ER of mature stands (>70 years old) were driven mainly by climate, while fluxes of young stands (<19 years old) were driven by both leaf area index and climate.

Although stand age of the afforested white pine plantations did not affect the GEP growing season lengths, the growing season length of the other forests increased with age until about 20 years and this coincided with the switch from carbon source to sink. With the exception of the afforested white pine, peak GEP/ER ratios of the youngest sites occurred later in the growing season compared to older sites. The strong influence of stand age on the seasonal dynamics of GEP fluxes needs to be considered to avoid confounding the impacts of climate change with those of disturbance. These age-related seasonality effects are continental in scope and should be important in interpreting the time series of atmospheric CO_2 concentration measurements at regional and global scales.

1. Introduction

Anthropogenic greenhouse gas emissions have been increasing since the beginning of the industrial age and the resulting increase in atmospheric CO_2 concentrations are now widely believed to be changing the planet's climate. The Earth's terrestrial and ocean ecosystems have been sequestering a large portion of these CO_2 emissions (Canadell et al., 2007a; Sarmiento and Gruber, 2002). By

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constraining the increases in atmospheric CO_2 concentrations with the observations of a weak north-south concentration gradient, Tans et al. (1990) concluded that there was a northern extratropical net carbon sink of $\sim$2 Pg C year^{-1}. Later studies suggest that the efficiency of the terrestrial carbon sink has been decreasing due to changes in the Earth's climate (Canadell et al., 2007b).

The spatial distribution of the terrestrial sink has been the subject of significant debate over recent years (Canadell and Raupach, 2008; Ciais et al., 2010; Le Quéré et al., 2007, 2009; Rödenbeck et al., 2003; Stephens et al., 2007) and the current and future role of northern forests in the terrestrial sink is still an active research question (Ciais et al., 2010). Using forest inventory data and long-term ecosystem carbon studies, Pan et al. (2011) concluded that boreal forests accounted for 21% (0.50 ± 0.08 Pg C year^{-1}) of the overall global carbon sink from established forests (2.41 ± 0.42 Pg C year^{-1}) between 1990 and 2007. Overall, the boreal carbon sink over this time period was found to be the sum of a reduction in Canadian forest carbon stocks due to disturbance that was offset by an increasing biomass sink in other boreal regions. Clearly ecological disturbance and forest management are having a major influence on the contribution of boreal forests to global carbon sequestration (Kurz et al., 2008a,b,c). It is also well recognized that northern forests contain large amounts of carbon (C) in both biomass and soils (Kurz and Apps, 1995, 1999; Tarnocai et al., 2009) and these reservoirs may be even more vulnerable to future changes in climate. Since Canada contains 10% of the world's forests, proper accounting and management of these large C stocks requires a solid scientific understanding of how disturbance and climate variability impact the emission and sequestration of carbon by these forests and how we might separate the effects of these two factors on regional C budgets.

Eddy covariance (EC) flux towers are one of the main tools used to monitor, understand and quantify CO_2 exchange between forests and the atmosphere (Baldocchi, 2008) because they provide near-continuous half-hourly time series of carbon, water, and energy exchange at the ecosystem scale. Regional networks of flux towers have been developed over the last two decades in different parts of the world. In Canada, the Fluxnet-Canada Research Network (2002–2007) and the follow-on Canadian Carbon Program (2007–2011) Research Network have had a leadership role in the study of the C cycle of Canada's forests and peatlands, as affected by disturbances and climate variability (Margolis et al., 2006). Amiro et al. (2010) presented an overview of how fire, harvest, windthrow, insects, and silvicultural treatments influence C exchange in North American forest ecosystems.

In this study, we focus on a continental-scale transect of forest flux towers across Canada to address how disturbance types, stand age and climate variability may impact the C exchange of northern and coastal forests. We use six different chronosequences to determine: (1) the age at which forests reach the C compensation point when they switch from a C source to a C sink, and the offset point when carbon sequestration equals carbon loss following disturbance or afforestation, (2) the influence of stand age on the seasonal dynamics of the fluxes, and (3) the extent to which climate versus stand structure are the main drivers of interannual variability following disturbance.

2. Materials and methods

2.1. Fluxnet-Canada and the Canadian Carbon Program

The Fluxnet-Canada Research Network (FCRN) was established in 2002 and consisted of a series of eddy-covariance flux towers installed in mature and disturbed forests as well as peatlands across the country. Continuous year-round measurements of carbon, water and energy exchanges between the land surface and the atmosphere were made using standard measurement protocols. The FCRN was the next logical step in the study of the interactions between Canadian forests and the atmosphere, following the Boreal Ecosystem-Atmosphere Study (BOREAS) which was carried out between 1994 and 1996 (Sellers et al., 1997). The FCRN was established using the main flux tower sites from BOREAS in Saskatchewan (which had become the Boreal Ecosystems Research and Monitoring Sites (BERMS) program) and Manitoba, as well as a few other existing sites, to which new sites were added so as to produce an east-west transect across Canada. Several chronosequences were included in the transect, facilitating the study of disturbance effects and stand age on the carbon cycle. The FCRN was succeeded in 2007 by the Canadian Carbon Program (CCP).

2.2. Study sites

The description and characteristics of the 26 forests sites, ranging in age from 1- to 153-years old, used in this study are given in Tables 1 and 2. Sixteen of these sites were supported by the FCRN/CCP (Coursolle et al., 2006; Margolis et al., 2006), four (WP39-ON, WP74-ON, WP89-ON, WP02-ON) were FCRN/CCP associated sites (Peichl and Arain, 2006), and six (BS1850-MB, BS30-MB, BS64-MB, BS81-MB, BS89-MB, BS98-MB) were part of the Ameriflux network (Goulden et al., 2006). The study, which included two burn chronosequences (BBS-MB, BJP-SK), three harvested chronosequences (HBS-QC, HDF-BC, HJP-SK) and an afforested plantation chronosequence (PWP-ON), was comprised of 10 black spruce (BS), seven jack pine (JP), three Douglas-fir (DF) and four white pine stands (WP), and one each of aspen (ASP) and a mixedwood stand (MW). Sites within a chronosequence were similar in climate, soil characteristics, disturbance history and topography (Goulden et al., 2006). Measurements were available for periods ranging from 2.5 to 5 years, with 50% of the sites having a full 5 year measurement record.

2.3. Measurements and data analysis

Meteorological and flux data for 105 site-years were obtained from either the FCRN Data Information System (http://fluxnet.ccrp.ec.gc.ca) or directly from Principal Investigators (PIs). Half-hourly C fluxes were measured using the EC technique (Aubinet et al., 2000; Morgenstern et al., 2004) and, with the exception of the BBS-MB chronosequence, were processed following FCRN protocols (Coursolle et al., 2006; Zha et al., 2009). Net ecosystem exchange (NEE) was computed as $NEE = F_c + S_c$, where F_c is the measured C flux and S_c is the rate of change in CO_2 storage between the measurement height and the ground. Depending on the site, F_c was measured using either a closed- or open-path infrared gas analyzer (IRGA). S_c was computed using a multi-level CO_2 concentration measurement system when available, or as a one-level storage term calculated using the CO_2 concentration measured by the EC IRGA. Initial quality control of all half-hourly data was carried out by each site's PI. With the exception of the BBS-MB chronosequenc, cross-validation of meteorological and eddy-covariance equipment was carried out as part of FCRN quality assurance activities using a standard set of roving flux and meteorological calibration equipment.

Night-time measurements were eliminated when atmospheric conditions were calm. These conditions were identified when the measured friction velocity (u_*, m s^{-1}) was lower than the site-specific threshold (u_{*th}). The threshold was estimated for each site by plotting nighttime NEE against u_* and selecting the minimum u_* value (aggregated in 0.05 m s^{-1} bins) when NEE was no longer dependent on u_* (Humphreys et al., 2006). Moreover, NEE outliers (30-min fluxes farther than four standard deviations away from