



Ecosystem CO₂ flux over two growing seasons for a sub-Boreal clearcut 5 and 6 years after harvest

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Abstract

We measured the ecosystem-level growing season CO₂ fluxes for a 6-year-old vegetated sub-Boreal clearcut from 24 May to 20 September 2000, and compared the results to CO₂ fluxes from the same clearcut in 1999 (27 June–3 September). Two independent approaches were used to measure ecosystem CO₂ flux for both years. A Bowen ratio energy balance (BREB) method was contrasted with a second approach using component fluxes. The Component model approach was based on scaling up from regressions relating in situ CO₂ flux measurements for conifer seedlings (*Picea glauca* × *engelmannii*), as well as representative herbaceous (*Chamerion angustifolium*), woody (*Lonicera involucrata*) plant species and soil surface CO₂ efflux to microclimate conditions. The BREB method and Component model estimated the clearcut to be a source of CO₂ 6 years post-harvest (24 May–20 September 2000) in amounts of 142 g C m⁻² (1.4 t ha⁻¹) and 103 g C m⁻² (1.0 t ha⁻¹), respectively. The positive net ecosystem CO₂ fluxes over the growing season resulted from a large soil surface CO₂ efflux (686 g C m⁻²) that surmounted the photosynthetic CO₂ uptake for the clearcut. The photosynthetic CO₂ uptake partially compensated for the soil surface losses: the conifer seedlings, herbaceous plants and woody shrubs were estimated to uptake –96, –315, –172 g C m⁻², respectively.

The results of 2000 contrasted with those of 1999. Over a comparable period of measurement (27 June–3 September), the clearcut was a sink for carbon in 1999 (–22.4 g C m⁻² using the BREB method and –85 g C m⁻² using the Component model) and a source in 2000 (65 g C m⁻² using the BREB method and 44 g C m⁻² using the Component model). The growing seasons of 1999 and 2000 experienced similar photosynthetic uptake over this same interval (–423 and –422 g C m⁻², respectively). The main difference between the two field seasons was an increase in the soil surface CO₂ efflux from 1999 to 2000. In 1999, the soil surface CO₂ efflux was 338 g C m⁻² and in 2000 the flux was 38% higher (466 g C m⁻²) for the same period. The results indicate that while there was notable inter-annual variation in CO₂ fluxes, particularly the soil surface CO₂ effluxes, this young regenerating sub-Boreal forest (≤6 years after harvesting) is a net source of CO₂ when the entire growing season is considered.

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Keywords: Bowen ratio; Clearcut carbon budget; Ecosystem CO₂ flux; Soil surface CO₂ efflux (soil respiration); Forest management

1. Introduction

Over the past several decades, the sign and magnitude of net CO₂ fluxes from forested stands has received much attention. Micrometeorological tech-

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39 niques have been used to quantify the flux of carbon
40 to and from forests in an effort to understand
41 soil–plant–atmosphere interactions. To date, ecosys-
42 tem CO₂ flux measurements have been disproportion-
43 ately occurring in mature forests, with little research
44 focusing on recently disturbed forests. For example,
45 most of the forests measured in North America are
46 mature forests that have been demonstrated to be sinks
47 for carbon (e.g. Goulden et al., 1996; Jarvis et al.,
48 1997; Barr et al., 2000; Black et al., 2000). How-
49 ever, northern latitude forest sinks are thought to be
50 relatively small (IPPC, 2000), and some black spruce
51 dominated forests may even be sources (e.g. Goulden
52 et al., 1998). While this information is clearly impor-
53 tant, less than 50% of forests in North America are
54 greater than 90-year-old (Kurz et al., 1995). Hence, it
55 is equally important to quantify fluxes from recently
56 disturbed forest sites so that we can better understand
57 and predict the impact of current and future distur-
58 bance on carbon fluxes.

59 The magnitude and direction of the carbon fluxes
60 in the years following forest harvest is of particular
61 interest because of the continued and growing need
62 for fuel/energy and wood products, combined with the
63 fact that half of the world's terrestrial organic soil and
64 vegetation carbon (~2477 Gt) is resident in the earth's
65 forest systems (IPCC, 2000). The uncertainty associ-
66 ated with the impact of forestry and forest clearing on
67 carbon pools relates to issues of how young forests
68 sequester carbon relative to old forests and the effect
69 of climate (e.g. warming) on fluxes and pools.

70 Boreal forests are of concern globally because
71 of their large aerial extent and consequently large
72 amounts of carbon stored (between ~300 and 560 Gt
73 of carbon), combined with the fact that perhaps 80%
74 or more of this carbon is below ground (Post et al.,
75 1982; Apps et al., 1993; IPCC, 2000). Thus, the
76 magnitude of the soil surface carbon flux subsequent
77 to forest harvesting of Boreal forests is of particular
78 interest.

79 Forest harvesting has at least three main effects on
80 forest carbon. First, timber harvesting effectively re-
81 moves the above ground carbon biomass and transfers
82 it into products with short (paper products) to inter-
83 mediate (lumber, building products) residency times
84 relative to natural forest carbon stocks. The diver-
85 sion of this biomass from forest ecosystems to wood
86 products generally results in greater atmospheric CO₂

87 concentrations (Harmon et al., 1990; Schulze et al.,
88 2000). Second, the removal of the photosynthetic tree
89 biomass results in a reduction in the uptake of carbon
90 through photosynthesis in the years immediately
91 following harvest. Finally, changes in below ground
92 carbon and soil properties following harvesting can alter
93 CO₂ fluxes. Together, these factors are believed to
94 cause a clearcut, to be a source of CO₂ for approxi-
95 mately 10 years after harvest (Kurz and Apps, 1994).
96 However, there are few empirical studies of CO₂ fluxes
97 from young northern cut blocks or clearcuts to quan-
98 tify the duration and strength of the source resulting
99 from harvesting activities.

100 The size of the soil surface CO₂ efflux after har-
101 vesting greatly impacts the magnitude and direction
102 of the net ecosystem CO₂ flux. Removal of above
103 ground vegetation is known to increase soil tempera-
104 ture (Lewis, 1998), and there is a strong positive cor-
105 relation between soil surface CO₂ efflux and soil tem-
106 perature (Kucera and Kirkham, 1971; Fernandez et al.,
107 1993; Striegl and Wickland, 1998) that can result in
108 the mobilization of below ground carbon stocks. There
109 is little doubt that the relative sizes of the soil surface
110 CO₂ efflux to plant photosynthesis have an important
111 impact on the overall net carbon balance of a clearcut.

112 In 1999, the growing season ecosystem CO₂ fluxes
113 from a clearcut within sub-Boreal British Columbia
114 (Pypker and Fredeen, 2002) indicated that it was a
115 sink of between -22.4 and -85 g C m⁻². However,
116 when CO₂ fluxes for the entire year were taken into
117 consideration, the 5-year-old clearcut was projected to
118 be a source of CO₂ rather than a sink. To corroborate
119 this projection, we measured ecosystem CO₂ fluxes
120 in the same clearcut over an extended growing season
121 in 2000. We further contrast and compare measured
122 ecosystem-level growing season CO₂ fluxes between
123 1999 and 2000, and establish if vegetated sub-Boreal
124 clearcuts are likely to be sources or sinks of CO₂ 6
125 years after harvesting.

126 2. Materials and methods

127 2.1. Site description

128 An 84.15 ha area was clearcut within the current
129 boundaries of the University of Northern British
130 Columbia/University of British Columbia Aleza Lake

131 Research Forest in Central British Columbia (BC),
 132 Canada in the winter of 1994. The site was treated
 133 with a broadcast burn and planted in the summer of
 134 1995 with 2-year-old interior hybrid white spruce
 135 (*Picea glauca* × *engelmannii*) with minor inclusions
 136 of lodgepole pine (*Pinus contorta* var. *latifolia*) at
 137 1200 seedlings ha⁻¹. In April 1999, we established a
 138 1 ha research plot in the clearcut to quantify the mag-
 139 nitude and direction of the CO₂ flux in a managed
 140 sub-Boreal forest clearcut. The clearcut is located in
 141 the central plateau region of the province (54°01'30''
 142 N and 122°07'30'' W) in a wet cool subzone (SBS
 143 wk1-8 biogeoclimatic zone) according to the ecosys-
 144 tem classification of BC (Meidinger and Pojar, 1991)
 145 with mean annual air temperatures ranging from 1.7
 146 to 5 °C. The snowfall is high relative to other areas
 147 in sub-Boreal BC, with snow typically accumulating
 148 in November and melting in late April/early May.
 149 The soils are sub-hygric, clay and nutrient rich, and
 150 are classified as Ortho Luvic Gleysols (Arocena and
 151 Sanborn, 1999).

152 In the summer of 2000, the spruce seedlings had
 153 an average height of 1.03 m with very few of the
 154 seedlings exceeding 1.25 m. Other vegetation in the
 155 clearcut included herbaceous deciduous species: fire-
 156 weed (*Chamerion angustifolium* (previously *Epilo-*
 157 *bium*)), bunch berry (*Cornus canadensis*), horsetail
 158 (*Equisetum arvense*), and several grasses dominated
 159 by *Calamagrostis canadensis*, in conjunction with
 160 short woody shrubs: twin berry (*Lonicera involu-*
 161 *crata*), pink spirea (*Spiraea douglasii* spp. *menziesii*),
 162 raspberry (*Rubus idaeus*), and goose berry (*Ribes la-*
 163 *custre*). Fireweed and twin berry contained a substan-
 164 tial portion of the biomass for the herbaceous (29%
 165 of total biomass and 44% of herbaceous biomass)
 166 and woody plants (13% of total biomass and 19% of
 167 woody shrub biomass), respectively. The deciduous
 168 vegetation represented the bulk of the above ground
 169 plant biomass (>90%) and had an average height of
 170 only 0.6 m. The high proportion of fireweed relative
 171 to the other species created a fairly homogenous site.

172 2.2. Bowen ratio energy balance (BREB) method

173 From 24 May to 20 September 2000, a full 50 days
 174 longer than in the 1999 growing season (see Pypker
 175 and Fredeen, 2002), BREB measurements were made
 176 in the clearcut. The CO₂ gradient was measured using

177 a commercial Bowen Ratio Energy Balance system
 178 (023/CO₂, Campbell Scientific, Edmonton, AB) and
 179 an infra-red gas analyzer (LI-6262, LI-Cor Inc., Lin-
 180 coln, NE) placed on a 3.3 m tall tower located a
 181 minimum of 300 m from the forest edge. The top
 182 arm of the Bowen ratio system was mounted at 2.8 m
 183 and the bottom arm 1.48 m beneath it (minimum
 184 fetch = 300 m). Q^* was measured every 10s with a
 185 Q7 radiometer mounted (3 m) over a representative
 186 site (Campbell Scientific). The temperature gradi-
 187 ent was measured using 75 μm chromel–constantan
 188 thermocouples mounted at the end of each arm. The
 189 ground heat flux (G) was determined by monitoring
 190 two soil heat flux plates placed at a depth of 6 cm
 191 (HFT-3, Campbell Scientific) and four soil thermo-
 192 couples (TCAV, Campbell Scientific) placed in pairs
 193 at depths of 2 and 8 cm. Soil temperature at 10 cm
 194 depth was continuously monitored using thermocou-
 195 ples (copper–constantan) at four additional locations.

196 2.3. Other meteorological measurements

197 A full complement of meteorological instruments
 198 were employed to measure wind speed and direc-
 199 tion (at 3.3 m) (R.M. Young, Wind Sentry, Camp-
 200 bell Scientific), light (at 2 m) (LI-Cor quantum sensor,
 201 LI-Cor Inc.), and air temperature and relative humidity
 202 (at 1.9 m) (HMP35C, Campbell Scientific) above the
 203 clearcut. A tipping rain gauge (TE-525M, Campbell
 204 Scientific) was placed in the clearcut to measure rain-
 205 fall (in 1999 we used a rain gauge located 5 km away
 206 from the clearcut). All the data was averaged over
 207 20 min, stored on two data loggers (21X, Campbell
 208 Scientific) and downloaded as necessary to a laptop
 209 computer in the field. To provide an historical record
 210 of the climate in the research forest, monthly climate
 211 averages (1993–1998) were attained from a meteoro-
 212 logical tower located in a clearcut within the Aleza
 213 Lake research forest approximately 5 km away from
 214 the clearcut in this study.

215 2.4. Conifer and deciduous plant photosynthesis

216 Average height of spruce seedlings in the clearcut
 217 was determined ($n = 100$) in May 2000, and 19
 218 seedlings ±1 standard deviation of the mean height
 219 were selected for further physiological study. Spruce
 220 photosynthesis and respiration measurements were

221 made on 1-year-old branchlets from either the north
 222 or south sides of the selected seedlings. Seedling
 223 photosynthesis and respiration were only measured
 224 on 1-year-old needles because: previous destructive
 225 biomass samples indicated very few needles >2 years
 226 of age; the conifer seedlings represented less than
 227 10% of the plant biomass (Pypker and Fredeen, 2002);
 228 and the difference between needle photosynthesis is
 229 generally small (Sullivan et al., 1997).

230 Leaf and branchlet gas-exchange measurements
 231 were made on a biweekly basis using a portable
 232 closed gas-exchange system (LI-6200, LI-Cor, Inc.)
 233 on green, healthy leaves, under ambient light levels
 234 between 1100 and 1500 h. The measurements were
 235 taken on deciduous plants that were randomly selected
 236 each week and on continuously monitored conifer-
 237 ous trees. Air temperature, atmospheric water vapor
 238 content, PAR, and RH were measured along with net
 239 CO₂ exchange in *P. glauca* × *engelmannii*, *C. an-*
 240 *gustifolium*, *L. involucrata* and *S. douglasii* spp. *men-*
 241 *ziesii* from May (leaf-out in deciduous plants in 2000
 242 was complete by 31 May) until mid-September. In-
 243 stantaneous measures of soil temperature (Reotemp
 244 instruments, San Diego, California) and gravimet-
 245 ric soil moisture (Nie-Co-Product Nieuwkoop B.V.,
 246 Aalsmeer, Holland) were also made concurrently with
 247 all gas-exchange measurements. Area-based photo-
 248 synthesis and respiration estimates for the deciduous
 249 plants were based on one side of the leaf area as de-
 250 termined by leaf traces on transparent acetate sheets.
 251 Area-based photosynthesis estimates for conifers
 252 were based on projected needle areas estimated using

a computerized image analysis system (WinNeedle, 253
 Regent Instruments Inc., PQ, Canada). 254

2.5. Soil CO₂ flux measurements 255

256 Six pairs of PVC collars (9.55 cm in diameter) were
 257 placed in randomly selected grid squares through-
 258 out the measurement area. Measurements were taken
 259 using an LI-6200 with the soil chamber attachment
 260 (6000-09, LI-Cor Inc.) as in Norman et al. (1992). The
 261 soil collars were measured on a biweekly basis at the
 262 same location throughout the summer. The soil collars
 263 were only moved if the measurement site degraded
 264 (i.e. shaky collars, gaps between collar and the soil).
 265 As in the case of photosynthesis measurements, both
 266 soil temperature (6000-09TC, LI-Cor Inc.) and gravi-
 267 metric moisture (Nie-Co-Product Nieuwkoop B.V.,
 268 Aalsmeer, Holland) were taken at a depth of 10 cm
 269 simultaneous with each gas-exchange measurement.

2.6. Component flux model 270

271 We scaled up from instantaneous component fluxes
 272 to ecosystem-level using a method which we call the
 273 component flux model approach (see Pypker and Fre-
 274 deen, 2002). Briefly, the approach is based on multiple
 275 regression equations relating the measured instantane-
 276 ous component fluxes from conifer, herbaceous dec-
 277 iduous plant, woody deciduous plant (shrub) and the
 278 soil surface, to microclimate variables using the best
 279 subset method and the R² difference test (P = 0.05;
 280 Table 1). Four additional steps were then used to scale

Table 1

The relationship between microclimate variables and the soil surface CO₂ efflux (G_R) and net photosynthesis (P_n) and respiration (P_R) in conifer, herbaceous plant and woody shrub components of a 6-year-old clearcut within the Aleza Lake Research Forest, British Columbia

Component	n	Regression equation ^a (μmol C m ⁻² s ⁻¹)	R ²	S.E.
Soil surface		G _R = 0.092 + 3.647 ^(A/10)	0.70	1.33
Conifer (day)	145	P _n = 0.613 - 0.0776A - 0.019275B + 0.00000763B ² + 0.2438C - 17.12D	0.54	3.04
Conifer (night)	50	P _R = 0.0912C/(1 - 0.0089C)	0.48	0.777
Herbaceous plants (day)	90	P _n = 3.23 - 3.88 ln B + 0.0524E	0.72	2.79
Herbaceous plants (night)	43	P _R = 0.912C/(1 - 0.0155C)	0.51	0.900
Woody shrubs (day)	88	P _n = -10.9 - 0.0141B + 0.000005B ² + 0.553C - 4.59F + 0.0162G	0.78	1.57
Woody shrubs (night)	38	P _R = 0.0576C/(1 - 0.0069C)	0.45	0.362

Multiple regressions were established using the best subset method and are based upon m² ground area when estimating soil CO₂ efflux and m² leaf area when estimating leaf CO₂ flux. Standard error of the estimate (S.E.) is provided; A, soil temperature (10 cm depth); B, light (μmol PAR m⁻² s⁻¹); C, air temperature; D, relative humidity (%); E, day of year; F, absolute humidity (kPa H₂O); G, soil moisture (%).

^a All regressions significant at the 0.95 level.

up from plant component flux regression equations to ecosystem level fluxes. First, component level CO₂ fluxes were extrapolated temporally using the multiple regressions equations in Table 1 and continuous micrometeorological information from the Bowen ratio tower. Second, leaf area to leaf biomass ratios (specific leaf areas) were calculated for representative conifer needles and herbaceous and woody plant leaves. Third, specific needle and leaf areas were multiplied by needle and leaf biomass totals per unit ground area in the clearcut (g biomass m⁻²) to estimate leaf area index (LAI: m² leaf m⁻² ground area) for each plant component. For deciduous plants, aboveground biomass was harvested from 12 randomly selected 0.5 m² quadrats within the measurement grid six times across the growing season. For conifer biomass, above ground components of 20 *P. glauca* × *engelmannii* seedlings were removed from the site in early May and again at the end of September and, along with the deciduous samples, separated into leaf and stem components and dried at 65 °C for 72 h before weighing. Finally, output from the multiple regressions for each plant component were multiplied by that component's LAI to give ground area based CO₂ flux estimates.

When modeling the plant respiration rates, it was assumed that 15% of leaf photosynthesis was lost to stem respiration (Ryan et al., 1994; Levy and Jarvis, 1998). Soil surface CO₂ efflux was already on a ground area basis, and hence, was scaled to the ecosystem level directly using multiple regressions and continuous micrometeorological information from the tower. Finally, overall Component model ecosystem level CO₂ flux ($F_{C \text{ clearcut}}$) was computed by summing component CO₂ flux estimates over 20 min intervals:

$$F_{C \text{ clearcut}} = F_{\text{conifers}} + F_{\text{herbaceous plants}} + F_{\text{woody plants}} + F_{\text{soil surface}}$$

2.7. Calculation and correction of BREB energy and CO₂ fluxes

The BREB calculations were based on that of Tanner (1960) and others (e.g. Webb et al., 1980; Price and Black, 1990; Steduto and Hsiao, 1998), with a full description in Pypker and Fredeen (2002). In keeping with biometeorological convention, pos-

itive ecosystem level fluxes of CO₂, LE and H are used to indicate movements of mass and energy away from the surface and negative toward the surface.

The BREB data for 2000 required some corrections. Specifically, fluxes during dusk, dawn and nighttime periods were commonly in error and were systematically replaced as in Pypker and Fredeen (2002). In brief, problem periods of short duration, i.e. dawn, dusk and short rain events, were replaced by interpolating from fluxes immediately surrounding the problem intervals (Baldocchi et al., 1997; Ham and Knapp, 1998). Longer periods, including rain events and equipment failure, were replaced using regressions interpolating from linear regressions between light and ecosystem CO₂ flux from days immediately bracketing the missing periods (Ham and Knapp, 1998). Unlike 1999, where 30% of the daytime measurements were replaced, regression equations were only required to fill data for 15% of the days in 2000. The nighttime BREB CO₂ flux estimates were very poor and were, with a few minor exceptions, replaced with Component model CO₂ fluxes. The pronounced inversions and low net radiation values experienced during the nighttime periods in this study typically result in poor nighttime BREB estimates (e.g. Tanner, 1960; Price and Black, 1990).

3. Results

3.1. Climate and microclimate

Growing season mean monthly air temperatures for the clearcut in 2000 ranged from 8.5 °C in September to 14.5 °C in July, with a growing season rainfall total of 395 mm (Fig. 1). The monthly mean air temperatures were significantly cooler than the past 6 (1993–1998) years in May and September ($P = 0.05$). Precipitation in 2000 was significantly greater than for the 5-year averages for July, August and September, 1993–1998 ($P = 0.05$). While soil moisture and soil temperature at 10 cm depth were not statistically different between 1999 and 2000 (Fig. 2), precipitation in 2000 was 56 mm greater than 1999 in July and August (Fig. 2a). There were no statistical differences in air temperature between 1999 and 2000.

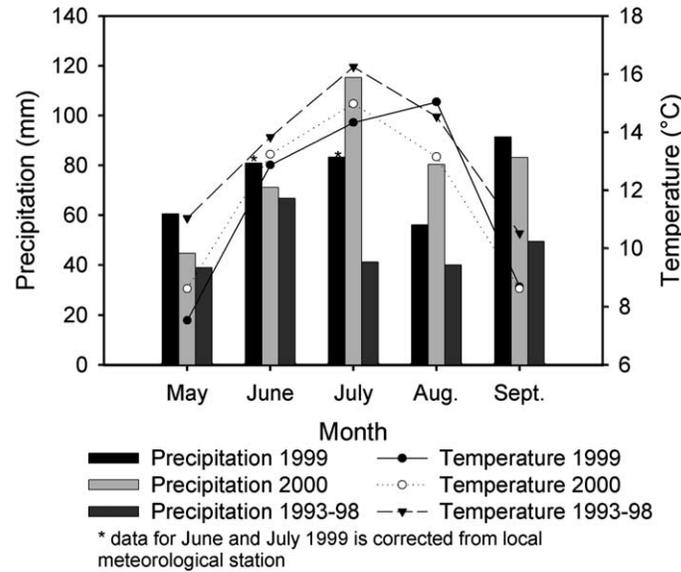


Fig. 1. The 1999 and 2000 growing season mean monthly air temperature and rainfall contrasted with the historical mean monthly air temperature and rainfall (1993–1998) for a clearcut located in the Aleza Lake Research Forest, British Columbia 5 and 6 years after harvesting. Precipitation data for June and July 1999 were created using a relationship to rainfall data collected at a local meteorological station (~40 km away).

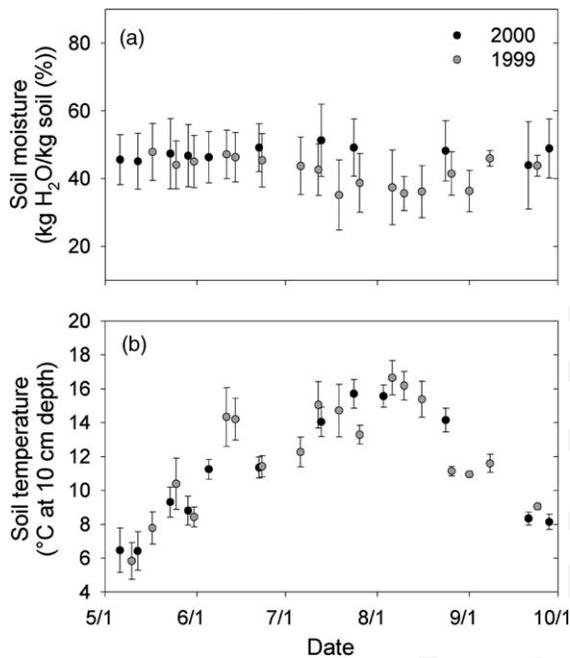


Fig. 2. Mean soil moisture (a) and temperature (b) in 1999 and 2000 for a clearcut located in the Aleza Lake Research Forest, British Columbia 5 and 6 years after harvesting.

3.2. Microclimate variables and ecosystem component CO₂ fluxes

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Ecosystem component fluxes correlated well with different subsets of microclimate variables (Table 1). With respect to net photosynthesis, light, soil and air temperature and RH were significant regressors for *P. glauca* × *engelmannii* ($R^2 = 0.54$), light and day of year for *C. angustifolium* ($R^2 = 0.72$), and light, air temperature, absolute humidity and soil moisture for *L. involucrata* ($R^2 = 0.78$). In all species, net photosynthesis was significantly correlated with light level (Table 1, Fig. 3a–c), saturating at levels from between 500 and 1000 $\mu\text{mol PAR m}^{-2} \text{s}^{-1}$. Light-saturated photosynthesis was approximately $-13 \mu\text{mol C m}^{-2} \text{s}^{-1}$ for *Picea*, $-16 \mu\text{mol C m}^{-2} \text{s}^{-1}$ for *Chamerion* and $-12 \mu\text{mol C m}^{-2} \text{s}^{-1}$ for *Lonicera*.

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Instantaneous measurements of daytime dark respiration for all three plant species examined in 2000 correlated significantly and positively with air temperature (Table 1, Fig. 4a–c). The best-fit function was hyperbolic with maximum respiration rates ranging from 2 to 3 $\mu\text{mol C m}^{-2} \text{s}^{-1}$ for *Lonicera* and 5 to 6 $\mu\text{mol C m}^{-2} \text{s}^{-1}$ for *Picea* and *Chamerion*. Instantaneous soil surface CO₂ efflux

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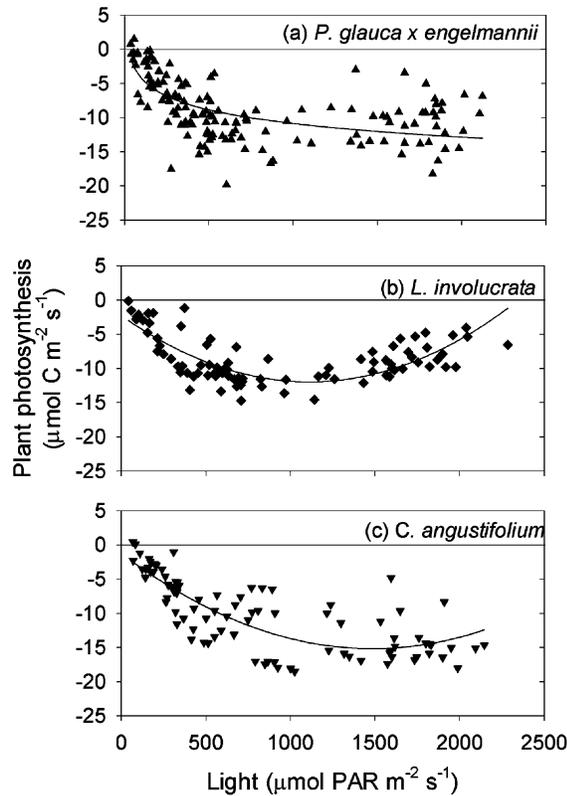


Fig. 3. The instantaneous net photosynthetic CO₂ uptake for (a) *P. glauca* × *engelmannii*, (b) *L. involucrata*, and (c) *C. angustifolium* versus ambient light from May to September 2000 in a 6-year-old clearcut located in the Aleza Lake Research Forest, British Columbia.

394 in 2000 was exponentially correlated with soil tem-
 395 perature at a depth of 10 cm (Fig. 5) with an R^2
 396 of 0.7 (Table 1). Instantaneous soil surface CO₂ ef-
 397 flux ranged from 1.2 $\mu\text{mol C m}^{-2} \text{s}^{-1}$ at 3.2 °C to
 398 9.2 $\mu\text{mol C m}^{-2} \text{s}^{-1}$ at 17 °C (Fig. 5). Soil surface
 399 CO₂ efflux was not correlated with soil moisture
 400 ($P = 0.05$, Table 1).

401 3.3. Above ground biomass and leaf area

402 In the summer of 2000, the plants in the clearcut
 403 allocated 276 g biomass m^{-2} to above ground com-
 404 ponents with the vast majority (93%) in deciduous
 405 plant (Table 2). The gains in above ground biomass
 406 from 10 May to 6 August 2000 were 163, 94

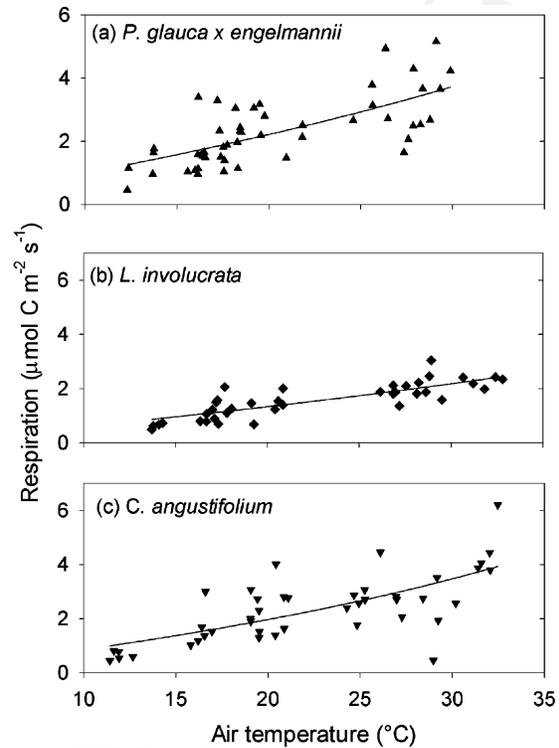


Fig. 4. Daytime respiration for coniferous and deciduous plant species (May–September 2000) in a 6-year-old clearcut located in the Aleza Lake Research Forest, British Columbia.

and 18.6 g biomass m^{-2} (dry weight) in herbaceous
 407 plants, woody shrubs, and conifers, respectively. In
 408 early August, when above ground biomass was at
 409 its peak, woody shrubs represented 51% of above
 410 ground biomass, herbaceous plants 35%, and conifers
 411 14%.
 412

Table 2

The amount of above ground biomass present on 10 May and 6 August 2000, and the change in biomass between these dates, for a 6-year-old clearcut within the Aleza Lake Research Forest, British Columbia

Component	10 May (g m^{-2})	6 August (g m^{-2})	Biomass change (g m^{-2})
Conifer	45.5	64.1	18.6
Herbaceous plants	- ^a	163	163
Woody shrubs	140	234	94
Total	186	461	276

^a No biomass present in the spring.

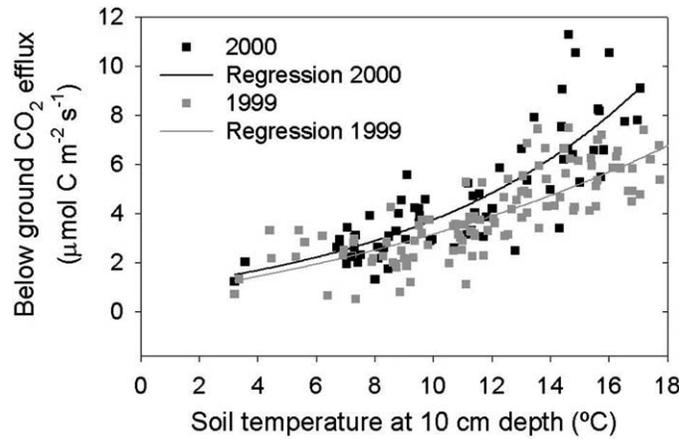


Fig. 5. Relationship between the instantaneous soil surface CO₂ efflux and soil temperature from May to September 2000 for a 5 (1999) and 6 (2000) year-old clearcut located in the Aleza Lake Research Forest, British Columbia.

413 3.4. Cumulative ecosystem CO₂ fluxes based on
414 component fluxes

415 Ecosystem CO₂ fluxes, modeled from component
416 fluxes, totaled 103 g C m⁻² for the 2000 growing
417 season (Table 3). The magnitude of the CO₂ ‘sinks’
418 provided by the plants (photosynthesis minus res-
419 piration) were in the order of herbaceous plants >
420 woody shrubs > conifers. The modeled maximum
421 daily CO₂ uptake by the different plant components
422 were 5.13 g C m⁻² per day for the herbaceous plants,
423 2.43 g C m⁻² per day for the woody shrubs and
424 1.12 g C m⁻² per day for the conifers. From 24 May
425 to 20 September 2000, the cumulative soil surface
426 CO₂ efflux was greater than the estimated cumula-
427 tive CO₂ uptake by plants resulting in the net loss of
428 CO₂ for the growing season from the ecosystem. The

Table 3

The BREB method and Component model estimates of the growing season CO₂ fluxes (24 May–20 September 2000) from the soil surface, the conifers, herbaceous plants and woody shrubs in a 6-year-old clearcut located in the Aleza Lake Research Forest

Components	Component model (g C m ⁻²)	BREB (g C m ⁻²)
Soil surface	686	–
Conifers	–96	–
Herbaceous plants	–315	–
Woody shrubs	–172	–
Total	103	142

Component model estimated soil surface CO₂ efflux
to range from 2.78 to 8.34 g C m⁻² per day.

3.5. Comparison of BREB and Component model
ecosystem CO₂ fluxes

The BREB and Component model ecosystem flux
estimates for 24 May–20 September 2000 corre-
sponded reasonably well. Representative data for 15
June and 17 August demonstrate the predominately
good fit between the methods during daylight hours
in contrast with the poorer fit during dusk, dawn and
nighttime periods (Fig. 6a and b). Abnormalities in
BREB data at night and during dawn and dusk were
corrected prior to calculation of daily totals. Both the
BREB method and the Component model estimated
the CO₂ fluxes to progress from being a source of CO₂
in late May to a sink in late June (Fig. 7). The clearcut
remained a CO₂ sink for approximately 23 days only
to return to being a source of CO₂ for the remainder
of the growing season. The BREB and Component
model estimates diverged at the beginning of August
only to return to agreement approximately 10 days
later and the difference coincides with the onset of
senescence. For the growing season, the estimates of
the Component model only slightly underestimated
the BREB method estimates when poor BREB night-
time data was removed ($R^2 = 0.7$) (Fig. 8). The slope
relating the BREB method to the Component model
estimates was 0.93 and it was statistically different

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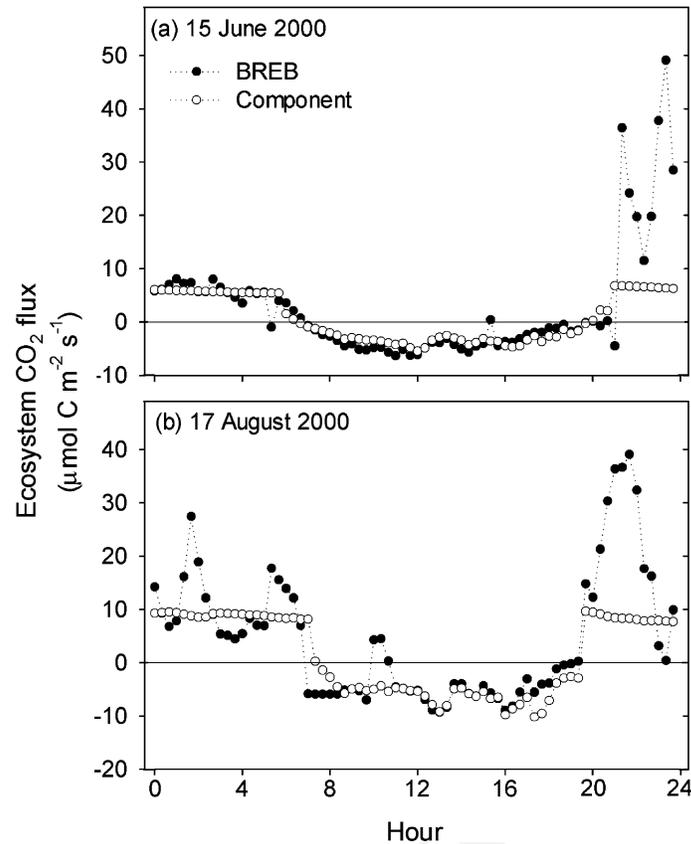


Fig. 6. A comparison of ecosystem CO₂ flux estimates of the BREB method and Component model for selected days in 2000 for a 6-year-old clearcut located in the Aleza Lake Research Forest, British Columbia.

457 from a slope of 1 ($P = 0.05$) for the whole summer. However, if the first 2 weeks of August (time
 458 of senescence) are removed from a regression relating the BREB method to the Component model the
 459 slope relating the two are not statistically different (slope = 1.01 ± 0.01 , $P = 0.05$). From 24 May to
 460 20 September 2000 the BREB method estimated the source of CO₂ to be 142 g C m^{-2} (Table 3). This total
 461 was similar in sign but 38% higher than that estimated using the Component model (Table 3).
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467 3.6. Comparison of 1999 and 2000 ecosystem
 468 CO₂ fluxes

469 Because of the extended measurement period in
 470 2000, a direct contrast of growing seasons between
 471 1999 and 2000 was not possible. However, in the

shared interval from 27 June to 3 September, the clearcut was a sink in 1999 and a source in 2000
 (Table 4). The size of the sink for the growing season interval in 1999 was -85 g C m^{-2} using the Com-
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Table 4
 The BREB method and Component model estimates of the growing season CO₂ flux in a 5- and 6-year-old clearcut, over a comparable interval, from 27 June to 3 September, in the Aleza Lake Research Forest, British Columbia

Component flux	1999 (g C m ⁻²)		2000 (g C m ⁻²)	
	Component model	BREB	Component model	BREB
Soil surface	338	–	466	–
Conifers	–47	–	–57	–
Herbaceous Plants	–211	–	–232	–
Woody shrubs	–165	–	–133	–
Total	–85	–22.4	44	65

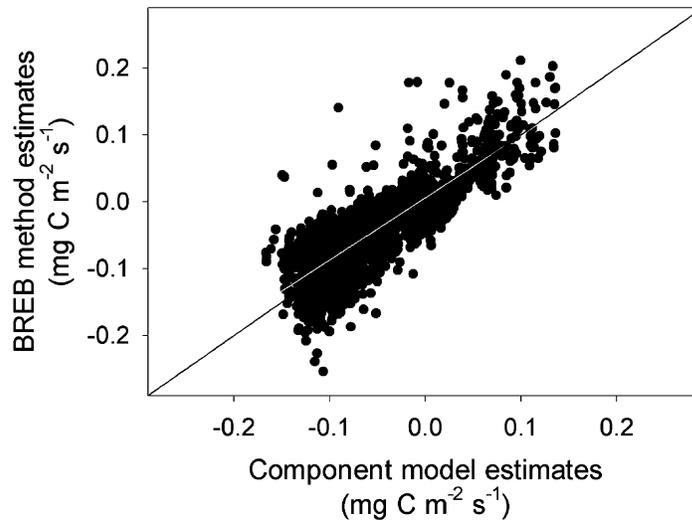


Fig. 7. Seasonal trends in BREB method and Component model estimates of CO₂ flux for 24 May–20 September 2000 in a 6-year-old clearcut located in the Aleza Lake Research Forest, British Columbia.

476 ponent model and -22.4 g C m^{-2} using the BREB
 477 method. In contrast, the clearcut was a source for
 478 CO₂ in 2000 using the comparable growing season
 479 interval, 44 g m^{-2} using the Component model and
 480 65 g C m^{-2} using the BREB method. The BREB daily
 481 CO₂ flux estimates for 1999 were generally lower

(a greater sink) than those in 2000, especially for
 the interval extending from mid July to mid August
 (Fig. 9).

The clearcut exhibited similar trends in daily pho-
 tosynthesis in 1999 and 2000 (Fig. 10) as well as sim-
 ilar uptake for individual plant components (Table 4).

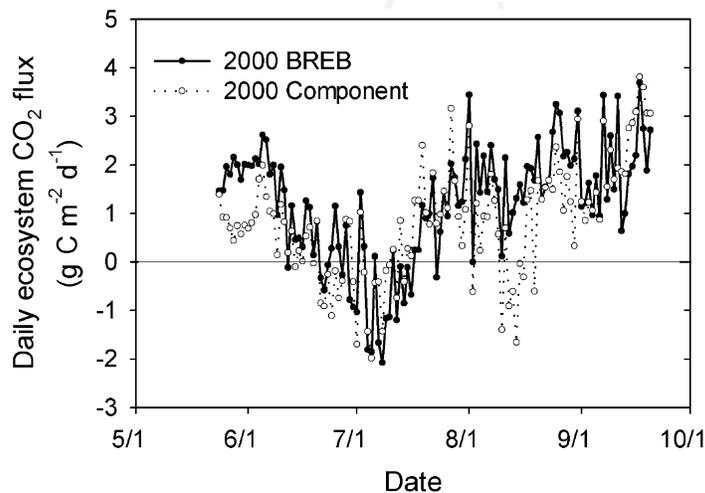


Fig. 8. Comparison between BREB method and Component model carbon flux estimates from 24 May to 20 September 2000 for a 6-year-old clearcut located in the Aleza Lake Research Forest, British Columbia. The black line represents the 1:1 line and the white line represents the slope of the relationship.

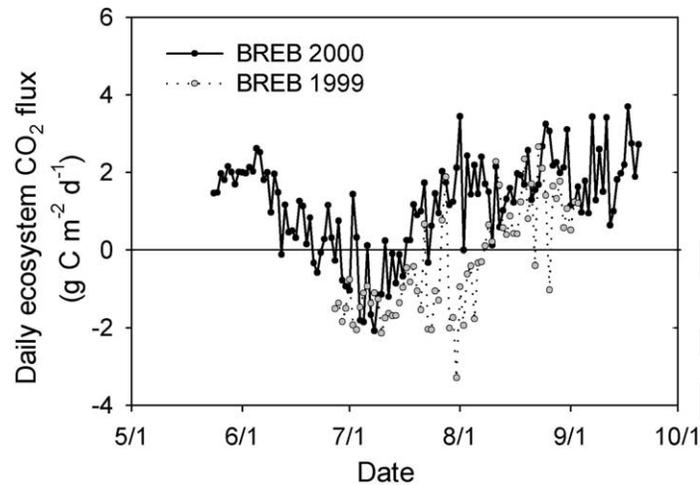


Fig. 9. BREB ecosystem CO₂ flux estimates for a clearcut 5 (1999) and 6 (2000) years after harvest in the Aleza Lake Research Forest, British Columbia.

488 Seasonal totals of net CO₂ uptake for plants were
 489 -423 g C m^{-2} in 1999 compared to -422 g C m^{-2} in
 490 2000 (Table 4). Herbaceous plants and conifers fixed
 491 more total CO₂ (increase of 21 and 10 g C m^{-2} re-
 492 spectively) in 2000 than 1999, while the woody shrubs
 493 showed a slight drop (19%) in net CO₂ uptake in
 494 2000. As in 1999, the deciduous plant contribution
 495 to ecosystem photosynthesis in 2000 was still much
 496 larger (86% of the total) than the contribution from

conifer seedlings (Table 4). Contributions of conifer
 seedlings to ecosystem photosynthesis in 2000 (14%)
 were similar to its fraction of above ground biomass
 in the clearcut (Table 2).

In contrast to plant photosynthesis, soil surface CO₂
 efflux was consistently higher in 2000 versus 1999
 at all dates prior to the convergence of values on 1
 September (Fig. 11). The maximum difference be-
 tween soil surface CO₂ efflux in 2000 versus 1999

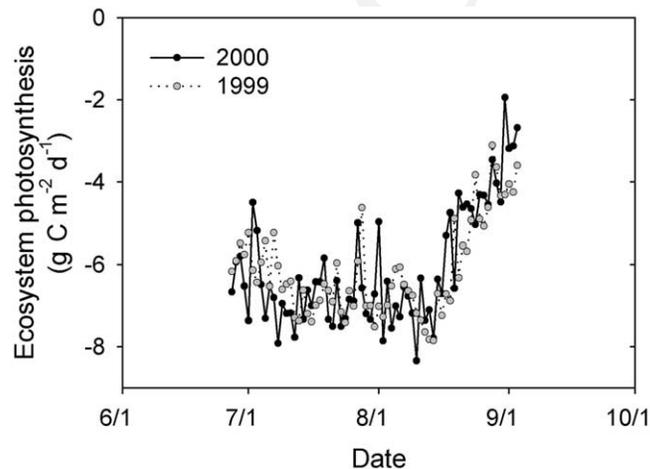


Fig. 10. Component model estimates of ecosystem photosynthesis for the 1999 and 2000 growing seasons (27 June–3 September) in a 5- and 6-year-old clearcut located in the Aleza Lake Research forest.

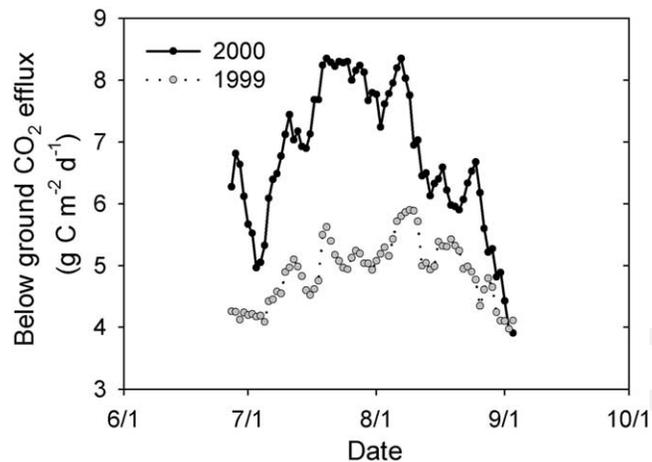


Fig. 11. Soil surface CO₂ efflux during the 1999 and 2000 growing seasons (27 June–3 September) in a 5- and 6-year-old clearcut located in the Aleza Lake Research Forest, British Columbia.

506 was a 56% higher level in late July of 2000 over 1999
 507 levels. In 1999, the cumulative soil surface CO₂ efflux
 508 was estimated at 338 g C m⁻² while in 2000 it was
 509 38% higher at 466 g C m⁻² (Table 4).

510 4. Discussion

511 4.1. Growing season ecosystem fluxes for a 512 sub-boreal clearcut

513 In two consecutive years, ecosystem CO₂ flux estimates
 514 made by two independent methods both indicated that a
 515 sub-boreal spruce clearcut (5 and 6 years after harvesting)
 516 switches from carbon source (early summer) to sink and
 517 back to source again (late summer) over the portion of
 518 the growing season extending from 27 June to 3 September.
 519 For this common interval, the clearcut was a net sink for
 520 CO₂ in 1999 but a net source for CO₂ in 2000. This
 521 magnitude of inter-annual variation in fluxes for a site
 522 is not uncommon. For example, Goulden et al. (1998),
 523 in a 3-year study of a mature Boreal black spruce forest
 524 (October 1994–October 1997), found the forest to be
 525 a source for CO₂ over 2 years from October 1994 to
 526 October 1996 (69.8 and 20 g C m⁻², respectively)
 527 and a small sink from October 1996 to October 1997
 528 (–10 g C m⁻²). Clearly, shifts in environmental conditions
 529 between years can greatly impact the size of
 530

the ecosystem CO₂ flux. For example, changes in the
 length of the growing season (Goulden et al., 1998;
 Black et al., 2000), rainfall (Grieu et al., 1988; Baldocchi,
 1997; Cienciala et al., 1997), and soil and air temperatures
 (Vapaavuori et al., 1992; Harrington et al., 1994) can
 alter photosynthetic CO₂ uptake and/or soil surface
 CO₂ efflux from one year to the next.

The shift in the clearcut from being a sink for CO₂
 in 1999 to source in 2000 (27 June–3 September) did
 not result from a decrease in ecosystem photosynthesis
 in 2000. In fact, the photosynthetic CO₂ uptake was
 remarkably similar for the 2 years (Fig. 10), with the
 Component model estimates showing a decrease in
 photosynthesis of only 1 g C m⁻² from 27 June to 3
 September in 2000 versus 1999. One of the primary
 drivers of this result was undoubtedly a relatively
 similar aboveground biomass between years (Table 2).
 Specifically, aboveground biomass increased from
 234 g biomass m⁻² in 1999 to 276 g biomass m⁻²
 in 2000, with the main difference between the years
 being an 8.6 g C m⁻² increase in conifer biomass and
 a 38 g C m⁻² increase in herbaceous plant biomass in
 2000. Thus, there was no evidence that a decrease in
 photosynthesis in 2000 could explain the increased
 ecosystem CO₂ efflux relative to 1999.

In contrast to photosynthesis, the soil surface CO₂
 efflux increased significantly from 1999 to 2000
 (Fig. 11). The Component model estimated the soil
 surface CO₂ efflux (27 June to 3 September) to be

338 g C m⁻² in 1999 compared to 466 g C m⁻² in 2000; an increase of 128 g C m⁻². While soil temperature would be the first factor to consider in explaining this difference, there were no obvious differences in soil temperature (Fig. 2b) between the two years and only a small difference in above ground biomass. The precipitation was 56 mm greater in July and August and while soil moisture was not measured to be significantly greater in 2000, it was consistently higher (Fig. 2b). Greater availability of moisture may have increased the positive relationship between soil temperature and soil surface CO₂ efflux. When soil moisture becomes limiting, its influence on the soil surface CO₂ efflux becomes greater (Londo et al., 1999), and in some situations, soil moisture is a better predictor of soil surface CO₂ efflux than soil temperature (Parker et al., 1983). Irvine and Law (in press) found a decrease in soil moisture influenced the relationship between temperature and soil CO₂ efflux in drier years. Furthermore, large variations in respiration are not uncommon in forest ecosystems. Granier et al. (2000) found that a beech forest experienced a 200 g C m⁻² per year increase in ecosystem C loss in two adjacent years and Weber (1990) found the soil surface C efflux to vary 145 g C m⁻² over two adjacent growing seasons in an immature aspen forest in Alaska. Hence, it is possible the greater precipitation in 2000, particularly in the warmest summer months, may well have combined to result in the 38% increase in soil surface CO₂ efflux in 2000 relative to 1999.

4.2. Ecosystem and soil surface CO₂ efflux relative to other forest ecosystems

There are currently few published studies of ecosystem CO₂ fluxes for young regenerating clearcuts to contrast with the present study. Perhaps the most comparable study to our own with respect to latitude and tree composition is that conducted in a 12-year-old Boreal cut block in Siberia (Valentini et al., 2000a). Though conducted over a very short time interval (14 days in July in 1 year), CO₂ fluxes from the 12-year-old cut block averaged -0.103 g C m⁻² per day, which were bracketed by average July BREB CO₂ fluxes for 1999 (-1.21 g C m⁻² per day) and 2000 (0.142 g C m⁻² per day) in our clearcut (Fig. 9). A greater tree age (12 years versus 6 years in the present study), tree size (2.5 m versus 1.03 m height in the present study), and tree density (1700 stems ha⁻¹ versus 1200 stems ha⁻¹ in the present study) would be expected to create a stronger sink in the Siberian cut block than in our clearcut. However, the restricted data set for the Siberian cut block and large inter-annual variability preclude our making any strong comparisons between the two studies.

Instantaneous soil surface CO₂ effluxes were similar to those of some studies (Ewel et al., 1987; Russell and Voroney, 1998; Weber, 1990), but higher than those of others (Edwards, 1975; Fernandez et al., 1993; Gordon et al., 1987; Lytle and Cronan, 1998; Striegl and Wickland, 1998) (Table 5). The

Table 5

The average daily soil surface carbon flux for a sub-Boreal clearcut located in the Aleza Lake Research forest, British Columbia, in relation to other clearcuts and forests

Study	Year	Forest type	Location	Dominant tree species	Stand age	Dates	Average (g C m ⁻² per day)	S.E.
Pypker and Fredeen	2000	Sub-boreal	British Columbia	Spruce	6	May–September	5.76	1.33
Gordon et al.	1980–1981	Boreal	Alaska	Red spruce	3–4	May–September	3.44	N/A
Lytle and Cronan	1992	Coniferous	Maine	Spruce-fir	0	May–November	2.43	0.15
Russell and Voroney	1994	Boreal	Saskatchewan	Aspen	70	July–August	7.07	N/A
Ewel et al.	1983–1984	Coniferous	Florida	Slash pine	0	Yearly	6.22	N/A
Ewel et al.	1983–1984	Coniferous	Florida	Slash pine	9	Yearly	2.25	N/A
Edwards	1973	Deciduous	Tennessee	Aspen	40–50	May–September	5.24	0.66
Weber	1986	Boreal	Alaska	Aspen	2	Yearly	6.23	2.97
Fernandez et al.	1990	Deciduous	Maine	Red pine	4	May–September	2.09	0.52
Striegl and Wickland	1994	Boreal	Saskatchewan	Jack pine	0	May–September	0.96	N/A

The forests have been divided up into forest type, location, dominant tree species and stand age.

619 high soil surface CO₂ effluxes in this study were
620 consistent with six other clearcuts (0, 2, 3, 5, 9
621 and 10-year-old) located within the Aleza Lake Re-
622 search Forest (Pypker and Fredeen, in press) and
623 are likely due to the high nutrient content and mois-
624 ture in these soils. In European forests, Valentini
625 et al. (2000b) have found northern forests to exhibit
626 greater total ecosystem respiration even though soil
627 and air temperatures decrease with increasing latitude.
628 Valentini et al. (2000b) suggests that this increase
629 may be in part due to greater losses of CO₂ from the
630 soil surface. However, many of the above studies cited
631 as having lower levels of respiration were also con-
632 ducted at similar northern latitudes to our study. As a
633 result, it could be moisture, i.e. the wetter conditions
634 of this sub-boreal interior BC clearcut, rather than
635 temperature alone that drives the differences in soil
636 surface CO₂ effluxes at similar latitudes. Furthermore,
637 seasonal fluctuations in soil temperature and moisture
638 appear to stimulate microbial activity and soil organic
639 matter decomposition more than differences in the
640 steady-state levels (Biederbeck and Campbell, 1973).
641 Thus, the increase in precipitation in 2000 over 1999
642 could well provide the explanation for the higher soil
643 surface CO₂ efflux in 2000. Certainly, our results
644 agree with the overall conclusion of Valentini et al.
645 (2000b) that respiration (rather than photosynthesis)
646 has a greater variability in northerly latitudes, even
647 with the lower associated soil temperatures.

648 4.3. Contrasting Bowen ratio and Component 649 model ecosystem CO₂ fluxes

650 The BREB method ecosystem CO₂ flux estimates
651 agreed well with Component model estimates dur-
652 ing the periods when the BREB method functioned
653 properly ($R^2 = 0.7$) (Figs. 6 and 8). The correla-
654 tion between scaled up chamber estimates and the
655 BREB method has also been demonstrated by others
656 (Angell et al., 2001). Nighttime measurements in this
657 study exhibit many of the common problems associ-
658 ated with the BREB approach (Tanner, 1960; Price
659 and Black, 1991). For example, temperature inver-
660 sions and low net radiation values caused erratic CO₂
661 flux estimates at night (Fig. 6), and rainfall and equip-
662 ment failure resulted in occasional prolonged gaps in
663 the dataset. However, it should be noted that during
664 rare periods of high wind speed at night, BREB es-

665 timates were in good agreement with the Component
666 model (e.g. Fig. 6a from 0 to 500 h). After correct-
667 ing for problem periods, seasonal ecosystem CO₂ flux
668 of the Component model closely matched the CO₂
669 flux from the BREB method, except for a slight di-
670 version in early August (Fig. 7) when the Compo-
671 nent model overestimated the fluxes provided by the
672 BREB method. This difference resulted in the slope
673 relating to the BREB method and Component model
674 estimates to be slightly less than one (Fig. 8). There
675 was a similar, but greater, difference between the two
676 methods in early August of 1999 (Pypker and Fre-
677 deen, 2002). During both growing seasons, the differ-
678 ence between BREB and Component model estimates
679 coincided with flowering, seed production and onset
680 of senescence in herbaceous plants that are likely to
681 have resulted in increased respiration not detected by
682 component flux measurements. When the 2 weeks in
683 August that correspond with the onset of senescence
684 are removed, the slope relating the Component model
685 to BREB method is not statistically different from 1
686 ($P = 0.05$). It is likely, the Component model could
687 not respond to rapid changes in component physiology
688 and phenology because the regression equations were
689 based on episodic measurements, typically made ev-
690 ery other week. More frequent and varied component
691 flux measurements during this interval would presum-
692 ably have enhanced the correspondence of these two
693 approaches. Hence, we view the BREB fluxes to be
694 more representative of the true ecosystem CO₂ flux
695 during August.

696 5. Conclusions

697 A number of conclusions can be made. First, this
698 6-year-old sub-Boreal clearcut is a source of CO₂
699 (based on 'growing season' fluxes only) of between
700 1.03 and 1.42 t C ha⁻¹. The magnitude of this source,
701 though variable between years, is undoubtedly a con-
702 servative estimate of the true annual efflux given that
703 non-growing season respiration was not accounted for
704 in the current study. Winter rates of soil surface CO₂
705 efflux measured at the Aleza Lake Research Forest
706 have been found to range from 0.6 to 0.76 g C m⁻² per
707 day (Evans et al., 1998). Such levels when summed
708 over the six non-growing season months could amount
709 to 1.25 t C ha⁻¹ of additional soil surface CO₂ efflux

710 for our site. Second, we have demonstrated that at least
 711 in relatively simple systems, such as clearcuts, mea-
 712 surement of and scaling up from component fluxes
 713 can assist in corroborating and correcting fluxes de-
 714 rived from ecosystem approaches, such as the BREB
 715 method. Third, the dominant photosynthetic compo-
 716 nent or 'sink' within the 6-year-old clearcut continued
 717 to be the deciduous ("non-crop") plants. Thus, from a
 718 carbon 'sink' perspective, management of plantations
 719 should as much as possible promote rather than re-
 720 move 'non-crop' species if the losses of CO₂ in the
 721 years immediately following harvest are to be mini-
 722 mized. Finally, more flux data from a variety of young
 723 managed forests are needed before a convincing state-
 724 ment on carbon storage in managed forests can be
 725 made.

726 Uncited reference

727 [Edwards and Ross-Todd \(1983\).](#)

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