

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 (R_n), 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 $216 \text{ g C m}^{-2} \text{ year}^{-1}$ 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 $3.92 \text{ g C kg}^{-1} \text{ H}_2\text{O}$ 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 CO₂ 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 (CO₂) 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 CO₂ 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 (Schleuß 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

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 _(CaCl2) (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.

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.

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 CO₂ (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

Table 2
Stand biometric values (annual mean \pm within-stand standard error, n/a = not available).

Values	2003	2004	2005	2006	2007	2008	2009
Mean Base Diameter (cm) ^a	n/a	2.54 \pm 0.053	4.73 \pm 0.079	6.46 \pm 0.094	7.56 \pm 0.105	9.17 \pm 0.127	10.92 \pm 0.156
Mean DBH (cm) ^a	n/a	n/a	n/a	n/a	n/a	5.34 \pm 0.108	7.00 \pm 0.134
Mean Tree Height (m) ^{a,d}	n/a	0.95 \pm 0.020	1.37 \pm 0.026	2.01 \pm 0.031	2.83 \pm 0.044	3.57 \pm 0.057	3.81 \pm 0.037
Mean Tree Basal Area (m ²) using base diameter	n/a	0.001 \pm 2.15 $\times 10^{-5}$	0.002 \pm 5.73 $\times 10^{-5}$	0.003 \pm 9.22 $\times 10^{-5}$	0.005 \pm 1.22 $\times 10^{-4}$	0.007 \pm 1.84 $\times 10^{-4}$	0.010 \pm 3.84 $\times 10^{-4}$
Mean Tree Basal Area (m ²) using DBH	n/a	n/a	n/a	n/a	n/a	0.002 \pm 9.04 $\times 10^{-5}$	0.004 \pm 1.65 $\times 10^{-4}$
Tree Density (trees ha ⁻¹)	n/a	1683 \pm 147 ^b	1683 \pm 147	1683 \pm 147	1683 \pm 189 ^c	1683 \pm 189	1683 \pm 189
Leaf area index (m ² m ⁻²)	2.64	2.64	2.91	3.65	3.43	4.4	5.08
Stand Basal Area (m ² ha ⁻¹) using base diameter	n/a	0.93	3.12	5.72	7.81	11.43	13.56
Stand Basal Area (m ² ha ⁻¹) using DBH	n/a	n/a	n/a	n/a	n/a	4.04	5.71
Stand Stem Volume (m ³ ha ⁻¹) using base diameter	n/a	0.45 \pm 0.22 ^b	2.14	5.74	11.05	20.40	25.83
Stand Stem Volume (m ³ ha ⁻¹) using DBH	n/a	n/a	n/a	n/a	n/a	7.21	10.88
Root Biomass (kg tree ⁻¹) ^e	n/a	n/a	n/a	n/a	n/a	0.33 \pm 1.16 $\times 10^{-6}$	0.79 \pm 2.32 $\times 10^{-6}$
Values	2010	2011	2012	2013	2014	2015	2016
Mean Base Diameter (cm) ^a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Mean DBH (cm) ^a	8.33 \pm 0.150	10.45 \pm 0.154	11.63 \pm 0.174	n/a	13.90 \pm 0.224	14.97 \pm 0.242	15.74 \pm 0.245
Mean Tree Height (m) ^{a,d}	n/a	5.07 \pm 0.126	5.79 \pm 0.168	n/a	n/a	6.50 \pm 0.204	6.85 \pm 0.033
Mean Tree Basal Area (m ²) using base diameter	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Mean Tree Basal Area (m ²) using DBH	0.006 \pm 2.36 $\times 10^{-4}$	0.009 \pm 2.57 $\times 10^{-4}$	0.011 \pm 3.20 $\times 10^{-4}$	n/a	0.016 \pm 5.29 $\times 10^{-4}$	0.017 \pm 6.30 $\times 10^{-4}$	0.020 \pm 6.30 $\times 10^{-4}$
Tree Density (trees ha ⁻¹)	1683 \pm 189	1683 \pm 189	1567 \pm 29 ^d	1567 \pm 29	1567 \pm 29	1567 \pm 29	1567 \pm 29
Leaf area index (m ² m ⁻²)	5.7	6.4	n/a	6.69	n/a	8.1	8.74
Stand Basal Area (m ² ha ⁻¹) using base diameter	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Stand Basal Area (m ² ha ⁻¹) using DBH	8.14	14.78	16.97	n/a	23.64	27.12	31.80
Stand Stem Volume (m ³ ha ⁻¹) using base diameter	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Stand Stem Volume (m ³ ha ⁻¹) using DBH	n/a	37.48	49.13	n/a	n/a	88.61	108.88
Root Biomass (kg tree ⁻¹) ^e	1.38 \pm 3.34 $\times 10^{-6}$	2.87 \pm 3.63 $\times 10^{-6}$	4.05 \pm 5.38 $\times 10^{-6}$	n/a	7.19 \pm 1.21 $\times 10^{-5}$	9.12 \pm 1.56 $\times 10^{-5}$	10.73 \pm 1.62 $\times 10^{-5}$

^a Data from NFI (National Forest Inventory) plots.

^b Measured by Peichl and Arain (2006).

^c Measured by Peichl et al. (2010c).

^d Tree heights could not be measured in NFI plots in 2013–2014 using clinometer due to dense canopy.

^e Calculated using the form $y_i = c(\text{DBH})^a$ for a 15-yr stand where $c = 0.0015$ and $a = 3.220$ (Peichl and Arain, 2007).

2 m distance above the tree tops. The trajectory of tree heights is given in Table 2. EC flux data capture was more than 90% from 2009 to 2016, excluding 2014 when a hard to detect gas analyzer malfunction resulted in loss of flux data over almost the entire growing season.

Meteorological variables, including air temperature (T_a) and relative humidity (RH) (model HMP45C, CSI), wind direction and speed (WS) (model 05103–10RE, R.M. Young), net radiation (R_n) (model NR-LITE, Kipp and Zonen Ltd), downwelling and upwelling photosynthetically active radiation (PARd and PARup) (model Li–200S, LI-COR Inc.), and atmospheric pressure (model 61,205 V, R.M. Young Co.) were also measured along with fluxes. Soil temperature (T_s) was measured at depths of 2, 5, 10, 20, 50, and 100 cm, using temperature probes (model 107B, CSI) at two locations. Soil volumetric water content (VWC) was monitored by water content reflectometers (model 615, CSI), which were buried at depths of 5, 10, 20, and 50 cm at the same two locations as the soil temperature probes. Soil heat flux (G) was measured using heat flux plates (model HFT3, CSI) installed at 3 cm depth at two locations. Precipitation (P) was measured using an all-season heated tipping-bucket rain gauge (model 52202, R.M. Young) installed at 1.5 m height in an open area near the tower. P measurements were cross checked and gap-filled with data from a weighted rain gauge (model T–200B, Geonor) installed in 2007 near the mature Turkey Point forest site (TP39; ~19 km to the east of TP02) and an Environment Canada Weather Station at Delhi, ON (~22 km to the north of TP02). All meteorological and soil data were recorded at half hourly intervals using data loggers (model CR10X and CR1000, CSI).

All flux and meteorological data were quality controlled and gap-filled using the Biometeorological Analysis, Collection, and Organizational Node (BACON) software (Brodeur, 2014). Small gaps of a few hours of duration within meteorological data were filled using linear interpolation, while larger gaps were filled using data from other TPFS flux sites.

Half-hourly CO_2 flux (F_c), measured using the OPEC system, was corrected for density fluctuations due to H and LE (Webb et al., 1980), as well as instrument heating effects (Burba et al., 2008). OPEC fluxes were also subjected to coordinate rotation (Tanner and Thurtell, 1969), as well as outlier removal using an automated detection algorithm method, similar to Papale et al. (2006). CPEC fluxes from 2008 to 2013 were quality controlled and gap-filled using a modified version of the nonlinear estimation model used by Richardson and Hollinger (2007). A friction velocity threshold (u_*^{Th}) was applied to all nocturnal (PARd < $15 \mu mol m^{-2} s^{-1}$) net ecosystem exchange (NEE) measurements, removing data for periods when turbulence was weak (Aubinet, 2008; Barr et al., 2013; Gu et al., 2005; Papale et al., 2006). u_*^{Th} values were $0.15 m s^{-2}$ from 2003 to 2007 that gradually increased from $0.29 m s^{-2}$ in 2008 to $0.49 m s^{-2}$ in 2016 due to stand growth and associated changes in canopy structure. Nocturnal NEE values were removed when measured u_* was below thresholds estimated using the Moving Point Test u_*^{Th} determination method described by Papale et al. (2006), which estimated u_*^{Th} from the relationship between nighttime NEE and u_* . A footprint model following Kljun et al. (2003) was applied to exclude fluxes when flux footprint extended outside of forest boundary. While using CPEC half-hourly NEE data capture was more than 90% in most years. However, due to limited footprint and u_*^{Th} filtering total portion of NEE data retained was less than 30%, which was even lower for OPEC. NEE was calculated as $NEE = F_c + S_c$, where S_c is the rate of change in CO_2 storage within the air column below the EC sensor, calculated from the difference in current and previous half-hourly CO_2 concentrations. Net ecosystem productivity (NEP) was calculated as $NEP = -NEE$, where a positive NEP represents C fixed by the ecosystem (sink) and a negative NEP represents C emission to the atmosphere (source).

Modelled GEP and RE were used to fill gaps in NEP due to instrument malfunction or when atmospheric conditions violated the assumptions of the EC technique. Ecosystem respiration (RE) was modelled as a function of T_s (5 cm depth) and soil water content (in the

upper 30 cm layer) estimated using measurements made at 5, 10 and 20 cm depths (VWC_{0-30cm}) using the following relationship (Richardson et al., 2007; Tjoelker et al., 2009):

$$RE = R_{10} \times Q_{10}^{\frac{(T_s-10)}{10}} \times f(VWC_{0-30cm}) \quad (1)$$

where R_{10} and Q_{10} are fitted temperature response parameters that describe the relationship between RE and T_s , $f(VWC_{0-30cm})$ is a sigmoidal function that characterizes the influence of root zone soil moisture in modifying the temperature response of RE and is described as:

$$f(x) = \frac{1}{[1 + \exp(\theta_1 - \theta_2 x)]} \quad (2)$$

where θ_1 and θ_2 are fitted parameters that allow this term to range between [0 and 1] as a function of the independent variable x (i.e. VWC_{0-30cm}), thus acting as a scaling function on the T_s -RE relationship.

Gross ecosystem productivity (GEP) was estimated by adding NEP to RE. GEP data were modelled using following formulation (Peichl et al., 2010a):

$$GEP = \frac{\alpha PARd A_{max}}{\alpha PARd + A_{max}} \times f(T_s) \times f(VPD) \times f(VWC_{0-30cm}) \quad (3)$$

where the first term in Eq. (3) defines a Michaelis-Menten relationship between PARd and GEP, α is the quantum yield (i.e. photosynthetic flux per quanta of PARd) and A_{max} is the photosynthetic capacity (i.e. light-saturated rate of CO_2 fixation). The second through fourth terms describe sigmoidal-type [0 to 1] scaling responses of GEP to T_s , VPD, and VWC_{0-30cm} , respectively.

OPEC flux data gaps were filled using similar methodology as described above, however RE and GEP data were pooled together from 2003 to 2007 to develop the relationships with environmental variables and fill gaps in C fluxes (Peichl et al., 2010c). The reader is cautioned about high level on uncertainty in seasonal and annual values of carbon fluxes due to large data gaps caused by random measurement errors and u_*^{Th} and footprint filtering and subsequent filling of these gaps as described above. Uncertainty in annual NEP values were about $\pm 130 g C m^{-2} yr^{-1}$ for 2003–2008, $\pm 50 g C m^{-2} yr^{-1}$ for 2009–2013 and $\pm 70 g C m^{-2} yr^{-1}$ for 2014–2016.

Gaps in H and LE were filled using the Artificial Neural Network technique. LE was modelled and filled using R_n , T_{s5cm} , WS, VWC_{0-30cm} , and VPD as training and modelling variables. Similarly, H was modelled and filled using PARd, R_n , LE, and T_a as training and modelling variables. Following Amiro et al. (2006), either windowed linear regression or windowed mean diurnal variation approaches were used to fill any remaining gaps in LE or H.

A linear relationship between half-hourly, gap-filled measurements of turbulent ($H + LE$) and radiative ($R_n - G$) fluxes over the study period (2003–2016) had a slope of 0.71, an intercept of $7.53 W m^{-2}$ and a correlation coefficient $r^2 = 0.93$ (Figure not shown). However, corrections to NEP, due to lack of energy balance closure, were not applied.

The onset of the growing season was defined as the first occurrence of five consecutive days when daily mean GEP values exceeded maximum observed growing season GEP by 15%. The end of the growing season was defined as the first occurrence when the daily mean GEP fell below 15% of the maximum value observed during the whole year for five consecutive days.

2.3. Biometric measurements

Annual biometric measurements of 205 individual trees were conducted following the growing season for most years in three permanent measurement plots within the stand since 2004, following the National Forest Inventory (NFI) guidelines (Canadian Forest Inventory Committee, 2008). Within these plots all trees were measured for height

(scale or clinometer (Suunto, PM5/360PC)) and diameter. Diameter at tree base (Dbase) was measured from 2004 to 2009 when trees were small and diameter at breast height ($DBH_{1.3m}$) from 2008 to 2016 as trees grew. Tree basal area (BA_T , m^2) was calculated following Peichl and Arain (2006) and Peichl et al. (2010c). Fine root biomass measurements were conducted as described by in Peichl and Arain (2007) and Skubel et al. (2015). Total belowground root biomass was calculated using allometric equations in the form $y_i = c(DBH)^a$ where $c = 0.0015$ and $a = 3.220$ (Peichl and Arain, 2007).

Leaf area index (LAI), defined as half of the three-dimensional total green leaf area, per unit ground surface area, was calculated using annualized Landsat 5 and Landsat 7 satellite radiation reflectance datasets at the 30 m resolution from 2003 to 2016. LAI was calculated through an empirical Simple Ratio model from Chen et al. (2002). The Simple Ratio was calculated as $\frac{\rho_{NIR}}{\rho_{red}}$, which is the ratio between reflectance at the infrared (ρ_{NIR}) and the red (ρ_{red}) wavelengths (Jones and Vaughan, 2010). Furthermore, the LAI derived from the satellite images are technically effective LAI because they do not contain corrections for clumping (Chen et al., 2002). LAI data was not estimated for 2012 and 2014, because of frequent cloudy conditions during satellite overpasses.

2.4. Data analysis

To determine environmental controls on daily variation of C fluxes and ET, the gap-filled, long-term flux data was de-trended to remove age effects during forest development. Linear regression curves of daily total GEP, RE, NEP and ET over the 14-year period were fitted and subtracted from the original flux data. Six environmental variables; including R_n , T_a , VPD, P, $T_{s_{5cm}}$, and VWC_{0-30cm} , were selected to evaluate their contributions to the variations in C fluxes and ET using multiple linear regression analysis. The percentage of variation in daily flux data explained by each of the environmental factors were calculated based on the ANOVA results of the multiple regression models. This analysis was conducted for the continuously measured CPEC flux data from 2008 to 2016, while the results for the whole research period (2003–2016) was also shown for comparison. All data processing, management and statistical analysis were conducted using MATLAB software (The Mathworks Inc.).

3. Results

3.1. Stand development and growth

In 2002, the site was plowed and one year old seedlings were machine planted with white pine seedlings in rows 2.5 m apart (~ 1800 seedlings ha^{-1}). Within the first year of planting, herbs and grasses grew rapidly and out-competed the seedlings for light, water, and nutrition. Mowing between rows was conducted during the initial 2–3 years of growth in the summer to suppress herbaceous growth. After 4 years, the white pine seedlings out-competed herbaceous growth without the need for further mowing maintenance. By the end of 2006 the mean tree height reached 2 m, after which tree height nearly doubled every three years (i.e. 2.8 m in 2009 and 5.79 m in 2012; Table 2). DBH and LAI measurements also increased in similar proportions after 2006 (Table 2). During the first 5 years since planting, annual LAI held constant around $3 m^2 m^{-2}$, after which it began to increase steadily (Table 2). By 2011–2012, the canopy closure occurred with pine trees dominating the forest cover, shading out all understory herbs and grasses. At this stage LAI was about 6.4 to $6.7 m^2 m^{-2}$ and showed a smaller annual increment as compared to previous years and signifies decreased growth rates due to canopy closure.

Stand DBH and basal area showed a consistent increase since the start of measurements in 2008. The mean tree base diameter increased at a rate of $1.7 cm year^{-1}$ in the first 7 years of growth, increasing from $2.54 \pm 0.05 cm$ in 2004 to $10.92 \pm 0.16 cm$ in 2009. The mean DBH

increased from $5.34 \pm 0.11 cm$ in 2008 to $15.74 \pm 0.25 cm$ in 2016, with an annual rate of increase of $1.3 cm year^{-1}$. By the end of 2016, basal area of stand was $31.8 m^2 ha^{-1}$. The stand root system developed substantially over the study period. The fine roots ($< 2 mm$) biomass in the upper 0–15 cm and 15–35 cm soil layer increased from $0.196 \pm 0.026 t ha^{-1}$ and $0.045 \pm 0.039 t ha^{-1}$, respectively in 2004 to $3.623 \pm 1.566 t ha^{-1}$ and $0.857 \pm 0.530 t ha^{-1}$, respectively in 2015. Similarly, small roots (2–5 mm) biomass in the upper 0–15 cm and 15–35 cm soil layer increased from $0.023 \pm 0.039 t ha^{-1}$ and $0 t ha^{-1}$, respectively in 2004 to $1.490 \pm 0.877 t ha^{-1}$ and $2.671 \pm 1.873 t ha^{-1}$, respectively in 2015.

A small decrease in annual tree density was also observed due to die off of suppressed trees during the study period. In 2016, tree density was $1567 \pm 29 trees ha^{-1}$ as compared to $1683 \pm 147 trees ha^{-1}$ when the plantation was established in 2002. Further details of stand characteristics are given in Table 2.

3.2. Environment and energy flux dynamics

Meteorological variables and soil water content (SWC) from January 2003 to December 2016 are shown in Fig. 1. Annual and growing season averages of these variables are given in Table 3. Annual T_a was highest ($10.2^\circ C$) in 2012 and lowest ($7.5^\circ C$) in 2014. Highest annual P value of 1293 mm was observed in 2011, followed by 1266 mm in 2013. 2006 and 2014 also had above normal P (1187 mm each). The lowest P value of 705 mm was observed in 2007, followed by 777 mm in 2016. The site experienced low P periods during the early growing season in 2005, 2007, 2012 and 2016 (Fig. 1f). SWC was typically highest in late winter and early spring due to snowmelt and spring precipitation ($\sim 0.15 m^3 m^{-3}$). SWC began to decline with the onset of photosynthetic activity in spring and reaches a minimum in July ($\sim 0.07 m^3 m^{-3}$), which coincides with greater atmospheric, as well as photosynthetic, water demand (Fig. 1a and c). SWC then rose again in autumn, when atmospheric and photosynthetic demand decreased and precipitation started to replenish soil water storage. During the first few years, SWC in the upper (5 cm) and lower (50 cm) soil layers showed large fluctuations (Fig. 1d). However, from 2006 onwards, the SWC of both soil depths developed strong characteristics of distinct annual drawdowns from spring through summer and then an increase from fall through winter. Furthermore, the differences between SWC in 5 cm and 50 cm soil layer largely diminished, reflecting the control of the expanding root system on the soil water dynamics.

The greatest impact of the expanding canopy cover was on the energy balance and hence the microclimate of the forest (Fig. 3). R_n values were lower during initial years, when trees were small and a large portion of the ground was not covered with forest canopy resulting in higher reflection of radiation. As the canopy developed, more energy was absorbed by trees as indicated by the decreasing trend of upwelling PAR (PARup) values (Fig. 2a) and increasing R_n values over the study period (Fig. 3). In the first few years when the seedlings were small, G values ranged from 1.2 to $2.9 W m^{-2}$ reaching a maximum in 2007 (Fig. 3). However, from 2009 onwards G values gradually declined as the canopy started to close. This was also reflected in the inter-annual variability of soil temperature (T_s). During initial years, the ground surface was warming up substantially compared to T_a such that the difference in T_a and T_s in the upper 0–30 cm soil layer was approximately $3^\circ C$ (Fig. 2b–c). As the canopy developed and shaded the ground, this difference gradually declined over the study period and approached $\sim 0.5^\circ C$, similar to those observed in a 77 year-old planted white pine stand (TP39) in the region (Fig. 2c).

Photosynthetic capacity (A_{max}), quantum yield (α) and DBH steadily increased with canopy LAI as shown by Landsat-derived values (Tables 2 and 4). Turbulent energy fluxes (LE and H) also reflected stand structural changes over the study period (Fig. 3). Mean annual sensible heat (H) values showed an increasing trend with stand age. Large increases in H were observed during years with unusually warm

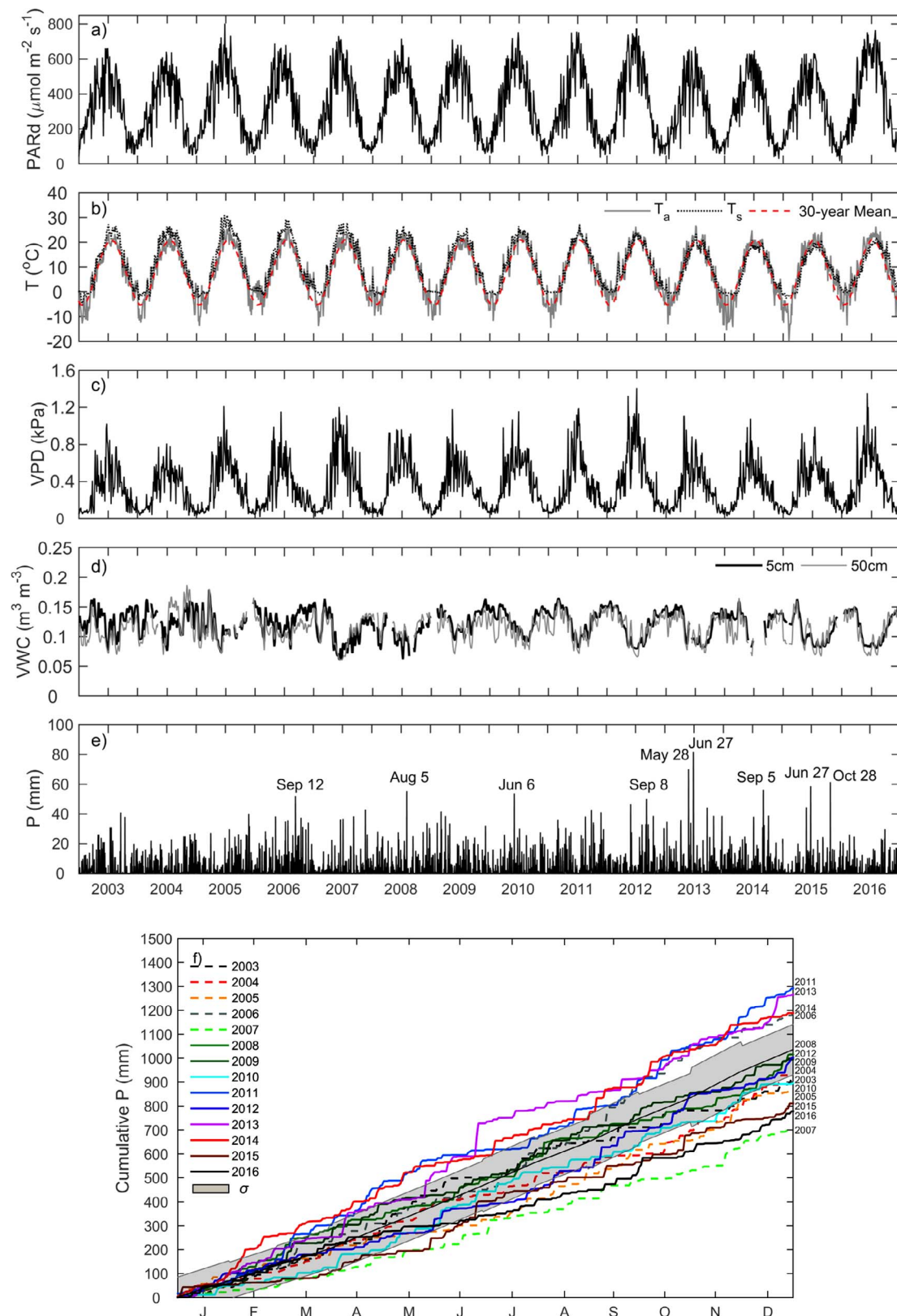


Fig. 1. (a) 3-day mean downward photosynthetically active radiation (PARd), (b) 3-day mean air temperature (T_a), soil temperature (T_s) at 5 cm depth, and 30-year mean air temperature, (c) 3-day mean vapour pressure deficit (VPD), (d) 3-day mean volumetric water content (VWC) at 5 cm and 50 cm depth, and (e) daily total precipitation (P) from January 2003 to December 2016. (f) Cumulative precipitation (P) from 2003 to 2016. 30-year normal P is shown as a thin black line with ± 1 standard deviation (σ) as a gray shaded band.

temperatures and/or dry conditions (e.g. 2005, 2007, 2012, and 2016). Mean annual LE also showed a slight increasing trend with stand age (Fig. 3), but relatively low LE values were also observed during years

which experienced prolonged dry periods (e.g. 2007 and 2012). Further details concerning evapotranspiration dynamics are described in Section 3.4.

Table 3
Summary of annual (A) and growing season (GS) meteorological variables.

Year	Mean Ta (°C)		Mean Ts0–30cm (°C)		Total PAR (MJ m ^{−2})		Mean VPD (kPa)		Mean VWC0–30cm (m ³ m ^{−3})		Total P (mm)		Growing Season Length (days)
	A	GS	A	GS	A	GS	A	GS	A	GS	A	GS	
2003	8.0	14.1	10.7	16.7	2190	1728	0.31	0.43	0.12	0.12	913	607	227 (85–312) ^a
2004	8.4	14.5	11.8	17.9	2170	1748	0.30	0.41	0.13	0.13	956	549	230 (87–317)
2005	8.7	15.5	12.0	17.8	2404	1952	0.35	0.50	0.10	0.10	862	556	233 (87–320)
2006	9.7	14.7	12.1	17.7	2181	1770	0.33	0.44	0.12	0.12	1187	826	230 (86–316)
2007	9.0	15.6	11.9	18.4	2292	1876	0.39	0.57	0.11	0.10	705	449	223 (86–309)
2008	8.7	15.0	10.7	17.0	2310	1878	0.38	0.53	0.11	0.11	1021	549	230 (92–322)
2009	8.3	13.3	11.9	15.3	2305	1948	0.35	0.45	0.12	0.11	995	655	252 (77–329)
2010	9.2	14.5	11.3	15.9	2370	2026	0.39	0.51	0.11	0.11	896	697	253 (74–327)
2011	9.1	15.0	10.7	15.7	2274	1838	0.36	0.49	0.12	0.11	1293	811	238 (94–332)
2012	10.2	14.5	10.8	14.7	2530	2226	0.43	0.56	0.11	0.10	1001	696	256 (73–329)
2013	8.5	14.8	9.2	14.4	2064	1654	0.33	0.46	0.11	0.10	1266	843	228 (96–324)
2014	7.5	14.8	7.1	12.4	2165	1682	0.32	0.45	0.11	0.11	1187	706	220 (98–318)
2015	8.6	14.6	9.1	13.0	2234	1783	0.34	0.45	0.10	0.10	811	599	245 (101–346)
2016	9.9	13.9	10.3	12.7	2659	2381	0.39	0.48	0.11	0.10	777	536	272 (71–343)
30-Year Normal ^b	8.0 ± 1.6	14.9 ± 1.4									1036	632	

^a The start and end Day-of-year of the growing season is given in parenthesis.
^b Environment Canada normal means from 1981 to 2010 at Delhi, ON. Growing season estimate is for day of year 91 to 305.

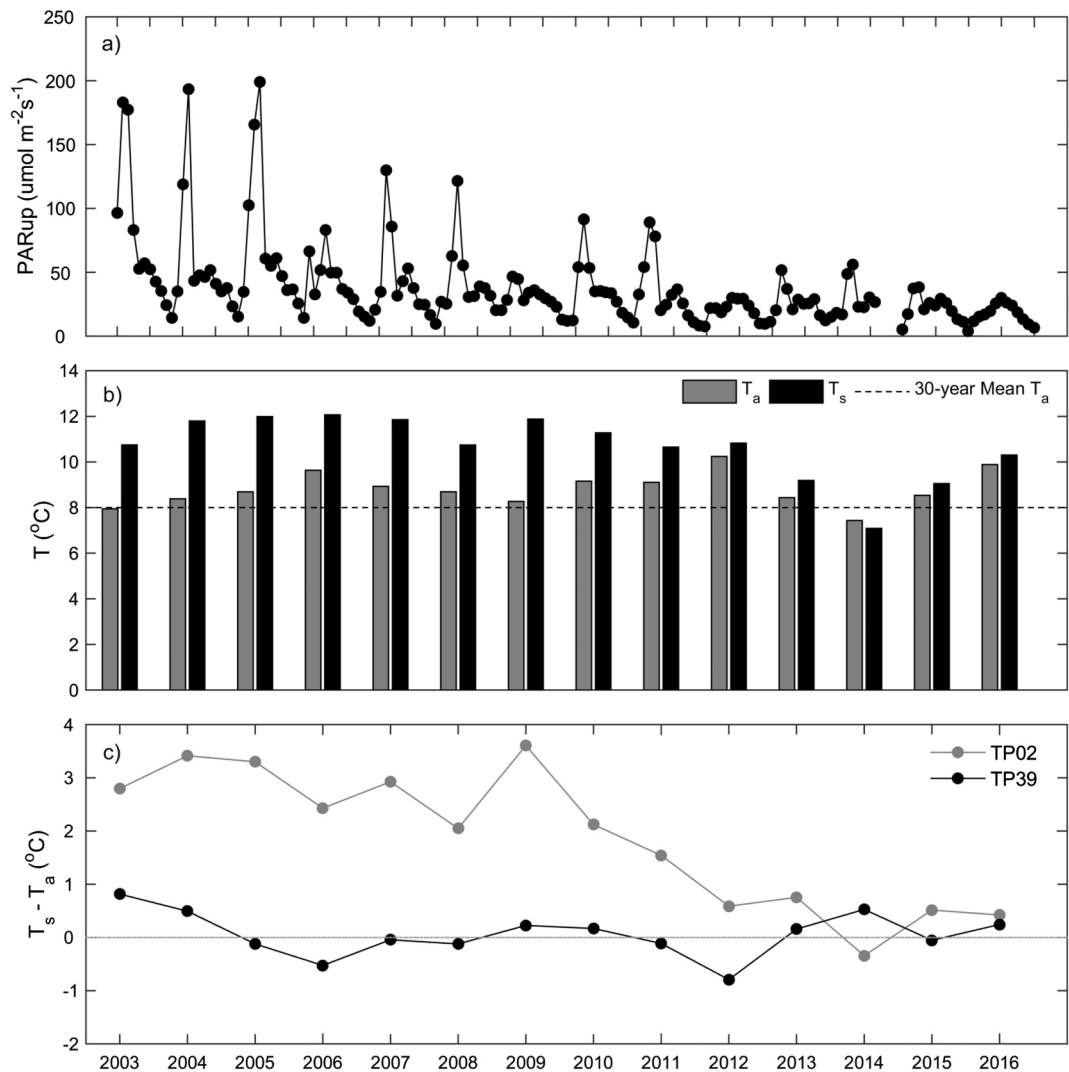


Fig. 2. (a) Mean monthly values of upwelling PAR (PARup), (b) mean annual air (Ta), root zone soil temperature from 0 to 30 cm depth (Ts0–30cm), and 30-year climate normal air temperature, and (c) the difference between mean annual Ta and Ts0–30cm at this site and measurements made in a 77-year pine forest site (TP39) in the region (~20 km east).

3.3. Carbon flux dynamics

Annual carbon uptake gradually increased with growth within this young stand (Figs. 4 and 5). Light use efficiency curves generated by plotting GEP against PARd indicate a strong influence of canopy development and expansion of photosynthesis capacity of the forest (Fig. 6a, Table 4). As the forest underwent structural change toward maturity, the GEP/PARd ratio was observed to increase which resulted in greater light efficiency per LAI. The increased efficiency occurred because of the photosynthetic contribution of shaded needles, thereby increasing the A_{\max} of the forest. Annual GEP curves also continued to rise and remain non-linear at higher values of PARd which suggest A_{\max} has not become saturated after fourteen years of growth.

Normalizing GEP with LAI condensed the curves (Fig. 6b), and suggest that LAI was a greater influence on annual GEP in the stand. While physiological factors such as needle age (Freeland, 1952, Ryan et al., 1999; Robakowski and Bielini, 2017) and shading (Robakowski and Bielini, 2017) are known to influence photosynthetic capacity of individual leaves in conifers, these factors appear to be small contributors to annual GEP. Daily NEP values doubled over the study period, ranging from -1.5 to $+1 \text{ g C m}^{-2}$ in 2003 to about -5 to $+9 \text{ g C m}^{-2}$ in 2016 (Fig. 4a). Although positive NEP were observed during the growing season in initial years due to intense weed growth, the site was an overall C source predominantly due to high respiration from the decomposition of soil organic matter (Fig. 4a and b).

Seasonal dynamics of NEP indicated that the forest experienced an early onset of C uptake during 2010, and 2012, whereas the latest onset occurred in 2013, 2015, and 2016 (Fig. 4b). During most growing seasons NEP peaked in June or early July. Mid-summer (July–August) NEP reductions during 2008, 2010, 2012 and 2013 was largely due to increase in RE in response to high temperature. During drought years (e.g. 2005, 2012 and 2016), reduction in GEP also contributed to this mid-summer decrease in NEP. NEP generally recovered from this mid-summer decline, except during the drought years 2005 and 2016, when it continued to decline after spring or early summer peak due to in the simultaneous reduction of GEP with increased RE caused by warmer temperature (heat stress) and drought (Fig. 1). Hence, the lowest values of NEP values were observed in 2005 and 2016 were primarily due to the combined effect of warm and dry conditions during the growing season (Fig. 4b; Table 3).

GEP, RE and NEP fluxes increased substantially after 2007 and the stand became a consistent and significant sink of C after five years after planting, excluding 2016 (Fig. 4b). Mean annual GEP, RE and NEP

Table 4

Water use efficiency (WUE; $\text{g C kg}^{-1} \text{ H}_2\text{O}$) from the monthly GEP and ET relationship. α and A_{\max} values for the rectangular hyperbolic curve ($\text{GEP} = \frac{\alpha \text{PAR} A_{\max}}{\alpha \text{PAR} + A_{\max}}$) fitted onto the GEP and PARd relationship. α is the quantum yield (i.e. photosynthetic flux per quanta of PAR; $\text{mol CO}_2 \text{ mol}^{-1} \text{ photons}$) and A_{\max} is the photosynthetic capacity (i.e. light-saturated rate of CO_2 fixation; $\mu\text{-mol m}^{-2} \text{ s}^{-1}$). The goodness of fit of each regression is given by r^2 .

Year	WUE	r^2	α	A_{\max}	r^2
2003	1.60	0.77	0.0185	5.86	0.86
2004	2.09	0.49	0.0172	12.99	0.92
2005	1.35	0.36	0.0322	4.37	0.84
2006	1.89	0.77	0.0223	6.67	0.90
2007	2.36	0.47	0.0551	6.60	0.94
2008	2.70	0.92	0.0206	19.75	0.99
2009	3.22	0.94	0.0277	17.41	0.99
2010	3.44	0.77	0.0306	23.56	0.99
2011	4.11	0.94	0.0304	28.20	0.99
2012	4.27	0.82	0.0294	23.50	0.99
2013	4.20	0.88	0.0375	27.30	0.99
2014	n/a	n/a	n/a	n/a	n/a
2015	5.11	0.92	0.0451	33.64	0.99
2016	4.29	0.84	0.0328	22.93	0.99

ranged from 494 to 1913, 515 to 1774 and -126 to $216 \text{ g C m}^{-1} \text{ yr}^{-1}$, respectively over the study period (Fig. 5). The maximum NEP values were recorded in 2011, which was wet year and had highest precipitation value (1293 mm, Fig. 1f). There was no soil water limitation, therefore NEP was high. In addition, growing season started much early in 2011, which contribute to high annual NEP (Fig. 4).

3.4. Water flux dynamics

Maximum daily ET values were about 1 to 2 mm d^{-1} during initial years which increased to 2 to 3 mm d^{-1} by 2011–2012 when the canopy started to close. The persistent increase in ET values was largely associated with the rise in photosynthetic capacity or GEP. During warm (e.g. 2012) and/or water limited (e.g. 2007) years, a marked reduction in peak growing season ET was observed. The highest total annual ET value of 429 mm was observed in 2010, which was a relatively warm and dry year with an earlier onset to the growing season (Fig. 7). The lowest annual ET value of 328 mm was observed in 2003 (Fig. 7). The forest showed increased inter-annual variability of ET as it grew older (Figs. 4 and 5).

The monthly ecosystem water-use efficiency (WUE) estimated by dividing monthly GEP with ET indicated that from 2003 to 2007, the

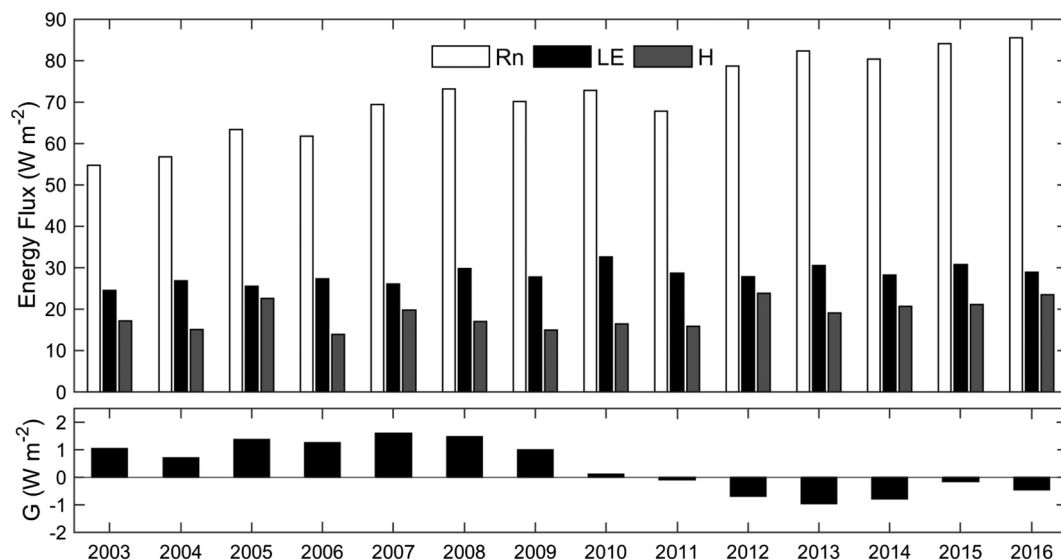


Fig. 3. Mean annual values of net radiation (Rn), latent heat flux (LE), sensible heat flux (H), and ground heat flux (G).

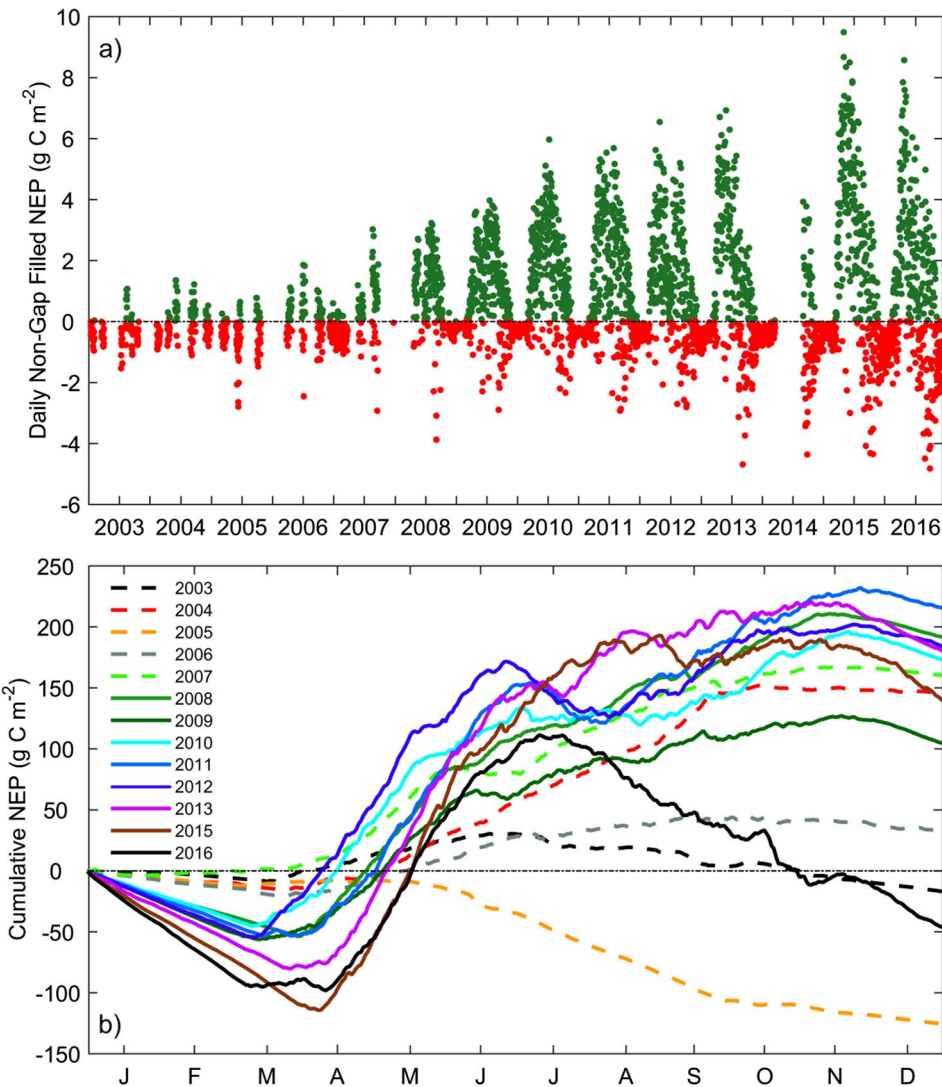


Fig. 4. (a) Daily sums of non-gap filled net ecosystem productivity (NEP), and (b) cumulative values of NEP from January 2003 to December 2016. Data measured with the OPEC system is represented as dashed lines while data measured by the CPEC system is represented by solid lines in panel (b). Cumulative NEP from 2014 is not shown due to extensive data loss due to gas analyzer malfunction during the growing season.

stand sequestered 1.35–2.36 g of C for every kg of water transpired, while from 2008 to 2016, when fluxes were measured year-round, the stand sequestered 2.70–5.11 g of C for every kg of water lost. The stand

showed a persistent increase in WUE with canopy development and growth with the highest WUE observed in 2015 (Fig. 8; Table 4). Stand water dynamics was severely stressed in the summer and fall of 2016

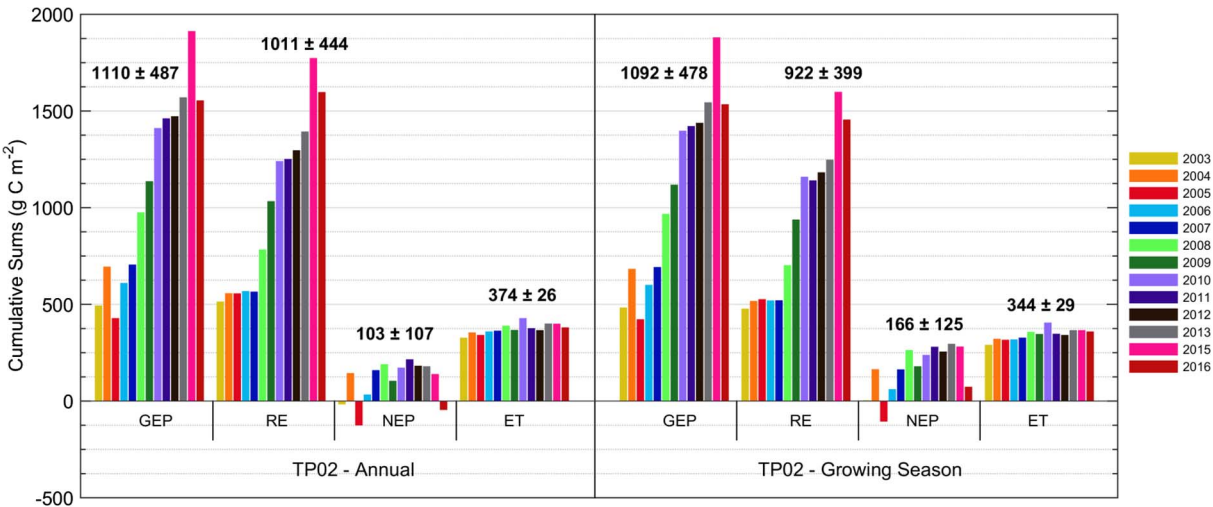


Fig. 5. Annual and growing season values of gross ecosystem productivity (GEP), ecosystem respiration (RE), net ecosystem productivity (NEP) and evapotranspiration (ET). Mean values for 14-years of data are shown as numbers with \pm one standard deviation. 2014 values were removed due to extensive data loss due to gas analyzer malfunction during the growing season.

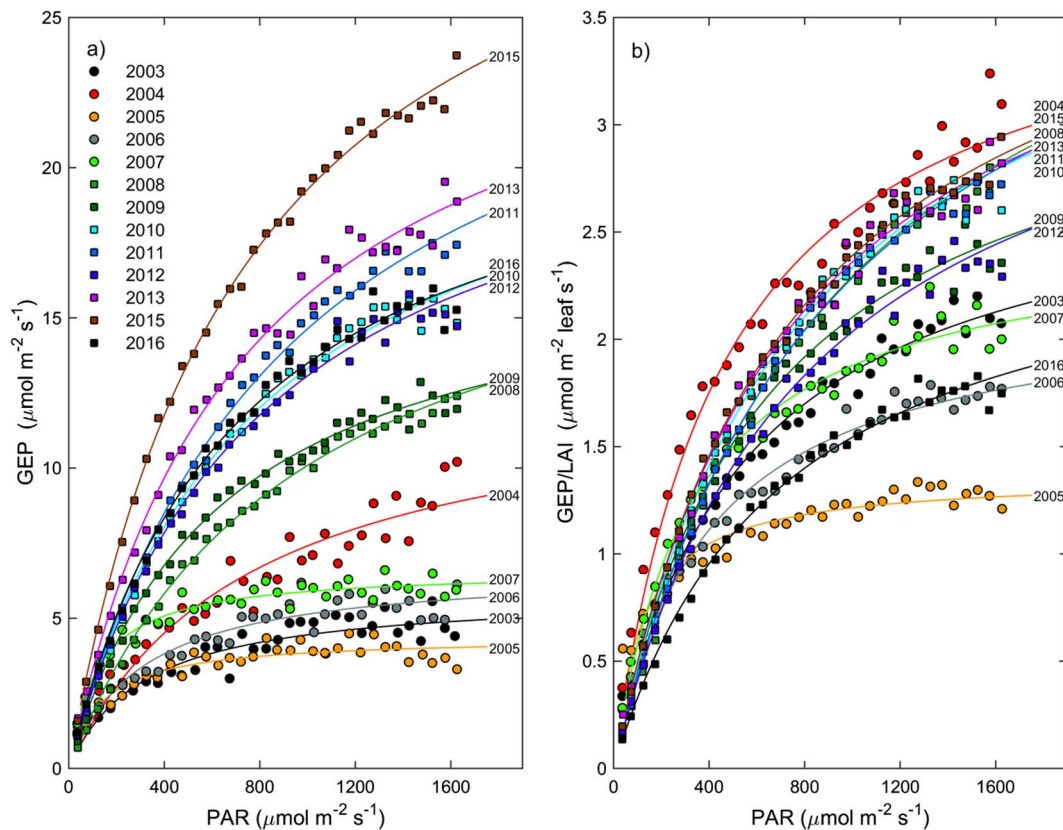


Fig. 6. (a) The rectangular hyperbolic curve ($GEP = \frac{\alpha PAR A_{max}}{\alpha PAR + A_{max}}$) fitted to bin-averaged (10 μmol m⁻² s⁻¹), half-hourly gross ecosystem productivity (GEP) and downward photosynthetically active radiation (PAR). α (mol CO₂ mol⁻¹ photons) and A_{max} (μmol m⁻² s⁻¹) values are derived from this relationship. The r^2 of the fitted regression line ranged from 0.84 to 0.99. (b) Same as panel (a) but GEP was normalized with annual LAI. GEP fluxes from 2014 were not fitted to this curve due to extensive gap-filling resulting from data loss during the growing.

when WUE dropped to values similar to earlier drought years such as 2012.

3.5. Environmental controls on fluxes

The results of multivariable regression analysis on C and water fluxes from 2008 to 2016 showed that GEP ($R^2 = 0.89$) was most influenced by R_n (55% variance explained) followed by T_s at 5 cm depth (23% variance explained). RE ($R^2 = 0.61$) was mostly influenced by T_s (43% variance explained) (Table 5). Dominant environmental control on NEP of this young stand was R_n (27% variance explained) followed by precipitation and soil water content ($R^2 = 0.34$). Finally, ET was found to be most influenced by R_n (52%) and T_s (23%) and similar to the pattern showed for GEP ($R^2 = 0.46$). The relative impotency of each factor in explaining the variation of C fluxes and ET over the entire study period (2003–2016), which included data from roving OPEC system, was similar to the results from the 2008–2016 period and had continuous flux data capture. However, the R^2 for each model was smaller using the data from the entire research period. This illustrates the higher uncertainty of C fluxes and ET due to younger stand age and different measurement methods.

4. Discussion

4.1. Stand development and growth

The stand showed almost near-linear increase in LAI and DBH over the study periods. However, we observed a decrease in A_{max} values in 2005, 2007, 2012, and 2016 due to water stress caused by summer drought and heatwave (Fig. 6b). Overall, the rate of growth towards the

end of study period was similar to another 15-year white pine stand (1989 plantation – TP89 or CA-TP2) in the region (Peichl and Arain, 2006; Peichl et al., 2010a,c). The DBH of this previously studied 15-year stand was 15.8 ± 0.2 cm which was very similar to mean DBH of 15.74 ± 0.25 cm for the 14-year TP02 stand reported in this study.

A_{max} and α measured in our stand were comparable to those observed in other temperate forests. For example, α in a mixed North Carolinian (U.S.) forest of loblolly pine, sweetgum, and yellow poplar (*Pinus taeda* L.; *Liquidambar styraciflua* L.; *Liriodendron tulipifera* L.) with mean tree DBH of 15 cm (similar to our site's mean DBH in 2016) was identified as $\alpha = 0.045$ for sun-exposed leaves (Herrick and Thomas, 1999). At the stand-age of 6 in 2008, α was greater for TP02 than that observed in a 6-year-old ponderosa pine stand in Oregon, U.S. (0.02 vs 0.01 mol CO₂ mol⁻¹ photons, respectively) while the A_{max} value was similar (19.8 vs 22.6 μmol m⁻² s⁻¹) (Law et al., 2001). Krishnan et al. (2009) observed $\alpha = 0.03$ and 0.06 mol CO₂ mol⁻¹ photons and $A_{max} = 14.15$ and 7.94 μmol m⁻² s⁻¹ in a 6-year-old Douglas-fir stand in British Columbia, Canada, during moist and dry conditions respectively. They also observed $\alpha = 0.06$ and 0.08 mol CO₂ mol⁻¹ photons and $A_{max} = 19.84$ and 8.08 μmol m⁻² s⁻¹ in an 18-year-old Douglas-fir stand during moist and dry conditions, respectively, as compared to $\alpha = 0.03$ mol CO₂ mol⁻¹ photons and $A_{max} = 22.93$ μmol m⁻² s⁻¹ when our stand was 14 years old in 2016. The elevated α values of the Douglas-fir sites relative to our stand are likely due to the highly productive nature of these coastal forests in the Pacific Northwest with generally abundant nutrients (Morgenstern et al., 2004; Krishnan et al., 2009). The lower values seen in our site may be related to structural development as canopy closure occurred. Greater shading of the ground may not liberate nutrients of decomposing ground litter, thereby reducing nutrient availability that occurs during stand development.

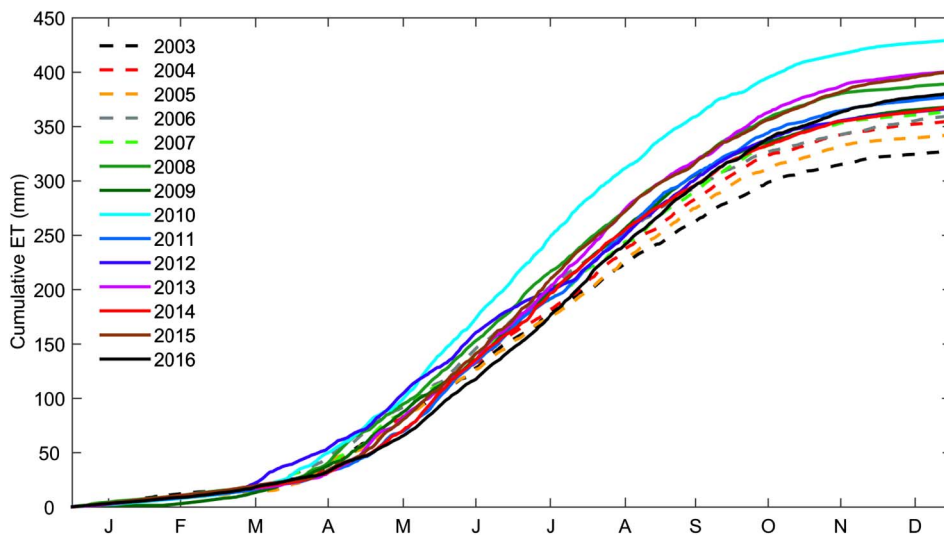


Fig. 7. Cumulative values of evapotranspiration (ET) from January 2003 to December 2016. Data measured with the open-path eddy covariance (OPEC) system is shown as dashed lines while data by the closed-path eddy covariance (OPEC) system is represented by solid lines.

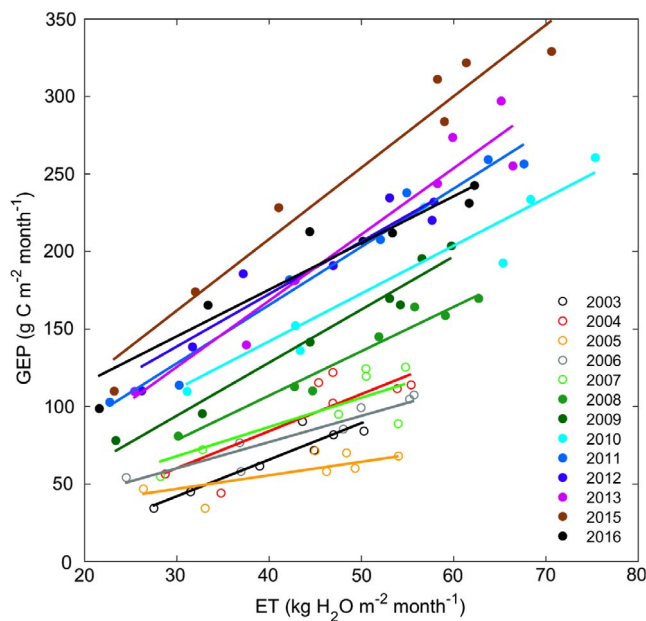


Fig. 8. Relationship between monthly gross ecosystem productivity (GEP) and evapotranspiration (ET), which represents forest water use efficiency (WUE), from April to October. From 2003 to 2007, 1.35 to 2.09 g of C was sequestered for every kg of water transpired. From 2008 to 2016, 2.36 to 5.11 g of C was sequestered for every kg of water transpired.

Reduced nutrient availability has been found to reduce photosynthetic capacity in needles (Ryan et al., 1999).

4.2. Energy dynamics

Our study shows that reflected PAR exhibited a decreasing trend with stand age which demonstrated the canopy's increased capacity to absorb PAR. Overall, the total annual and growing season downward PAR values were highest in 2016 with 2659 and 2381 MJ m⁻² yr⁻¹ respectively. Similarly, Rn was low in the initial years, due to the lack of canopy cover and high reflection of radiation. Winter accumulation of snow on the ground surface further increased surface albedo, causing lowest Rn values of the study period. In later years, Rn showed an increasing trend and G showed a decreasing trend as the canopy developed.

As reported in literature the magnitude of radiation fluxes such as Rn and G vary with canopy cover, solar irradiance and soil water

Table 5

Percentage of variations of daily gross ecosystem productivity (GEP), ecosystem respiration (RE), net ecosystem productivity (NEP) and evapotranspiration (ET) explained by each environmental factors in the multivariable linear regression analyses from 2008 to 2016. R² and p value of each model are also shown. Environmental factors included in the model are daily net radiation (Rn), air temperature (T_a), soil temperature at 5 cm depth (T_s), vapor pressure deficit (VPD), precipitation (P), and volume soil water content at 0–30 cm horizon (VWC30). Results using data from 2003 to 2016 are shown in parentheses.

	GEP	RE	NEP	ET
Rn	54.88 (26.39)	4.83 (2.62)	27.42 (22.63)	52.79 (46.06)
T _a	4.28 (5.00)	5.28 (7.64)	0.08 (0.03)	0.02 (0.06)
T _s	22.60 (3.51)	43.10 (9.59)	0.15 (0.62)	23.02 (14.48)
VPD	5.81 (3.21)	3.63 (2.36)	0.74 (0.56)	2.34 (4.77)
P	1.71 (0.36)	0.58 (0.46)	3.05 (2.12)	1.21 (0.28)
VWC30	0.09 (1.56)	3.43 (8.44)	2.68 (1.47)	5.31 (2.76)
R ²	0.89 (0.40)	0.61 (0.31)	0.34 (0.27)	0.85 (0.68)
p-value	< 0.01 (< 0.01)	< 0.01 (< 0.01)	< 0.01 (< 0.01)	< 0.01 (< 0.01)

content (Sauer and Horton, 2005). In early years of plantation growth, the soil surface is usually exposed to more direct solar radiation and conducts more energy into the soil (Kustas and Daughtry, 1990). Furthermore, afforested stands on former agricultural soils do not have the benefit of litter layers shading the soil and helping to control soil temperature and moisture. Our stand was bare sandy soil at the start of the experiment when the trees were planted. G was influenced by the stand development and peaked in 2007 (1.61 W m⁻²), while soil temperature steadily declined from 2003 to 2013. The conduction of G from the subsurface to the soil surface may have offset the cooling effect from canopy shading and litter accumulation and also subsequent prolonged snow accumulation under the canopy. However, in 2015 and 2016, G fluxes increased (less negative) due to increasing T_s resulting from high needle senescence observed in the site during these years. This allowed less shading of the ground coupled with summer heatwave conditions. The increased T_s may have influenced the overall radiation balance, including Rn of the site. Overall, the energy balance of our site was largely dominated by the developing stand structure, except during extreme years. Our results show changing dynamics of various components of energy fluxes over the initial 14 years of stand development.

4.3. Carbon dynamics

NEP of a newly planted forest is typically negative for several years after establishment due to low NPP of the young trees and high C losses through heterotrophic respiration (Rh) (Bjarnadottir et al., 2009;

Table 6
Summary characteristics and net ecosystem productivity (NEP) at young forest sites across North America.

Site	Climate	Species	Stand Establishment	Year	Age	NEP (g C m ⁻²)	Density (tree m ⁻²)	NEP (g C tree ⁻¹)	Site reference
Saskatchewan (HJP94)	Boreal	Jack pine	Clearcut in 1975, natural regeneration	2001	7	-32	1.25	-26	Zha et al. (2009)
				2002	8	-67	1.25	-54	
				2003	9	-16	1.25	-13	
				2004	10	4	1.25	3	
				2005	11	34	1.25	27	
Florida (MT)	Sub-tropical	Slash pine	Stem-only clearcut, bedded, herbicide, planted in 1999, fertilized in 2002	1999	1	-885	0.18	-4917	Bracho et al. (2012)
				2000	2	-528	0.18	-2933	
				2001	3	-237	0.18	-1317	
				2002	4	97	0.18	539	
				2003	5	458	0.18	2544	
				2004	6	527	0.18	2928	
				2005	7	718	0.18	3989	
				2006	8	400	0.18	2222	
				2007	9	384	0.18	2133	
Florida (DT)	Sub-tropical	Slash pine	Clearcut, planted in 1989, fertilized in 1993 and 2001	1999	10	700	0.18	3889	Bracho et al. (2012)
				2000	11	663	0.2	3315	
				2001	12	640	0.2	3200	
				2002	13	569	0.2	2845	
				2003	14	818	0.2	4090	
				2004	15	775	0.2	3875	
				2005	16	735	0.2	3675	
				2006	17	491	0.2	2455	
				2008	19	613	0.2	3065	
				2008	1	-17	n/a	n/a	This Study
Turkey Point (TP02)	Temperate	White pine	Afforestation on fallow agricultural land in 2002	2004	2	145	0.1683	862	
				2005	3	-126	0.1683	-749	
				2006	4	34	0.1683	202	
				2007	5	160	0.1683	951	
				2008	6	191	0.1683	1135	
				2009	7	100	0.1683	594	
				2010	8	173	0.1683	1028	
				2011	9	221	0.1683	1313	
				2012	10	184	0.1567	1174	
				2013	11	198	0.1567	1264	
BC (HDF00)	Coastal Temperate	Douglas-fir	Clearcut, pile burn, planted in 2000	2014	12	n/a	n/a	n/a	Krishnan et al. (2009)
				2015	13	140	0.1567	893	
				2016	14	-46	0.1567	-294	
				2001	1	-571	0.15	-3807	
				2002	2	-606	0.15	-4040	
				2003	3	-614	0.15	-4093	
				2004	4	-642	0.15	-4280	
				2005	5	-450	0.15	-3000	
				2006	6	-515	0.15	-3433	
				2007	7	-522	0.15	-3480	
Quebec (HBS00)	Boreal	Black Spruce/ Jack Pine	Clearcut in 2000; planted in 2004	2002	2	-137	0.2	-685	Bergeron et al. (2008) and Grant et al. (2010)
				2003	3	-119	0.2	-595	
				2004	4	-168	0.2	-840	
				2005	5	-125	0.2	-625	
				2006	6	-109	0.2	-545	
				2007	7	-76	0.2	-380	

Note: Uncertainty in annual NEP values at TP02 site is ± 130 g C m⁻² yr⁻¹ for 2003–2008, ± 50 g C m⁻² yr⁻¹ for 2009–2013 and ± 70 g C m⁻² yr⁻¹ for 2014–2016 due to large data gaps caused by random measurement errors, and uTh and footprint filtering.

Lorenz and Lal, 2010). As forests grow older, the assimilation of C in tree biomass eventually exceeds C loss from respiration and NEP becomes positive (Lorenz and Lal, 2010; Giasson et al., 2006). Our site was afforested on an abandoned agricultural field, containing low residual soil C that resulted in significantly lower RE values. It is this low soil C pool that allowed our site to achieve higher NEP values and become a C sink within five years of its establishment. In contrast to our site, a highly productive, harvested Douglas-fir stand in British Columbia, Canada reached the C compensation point in 18 years, primarily due to higher woody detritus C pools after harvesting that resulted in high RE (Coursolle et al., 2012). Bracho et al. (2012) reported similar high rates of NEP and a C compensation point of 4 years in slash pine plantations in Florida, USA, although this stand was a strong C source with a 3-year mean NEP of -550 g C m⁻² before becoming a C sink. Kolari et al. (2004) reported that a Scots pine chronosequence in Finland reached the C compensation point after 12 years. Amiro et al.

(2010) demonstrated that chronosequence forests across North America became C sinks within 10 to 20 years after disturbance events, regardless of disturbance type. Thornton et al. (2002) showed that needle-leaf forests became C sink within 4 years post-harvest.

Comparison of the NEP trajectory of our stand with other managed or natural young stands in North America in varying climate zones is shown in Table 6. This comparison shows that at 10 years of age, the NEP of our stand (183 g C m⁻² yr⁻¹ with a density of 1567 ± 29 trees ha⁻¹) was much lower than the NEP of about 700 g C m⁻² yr⁻¹ in slash pine plantations (both 1998 and 1999 plantations) in sub-tropical Florida, USA with 2084 ± 132 trees ha⁻¹ (Bracho et al., 2012; Clark et al., 2004). In comparison to our stand, a 10 year-old naturally regenerated jack pine forest in the southern boreal region in Canada ($12,500 \pm 2458$ trees ha⁻¹) was a weak sink of C with NEP value of 4 g C m⁻² year⁻¹ (Zha et al., 2009). In contrast a coastal Douglas-fir stand that was clear-cut and planted in 2000 was a high sources of

carbon with NEP values ranging from -450 to $-642 \text{ g C m}^{-2} \text{ year}^{-1}$ (Table 6; Krishnan et al., 2009). Similar observations were made in a Black spruce/Jack pine stand that was harvested in 2000 and planted in 2004 (Bergeron et al., 2008; Grant et al., 2010). This stand was also a carbon source with NEP values ranging from -76 to $-168 \text{ g C m}^{-2} \text{ year}^{-1}$ (Table 6). These comparisons demonstrates that apart from management history, the climate of the region plays a major role in net C uptake during initial stand development.

4.4. Water dynamics

The WUE ($= \text{GEP}/\text{ET}$) of our stand continually increased with age over the course of this study, with the exception of 2016. The measured WUE was $1.35 \text{ g C m}^{-2} \text{ kg}^{-1} \text{ H}_2\text{O}$ in 2003 and reached a high value of $5.11 \text{ g C m}^{-2} \text{ kg}^{-1} \text{ H}_2\text{O}$ in 2015. Over time GEP increased while water loss remained relatively constant, resulting in the gradual increase in WUE (Skubel et al., 2015). In 2016, high ET and lower GEP resulted in WUE values similar to 2012 and 2013. During the initial years, the lack of canopy closure exposed the stomata to warm and dry air and hence a higher VPD at the site. The young trees had a shallow root system that restricted the use of water from deeper soil layers which left the stand more vulnerable to water stress (Skubel et al., 2015). When large declines in ET occurred at our site during drought events (i.e. 2007 and 2012), a corresponding peak in WUE was recorded. Similar WUE-values were reported by Jassal et al. (2009) for a 7-year-old Douglas-fir stand in British Columbia, Canada, where WUE ranged from 0.5 to $4.1 \text{ g C m}^{-2} \text{ kg}^{-1} \text{ H}_2\text{O}$ with stand age. Our site's WUE exceeded that of a 25-year old naturally regenerating ponderosa pine stand ($2.4 \text{ g C m}^{-2} \text{ kg}^{-1} \text{ H}_2\text{O}$) in semi-arid central Oregon, US (Irvine et al., 2004). Furthermore, Law et al. (2002) determined the WUE of 15 evergreen coniferous forests of different ages from the Fluxnet network was approximately $3.0 \text{ g C m}^{-2} \text{ kg}^{-1} \text{ H}_2\text{O}$, which corresponds well to WUE values of our stand during later years.

Overall, our annual ET values ranged from 328 to 429 mm, which were similar to ET values reported by Jassal et al. (2009) in their 7-year old (239–322 mm) and 19-year old (362–454 mm) Douglas-fir stands and they were higher than that of a 20-year old ponderosa pine stand ($224 \pm 36 \text{ mm}$ and $269 \pm 43 \text{ mm}$) growing in central Oregon (Schwarz et al., 2004).

4.5. Analysis of environmental controls

At our site, seasonal variation in C fluxes was strongly influenced by the behavior of photosynthetic activity at the onset of the growing season and its termination in autumn, as reported in literature for other sites (Euskirchen et al., 2006). In the middle of growing season (July–August), warm temperatures and dry air masses induced a seasonal drawdown of soil water content. Due to this phenomenon, we observed a frequent decrease in NEP during these two months, which is characteristic of other conifer forests that experience soil water limitations during the summer (Arain and Restrepo-Coupe, 2005; Law et al., 2001). During water stress periods in late summer (July–August), stomata likely closed to decrease water loss, inhibiting photosynthesis (Lorenz and Lal, 2010). In addition, sharp decreases in ET were subsequently observed during periods of seasonal drought. RE followed a similar trajectory to GEP; however RE peaked shortly after low-period GEP resulting in a moderate to severe decline in NEP depending on the severity of the seasonal summer drought. Seasonal changes in radiation decreased atmospheric and physiological demand during late August and September. Cooler temperatures reduced soil water stress and allowed stomata to open. The higher uptake of CO_2 in late growing season or early autumn contributed to the second peak in observed NEP and hence ET. A unique phenomenon was observed in 2005 and 2016, which experienced both drought and heat stresses during the growing season (Fig. 1). Both years experienced a significant decrease in NEP, primarily due to decline in GEP and large increase in RE for much of the

summer due to warming periods (Fig. 5). The site was a net source of C during both years. It was surprising to see such as rapid and persistent decline in NEP when stand was approaching canopy closure and highest photosynthetic capacity. This might be a strong indication of how pine forest ecosystem in the region may respond to climate change and extreme events in future. Overall, our site had a longer growing season compared to stands of similar age in more northern regions of Canada (Brummer et al., 2012; Coursolle et al., 2012).

We found that environmental factors have a strong impact on carbon fluxes on a daily basis. Meteorological and edaphic variables predicted most of the variability in daily GEP, RE, and NEP. Rn had the largest effect on GEP, while temperature (T_a and T_s) play a secondary but much weaker role in determining GEP. This suggests that the rate of photosynthesis in this young forest was predominantly limited by energy availability, except during extreme events such as in 2016. In contrast, RE was more sensitive to temperature variability (T_a and T_s) and atmospheric dryness represented by VPD. Large proportions of the variation in RE could not be explained by environmental factors alone (Aubinet et al., 2012). Other factors, such as the availability of decomposition substrates may have a greater impact on respiration in young forests. NEP is a direct balance between GEP and RE. It is difficult to predict how NEP may change due to environmental variability which may have a large daily, seasonal and inter-annual variation. However, at our site 27% of the variation in NEP could be explained by radiation. Most of the variation in NEP was driven by variation in GEP.

At our site, VWC commonly reached a maximum in spring and minimum in summer. Warming along with elevated VWC was found to increase RE more than GEP, while low VWC decreased GEP, resulting in lower net C sink (Xie et al., 2014). Soil water stress may induce stomata closure in forests when VWC reaches a site-specific threshold (Granier et al., 2007). Piechl et al. (2010a) estimated that the VWC at field capacity and wilting point at our site was 0.16 and between 0.1 and $0.04 \text{ m}^3 \text{ m}^{-3}$. Additionally, McLaren et al. (2008) estimated plant stress to occur at VWC below $0.07 \text{ m}^3 \text{ m}^{-3}$ at our older white pine forest. While NEP may decrease with increased water stress, it is likely to a lesser extent than GEP, due to the compensating effect of decreased RE (Granier et al., 2007).

The results of our analysis contribute to knowledge of how environmental factors affect carbon sequestration in young developing forest plantations. For example, Krishnan et al. (2009) analyzed seasonal environmental controls on C fluxes in 6 year- and 18 year-old Douglas-fir stands. They found that at the 18 year-old stand, NEP had significant ($p < 0.05$) negative relationships with T_a , T_s , and $\text{VWC}_{0-30\text{cm}}$, whereas GEP was negatively related to PARd, and VPD, while RE was positively related to both T_a and T_s . At the 6-year old site, NEP had no significant relationships with any dependent environmental variable. However, GEP and RE both were significantly positively related to T_a (Krishnan et al., 2009). A 21-year old loblolly pine forest in North Carolina, USA found that both PAR and Rn were correlated to NEP at short time scales; however the main environmental controls in that ecosystem were due to hydrologic drivers, both VPD and VWC (Stoy et al., 2005). Although these studies did not conclude as significant of an emphasis on Rn as found at our site, their analyses did find similar results. At our site the main factors driving variability in GEP and NEP were radiation (PAR and Rn) while RE was driven by T_a and T_s . However, these results illustrate the difficulty in quantifying the environmental controls of a young, developing forest such as our site.

5. Conclusions

Stand growth characteristics as well as eddy covariance fluxes of energy, water, and carbon were studied in a 14 year-old afforested white pine stand in southern Ontario, Canada since its plantation. We found that the stand functioned as an annual C sink after 5 years of planting, and had continuously sequestered CO_2 since then, except during years that experienced extremes drought and heat stress during

the growing season such as those in 2016. The low Rh from a relatively small woody detritus C stock from the site's history as an agricultural farmland allowed the plantation to reach the C compensation point much faster than other temperate conifer plantation forests following harvest in North America. Energy fluxes of R_n , G , LE , and H were largely influenced by canopy development. A gradual decrease in G was observed as canopy started to close and shaded the ground, reducing soil temperature. LE fluxes increased with stand age, however, during years with extreme drought and/or heatwave (e.g. 2005, 2007, 2012, and 2016), H increased while LE fluxes were low and this demonstrates the influence of climate on the magnitude of these fluxes. The inter-annual variability of C and water fluxes was strongly influenced by stand age (e.g. canopy development) which was influenced by water availability and temperature variations during the growing season. Variability of ET gradually increased with stand age but it was affected by extreme climate conditions during some years such as 2007, 2010, and 2012. The inter-annual stand structure allowed the forest to continue to grow while being conservative with water usage, thus maximizing WUE . These findings also highlight the influence of extreme climate conditions that occur during the growing season and how they impact carbon sequestration in water deprived and heat stressed young afforested monocultures in afforestation settings. Our findings demonstrate the potential of white pine as a viable plantation species for afforestation of abandoned fields that were previously un-forested or those lands no longer suitable for agriculture in southern Ontario. The trends discussed here could also be extended to afforestation projects for other similar settings throughout the North America. These findings will help in developing policies for better management of forest ecosystems and what we can expect as viable carbon sequestration capacity of these young stands in the first decade of establishment. Extreme drought and heat stress must be taken into consideration when estimating the carbon sequestration potential for young plantation forests in light of predicted increase in frequency for abrupt climate change events. As has been observed in this monoculture plantation and others across North America, climate events have a significant impact on forest carbon sequestration potential.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.foreco.2017.12.024>.

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