

Increased carbon sequestration by a boreal deciduous forest in years with a warm spring

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Abstract. A boreal deciduous forest in Saskatchewan, Canada, sequestered 144 ± 65 , 80 ± 60 , 116 ± 35 and 290 ± 50 g C m⁻² y⁻¹ in 1994, 1996, 1997 and 1998, respectively. The increased carbon sequestration was the result of a warmer spring and earlier leaf emergence, which significantly increased ecosystem photosynthesis, but had little effect on respiration. The high carbon sequestration in 1998 was coincident with one of the strongest El Niño events of this century, and is considered a significant and unexpected benefit.

Introduction

The temperature of the Northern Hemisphere has increased significantly over the past 100 years [Nicholls *et al.*, 1996]. There is strong evidence of an associated increase in biospheric activity because of increased growing season length [Keeling *et al.*, 1996; Frohking, 1997; Myneni *et al.*, 1997; Menzel and Fabian, 1999; Randerson *et al.*, 1999; Running *et al.*, 1999a]. However, the response of the boreal forest, which contains 13 percent of the carbon stored in the global terrestrial biomass and 43 percent of the C stored in soil [Schlesinger *et al.*, 1991], to climate warming (especially the response of boreal soils) is not well understood [Sellers *et al.*, 1997]. Previous studies have suggested that early thaws due to warmer spring temperatures can result in the net loss of C from boreal black spruce [Goulden *et al.*, 1998] and tundra [Oechel *et al.*, 1993] ecosystems.

Methods and Data

We investigated the response of a boreal deciduous forest (trembling aspen, *Populus tremuloides* Michx. with scattered balsam poplar, *Populus balsamifera* L. and hazelnut, *Corylus cornuta* Marsh. understory) to climate change by measuring net ecosystem productivity (NEP = -NEE, net ecosystem exchange of CO₂) for four years (1994 and 1996-98). This research was initiated as a part of the Boreal Ecosystem-Atmosphere Study (BOREAS) [Black *et al.*, 1996; Sellers *et al.*, 1997] and has continued under the Boreal Ecosystem Research and Monitoring Sites (BERMS) program and the AmeriFlux Tower Network [Running *et al.*, 1999b]. The study site (53.7°N, 106.2°W) is located in

Prince Albert National Park, Saskatchewan, Canada. This mature aspen forest was regenerated after a natural fire in 1919 [Weir, 1996], and in 1998 had a mean height of 21.5 m and a stand density of ~830 stems ha⁻¹. The soil is an Orthic Luvisol with a silty-clay texture and an 8-10 cm deep surface organic layer. In 1994, the site contained about 9.9, 7.9 and 3.6 kg C m⁻² in the live biomass, detritus and mineral soil layer, respectively [Gower *et al.*, 1997; Chen *et al.*, 1999]. Annual average air temperature and cumulative precipitation are about 1 °C and 400 mm [Chen *et al.*, 1999], respectively.

Half-hourly fluxes of CO₂ (F_c , positive upward) were measured using the eddy covariance (EC) technique at 39.5 m above the ground from February 2 to September 20, 1994 and from April 20, 1996 to December 31, 1998. The EC sensors consisted of a 3-dimensional sonic anemometer and a closed-path infrared gas analyzer [Chen *et al.*, 1999]. Daytime F_c was corrected by increasing its magnitude by the fraction (a function of friction velocity, u_*) required to close the forest energy balance (15-17 percent) [Blanken *et al.*, 1998]. Nighttime F_c was corrected by (i) applying the energy balance closure correction to high wind speed ($u_* > 0.35$ m s⁻¹) fluxes and (ii) using the annual relationships between these corrected nighttime fluxes (i.e. respiration (R)) and soil temperature at the 2-cm depth to replace low wind speed ($u_* < 0.35$ m s⁻¹) fluxes [Black *et al.*, 1996]. The first correction, which increased high wind speed nighttime fluxes by 10-13 percentage, is consistent with the results of a comparison between EC fluxes and scaled-up chamber measurements in boreal forests [Lavigne *et al.*, 1997], while the second gave fluxes consistent with chamber measurements of soil CO₂ effluxes at the site in low wind speed conditions [Russell *et al.*, 1998]. Flux measurements were not made in 1995, but climate and tree ring data indicated that 1995 fluxes were similar to 1997. NEP was calculated by subtracting values of F_c from the changes in CO₂ storage in the air column below the EC sensors [Yang *et al.*, 1999]. Uncertainties in annual NEP values caused by measurement uncertainty and gap filling were estimated to be ± 65 , ± 60 , ± 35 and ± 50 g C m⁻² y⁻¹ in 1994, 1996, 1997, and 1998, respectively. Gross ecosystem photosynthesis (GEP) was obtained by adding values of growing season daytime NEP to daytime R during the four years. R was calculated using the above mentioned annual ecosystem respiration relationships and daytime soil temperatures at the 2-cm depth [Black *et al.*, 1996]. Data gaps due to measurement schedule, instrument malfunction and power failure were filled using linear interpolation and relationships between R and photosynthesis and various climatic and biological variables. Leaf area index (LAI) was measured every 2-3 weeks using a LI-COR Inc. canopy analyzer (model LAI-2000) [Chen *et al.*, 1997], except in 1996 when it was measured once in mid-July. For the remainder of the 1996 growing season, LAI was

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Table 1. Productivity and Climate Statistics

Description	1994	1996	1997	1998
Average annual air temperature (°C)	1.09	-0.36	2.74	3.13
Average April-May air temperature (°C)	6.67	4.24	5.93	9.89
Date of aspen leaf emergence	April 28	May 19	May 8	April 10
Day of first detectable photosynthesis	May 12	May 31	May 19	May 1
Growing season (GS) length (days) ⁱ	134	128	134	154
Absorbed GS PAR (kmol photons m ⁻²) ⁱⁱ	2.04	1.89	2.12	2.54
GS daytime NEP (g C m ⁻²)	727	619	692	834
Annual GEP (g C m ⁻²)	1284	1181	1212	1420
Annual ecosystem respiration (g C m ⁻²)	1140	1101	1096	1130
Annual NEP (g C m ⁻²)	144	80	116	290

ⁱFrom the first to the last day of photosynthesis detectable by EC measurements. ⁱⁱCalculated for the GS as described in [Chen *et al.*, 1999]. The uncertainties are: date of leaf emergence ± 7 days, first day of detectable photosynthesis ± 3 days, GS length ± 6 days, absorbed GS PAR (photosynthetically active radiation) ± 0.05 kmol photons m⁻², GS daytime NEP ± 30 g C m⁻², annual GEP ± 100 g C m⁻², annual ecosystem respiration ± 110 g C m⁻² and annual NEP ± 65 , ± 60 , ± 35 and ± 50 g C m⁻² for the respective years.

calculated from incident PAR above and below the aspen canopy [Chen *et al.*, 1999]. Stemwood and foliar C production was estimated from tree ring widths measured at the 1.3-m height on 8 trees near the flux tower and annual leaf fall (overstory and understory) measured using litter traps [Gower *et al.*, 1997].

Results

The annual courses of daily NEP are shown in Figure 1a. During winter and early spring, values of NEP were negative (i.e., respiratory loss) and their magnitude increased with increasing air temperature. The sharp increase in NEP in spring indicated the occurrence of significant photosynthesis as a result of emerging and developing leaves. Carbon release into the atmosphere was maximum in autumn when the leaves had just senesced and soil temperatures were highest for the leafless forest. The most striking difference in NEP between the four years was in the timing of its increase in spring (Figure 1). Photosynthesis was first detected in the daytime EC flux measurements on May 12, 31, 19 and 1 in 1994, 1996, 1997 and 1998, respectively (Table 1). This occurred 12-21 days after the beginning of overstory aspen leaf emergence (Figure 2) and 4-6 weeks after snow melt. The first day of photosynthetic activity was detected from the decrease in daytime EC CO₂ fluxes below the trend in respiratory fluxes. Daily (24-h) NEP began to increase 2-3 days after this. The emergence of the understory hazelnut leaves was slightly later than that of the overstory, but showed similar interannual differences. Aspen leaf emergence date was highly correlated ($r^2 = 0.99$) with spring (April-May 24-hour average) air temperature (Figure 3) and significantly correlated ($r^2 = 0.72$) with spring soil temperature at the 2-cm depth. Air temperatures were well above normal during and immediately after the 1997-98 winter, and were likely the result of one of the strongest El Niño Southern Oscillation (ENSO) events of this century occurring at this time [Mason *et al.*, 1999]. The spring air temperature in 1998 was 9.9 °C, which was 3.2, 5.7 and 4.0 °C higher than that in 1994, 1996 and 1997, respectively (Table 1).

The impact of these differences in photosynthetic activity is clearly evident in the cumulative NEP of the four years (Figure 1b and Table 1), with annual carbon sequestration of 144 ± 65 , 80 ± 60 , 116 ± 35 and 290 ± 50 g C m⁻² y⁻¹ in 1994, 1996, 1997 and 1998, respectively. Annual carbon sequestration was highly correlated ($r^2 = 0.99$) with spring air temperature. We attribute the large impact of spring air temperature on NEP to its associated impact on leaf emergence, and to the observation that annual maximum NEP

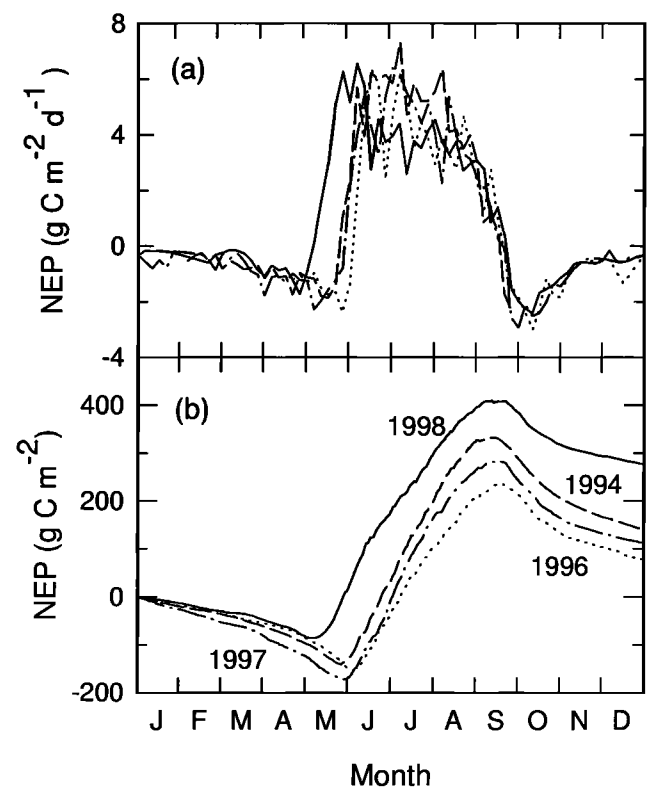


Figure 1. (a) Daily net ecosystem productivity (NEP) (b) Cumulative NEP.

occurs in the spring, when the days are relatively long and the temperatures are optimal for photosynthesis. These results have helped to quantify the effect of increased growing season length in this forest ecosystem and show that the seasonal-scale climate differences were more important than the differences in the annual means. These results have also shown that, because of the marked effect of inter-annual climatic variability on forest NEP, a few years of measurements of CO₂ fluxes using the EC technique can provide an estimate of the sensitivity of the forest carbon balance to climatic change.

Root-zone soil water content was generally high in 1994, 1996, 1997 and after June 15, 1998. Lack of rainfall between May 15 and June 15, 1998 caused soil water content to drop significantly, which probably accounts for the sudden cessation of leaf growth in late May (Figure 2). Despite this drought in the growing season, annual carbon sequestration doubled in 1998, which was the year with the highest spring air temperature and earliest leaf emergence date of the four years. 1998 illustrates two competing influences of climate change on NEP: spring warming, which promotes increased NEP, and drought stress, which reduces NEP.

Differences in annual NEP were largely due to differences in annual GEP. GEP in 1998 was over 200 g C m⁻² higher than in 1996, while ecosystem respiration was about the same (Table 1). One reason that annual GEP increased with earlier leaf emergence is that the latter resulted in significantly higher total incident and absorbed photosynthetically active radiation (PAR) during the growing season [Chen *et al.*, 1999]. Absorbed PAR totals for the growing season were 2.04, 1.89, 2.12 and 2.54 kmol photons m⁻² for 1994, 1996, 1997 and 1998, respectively, which closely corresponded to the pattern of annual GEP over the four years. Annual differences in NEP were also similar to those in daytime NEP

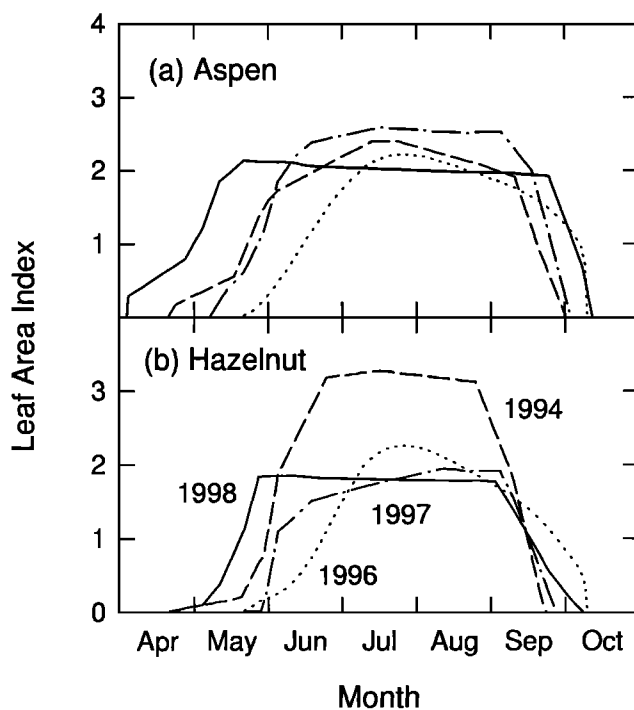


Figure 2. Leaf area index (LAI) of the overstory aspen and understory hazelnut.

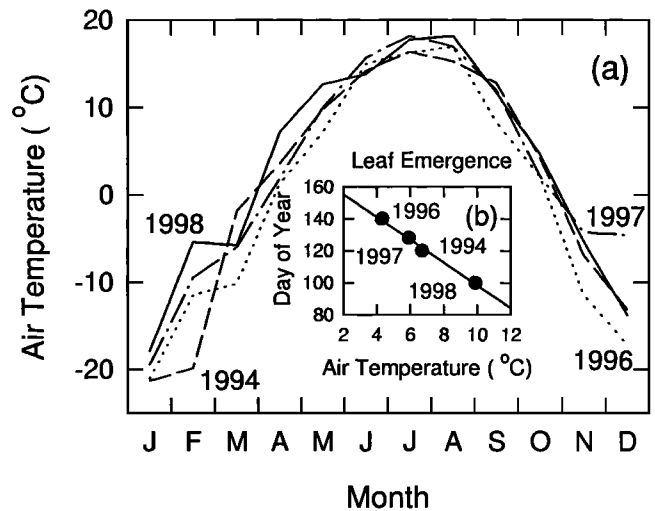


Figure 3. (a) Monthly average air temperature measured at 39.5 m above the ground (b) The relationship between April-May average (24-hour) air temperature and the day of the year when leaf emergence began.

during the growing season (Table 1) because ecosystem respiration was much less variable than photosynthesis in the four years. The variation of annual NEP over the four years was also apparent in stemwood and foliar carbon production. However, variation in the sum of these components of net primary productivity (NPP) (e.g., 259 g C m⁻² in 1996 vs. 285 g C m⁻² in 1998) was much less than that in NEP suggesting the importance of below-ground NPP (coarse and fine root growth) in this forest [Steele *et al.*, 1997].

Discussion and Conclusions

This study has shown that, over the past five years, the highest carbon sequestration by a boreal aspen ecosystem occurred during years with the warmest springs and earliest leaf emergence. Differences in spring temperature had a larger impact on carbon sequestration at this site than differences in annual mean temperature. Carbon sequestration doubled in 1998 during one of the strongest El Niño Southern Oscillation (ENSO) events of this century, despite the coincident occurrence of drought during leaf development. The increased NEP in 1998 was not accompanied by increased respiration, as 1998 had cooler temperatures later in the year. These results are in contrast with findings at a boreal black spruce site [Goulden *et al.*, 1998] showing that earlier spring thaws can decrease carbon sequestration as a result of increased soil respiration. The large increase in carbon sequestration by this ecosystem is considered a significant and unexpected benefit from spring weather attributed to the 1997-98 ENSO event.

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