The growing season carbon balance of a sub-boreal clearcut 5 years after harvesting using two independent approaches to measure ecosystem CO_2 flux

Thomas G. Pypker and Arthur L. Fredeen

Abstract : From 27 June to 3 September 1999, CO_2 fluxes from a 5-year-old, 84.15-ha vegetated clearcut in sub-boreal British Columbia were measured using a Bowen ratio energy balance (BREB) system and a second approach (the component model) that was based on scaled up CO_2-flux measurements from belowground and plants (spruce seedlings and representative deciduous species). Over the 69-day study period both methods estimated the site to be a small sink for CO_2 (–22.4 and –85 g $C{\cdot}m^{-2}$, respectively). Differences between the sink size of the two approaches largely resulted from a divergence in the data after 7 August when the BREB data indicated a switch from sink to source approximately 14 days in advance of the same change from sink to source seen in the component model data. The main components of the CO_2 flux within the clearcut were belowground respiration (338 g $C{\cdot}m^{-2}$) and deciduous plant photosynthesis (–375 g $C{\cdot}m^{-2}$). The conifer seedlings were only a minor component in overall CO_2 flux over the growing season (–48 g $C{\cdot}m^{-2}$). The small overall sink estimated for the site for the approximately 2.5-month growing period would likely have been surmounted by the belowground respiration if the yearly CO_2 fluxes had been taken into account. For example, an additional 68 g $C{\cdot}m^{-2}$ was added to the atmosphere from 3 to 23 September (based on belowground respiration data only), after deciduous plants senesced. This source alone was enough to push the site from a sink to a source for CO_2.

Résumé : Du 27 juin au 3 septembre 1999, les flux de CO_2 dans une coupe à blanc datant de 5 ans, couvrant 84,15 ha et située dans la partie sub-boréale de la Colombie-Britannique ont été mesurés à l’aide d’un système de bilan énergétique basé sur le rapport de Bowen et à l’aide d’une seconde approche (le modèle par composantes) basée sur l’extrapolation de mesures de flux de CO_2 effectuées dans le sol et sous les plantes (semis d’épinette et d’espèces décidues représentatives). Pendant la période de mesure de 69 jours, les deux méthodes ont montré que le site constitue un faible puits de CO_2 (respectivement –22,4 et –85 g $C{\cdot}m^{-2}$). La différence dans la taille du puits entre les deux approches est essentiellement le résultat d’une divergence dans les données après le 7 août. Selon les données du bilan énergétique, le puits devenait une source approximativement 14 jours plus tôt que l’indiquaient les données du modèle par composantes. Les composantes principales du flux de CO_2 dans la coupe à blanc provenaient de la respiration souterraine (338 g $C{\cdot}m^{-2}$) et de la photosynthèse des plantes décidues (–375 g $C{\cdot}m^{-2}$). Pendant la saison de croissance, les semis de conifères représentaient seulement une composante mineure du flux total de CO_2 (–48 g $C{\cdot}m^{-2}$). Il est probable que le faible flux négatif aurait été contrebalancé par la respiration souterraine si les flux de CO_2 avaient été pris en compte pour toute l’année. Par exemple, 68 g $C{\cdot}m^{-2}$ supplémentaires se sont ajoutés à l’atmosphère entre le 3 et le 23 septembre (seulement sur la base de la respiration souterraine), après la sénescence des plantes décidues. Cette seule source est suffisante pour faire basculer le site de l’état de puits à celui de source de CO_2.

[Traduit par la Rédaction]

Introduction

Within the last two centuries, anthropogenic CO_2 emissions have increased the levels of atmospheric CO_2 from 280 to over 360 ppm (Keeling et al. 1996). This rise in atmospheric CO_2 has largely been the result of three sources: burning of fossil fuels, cement manufacture, and land-use change. Landscape modification alone is thought to explain approximately 50% of the rise in atmospheric CO_2 prior to 1980 (Woodwell et al. 1983) and to represent 23% of the rise in the 1980s (Schimel 1995). Most of the rise in CO_2 from land-use change is from timber harvesting (Harmon et al. 1990) and the conversion of forests to agriculture and pasture (Tans et al. 1990).

Attempts to quantify the sources and sinks for CO_2 to the atmosphere have unveiled a large missing carbon sink thought to reside in the Temperate Zone of the Northern Hemisphere (Tans et al. 1990; Ciais et al. 1995). While the size of the missing sink is reasonably well established

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(1.5–2.0 Pg C·year^{-1}), its location has not been resolved (Post et al. 1990; Dale et al. 1991; Sarmiento 1993; Dixon et al. 1994). The inability of researchers to pinpoint the area(s) responsible for the accumulation of carbon displays a lack of information about the carbon in the atmosphere and its interaction with the biosphere.

Several complex large-scale models have been created in an attempt to estimate the fluxes of carbon to and from the atmosphere (Birdsey et al. 1993; Burschel et al. 1993; Heath et al. 1993; Kolochugina and Vinson 1993*a*; Kolochugina and Vinson 1993*b*; Melillo et al. 1993; Kurz and Apps 1994; Turner et al. 1995; Cohen et al. 1996). These models are forced to make broad assumptions regarding size and direction of carbon fluxes after disturbance events such as fire, insect outbreak, and timber harvesting (i.e., Burschel et al. 1993; Kolochugina and Vinson 1993*b*; Kurz et al. 1996). With greater empirical knowledge, perhaps, the magnitude of the assumptions could be reduced.

The obvious impact of timber harvesting on forest carbon budgets is the removal of tree carbon and the loss of tree photosynthesis. With CO_2 uptake reduced, it is generally assumed that forest ecosystems will become a source for carbon to the atmosphere, and only when the trees or associated vegetation have been reestablished will the sites revert back to being a sink (Kurz and Apps 1994). The environment (both climate and microclimate) in which the seedlings are grown is crucial in determining when a clearcut will change from a source to a sink for CO_2. For example, sites that are subjected to waterlogging or drought stress may have inhibited forest regrowth, prolonging the length of time the site acts as a source for CO_2.

The impact soil has on the overall carbon budget is poorly understood because information regarding the world's soil carbon pools are limited. Currently, Post et al. (e.g., 1982) and Zinke et al. (e.g., 1984) are the main sources for information on world soil carbon stores. In the boreal forests, a pool of between 65 and 104 Gt carbon, or eight times the amount of carbon stored in the plant biomass, is stored in the soil. Therefore, the size of the carbon flux from belowground may also determine when a site converts from being a source to a sink for carbon. It is often assumed that soil carbon is reduced in the years following a clearcut because of reduced litterfall from the canopy (Covington 1981; Federer 1984; Kawaguchi and Yoda 1989; Yarie 1993; Olsson et al. 1996; Pennock and van Kessel 1997). However, most studies indicate only a small change in soil carbon stores following tree harvest unless the site is exposed to an intense burn (Johnson 1992).

The main microclimate controls on belowground respiration are moisture and temperature (Kucera and Kirkham 197; Fernandez et al. 1993; Striegl and Wickland 1998). The microorganisms responsible for the decomposition of the organic matter generally demonstrate a positive relationship to moisture and temperature. However, if the temperature of the soil becomes too warm or the moisture increases to a level where the soil is waterlogged, a decrease in respiration may result. Therefore, the microclimate initiated by clearing the forest will heavily influence how soils respond. The removal of trees lowers evapotranspiration and may increase solar radiation at the soil surface (Lewis 1998). These environmental changes may result in an increase in soil moisture and temperature. However, the increase in soil temperature could also remove more moisture than is gained from the decrease in evapotranspiration, thus leading to drier soils and lower belowground respiration.

In this paper, we attempt to quantify the flux of CO_2 from a 5-year-old sub-boreal clearcut in central British Columbia using two independent methods. The Bowen ratio energy balance (BREB) method is contrasted with another independent estimate, whereby component fluxes are individually measured and modeled using microclimate data and scaled to the ecosystem level using biomass information for the site. There has been very little research on the overall fluxes of CO_2 from very young disturbed forest sites. It is the intent of this paper to not only establish the magnitude of the CO_2 sink or source strength of this 5-year-old sub-boreal clearcut over the growing season but also to determine the relative importance of the component fluxes, from aboveground and belowground components, on the overall carbon budget.

Methodology

The site

We made CO_2 flux measurements in the summer of 1999 from 27 June to 3 September in a clearcut in the University of Northern British Columbia – University of British Columbia Aleza Lake Research Forest (54°01′30″N, 122°07′30″W). An 84.15-ha stand of sub-boreal spruce–fir forest at 710 m a.s.l. was harvested in 1994 and, after mounding, planted with 2-year-old hybrid white spruce (*Picea glauca* (Moench) Voss × *Picea engelmannii* Parry ex Engelm.) with a smaller component of lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia*) in 1995. The site is described as SBSwk1-8 (wet, cool subzones of the Sub-Boreal Spruce zone) using the forest ecosystem classification of British Columbia (Meidinger and Pojar 1991). The site is cool and wet and has a relatively high snowfall relative to other areas in the central plateau region of sub-boreal British Columbia (mean annual air temperature 1.7–5.0°C). Snowfall typically accumulates by November and melts by the end of April to early May.

Prior to harvesting the site contained a combination of hybrid white spruce and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) with an understory of *Ribes lacustre* (Pers.) Poir., *Lonicera involucrata* (Richardson) Banks ex Spreng, *Viburnum edule* (Michx.) Raf., *Oplopanax horridus* (J. E. Smith) Miq., and *Rubus idaeus* L. The soils are clay and nutrient rich, sub-hygric and have been classified as Orthic Luvic Gleysols (Arocena and Sanborn 1999). At 5 years post-harvest the site contained 1200 spruce seedlings/ha along with a variety of natural deciduous plants dominated by *Chamerion angustifolium* L., *Spiraea douglasii* ssp. *menziesii* (Hook.) Presl, *Rubus idaeus*, *Ribes lacustre*, *L. involucrata*, *Equisetum arvense* L. Fernald, and a variety of grasses dominated by *Calamagrostis canadensis* Michx.

The site was well suited for the Bowen ratio system approach. The canopy was short (mean height 0.6 m), with few of the seedlings exceeding 1.2 m in height (mean seedling height 0.82 m). The dominant wind direction was from the southwest, and the forest edge was well over 400 m from the tower in that direction. The tower had a minimum of 300 m of fetch in all directions, well within the recommended 100 m of fetch for every meter in height suggested by others (Horst and Weil 1992; Stannard 1997). In addition, the site was relatively flat with a slope of approximately 1% overall. The 100 × 100 m measurement area was subdivided into a 20 × 20 m grid network and the BREB tripod placed in the center grid square. Gridlines were also used as a trail network to prevent excessive trampling of the site.

Measurement of ecosystem CO_2 flux

Ecosystem CO_2 flux was measured using a commercial Bowen ratio system (023/CO_2, Campbell-Scientific, Edmonton, Alta.) and the Bowen ratio energy balance (BREB) approach (Tanner 1960; Price and Black 1990). The CO_2 gradient was measured from 27 June to 3 September 1999 by means of a closed-path CO_2–H_2O analyzer (LI-6262, LI-COR Inc., Lincoln, Nebr.) connected to intake tubes situated in arms off the instrument tripod. The top arm of the Bowen ratio system was 2.5 m above ground level and the bottom arm was situated 1.4 m directly beneath it. Flow rates through the system tubing were maintained at 700–800 $cm^3 \cdot min^{-1}$. Every 2 min the air drawn in through the intake tubes was reversed between the reference and sample cells of the infrared gas analyzer (IRGA), and 40 s was allowed for the pump to purge the IRGA and resume measurements. The mean CO_2 gradients were calculated every 20 min. At the beginning of every hour, one cell of the IRGA was scrubbed to establish the absolute concentrations of CO_2 and H_2O, because during the rest of the hour, air from either the upper or lower arm was flowing through the reference cell of the IRGA. The hourly scrub related the millivolt signal to the concentration of CO_2 in each cell within the IRGA. The system was calibrated, at a minimum, two times per week.

The energy balance for the site was determined based on BREB system measures of net radiation (Q^*) and its components sensible heat (H), latent heat (LE), and ground heat flux (G). The Q^* was measured every 10 s with a Q7 net radiometer (Campbell Scientific) that was mounted over a representative surface (2.8 m in height) and averaged over a 20-min interval. To establish the temperature gradient 75-μm chromel–constantan fine-wire thermocouples were placed at the end of each arm. The ground heat flux was estimated using two heat flux plates (HFT-3, Campbell Scientific) each inserted 6 cm below the surface of the ground in conjunction with thermocouple probes (TCAV, Campbell Scientific) placed 4 cm above and 2 cm below each plate. The four leads of the thermocouple averaged the temperature changes between 2 and 8 cm of depth within the soil column.

Calculation of energy and CO_2 fluxes

All BREB calculations were performed using the computer program SPLIT (PC208 Software, Campbell Scientific). In brief, G was calculated in three steps. First, soil characteristics were used to calculate c_S, the heat capacity ($J \cdot m^{-3} \cdot K^{-1}$) of the moist soil:

$$[1] \qquad c_S = \rho_b(c_d + \theta_m c_W)$$

where ρ_b ($kg \cdot m^{-3}$) is the bulk density of the soil, c_d ($J \cdot kg^{-1} \cdot K^{-1}$) is the specific heat of a dry mineral soil, θ_m (no units) is percent water content on a mass basis, and c_W ($J \cdot kg^{-1} \cdot K^{-1}$) is the specific heat of water. Second, the rate of energy storage between the thermocouples belowground (S) ($W \cdot m^{-2}$) over each 20-min interval was then calculated:

$$[2] \qquad S = \frac{\Delta T_S c_S d}{t}$$

where ΔT_S (K) is the change in soil temperature, d (m) is the depth of the sensors, and t is time. The G values were then calculated by summing S and the heat flux ($W \cdot m^{-2}$) values provided by the heat flux plates (G_g) ($W \cdot m^{-2}$):

$$[3] \qquad G = G_g + S$$

Flux densities of LE, H, and CO_2 (F_C) through the atmosphere above the clearcut were calculated based on the following equations that have been used by others (e.g., Price and Black 1990):

$$[4] \qquad \mathrm{LE} = \frac{-L_V K_E \partial \rho_V}{\partial z}$$

$$[5] \qquad \mathrm{H} = \frac{-\rho C_P K_H \partial T}{\partial z}$$

$$[6] \qquad F_C = \frac{-K_C \partial \rho_C}{\partial z}$$

where K_E, K_H, and K_C are the eddy diffusivities for water vapour, heat, and CO_2 respectively; ρ_V ($kg \cdot m^{-3}$) is water vapour density; ρ_C ($kg \cdot m^{-3}$) is CO_2 density; ρ ($kg \cdot m^{-3}$) is air density; C_P ($J \cdot kg^{-1} \cdot K^{-1}$) is the heat capacity of air; L_V ($J \cdot kg^{-1}$) is the latent heat of vapourization; T (K) is the absolute air temperature; and z (m) is height.

Using the universal gas law, eqs. 4 and 6 can be transformed to

$$[7] \qquad \mathrm{LE} = -L_V K_E \frac{P M_W \partial W}{T R \partial z}$$

$$[8] \qquad F_C = -K_C \frac{P M_C \partial C}{T R \partial z}$$

where P (kPa) is pressure, M_W ($g \cdot mol^{-1}$) is the molecular weight of water, W is the mole fraction of water to air, R ($J \cdot kg^{-1} \cdot mol^{-1}$) is the universal gas constant, M_C ($g \cdot mol^{-1}$) is the molecular weight of CO_2, and C is the mole fraction of CO_2 to air.

The BREB system estimates the fluxes of H, LE, and F_C through a number of steps beginning with the simplified energy balance equation:

$$[9] \qquad Q^* = H + \mathrm{LE} + G$$

the similarity assumption ($K_H = K_E = K_C$) (Monteith and Unsworth 1990) and the Bowen ratio. The Bowen ratio, defined as the ratio of sensible to latent energy, was calculated by

$$[10] \qquad \beta = \frac{H}{\mathrm{LE}} = \frac{C\mathrm{p} \partial T}{L_v \varepsilon \partial W}$$

where ∂T (K) is the temperature gradient and ε is the ratio of molecular weight of water vapour to dry air. Combining eqs. 9 and 10 to eliminate LE gives the following equation for H:

$$[11] \qquad H = \frac{\beta(Q* - G)}{1 + \beta}$$

Using H from eq. 11, the eddy diffusivity for CO_2 was estimated by rewriting eq. 5 in finite form as follows:

$$[12] \qquad K_C = K_H = \frac{(z_1 - z_2)\,H}{(T_1 - T_2)\rho C_P}$$

Then, eq. 8 was used in finite form to calculate the CO_2 flux. The fluxes of CO_2 were corrected using the equations established by Webb et al. (1980). In keeping with biometeorological convention, positive fluxes of F_C, LE, and H are used to indicate movement away from the surface and negative toward the surface.

Other meteorological measurements

Additional meteorological variables were measured at the site. Wind speed and direction were estimated using a wind sensor placed at the top of the tower (3.0 m) (R.M. Young Wind Sentry, Campbell Scientific). Light levels were taken at 1.9 m using a quantum sensor (LI-COR quantum sensor, LI-COR Inc., Lincoln, Nebr.). Four thermocouples (chromel–constantan), two at 10 cm and two at 15 cm depth, were inserted into the soil to increase the spatial sampling of soil temperature for modeling purposes. The soil and light measurements were taken every minute and then averaged over 20 min. Lastly, air temperature and relative humidity were measured at 1.7 m with a single probe (HMP35C, Campbell Scientific) every 10 s and then averaged over 20 min. All the data were stored on two data loggers (21X, Campbell Scientific) and downloaded to a field-portable laptop computer as required.

Conifer photosynthesis

At the beginning of the field season, the mean heights of the spruce seedlings were calculated and 20 randomly selected seedlings that were within 1 SD of the mean were selected. A 1-year-old branchlet and either a 3-year-old, 2-year-old, or a second 1-year-old branchlet were selected for photosynthesis measurements on either the north or south side of the seedlings.

Photosynthesis and respiration measurements were made using a portable closed gas-exchange system (LI-6200, LI-COR Inc.) on a weekly basis between 08:00 and 20:00. Microclimate variables of light (photosynthetically active radiation, $\mu mol \cdot m^{-2} \cdot s^{-1}$) (LI-COR quantum sensor, LI-COR Inc.), relative humidity, air temperature, and atmospheric water vapour content were measured by the LI-6200 while soil temperature (Reotemp instruments, San Diego, Calif.) and soil moisture (kg H_2O/kg soil) (Nie-Co-Product Nieuwkoop B.V., Aalsmeer, Holland) were made independently but simultaneous with gas-exchange measurements. Microclimate variables were later used in regression models to establish relationships that were used to estimate carbon uptake (see below).

Deciduous plant photosynthesis

The deciduous plants on site leafed out around 31 May. Throughout the field season photosynthetic and respiration rates of *Chamerion angustifolium*, *S. douglasii* spp. *menziesii*, *L. involucrata*, and *Calamagrostis canadensis*, were measured with the LI-6200 (as above) under varying microclimate conditions between 08:00 and 20:00. The plants were randomly selected on each measuring day within the study area. Area-based photosynthesis was based on one side of the leaf area as determined by leaf traces on transparent acetate sheets.

Soil CO_2 flux measurements

Six pairs of polyvinylchloride collars (9.55 cm in diameter) were placed in randomly selected grid squares throughout the measurement area. Measurements were taken using the LI-6200 with the soil chamber attachment (model No. 6000-09, LI-COR Inc.) as in Norman et al. (1992) on a weekly basis between 08:00 and 20:00. During the soil measurements both soil temperature (model No. 6000-09TC, LI-COR Inc.) and moisture (as above) were taken at a depth of 10 cm.

Biomass

On 7–8 July and 17–18 August, the aboveground living biomass for the deciduous plants was destructively sampled in 24 randomly selected 1-m^2 plots within the measurement grid. On 25 September, the aboveground components of 20 *P. glauca* × *P. engelmannii* seedlings were randomly selected and removed from the site. The seedling branchlets were further divided up into their individual ages and, along with conifer stem and deciduous samples, dried at 65°C for 72 h and weighed.

System flux estimates based on component fluxes

Extrapolations from instantaneous component fluxes to the ecosystem scale were made using regression relationships between component gas-exchange and microclimate data. The ecosystem flux was composed of four primary components: conifer, herbaceous deciduous plant, woody deciduous plant (shrub), and belowground respiration. Multiple regressions relating CO_2 flux from the four components to microclimate variables were established using the best subset method and the R^2 difference test ($p = 0.05$). The regressions provided estimates of the CO_2 fluxes in micromoles C per square metre leaf or ground area per second.

The component model required four steps to scale from the leaf to the clearcut. First, the leaf area to leaf biomass ratios (specific leaf area) were calculated for representative conifer needles and herbaceous and woody plant leaves. Second, specific needle and leaf areas were multiplied by the needle or leaf biomass totals per unit ground area in the clearcut ($g \cdot m^{-2}$) taken throughout the study period to estimate the leaf area per square metre for each plant component. Third, component-level CO_2 fluxes were extrapolated temporally by using continuous micrometeorological information from the Bowen ratio tower in conjunction with the multiple regression equations (Table 1). Finally, estimates from the multiple regressions were multiplied by the leaf area calculated in the second step, producing the carbon flux estimates for the different plant components on a per square

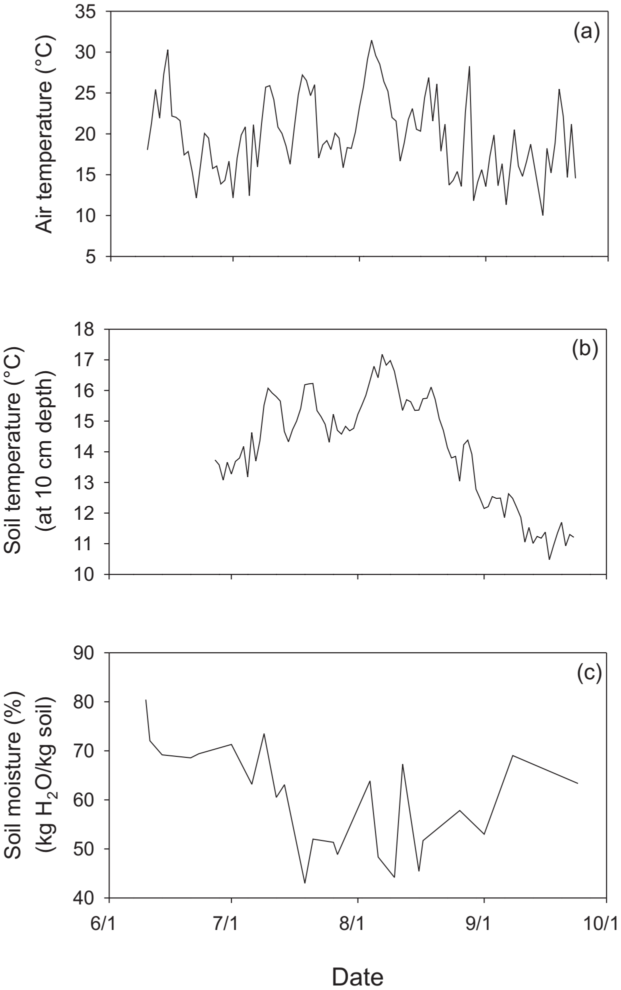
Table 1. Multiple regression equations for estimation of component CO_2 fluxes (belowground respiration (R) and net photosynthesis (P_n) by plant type, day of year and time of day) in a 5-year-old clearcut in the Aleza Lake Research Forest, British Columbia.

Component flux	n	Regression equation (μmol $C\cdot m^{-2}\cdot s^{-1}$)*	R^2	SE
Belowground	115	$R = 0.953 + 0.354A - 0.0198D$	0.66	0.978
Conifer (day)	447	$P_n = -1.61 - 0.22A - 1.8\ln(B) + 0.323C$	0.76	2.74
Conifer (night)	77	$R = 0.056C/(1 - 0.019\,18\ C)$	0.72	0.915
Herbaceous plants (day)	99	$P_n = -7.89 - 0.666A - 1.88\ln(B) - 0.0247C + 0.0416E + 0.007\,291\,F$	0.53	3.30
Herbaceous plants (night)	29	$R = -0.534 - 0.137A + 0.161C + 0.0202G$	0.81	0.465
Woody plants	47	P_n and $R = -4.72 - 1.26\ln(B) + 0.239C$	0.77	1.77

Note: Multiple regressions were established using the best subset method and are based upon a square metre ground area when estimating soil CO_2 efflux and square metre leaf area when estimating leaf CO_2 flux. A, soil temperature; B, quantum flux; C, air temperature; D, soil moisture; E, day of year; F, time of day; G, relative humidity.

*All regression equation variables were significant at the 0.95 level.

Fig. 1. Maximum daily (*a*) air temperature, (*b*) soil temperature, and (*c*) mean soil moisture from 14 June to 23 September 1999 for a clearcut in the Aleza Lake Research Forest, British Columbia (54°01′30″N, 122°07′30″W).



metre basis. When modeling the plant photosynthetic and respiration rates it was assumed that 15% of leaf photosynthesis was lost to stem respiration (Ryan et al. 1994; Levy and Jarvis 1998). The belowground CO_2 flux estimates were already in square metres. Hence, the belowground CO_2 fluxes were estimated based on the regressions and the micrometeorological values given by the tower. Upon completing the CO_2 flux estimates for each component, the overall flux of the site was estimated for 20-min intervals using

$$[13] \quad F_C = F_{\text{conifers}} + F_{\text{herbaceous plants}} + F_{\text{woody plants}} + F_{\text{belowground}}$$

Corrections of BREB data

To estimate a continuous CO_2 flux for the cut block, various corrections of the BREB data were necessary. The site itself, with its shallow slope and large area of fairly uniform terrain and vegetation, was suitable for the BREB approach. However, the data did suffer from the typical problem of poor estimates for dusk, dawn, and most nighttime periods, as well as rainy days (Tanner 1960). The problem periods around dusk and dawn were common but occurred over a short time period, often for less than an hour. Hence, these values were systematically replaced by extrapolating from BREB CO_2 fluxes immediately surrounding the problem periods (Baldocchi et al. 1997; Ham and Knapp 1998). In contrast, during longer periods of equipment failure or extended rain events, CO_2 fluxes were estimated using a regression with light from the days immediately surrounding the missing data. The regression was then used to fill in the gaps in the data (Ham and Knapp 1998). Of the total measurement days, 30% required the use of regressions to fill in lost data.

Nighttime CO_2 fluxes were overestimated because of stratification of the atmosphere as evidenced from high CO_2 concentrations and low wind speeds at the tripod level. Stratification is problematic, because the assumption of equivalence of eddy diffusivity coefficients may not hold true (Verma et al. 1978; Angus and Watts 1984). In addition, the small Q^* values associated with nighttime flux estimations can further exacerbate the problem by inaccurately estimating the eddy diffusivity coefficient resulting in an exaggeration of the CO_2 flux (Price and Black 1990). The nighttime values for the BREB method were extremely poor because of low wind speeds. Therefore, a strict criteria was used to edit data. In conditions when stratification was a problem (lower arm 2 $\mu mol\cdot mol^{-1}$ greater than the upper arm) and (or) the net radiation values were low (between –20 and 20 $W\cdot m^{-2}$), the component flux approach estimates of ecosystem flux were used in place of BREB nighttime estimates. This resulted in the replacement of almost all nighttime BREB data.

Fig. 2. Comparison of Bowen ratio (BREB) and component model daily flux estimates (Table 1) for a 5-year-old clearcut from 27 June to 3 September 1999 in the Aleza Lake Research Forest, British Columbia. Values are similar from 27 June to 7 August after which the two estimates diverge for approximately 14 days. BREB data was corrected with component model data for nighttime periods.

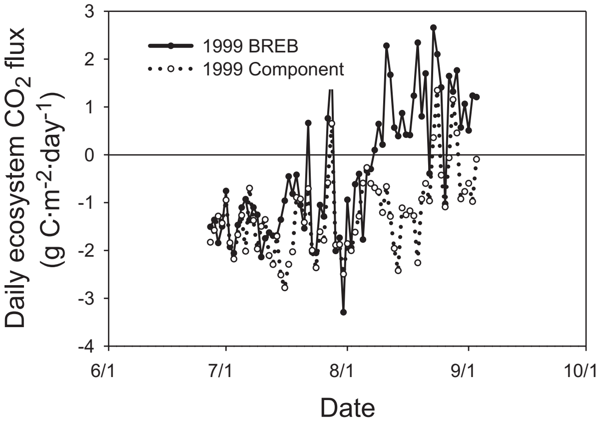


Table 2. Herbaceous and woody biomass for deciduous vegetation early (7–8 July 1999) and late (17–18 August 1999) in the growing season in a 5-year-old clearcut in the Aleza Lake Research Forest, British Columbia.

Date	Herbaceous plant ($g\cdot m^{-2}$)	Woody plant ($g\cdot m^{-2}$)	Total ($g\cdot m^{-2}$)
7–8 July	95	48	143
17–18 August	125	64	189
Biomass increase	30	16	46

Note: The woody estimates are leaf biomass only.

Table 3. Carbon allocation in the stems and needles of interior spruce seedlings from a 5-year-old clearcut in the Aleza Lake Research Forest, British Columbia.

Needle age-class (years)	Stems ($g\cdot m^{-2}$)	Needles ($g\cdot m^{-2}$)	Total ($g\cdot m^{-2}$)
<1	4.34	10.6	14.9
>1	19.9	10.6	30.5
Total	24.2	21.2	45.4

Note: The biomass was sorted according to the age-class of the needles.

Results

Physical environment

The summer of 1999 was cool with few periods of warm weather (Fig. 1*a*). During the study period, the daily high air temperatures ranged from a low of 12.2°C on 1 July to a high of 31.4°C on 6 August. The mean daily temperature over the study period was 13.3°C. Soil temperatures remained between 13 and 15°C for the month of July and peaked at 17.2°C on 7 August. Between 5 May and 24 September the soil remained moist, with levels ranging between 43% on 4 July to a high of 72% on 10 June. Hence, the site was cool during the study period and the soil remained moist for most of the summer.

Microclimate variables and the ecosystem component CO_2 flux

The component fluxes correlated well with microclimate variables. Conifer net photosynthesis correlated well with the microclimate variables of light, soil temperature, and air temperature producing an R^2 of 0.76 (Table 1). Conifer night respiration was well described by air temperature alone (R^2 = 0.72). Estimation of CO_2 exchange in herbaceous plants, based on gas-exchange measurements on *Chamerion angustifolium*, required two separate regressions. Light, soil moisture, and soil temperature were used to estimate photosynthesis, while air temperature, relative humidity, and soil temperature were used to estimate nighttime CO_2 fluxes. Woody deciduous plant carbon uptake was adequately described by a single equation based on the variables light and air temperature for the entire study period. The woody plant regression was established using measurements on *S. douglasii* spp. *menziesii*. Belowground respiration was well correlated with soil moisture and soil temperature at 10 cm depth.

Change from sink for CO_2 to source for CO_2 in early August

The clearcut rapidly changed from a sink to a source in early August (Fig. 2). The days prior to the crossover point were quite warm (Fig. 1), and the plants were beginning to set seed and senesce. Prior to the downturn in photosynthetic uptake of CO_2 the BREB approach estimated CO_2 fluxes that were only 0.005 mg $C\cdot m^{-2}\cdot s^{-1}$ greater (more positive) than the component model, but the difference increased to 0.033 mg $C\cdot m^{-2}\cdot s^{-1}$ after 7 August. The difference in fluxes before and after 7 August was significant at the 99% confidence level ($p < 0.001$).

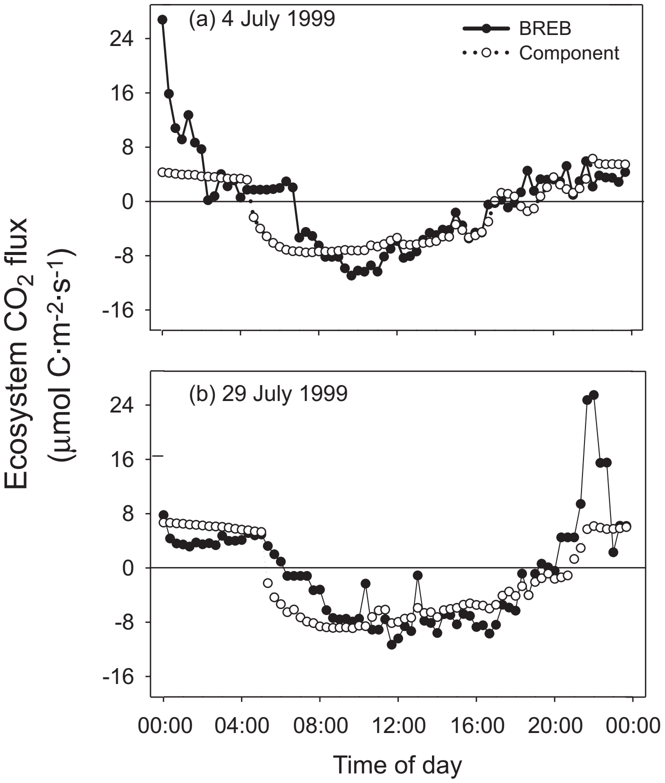
Biomass

The deciduous plants were a much more important sink for CO_2 over the summer than the coniferous plants. The deciduous plants began to leaf out on approximately 1 June and by the middle of August the plants had accumulated over 189 $g\cdot m^{-2}$ of new aboveground biomass (the whole aboveground parts of the herbaceous plants and leaves only for woody plants) (Table 2). By this date most of the deciduous plants had set seed and begun to senescence. The conifers had a planting density of 1200 stems/ha and averaged 379 g/seedling. By the end of the growing season the conifers had only allocated 14.9 $g\cdot m^{-2}$ of new growth to stems and needles (Table 3). In total, plants produced 204 $g\cdot m^{-2}$ of aboveground biomass, with >90% of the new aboveground biomass resulting from deciduous plants.

The BREB method and component model estimates of ecosystem CO_2 fluxes

The component model agreed with the BREB method during the day, but their estimates diverged at night. Typical flux estimates for the clearcut from the component model and BREB methods are shown for 4 July and 29 July 1999 (Figs. 3*a* and 3*b*). For sake of contrast, and to illustrate the

Fig. 3. The estimated CO_2 fluxes using the BREB and component model approaches for (*a*) 4 July and (*b*) 29 July 1999 in a 5-year-old clearcut within the Aleza Lake Research Forest, British Columbia. For the sake of contrast, the BREB nighttime estimates have not been corrected.



problems with nighttime measurement, the BREB nighttime fluxes were not corrected using component model data in these figures. However, by substituting the component model nighttime estimates for poor predictions by the BREB method, the estimated CO_2 efflux from the site is much diminished resulting in both approaches estimating similar daily CO_2 losses or gains for the study area prior to 7 August (Fig. 2). Subsequent to 7 August, the BREB estimates switched from a sink to a source for CO_2, but the component model lagged behind indicating a site transition from sink to source a full 14 days later.

After making nighttime corrections to the BREB data, both the component model and BREB approaches estimated the clearcut to be a sink over the 69-day measurement period (–85 and –22.4 g C·m^{-2}, respectively) (Table 4). Component fluxes indicated that herbaceous and woody plants absorbed the bulk of the carbon removing 210 and 165 g C·m^{-2}, respectively. In comparison, the conifers only removed an estimated 45 g C·m^{-2} or eight times less than the deciduous plants. Belowground respiration acted as a constant CO_2 source throughout the season. From 27 June to 3 September the roots and soil flora and fauna released 338 g C·m^{-2}, thereby counteracting most of the carbon sink generated via plant photosynthesis.

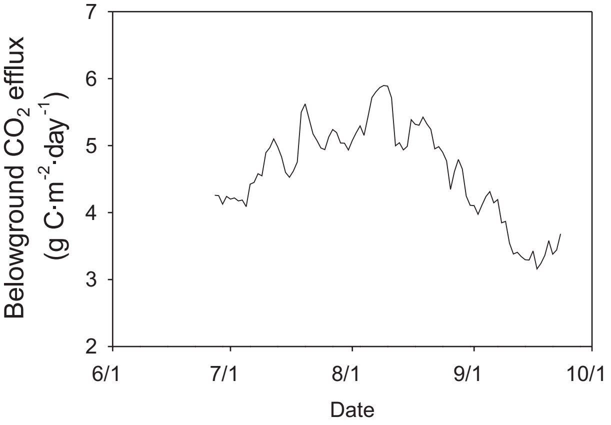
Belowground CO_2 efflux

Belowground CO_2 efflux was sizable both during the growing season (4.12–5.89 g C·m^{-2}·day^{-1}) (Table 4) and for measurement dates following the study period (3.16–4.2 g C·m^{-2}·day^{-1}) (Fig. 4). In fact, belowground respiration from 4 through 23 September, a time when herbaceous plants were without foliage and woody plants mostly senescent, contributed a further 68 g C·m^{-2} to the atmosphere (Fig. 4), enough to convert the site into an overall source for CO_2.

Table 4. Seasonal estimates of CO_2 accumulation in the various components using the component model from 27 June to 3 September 1999 in a 5-year-old clearcut at the Aleza Lake Research Forest, British Columbia.

Component	Component model (g C·m^{-2})	BREB method (g C·m^{-2})
Conifers	–48	—
Herbaceous plants	–210	—
Woody plants	–165	—
Belowground	338	—
Total	–85	–22.4

Fig. 4. Belowground efflux of CO_2 from 27 June to 23 September 1999 from a 5-year-old clearcut in the Aleza Lake Research Forest, British Columbia. Belowground efflux totaled 68 g CO_2·m^{-2} during the 19 days following the last Bowen ratio ecosystem flux measurement.



Discussion

BREB flux estimates

The component model and BREB methods produce very similar flux estimates during daylight hours. Daytime estimates were very comparable (Figs. 3*a* and 3*b*) as were the corrected daily fluxes until approximately 7 August (Fig. 2). The two models diverged after 7 August with the BREB method estimating the site to be a larger source for CO_2 than the component model. The major problem associated with the component model was its reliance on measured leaf-level CO_2 fluxes that were only measured once or twice every 2 weeks. A rapid decrease in photosynthetic uptake due to senescence, flowering and seed set, heat stress or frost damage could not be accommodated by the discrete sampling regime associated with the component model approach. As a result, the component model estimated the clearcut to be a larger sink for CO_2 than the BREB method.

Both approaches estimated the site to be a sink for CO_2 for the 69-day study period (Table 4). The component model's estimate is likely too large because of its inability to interpolate fluxes during the 2 weeks subsequent to 7 August. Prior to 7 August, the discrepancy between the BREB method and the component model was only 0.005 mg $C{\cdot}m^{-2}{\cdot}s^{-1}$, but after 7 August the difference increased to 0.033 mg $C{\cdot}m^{-2}{\cdot}s^{-1}$. While this difference appears small difference, it was significant enough to result in a sink of –22 g $C{\cdot}m^{-2}$ for the BREB method versus –85 g $C{\cdot}m^{-2}$ for the component model.

The carbon uptake estimated by the component model for deciduous plants was in line with aboveground biomass carbon measured. If we assume that biomass is 50% carbon, aboveground biomass of 204 $g{\cdot}m^{-2}$ would translate into 102 g $C{\cdot}m^{-2}$. In comparison, the component model estimates that between 27 June and 18 August, the plants absorbed 342 g $C{\cdot}m^{-2}$. Assuming 50% of CO_2 uptake went into belowground biomass (Raich and Nadelhoffer 1989; Broderick 1990) and 55% of the remainder was lost to respiration (Waring et al. 1998), the component model would estimate an uptake of 77 g $C{\cdot}m^{-2}$. These values are relatively close considering the assumptions involved and the loss of biomass through seeds, flowers, stem growth, and leaf turnover was not captured, and a portion of the growing season between 1 and 26 June was missed.

Following 3 September the deciduous plants senesced and the conifers hardened off for the winter, but CO_2 efflux from belowground continued (Fig. 4). Belowground respiration emitted an estimated 68 g $C{\cdot}m^{-2}$ between 3 September and 23 September alone, and the efflux of CO_2 would have continued, albeit at a reduced rate, under the snowpack (Coxson and Parkinson 1987; Sommerfeld et al. 1993; Clein and Schimel 1995; Evans et al. 1998). The snow insulates the soil, buffering it against the colder air temperatures thereby allowing for greater belowground respiration (Bleak 1970; Moore 1983). A study conducted during the winters of 1997 and 1998 by Evans et al. (1998) within the Aleza Lake Research Forest at a site with an identical site class (SBS week1–8) observed winter fluxes from between 0.60 to 0.77 g $C{\cdot}m^{-2}{\cdot}day^{-1}$. Others have measured similar winter CO_2 fluxes of between 0.41 to 0.77 g $C{\cdot}m^{-2}{\cdot}day^{-1}$ (Sommerfield et al. 1993) and 0.20 to 0.82 g $C{\cdot}m^{-2}{\cdot}day^{-1}$ (Coxson and Parkinson 1987) in southeastern Wyoming and southwestern Alberta, respectively.

Using the values from Evans et al. (1998) the loss of CO_2 from the site can roughly be estimated to be between 83 and 121 g $C{\cdot}m^{-2}{\cdot}year^{-1}$. The estimate contains four specific assumptions: CO_2 losses range between 0.60 and 0.77 g $C{\cdot}day^{-1}$ under the snowpack (1 November to 30 April); fluxes linearly decreased to the winter flux in the fall (4 September to 31 October); fluxes decreased from the winter flux to a net uptake of –1.41 g $C{\cdot}day^{-1}$ in the spring (1 May to 1 June) when the site flushed (–1.41 g $C{\cdot}day^{-1}$ is the average daily C flux from 27 June to 5 July); and after June 1 the flux remained at –1.41 g $C{\cdot}day^{-1}$ until 27 June when the BREB flux estimates resumed. While the assumptions do not provide a confident estimate of the annual ecosystem C flux, it does demonstrate that the loss of CO_2 from belowground during the winter months (109–139 g $C{\cdot}m^{-2}$) is enough to surmount any gain by the plants during the summer months.

Considering the size of the CO_2 efflux from belowground in the years immediately following timber harvest, the relatively larger CO_2 uptake by the deciduous plants to coniferous plants becomes important. If the loss of CO_2 in the years immediately following timber harvest is to be reduced, an attempt must be made to minimize the removal of deciduous plants by mechanical and chemical brushing. Clearly, a balance must be established between reestablishing the conifers and supporting the deciduous plants present.

The component CO_2 fluxes

Mid-day conifer photosynthesis was similar to rates measured by others under a variety of conditions (Watts and Neilson 1978; Bassman 1989; Man and Lieffers 1997), typically ranging between 5 and 9 μmol $C{\cdot}m^{-2}{\cdot}s^{-1}$ depending on the climate and microclimate. The deciduous plants had much higher mid-day photosynthetic rates than in conifers, typically ranging from between 6 and 16 μmol $C{\cdot}m^{-2}{\cdot}s^{-1}$ depending on the species and the micrometeorological conditions.

Belowground CO_2 efflux, between 27 June and 23 September, totaled 406 g $C{\cdot}m^{-2}$, with values ranging from 3.16 to 5.90 g $C{\cdot}m^{-2}{\cdot}day^{-1}$. Other studies involving recently cleared forest have found fluxes that were comparable with our values (Edwards 1975; Ewel et al. 1987; Gordon et al. 1987). However, some studies have estimated CO_2 fluxes that were lower than those found in this study (Weber 1990; Fernandez et al. 1993; Lytle and Cronan 1998; Striegl and Wickland 1998). This variation is likely due to site-specific constraints on soil respiration and (or) plant productivity. The high moisture levels (rarely below 50%) and relatively high nutrient status of the site may have enhanced decomposition and root activity (Fig. 1).

The overall CO_2 fluxes in comparison to other northern forests

The observed BREB method fluxes of –0.05 to –0.21 mg $C{\cdot}m^{-2}{\cdot}s^{-1}$ (based on 20-min averages for July and early August) between 09:00 and 15:00 in this study are similar to those found in the literature for young clearcuts and some mature stands. For example, Price and Black (1990) found daytime (09:00 and 15:00) CO_2 fluxes above a juvenile Douglas-fir stand during 24 and 29 July and 4 August to be –0.05 to –0.14 mg $C{\cdot}m^{-2}{\cdot}s^{-1}$ (from 30-min averages). The main difference between the Douglas-fir stand and the planted spruce clearcut was that the former was a source for CO_2 for a longer period of the day. This may have resulted from drier conditions and shorter summertime daylight hours at the lower latitude site used in the Price and Black (1990) study. Similarly, during the month of July 1996, Valentini et al. (2000) measured the CO_2 exchange above a 12-year-old regenerating boreal forest in central Siberia and found it to be a small sink for CO_2 (–0.093 g $C{\cdot}day^{-1}$) during two measurement periods (6–15 and 21–26 July).

The maximum CO_2 uptake rate observed for the clearcut was ≈0.22 mg $C{\cdot}m^{-2}{\cdot}s^{-1}$, but it averaged approximately 0.11 mg $C{\cdot}m^{-2}{\cdot}s^{-1}$at mid-day across the study period. Mature stands in the boreal forest tend to have equivalent or lower fluxes of CO_2 when compared with the clearcut in this study. Values of growing season fluxes in high-latitude forests range from maximum values of 0.15 mg C·m^{-2}·s^{-1} in an ecotonal boreal forest to a minimum of 0.049 mg C·m^{-2}·s^{-1} in a Siberian larch forest (Hollinger et al. 1998, 1999). Maximum CO_2 uptake for Canadian boreal forests average between ≈0.084 mg C·m^{-2}·s^{-1} (Jarvis et al. 1997) at the southern BOREAS black spruce site to ≈0.095 mg C·m^{-2}·s^{-1} in a black spruce – lichen woodland near Scheferville, Que. (Fan et al. 1995), and a jack pine forest in central Saskatchewan (Baldocchi et al. 1997). A deciduous aspen site within the boreal forest attained net CO_2 uptake rates of ≈0.24 mg C·m^{-2}·s^{-1} (Black et al. 1996), and this is closer to the maximum values found in this study. Deciduous plants performed the majority of the CO_2 uptake in the clearcut, and they tended to have a greater ability to absorb CO_2 over the short term than the conifer seedlings. However, the growing season for deciduous plants is shorter, because they are not able to take advantage of climatically favourable days in spring and autumn. The site's transition from being a sink to a source was rapid in early August, possibly as a result of increased deciduous plant respiration from seed production and (or) respiration and senescence associated with high air temperature at that time. Given the low growing season sink strength calculated for the clearcut, year-to-year variations in climate could dictate whether such sites act as a source or sink for CO_2.

While there is little information that is useful regarding boreal or sub-boreal cut block carbon budgets, there is a growing body of information on mature forests. Recently, it has been found that northern mature forests may be tenuously balanced between being a carbon source or sink. For example, Goulden et al. (1998), demonstrated that a boreal black spruce site was a source for CO_2 over the span of 1 year (≈70 g C·m^{-2} for October 1994 to October 1995 and ≈20 g C·m^{-2} for October 1995 to October 1996) but a sink over the year from October 1996 to October 1997 (≈10 g C·m^{-2}). Furthermore, Lindroth et al. (1998), found that a forest in Sweden lost ≈90 g C·m^{-2} between 1 June 1994 and 31 May 1995 and ≈60 g C·m^{-2} during the same period in 1995–1996.

Conclusion

Over the study period, roughly coinciding with the growing season, the vegetated clearcut in this study acted as a small sink for CO_2. However, if estimates for belowground fluxes for the entire year are considered, losses of CO_2 from the soil would easily exceed that taken up through photosynthesis by deciduous "brush" species and conifers at the site. The conifer seedlings, because of their small biomass, were only a small contributor to the overall carbon budget for the clearcut. It was the deciduous plants that acted as the primary sink for CO_2 for the clearcut, even after 4 years of conifer growth. For this reason, mechanical (brushing) or herbicidal removal of deciduous ("noncrop") vegetation after clear-cutting should be avoided if our goal is to minimize the accumulation of greenhouse gases in atmosphere during the years immediately after forest harvest.

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