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Trends of carbon fluxes and climate over a mixed temperate–boreal transition forest in southern Ontario, Canada

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ABSTRACT

The exchanges of carbon dioxide (CO_2), water vapor, and energy were measured nearly continuously since 1996 over a mixed mature transition forest at the Borden Forest Research Station, in southern Ontario, Canada. Borden Forest, one of the longest running flux towers in North America, is located in the temperate–boreal ecotone. This transitional region, which includes species close to the limits of their environmental range, may be particularly susceptible to changes in forest composition as a result of climate change. Here we analyze net CO_2 exchange, measured using the eddy covariance method, and concurrent meteorological variables. The forest was found to be a low-to-moderate CO_2 sink, with uptake of $177 \pm 28\,gC\,m^{-2}\,yr^{-1}$ (mean ± standard error). In two of the years, however, the forest was a weak CO_2 source (i.e., 1996: $-36\,gC\,m^{-2}\,yr^{-1}$ and 2001: $-35\,gC\,m^{-2}\,yr^{-1}$), demonstrating that the forest can switch between source and sink. Over the 17 years of measurement, annual net ecosystem productivity (NEP) increased by $15.7\,gC\,m^{-2}\,yr^{-1}\,yr^{-1}$, due to a decline in ecosystem respiration of $4.2\,gC\,m^{-2}\,yr^{-1}\,yr^{-1}$ and an increase in gross ecosystem productivity of $11.6\,gC\,m^{-2}\,yr^{-1}\,yr^{-1}$. There were notable long-term indications of climatic warming: annual air temperature rose by $0.09\,^\circ C\,yr^{-1}$, while soil temperature increased by $0.08\,^\circ C\,yr^{-1}$. Photosynthetically active radiation and soil temperature were found to be the dominant environmental drivers of interannual variations and long-term trends in NEP; on seasonal or monthly time-scales, air temperature and precipitation also influenced CO_2 uptake. NEP is positively correlated with the length of the net carbon uptake period, which varied from 111 to 164 days. The large interannual variations in CO_2 flux in this dataset demonstrate the need for long time series of CO_2, water vapor, and energy fluxes, together with meteorological measurements; such measurements show long-term trends, which can be used to understand and predict future changes in forest-atmosphere exchanges in response to anticipated changes in climate.

1. Introduction

Forests play a crucial role in the global carbon (C) cycle through the sequestration of large amounts of C from the atmosphere (Beer et al., 2010). Pan et al. (2011) estimated that global forest stocks of 861 ± 66 PgC (42% in live biomass, 44% in the upper 1 m of soil, 8% in deadwood, and 5% in litter) are increasing at 2.4 ± 0.4 PgC yr^{-1}. Yet, there is a need for better accounting of regional budgets and projections of how climate change may affect C stocks and their fluxes. This requires thorough quantification and description of net ecosystem productivity (NEP) and its component parts – gross ecosystem productivity (GEP) and ecosystem respiration (R_E) – and the biophysical and climatic influences on them. Much work has been done on these problems in recent decades. Eddy covariance measurements indicate that NEP in forests ranges from 750 to $-150\,gC\,m^2\,yr^{-1}$ (Yi et al., 2010), with mature forests generally close to being CO_2 neutral (Coursolle et al., 2012). However, forests can quickly change from an annual C sink to a C source, as uptake is affected by such factors as species composition, age structure, environmental conditions, and exposure to disturbance (Baldocchi, 2008; Luyssaert et al., 2008). The interannual variability of NEP has been attributed to a number of variables, including: spring rainfall (Allard et al., 2008), land surface phenology (Richardson et al., 2009), seasonal air temperature (Barr et al., 2007; Hollinger et al., 2004), summer drought (Granier et al., 2007), forest disturbance (Baldocchi, 2008), snow conditions (Nobrega and Grogan, 2007), and carbon uptake phenology, particularly in autumn (Wu

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et al., 2013). While considerable progress has been made, uncertainties still remain regarding the spatial distribution of C sinks, the interannual variability of NEP, the complex interrelationships of GEP and R_E with environmental and ecosystem controls, and, ultimately, the vulnerability of C pools (Baldocchi, 2008; Luyssaert et al., 2008; Pan et al., 2011). There continues to be a need for additional measurements to better assess the interannual variability in fluxes and to understand the ecophysiological processes, as well as the climatic and biophysical controls on these processes. Long-term eddy covariance measurements are particularly well-suited for this purpose (Baldocchi, 2008; Barr et al., 2007; Zha et al., 2013).

The Borden Forest Research Station offers many possibilities for such research. Borden Forest is in the Great Lakes–St. Lawrence forest ecotone, which extends across eastern North America between 44 and 47°N. This forest ecotone is a transition zone containing both southern temperate forest species (e.g., red maple (*Acer rubrum*), red oak (*Quercus rubra*), eastern white pine (*Pinus strobus*)) and northern boreal species (e.g., black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*)), many of which are at or near the limits of their temperature and moisture ranges (Goldblum and Rigg, 2005, 2010; Leithead et al., 2010). Consequently, this transitional region is identified as being particularly susceptible to climate change, and may experience substantial changes in forest composition, with northward migration of temperate species into boreal forest, as a result of small variations in climate (Fisichelli et al., 2013; Frelich and Reich, 2010; Leithead et al., 2010). Long-term datasets of carbon budgets and their drivers are required to better understand which environmental and climatic factors affect forest composition and what impacts these changes in species composition will have on carbon budgets, especially in light of a changing global climate.

Borden Forest Research Station has been the site of eddy covariance measurements of carbon dioxide, water, and energy fluxes for almost two decades. This makes the Borden site an important contributor among the group of long-term flux tower sites located in predominantly deciduous forests; other such sites include Harvard Forest, USA (Goulden et al., 1996), Takayama Forest, Japan (Saigusa et al., 2002), the Southern Old Aspen site, Canada (Black et al., 2000) and the Walker Branch forest, USA (Greco and Baldocchi, 1996). Previous investigations of forest–atmosphere exchange at Borden Forest have been reported for the periods 1995–1998 (Lee et al., 1999) and 1996–2003 (Teklemariam et al., 2009). This paper extends the analysis from 1996 to 2013. The availability of such an extensive near-continuous dataset makes it possible to examine longer term trends and to draw more robust conclusions about the main environmental controls on forest productivity. The aims of this paper are: (1) to investigate the changing patterns of both CO_2 exchange and meteorological variables across monthly, seasonal, annual, and multi-year time scales and (2) to identify the environmental and climatic drivers of interannual CO_2 flux variability at this mixed temperate forest.

2. Materials and methods

2.1. Borden Forest Research Station

The Borden Forest Research Station, hereafter referred to as Borden Forest, is located in a mixed deciduous and coniferous boreal–temperate transition forest near the southern tip of Georgian Bay in southern Ontario (44°19′N, 79°56′W) in the Great Lakes/St. Lawrence forest region (Fig. 1). According to tree surveys conducted in 1995 (Lee et al., 1999) and 2006 (Teklemariam et al., 2009), red maple (*A. rubrum*) accounts for approximately 50% of the stems in the forest; Eastern white pine (*P. strobus*), large-tooth and trembling aspens (*Populus grandidentata* and *Populus tremuloides*), white and red ash (*Fraxinus americana* and *Fraxinus pennsylvanica*), and American beech (*Fagus grandifolia*) are among the other main species. The forest is a natural regrowth from farmland abandoned in the early 20th century. Mean canopy height is 22 m and the leaf area index has been measured to be between 4.1 and 5.1 m^2 m^{-2} in mid growing season (Neumann et al., 1989; Staebler et al., 2000; Teklemariam et al., 2009). Over the last 15 years, mean annual temperature at the site was 7.4 °C and mean annual total precipitation was 784 mm.

Fig. 1. Location of the Borden Forest flux tower site, within the deciduous-boreal ecotone. Source: Goldblum and Rigg (2010).

The flux tower is located near the northern edge of a tract of forest approximately 5 km wide, surrounded by agricultural lands. The fetch of largely uninterrupted forest extends to distances of 1.5–4 km in southeastern and southwestern quadrants, and to 1000 m in the northeastern direction; however, in the northwest quadrant, there are extensive grass- and crop-lands at distances as small as ∼400 m. The topography within a 4 km radius of the tower is relatively flat. On length-scales on the order of a few hundred meters, the terrain slopes by 1–2 m (downslope toward the northeast). On shorter length-scales, however, larger variations in elevation do occur, including a river valley of 20 m depth and 40 m width, approximately 1 km south of the tower and a small stream valley of 5 m depth and a few 10s of m width, approximately 100 m south of the tower.

2.2. Instrumentation

The main measurement platform is a tower instrumented for eddy covariance and profile measurements (44 m tall from 1995 to 2003; the replacement tower constructed at the same location in 2004 is 42 m tall). Details on instrumentation can be found in Appendix A.

Measurements of turbulent fluctuations of wind velocity, temperature, water vapor, and CO_2 – used in computing ecosystem fluxes – are made at a height of 33 m using a sonic anemometer (Kaijo Denki prior to 2001, CSAT from 2001 to 2003, and ATI K-type since 2004) coupled with a closed-path infrared gas analyzer (IRGA, LI-COR Li-6262). The IRGA is located in a temperature-controlled hut at the base of the tower; air is drawn from an inlet ∼0.5 m from the anemometer to the IRGA at a rate of 20 L/min, sufficient to maintain turbulent flow. Both the IRGA and the anemometer are operated at 10 Hz.

Meteorological measurements that have been made since 1995 include: temperature and relative humidity at two heights (33 and 41 m); temperature at 12 heights (from 1.5 to 44 m); incoming photosynthetically active radiation (PAR) and shortwave radiation (both at 44 m until 2003, then at 41 m); net global radiation (at 33 m); wind speed and direction (at 44 m); and barometric pressure (at 2 m). Additional meteorological instruments were added more recently, including: 4-component incoming & outgoing radiation (33 m), downwelling PAR transmitted through the canopy to a height of 1.5 m, and reflected PAR (see Appendix A for dates