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Carbon, water and energy exchange dynamics of a young pine plantation forest during the initial fourteen years of growth

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ABSTRACT

This study presents the energy, water, and carbon (C) flux dynamics of a young afforested temperate white pine (*Pinus strobus* L.) forest in southern Ontario, Canada during the initial fourteen years (2003–2016) of establishment. Energy fluxes, namely, net radiation (Rn), latent heat (LE), and sensible heat (H) flux increased over time, due to canopy development. Annual values of ground heat flux (G) peaked in 2007 and then gradually declined in response to canopy closure. The forest became a consistent C-sink only 5 years after establishment owing in part to low respiratory fluxes from the former agricultural, sandy soils with low residual soil organic matter. Mean annual values of gross ecosystem productivity (GEP), ecosystem respiration (RE), and net ecosystem productivity (NEP) ranged from 494 to 1913, 515 to 1774 and −126 to 216 $g\,C\,m^{-2}\,year^{-1}$ respectively, over the study period. Annual evapotranspiration (ET) values ranged from 328 to 429 $mm\,year^{-1}$ over the same period. Water use efficiency (WUE) increased with stand age with a mean WUE value of 3.92 $g\,C\,kg^{-1}\,H_2O$ from 2008 to 2016. Multivariable linear regression analysis conducted using observed data suggested that the overall, C and water dynamics of the stand were primarily driven by radiation and temperature, both of which explained 77%, 48%, 28%, and 76% of the variability in GEP, RE, NEP, and ET, respectively. However, late summer droughts, which were prevalent in the region, reduced NEP. The reduction in NEP was enhanced when summer drought events were accompanied by increased heat such as those in 2005, 2012 and 2016. This study contributes to our understanding of the energy, water and C dynamics of afforested temperate conifer plantations and how these forests may respond to changing climate conditions during the crucial initial stage of their life cycle. Our findings also demonstrate the potential of pine plantation stands to sequester atmospheric CO_2 in eastern North America.

1. Introduction

Forest ecosystems cover about 30% of Earth's land surface (FAO, 2015) and play an important role in the global carbon (C) cycle (Lorenz and Lal, 2010; Houghton, 2007; Bonan, 2008). Atmospheric carbon dioxide (CO_2) concentration can be significantly reduced through C sequestration and storage in forest ecosystems, in particular, through increased area of planted forests (Jandl et al., 2007; Pan et al., 2011, 2013). The practice of afforestation, the establishment of new forests, consists of the planting of a single, pre-successional canopy species on formerly unforested terrain. From 1990 to 2015, the proportion of total global forested area covered by planted forests through afforestation increased from 167.5 to 277.9 million hectares (4.06 to 6.95%) (Payn et al., 2015). The majority of these new forest plantations (56%) were established in the temperate regions, including Canada, where land area covered by plantation forests was 15.7 million ha by 2015 (Payn et al., 2015). These plantation forests are a major sink of C with an estimated mean net C uptake of about 64 $t\,C\,ha^{-1}$ (Bracho et al., 2012; Laganière et al., 2010; Li et al., 2012; Niu and Duiker, 2006; Winjum and Schroeder, 1997). Planted forests are also a major source of timber

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because of their higher productivity rate per unit area than that of natural forests (Buongiorno and Zhu, 2014). A study of the global economic value of plantation forests suggests that as much as 46.3% of commercial wood is provided by planted forests, while occupying only 6.95% of total global forested area (Payn et al., 2015). Wood products may play an important role in the long-term storage of C and to offset fossil fuel CO_2 emissions (McKinley et al., 2011). Plantation forest soils have been shown to have lower nutritional content and lower litter fall, thereby reducing the diversity and size of the microbial community in the soil allowing for faster turnover of soil organic carbon (Schleuβ et al., 2014; Liu et al., 2016; Chen et al., 2016).

Forests undergo many structural and physiological changes over their life cycle which affect their C assimilation and evapotranspiration capacities (Clark et al., 2004; Ryan et al., 2004; Kaipainen et al., 2004; Coursolle et al., 2012). These changes have been shown to be more rapid and substantial during the early stages of forest growth. For example, the age of transition from a C source to sink is an important stage of growth for young planted forests. The onset of this stage has been found to be quite variable even among the same species and depends on regional climate, soil characteristics, site management and disturbance history (Laganière et al., 2010; Li et al., 2012). Such a timeframe may require several years or even a few decades (Amiro et al., 2010; Bracho et al., 2012; Thornton et al., 2002; Coursolle et al. 2012). Young forests may respond to seasonal and inter-annual climate variability and extreme weather events very differently compared to well established, mature forests. While the C, water and energy balance of different age forest ecosystems has been widely evaluated in the literature (Amiro, 2001; Amiro et al., 2006; Baldocchi and Vogel, 1996; Chen et al., 2004; Foken, 2008; McCaughey et al., 1997; Williams et al., 2014; Wilson et al., 2002), to our knowledge the long-term trends of these fluxes in newly established planted forests are sparse in the literature. Furthermore, the growth trajectory and C uptake of afforested stands is poorly understood, in particular over lands that underwent non-forestry land-use such as former agricultural fields (Bjarnadottir et al., 2009, Peichl et al., 2010c; Whitehead, 2011). To our knowledge, only a handful of flux studies have been published for young plantation stands characterizing C and water flux dynamics for the entire first decade following stand development (Bracho et al., 2012; Bjarnadottir et al., 2009; Hyvönen et al., 2007; Krishnan et al., 2009; Peichl et al., 2010a,b).

This study provides insight into the early stage of the life cycle of an afforested white pine forest that was established on an abandoned agricultural land in Southern Ontario, Canada by analyzing eddy covariance flux observations over the initial 14 years of growth (2003–2016). The main objectives are (i) to assess changes in forest growth and stand characteristics, (ii) to examine C, water and energy flux dynamics and (iii) to determine major controls on C, water and energy exchanges.

2. Methodology

2.1. Study site

This study was conducted at the youngest forest (2002 plantation) of the Turkey Point Flux Station (TPFS) (42° 39′ 41.93″N, 80° 33′ 35.60″W), which is part of the Ameriflux and global Fluxnet networks (Arain and Restrepo-Coupe, 2005). The site has also been a part of the Fluxnet-Canada Research Network (Fluxnet-Canada, 2003). It is known as CA-TP1 within the global Fluxnet and TP02 or PWP-ON in some studies in literature (Coursolle et al., 2012; Peichl et al., 2010a–c). It is located approximately 2 km southwest of the town of Walsingham, near Long Point Provincial Park, on the northern shore of Lake Erie in southern Ontario, Canada. The landscape of the region is largely agricultural, scattered with monoculture conifer plantation and mixed deciduous (Carolinian species) forests.

The forest (white pine; *Pinus strobus* L.) was planted on 250 m × 250 m area (6.25 ha) of former agricultural land which was abandoned approximately 10 years prior to plantation. The site is surrounded by deciduous forest from southeast to southwest (~700 m), which is the prevailing wind direction. The terrain at the site is relatively flat with the exception of approximately 2 m of high ground in the northeastern area of the forest, where the flux tower is installed. The site is a monoculture white pine stand with small patches of bryophytes to almost no ground vegetation. The soil is classified as Brunisolic Gray Brown Luvisol according to the Canadian System of Soil Classification (Presant and Acton, 1984). The soil is composed of approximately 98% sand, 1% silt, and < 1% clay, with mean values of soil nitrogen (N; 0.06%), soil organic carbon (C; 0.56%) and C:N ratio (11.4) in the upper 10 cm mineral soil layer. The soil is well-drained with a low to moderate moisture retention capacity. Further site characteristics are given in Table 1.

Table 1
Site characteristics.

Tree planting year	2002–2003; (2014)
Site coordinates	42.39′,39.37″ N; 80.33′,34.27″ W
Elevation (m)	265
Tree spacing (m × m)[a]	2 × 2.5
Water table depth (m)	2–3.5
Soil classification[b]	Brunisolic Gray Brown Luvisol
Soil texture[b]	98% sand, 1% silt, < 1% clay
LFH depth (cm)	0; (0.6 ± 0.7 in 2014)
Soil $pH_{(CaCl)}$ (0–15 cm)	7.4 ± 0.4; (7.5 ± 0.6 in 2014)
Bulk density (0–15 cm) ($g\,cm^{-3}$)	1.49
Mineral soil C:N ratio (0–15 cm)	11.4; (7.9 in 2014)
Soil N (0–15 cm) ($g\,m^{-2}$) or (%)	86 $g\,m^{-2}$ or 0.06%
Soil TOC (0–55 cm) ($g\,m^{-2}$) or (%)[b]	3724 $g\,m^{-2}$ or 0.56%
Mineral soil available P (ppm)[c]	169 ± 82 (150 in 2014)
Mineral soil Mg (ppm)[c]	44 ± 5 (47.5 in 2014)
Mineral soil K (ppm)[c]	48 ± 18 (17.2 in 2014)
Mineral soil Ca (ppm)[c]	1779 ± 753 (1492 in 2014)

2014 values are in parentheses.
[a] Peichl and Arain (2006).
[b] Peichl et al. (2010b), measured in 2007.
[c] Khomik et al. (2010) measured in 2004 for top 20 cm soil layer.

The climate of the region is continental with warm summers and very cold winters. The 30-year normals (1981–2010 period) for the area show a mean annual air temperature (T_a) of 8.0 °C and total annual precipitation (Pa) of 1036 mm with 135 mm of the total P falling as snow. During the main growing season, from April to October, the normal P is 632 mm and falls as rain (Environment Canada, Norms at Delhi, ON).

2.2. Flux and micrometeorological measurements and gap filling

The eddy covariance (EC) technique was used to measure half-hourly fluxes of sensible heat (H), latent heat (LE) and CO_2 (Fc) at 20 Hz. From January 2003 to April 2008, fluxes were measured using an open path EC (OPEC) system consisting of an infrared gas analyzer (IRGA) (model LI-7500, LI-COR Inc.), a sonic anemometer (model CSAT-3, Campbell Scientific Inc. (CSI), an air temperature/relative humidity sensor (model HMP45C, CSI), and a data logger (model CR5000, CSI) (Peichl et al., 2010a). This roving OPEC was circulated among three forest sites, including TP02, at biweekly (2003–2004) and monthly (2005–2008) intervals. This resulted in measurements of about 4 months of flux data per year from 2003 to 2008 as reported in Peichl et al. (2010a). Since May 2008, continuous flux measurements were made at this site using a closed path EC (CPEC) system consisting of an IRGA (model LI-7000, LI-COR Inc.) and sonic anemometer (model CSAT3, CSI). The IRGA was placed in a climate control box with a short (4 m) heated sampling tube and was calibrated biweekly or monthly. Flux measurements were made at about 2 m height above the canopy during the first few years after tree planting. The height of EC sensors was gradually increased with tree growth to maintain approximately