CARBON SEQUESTRATION IN BRITISH COLUMBIAN SUB-BOREAL CUT BLOCKS

by

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Abstract

During the summers of 1999 and 2000 measurments of component and ecosystem-level CO_2 fluxes were taken in seven cut blocks aged 0, 2, 3, 5, 6, 9 and 10 years since harvest in the Aleza Lake Research Forest, near Prince George, British Columbia. A Bowen ratio energy balance (BREB) system was placed within a 5 to 6 year-old planted interior spruce (*Picea glauca x Picea engelmannii*) clearcut to measure the ecosystem CO_2 flux during the 1999 and 2000 growing seasons. To substantiate the BREB measures of the ecosystem CO_2 flux a second method, called the component model, was established based on instantaneous measurements of component CO_2 fluxes (conifer, herbaceous plant, woody shrub and below ground) scaled up to the ecosystem-level. Both approaches indicated inter-annual variation in the growing season CO_2 fluxes. The 1999 growing season ecosystem CO_2 flux measurements estimated the clearcut to be a sink of -20 ± 43 g C m^{-2} and -86 g C m^{-2} from 27 June to 3 September, using the BREB method and component model respectivly. In contrast, in 2000 the growing season CO_2 flux during the same timeperiod was a source of 43 g C m^{-2} (BREB method) and 66 ±44 g C m^{-2} (component model) during the same period. In 2000, an addtional 50 days of measurement, from 24 May to 20 September, indicated an even larger source of CO_2 totaling 143 ±57 and 103 g C m^{-2} using the BREB method and component model, respectively. However, regardless of the approach used, both years would have been sources of CO_2 if additional measures were taken for the entire year.

The component fluxes were dominated by the CO_2 source from below ground (338 and 466 g C m^{-2} in 1999 and 2000, respectively) and the CO_2 sink provided by the deciduous plants (-382 and -365 g C m^{-2} in 1999 and 2000 respectively). The conifer photosynthetic CO_2 uptake for the 5 to 6 year-old clearcut was meager in comparistion (-47 and –57 g C m^{-2} in 1999 and 2000, respectively). During the 2000 growing season, the below ground CO_2 flux and above ground biomass was measured in 7 cut blocks aged 0, 2, 3, 5, 6, 9 and 10 years and one mature stand. All sites were in the SBS wk1 08 or 07 except the 0 and 9 year-old sites that were of the sub series 01. The growing season below ground CO_2 flux was similar for all cut blocks, including the mature forest. Furthermore, there was little change in above ground biomass carbon uptake between the different aged cut blocks. Hence, when biomass was incorporated with the below ground CO_2 fluxes all cut blocks were sources for CO_2. Therefore, cut blocks within theAleza Lake region (SBS wk1 07 or 08) are sources of CO_2 for at least 10 years after harvest because the conifer component of the CO_2 flux is incapable of surmounting the loss of CO_2 from below ground.

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GLOSSARY

Word

BREB - Bowen ratio energy balance

C_P – Heat capacity of air ($J\ kg^{-1}\ K^{-1}$)

C_S – Heat capacity of moist soil ($J\ m^{-3}\ K^{-1}$)

C_d – Specific heat of dry mineral soil ($J\ kg^{-1}\ K^{-1}$)

C_w – Specific heat of water ($J\ kg^{-1}\ K^{-1}$)

d - depth (m)

F_C – flux of CO_2 ($g\ C\ m^{-2}\ s^{-1}$ or $g\ C\ m^{-2}\ d^{-1}$)

G – Ground heat flux ($W\ m^{-2}$)

H – Sensible heat flux ($W\ m^{-2}$)

K_C – eddy diffusivity coeficient for CO_2 ($m^2\ s^{-1}$)

K_E- eddy diffusivity coefficient for latent heat ($m^2\ s^{-1}$)

K_H – eddy diffusivity coefficient for sensible heat ($m^2\ s^{-1}$)

LE – Latent heat flux ($W\ m^{-2}$)

L_V – Latent heat of vaporization ($J\ kg^{-1}$)

Q* - Net radiation ($W\ m^{-2}$)

S – Stored energy below ground ($W\ m^{-2}$)

T – absolute air temperature (K)

z – height (m)

β - Bowen ratio (dimensionless)

ε - Ratio of the molecular weight of water vapour to dry air (dimensionless)

θ_m – Water content of soil on a mass basis (kg (H_2O) kg^{-2} (soil))

ρ - Air density (kg m^{-3})

ρ_C – CO_2 density (kg m^{-3})

ρ_V – Water vapour density (kg m^{-3})

THESIS STRUCTURE AND OVERVIEW

For presentation purposes this thesis is organized into four chapters. Each chapter has a distinct purpose in addressing the overall question regarding carbon sequestration in sub-Boreal cut blocks. The two middle chapters (2 and 3) are stand alone papers while the first acts to introduce the topic of carbon sequestration and the last attempts to tie the results from the study together. The four chapters are:

- Chapter 1 – Introduction
- Chapter 2 – BREB and Component Model Estimates of Growing Season CO_2 Flux
- Chapter 3 – Below ground CO_2 Fluxes of Seven Cut Blocks and One Mature Stand
- Chapter 4 – Conclusions and Summary

Chapter 1 identifies the importance of studying carbon fluxes from cut blocks and provides a basic overview of the methods used to identify the size of the CO_2 fluxes from the seven cut blocks investigated. Chapter 2 examines, in detail, the size of the carbon flux over two growing seasons (27 June to 3 September 1999 and 24 May to 20 September 2000) in a 5-6 year-old clearcut. Two methods are contrasted and compared to identify the size and direction of the CO_2 flux for each growing season. Furthermore, the magnitudes of the CO_2 flux components were established for both growing seasons. It was noted in 1999 that the below ground portion of the CO_2 flux was substantial, causing the clearcut to ultimately be a source of CO_2. Chapter 3 investigates the impact below ground CO_2 fluxes have on cut block carbon budgets. The CO_2 flux and above ground biomass uptake for seven cut blocks aged 0, 2, 3, 5, 6, 9, and 10 years of age were compared and contrasted. Ultimately chapter 3 indicates how below ground CO_2 fluxes change with time since harvest and using the biomass values, estimates the carbon budget for each cut block. Chapter 4 serves as a concluding chapter. It compares and contrasts the results from chapters 2 and 3, and discusses the implication of the results on current global carbon budgets and management practices.

INTRODUCTION

In December of 1997, 160 countries, including Canada, signed the Kyoto protocol. Under the agreement Canada committed to reducing greenhouse gases emissions by 8% below 1990 levels by 2012. Recently, several nations including Canada, have argued that they should be given credit for CO_2 uptake by forest and agricultural processes in greenhouse gas emission calculations. While Canada argued for the implementation of the forest carbon credits during recent meetings at The Hague, there is little agreement within the scientific community regarding the costs and benefits of reforestation and afforestion on atmospheric CO_2 levels (e.g. Schulze et al. 2000). Proponents for carbon credits point to evidence of a possible CO_2 sink in the Northern Hemisphere (Schimel 1995; Keeling et al. 1996; Myneni et al. 1997), arguing that part of the carbon sequestration is due to CO_2 uptake from regenerating forests. There is little doubt that forests absorb CO_2, and for a least part of their life cycle, take up more CO_2 than they lose. Furthermore, the terrestrial biosphere contains a large portion of the active carbon pool (≈2000Gt) (Falkowski et al. 2000) and how it interacts with the atmosphere will have an impact on CO_2 concentrations. However, for carbon credits to have any merit, the sinks created from timber harvesting and reforestation must be greater than if the forests were left undisturbed. Forests in British Columbia's Boreal and sub-Boreal forests may be harvested on a rotating basis that will result in a finite opportunity for CO_2 uptake. During the early years cut blocks are assumed to be sources of CO_2 because of reduced photosynthetic uptake. Both the time required for cut blocks to switch from a source to a sink for CO_2, and the size of the CO_2 flux from the cut block during its early years, is critical to understanding the magnitude and the direction of fluxes from regenerating forests.

Numerous complex models have attempted to quantify the CO_2 flux from forested stands (e.g. Birdsey et al. 1993; Burschel et al. 1993; Kolochugina & Vinson 1993b; Kolochugina & Vinson 1993a; Kurz & Apps 1993; Kurz & Apps 1994; Kurz et al. 1995; Turner et al. 1995; Cohen et al. 1996; Kurz et al. 1996), but they are based on broad assumptions and often do not properly incorporate disturbance events such as fire, insect outbreak, or timber harvesting (e.g.Burschel et al. 1993; Kolochugina & Vinson 1993b). Disturbance is of great importance for the forests around the world including those of British Columbia. Models of British Columbian forests that attempt to incorporate fire, insect outbreat and timber harvesting, are forced to rely on very broad assumptions. For example, Kurz et al. (1996), assumed that areas burned were evenly distributed among the four ecoclimatic provinces (Boreal, Cordilleran, Interior Cordilleran and Pacific Cordilleran), ignoring the fact that each region has greatly differing fire intervals. Likewise, timber harvesting was divided up evenly between 6 administrative units, ignoring the fact that different tree species, forest types, and age-classes are harvested at greatly varying intensities across those units. Post disturbance, assumptions are equally broad. For example, it is generally assumed that after a disturbance, forests advance through four stages: regeneration, immature, mature and over mature (Kurz & Apps 1994). During the first stage, regeneration, the site is recovering from disturbance and is assumed to act as a source of CO_2 for approximately 10 y (Kurz & Apps 1994). However, there are few *in situ* studies that actually verified the size and duration of the source of CO_2 from young regenerating stands. If timber harvesting results in forests that act as large sources of CO_2 over longer periods of time, then the overall size of the CO_2 uptake from harvested stands would diminish and the argument for carbon credits would be weakened.

Ecosystem-level CO_2 flux measurements for forest ecosystems following harvesting are still relatively rare. There have been several tower based ecosystem CO_2 flux studies in the sub-Boreal and Boreal forests (Fan et al. 1995; Black et al. 1996; Baldocchi et al. 1997; Jarvis et al. 1997; Goulden et al. 1998; Lindroth et al. 1998; Hollinger et al. 1999), but apart from the 14 day study by Valentini et al. (2000), none document CO_2 fluxes from young regenerating Boreal cut blocks or clearcuts. In 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 (-0.09 g C d^{-1}) during two measurement periods (July 6-15 and 21-26). Price & Black (1990), measured summertime CO_2 fluxes from a 22 year-old low-productivity coastal Douglas-fir cut block on Vancouver Island and found that on many days during the summer the nighttime flux of CO_2 negated any gains during the day. Therefore, information on CO_2 fluxes from young sub-Boreal cut blocks is greatly needed to validate assumptions used in large-scale models and to give a better understanding of the environmental controls on CO_2 fluxes in disturbed northern forests. This is especially critical if we are to contemplate moving to shorter rotation ages in Northern BC.

There are currently three common methods for measuring the ecosystem CO_2 flux from tower based instruments: Aerodynamic, Bowen ratio, and eddy covariance. In this study we employed the Bowen ratio energy balance method, which, as with other tower based CO_2 flux methods, is based on a number of assumptions and restrictions.

The Bowen ratio method for measurement of ecosystem CO_2 flux

The Bowen ratio energy balance (BREB) method attempts to distribute the net radiation (Q^*) into the sensible heat (H), latent heat (LE) and ground heat (G) terms using the Bowen ratio ($\beta = H/LE$) in the equation:

$$H = \frac{(Q^* - G)}{(1+\beta)} \quad (1)$$

(For a full description of how the fluxes are partitioned see the methodology section in Chapter 2)

The Bowen ratio energy balance (BREB) method is underlain by two fundamental assumptions. First, the eddy diffusivity coefficients for H, LE and CO_2 (F_C) must be equivalent ($K_H = K_E = K_C$). For this to be true, eddies moving entities up or down, assumed to be analogous to molecular diffusion, do not discriminate between the movement of sensible heat, H_2O, or CO_2. Second, that there are no large fluctuations in radiation or wind speed/direction during the sampling period. Hence, conditions such as intermittent cloud negatively impacts the ability of the BREB method to measure CO_2 fluxes from a site because fluxes are temporally averaged over 20 to 30-minute intervals (Price & Black 1990; Steduto & Hsiao 1998). Nighttime measurements and the periods surrounding dusk and dawn are also problematic for the BREB method. The BREB method relies on strong eddies to move the entities from or to the ground. During inversions, air temperature and CO_2 and H_2O concentrations stratify, frequently resulting in an overestimate of CO_2 losses from a site (Price & Black 1990). At dawn and dusk the Bowen ratio typically approaches −1 causing equation

(1) to be indeterminate because the denominator approaches zero (Angus & Watts 1984). Furthermore, energy storage is sometimes ignored in the BREB method because the amount of heat energy stored in the canopy is negligible during the day. However, at dawn and dusk the values for LE and H and net radiation (Q*) are small and the change in stored energy over time is relatively large resulting in inaccurate readings (Tanner 1960).

The dependence on unidirectional eddies further inhibits the use of the BREB. Tall canopies produce turbulent eddies that results in counter-current transport within the canopy (Baldocchi et al. 1988; Oke 1992). For the BREB to be accurate the sensors must be sufficiently higher than the canopy to avoid being influenced by wake eddies. Therefore, the BREB ideally should be used on short canopies.

The BREB is further limited by other restrictions on the physical parameters of a research site. There should be no divergence or convergence of airflow, such as from complex terrain. If such complex terrain is present the movement of fluxes to and from the ground will not be consistent across a site which may result in over or underestimates of BREB fluxes. Furthermore, at night during inversions, the air may flow downhill causing CO_2 respired during the night to by pass the sensors.

Instrumentation should be within a homogenous stand of sufficient size to prevent advection of H, LE or F_C from adjacent stands. If the fetch length (distance from adjacent stands to the BREB system) is not sufficient, sites upwind may influence the sensors. This will provide false readings and ultimately lead to inaccurate flux predictions. In general the fetch should be equal to or greater than 100m for every m in instrument height (Horst & Weil 1992; Stannard 1997). In cases of extreme advection even a large fetch length may not be sufficient to prevent influences from adjacent fields. This is especially the case with the advection of sensible heat to a site. In these situations, the Bowen ratio becomes negative and the K_E/K_H departs from unity (Verma et al. 1978). Such advection events are often associated with high winds in areas that are semi-arid to arid (Verma et al. 1978). To prevent inaccurate estimates of fluxes, wind speed should be measured to detect instances of extreme advection and the data rejected during these intervals.

Extremely dry conditions preclude the use of the BREB method because LE is small and consequently, estimates of LE become inaccurate (Angus & Watts 1984). As Bowen ratios increase energy is increasingly dissipated by sensible heat loss and decreasingly via LE. The measured values of LE then begin to approach their error values. However, the BREB approach is a robust method for measuring fluxes when sufficient consideration is given to the constraints and assumptions mentioned (Tanner 1960; Spittlehouse & Black 1979; Held et al. 1990; Price & Black 1990; Steduto & Hsiao 1998). In addition, the BREB approach compares favourably with other techniques for the measurement of latent and sensible heat (Dugas et al. 1991; Rana & Katerji 1996; Ham & Knapp 1998).

Substantiating BREB CO_2 flux estimates by scaling up from component CO_2 fluxes

To substantiate as well as augment the Bowen Ratio system estimates of the ecosystem CO_2 flux, we utilized a completely independent approach that we have called the component model. An LI-6200 was used to measure the instantaneous component CO_2 fluxes of conifer and deciduous plant photosynthesis and respiration, and below ground respiration. The instantaneous component CO_2 flux measurements were extended temporally using multiple regressions based on instantaneous and continuous microclimate variables and scaled to ecosystem level using foliar biomass measurements made across the growing season.

Thesis purpose

In the summer of 1999 and 2000 we employed a Bowen ratio system in a 5 and 6 year-old clearcut within the Aleza Lake Research Forest. The Bowen ratio and component model CO_2 flux estimates of the 5 and 6 year-old clearcut CO_2 flux were done in conjunction with measures of below ground CO_2 fluxes and above ground biomass in seven cut blocks aged 0 to 10 years. The BREB method and component model measurements of two growing seasons, coupled with the measurements of CO_2 fluxes from multiple aged stands provided a unique view of the carbon status of young cut blocks in the Aleza Lake region. The overall intent of this thesis research was to establish when cut blocks in the Aleza Lake region of British Columbia revert to being sinks for CO_2 after harvesting, and to establish the magnitude and importance of the component CO_2 fluxes (deciduous, conifer and below ground) to the overall ecosystem CO_2 flux in these systems.

References

Angus, D. & Watts, P. 1984: Evapotranspiration – How good is the bowen ratio method? Agricultural Water Management **8**, 133-150.

Baldocchi, D., Hicks, B. & Meyers, T. 1988: Measuring bioshere-atmosphere exchanges of biologically related gases with micrometeorological methods. Ecology **69**, 1331-1340.

Baldocchi, D., Vogel, C. & Hall, C. 1997: Seasonal variation of carbon dioxide exchange rates above and below a Boreal forest. Agricultural and Forest Meteorology **83**, 147-170.

Birdsey, R. A., Planinga, A. J. & Heath, L. S. 1993: Past and prospective carbon storage in United States forests. Forest Ecology and Management **58**, 33-40.

Black, T., Hartog, G. d., Neumann, H., Blacken, P., Yang, P., Russell, C., Nesic, Z., Lee, X., Chen, S., Staebler, R. & Novak, M. 1996: Annual cycles of water vapour and carbon dioxide fluxes in and above a Boreal aspen forest. Global Change Biology **2**, 219-230.

Burschel, P., Korsten, E., Larson, B. & Weber, M. 1993: Present role of the German forests and forestry in the national carbon budget and options to its increase. Water, Air, Soil Pollution 70, 325-340.

Cohen, W. B., Harmon, M. E., Wallin, D. & Fiorella, M. 1996: Two decades of carbon flux from forests of the Pacific Northwest. Bioscience **46**, 836-844.

Dugas, W., Fritschen, L., Gay, L., Held, A., Matthias, A., Reicosky, D., Steduto, P. & Steiner, J. 1991: Bowen ratio, eddy correlation, and portable chamber measurements of sensible and latent heat flux over irrigated spring wheat. Agricultural and Forest Meteorology **56**, 1-20.

Falkowski, P., Scholes, R., Boyle, E., Canadell, J., Canfield, D., Elser, J., Gruber, N., Hibbard, K., Högberg, P., Linder, S., Mackenzie, F., III, B. M., Pedersen, T., Rosenthal, Y., Seitzinger, S., Smetacek, V. & Steffen, W. 2000: The global carbon cycle: A test of our knowledge of Earth as a system. Science **290**, 291-296.

Fan, S.-M., Goulden, M., Munger, J., Danube, B., Bakwin, P., Wofsy, S., Amthor, J., Fitzjarrald, D., Moore, K. & Moore, T. 1995: Environmental controls on the photosynthesis and respiration of a Boreal lichen woodland: a growing season of whole-ecosystem exchange measurements by eddy correlation. Oecologia **102**, 443-452.

Goulden, M., Wofsy, S., Harden, J., Trumbore, S., Crill, P., Gower, S., Fries, T., Daube, B., FAn, S.-M., Sutton, D., Bazzaz, A. & Munger, J. 1998: Sensitivity of Boreal forest carbon balance to soil thaw. Science **279**, 214-217.

Ham, J. & Knapp, A. 1998: Fluxes of CO_2, water vapor, and energy from a prairie ecosystem during the seasonal transition from a carbon sink to a carbon source. Agricultural and Forest Meteorology **89**, 1-14.

Held, A., Steduto, P., Orgaz, F., Matista, A. & Hsiao, T. 1990: Bowen ratio/energy balance technique for estimating crop net CO_2 assimilation and comparison with a canopy chamber. Theoretical and Applied Climatology **42**, 203-213.

Hollinger, D., Goltz, S., Davidson, E., Lee, J., Tu, K. & Valentine, H. 1999: Seasonal patterns and environmental control of carbon dioxide and water vapour exchange in an ecotonal Boreal forest. Global Change Biology **5**, 891-902.

Horst, T. & Weil, J. 1992: Footprint estimation for scalar flux measurements in the atmospheric surface layer. Boundary Layer Meteorology **59**, 279-296.

Jarvis, P., Massheder, J., Hale, S., Moncieff, J., Rayment, M. & Scott, S. 1997: Seasonal variation of carbon dioxide, water vapor, and energy exchanges of a Boreal black spruce forest. Journal of Geophysical Research **102**, 28953-28966.

Keeling, C. D., Chint, J. F. S. & Whorf, T. P. 1996: Increased activity of northern vegetation inferred from atmospheric $C0_2$ measurements. Nature **382**, 146-149.

Kolochugina, T. & Vinson, T. 1993a: Comparison of two methods to assess the carbon budget of forest biomes in the former Soviet Union. Water, Air, and Soil Pollution **70**, 207-221.

Kolochugina, T. & Vinson, T. 1993b: Equilibrium analysis of carbon pools and fluxes of forest biomes in the former Soviet Union. Canadian Journal of Forest Research **23**, 81-88.

Kurz, W. & Apps, M. 1993: Contribution of northern forests to the global C cycle: Canada as a case study. Water, Air and Soil Pollution **70**, 163-176.

Kurz, W. & Apps, M. 1994: The carbon budget of Canadian forests: A sensitivity analysis of changes in disturbance regimes, growth rates, and decomposition rates. Environmental Pollution **83**, 55-61.

Kurz, W., Apps, M., Beukema, S. & Lekstrum, T. 1995: Twentieth century carbon budget of Canadian forests. Tellus **47B**, 170-177.

Kurz, W., Apps, M., Comeau, P. & Trofymow, J. (1996): The carbon budget of British Columbia's forests 1920-1989: Preliminary analysis and recommendations for refinements., pp. 62, Canadian Forest Service and BC Ministry of Forests.

Lindroth, A., Grelle, A. & Morén, A.-S. 1998: Long-term measurements of Boreal forest carbon balance reveal large temperature sensitivity. Global Change Biology **4**, 443-450.

Myneni, R., Keeling, C., Tucker, C., Asrar, G. & Nemani, R. 1997: Increased plant growth in the northern high latitudes from 1981 to 1991. Nature **386**, 698-702.

Oke, T. 1992: Boundry Layer Climates. Routledge, New York.

Price, D. & Black, T. 1990: Effects of short-term variation in weather on diurnal canopy CO_2 flux and evapotranspiration of a juvenile Douglas-fir stand. Canadian Journal of Forest Research **23**, 139-158.

Rana, G. & Katerji, N. 1996: Evapotranspiration measurement for tall canopies: the sweet sorghum case. Theoretical and Applied Climatology **54**, 187-200.

Schimel, D. 1995: Terrestrial ecosystems and the carbon cycle. Global Change Biology **1**, 77-91.

Spittlehouse, D. & Black, T. 1979: Determination of forest evapotranspiration using Bowen ratio and eddy correlation measurements. Journal of Applied Meteorology **18**, 647-653.

Stannard, D. 1997: A theoretically based determination of Bowen-ratio fetch requirements. Boundary Layer Meteorology **83**, 375-406.

Steduto, P. & Hsiao, T. 1998: Maize canopies under two soil water regimes IV. Validity of Bowen-ratio-energy balance technique for measuring water vapor and carbon dioxide fluxes at 5-min intervals. Agricultural and Forest Meteorology **89**, 215-228.

Tanner, C. 1960: Energy balance approach to evapotranspiration from crops. Soil Science Society of America Proceedings **24**, 1-9.

Turner, D., Koerper, G., Harmon, M. & Lee, J. 1995: A carbon budget for forests of the conterminous United States. Ecological Applications **2**, 421-436.

Valentini, R., Dore, S., Marchi, G., Mollicone, D., Panfyorov, M., Rebmann, C., Kolle, O. & Schulze, E.-D. 2000: Carbon and water exchanges of two contrasting central Siberia landscape types: regenerating forest and bog. Functional Ecology **14**, 87-96.

Verma, S., Rosenberg, N. & Blad, B. 1978: Turbulent exchange coeficients for sensible heat and water vapor under advective conditions. Journal of Applied Meteorology **17**, 330-338.

THE GROWING SEASON CARBON BALANCE OF A SUB-BOREAL CLEARCUT FIVE AND SIX YEARS AFTER HARVEST USING TWO INDEPENDANT APPROACHES TO MEASURE CO_2 FLUX

Abstract

While northern forests, including those in northern and central British Columbia, have come under increasing harvesting pressure in recent decades, the impact of this on global atmospheric carbon dioxide (CO_2) concentration is poorly understood. It is often assumed that after forest harvesting, clearcuts remain a source for CO_2 for many years. However, few studies have actually quantified the *in situ* fluxes of CO_2 from young clearcuts. To help address this issue, a Bowen ratio energy balance (BREB) system was deployed in a sub-Boreal clearcut (SBS wk1 08) 5 and 6 years after harvesting, approximately 80 km east of Prince George, British Columbia (54°01'30" N and 122°07'30" W). The BREB system continuously monitored net ecosystem CO_2 fluxes from the clearcut from 27 June to 3 September 1999 and 24 May to 20 September 2000. A second independent method was also used to estimate ecosystem CO_2 flux (the component model approach). In the second approach, component fluxes including plant (spruce seedling and representative deciduous species) and below ground fluxes of CO_2 were measured separately, correlated with microclimate variables, and then scaled to the ecosystem level using regression equations coupled with biomass estimates from the clearcut.

The two approaches predicted very similar flux during the daytime periods but their estimates diverged at night. Over the study periods BREB and component model approaches predicted that the clearcut was a small sink for CO_2 in 1999 (27 June to 3 September) and a source in 2000 (24 May to 20 September). Specifically, in 1999, the BREB method and the component model estimated the site to be a sink of -20 ± 43 g C $m^{-2}$and –86 g C m^{-2}, respectively. In contrast, in 2000 the clearcut was a source of 143 ±57 and 103 g C m^{-2} using the BREB and Component model, respectively.

The main components of the CO_2 flux within the regenerating clearcut were below ground respiration and deciduous plant photosynthesis. The conifer seedlings were only a minor component in overall CO_2 flux over the growing season, removing only 47 and 57 g C m^{-2} in 1999 and 2000 respectively. In contrast, the herbaceous and woody shrubs removed 376 g C m^{-2} in 1999 and 365 g C m^{-2} in 2000. The below ground respiration counterbalanced much of the carbon uptake during the study period by releasing 338 (1999) and 587 (2000) g C m^{-2}. The small overall sink predicted for the clearcut in 1999 for the approximately 2.5 month growing period would likely be surmounted by the below ground respiration if annual CO_2 fluxes are considered. For example, an additional 68 g C m^{-2} was added to the atmosphere from Sept. 3 to 23 (based on below ground respiration data only) after the deciduous plants had senesced. This source alone would nearly be enough to push the clearcut from a sink to a source for CO_2. Therefore, even though there was variability in the carbon uptake during the two growing seasons, the young clearcut was a source of CO_2 for both years.

In summary, the results suggest that while sub-Boreal clearcuts in the SBS wk1 08 may already be sinks for CO_2 over some growing seasons. However, based on previous work, the clear cuts will continue to be a source for CO_2 for more than 5 years if nongrowing season sources of CO_2 are considered. In addition, the results clearly show that the deciduous component of these northern clearcuts (often collectively called brush in the forest industry) is very important for at least the first 6 years after harvesting in counterbalancing the large CO_2 efflux from below ground.

Introduction

Within the last two centuries, anthropogenic CO_2 emissions have increased the level of atmospheric CO_2 from 280 ppm 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 landscape modification. Landscape modification alone explains approximately 50% of the rise in atmospheric CO_2 prior to 1980 (Woodwell et al. 1983) and 23% of the rise in the 1980s (Schimel 1995). Most of the rise in CO_2 resulting from landscape modification can be accounted for in timber harvesting (Harmon et al. 1990) and conversion of forests to agriculture and pasture (Tans et al. 1990).

Attempts to quantify the sources and sinks of 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 (1.5 to 2.0 Pg C yr^{-1} or approximately 50% of anthropogenically derived CO_2) 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 & Vinson 1993a; Kolochugina & Vinson 1993b; Melillio et al. 1993; Kurz & Apps 1994; Turner et al. 1995; Cohen et al. 1996). While some of the models benefit from large databases describing stand age and vegetation (i.e. Kurz et al. 1996), many have the difficult task of estimating CO_2 fluxes without basic information on the vegetation cover types present. To fill in the gaps, modelers must make assumptions about the carbon budgets of the forests by extrapolation from a limited number of study sites (i.e. Birdsey et al. 1993; Kolochugina & Vinson 1993a; Turner et al. 1995). Disturbance events, such as disease, insect outbreak, forest fire and timber harvesting, are common in many of the world's forests and affect the accumulation of carbon to varying degrees. Currently, none of the models account for all disturbance effects or are based on very broad generalizations (i.e. Burschel et al. 1993; Kolochugina & Vinson 1993b; Kurz et al. 1996). Hence, black-box models (a black-box model is one where x predicts y but the processes involved are not understood) are created with little understanding of the processes involved. If black-box models are to incorporate actual processes (i.e. become grey-box models), there will be a need for greater empirical data.

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 carbon sink (Kurz & Apps 1994). The environment (both climate and microclimate) that the seedlings grow in is crucial in determining when a clearcut will change from a source to a sink of CO_2. For example, waterlogging or drought-stress may restrict 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. A pool of between 65 to 104 Pg carbon, or eight times the amount of carbon stored in the plant biomass, is stored in the soils of the Boreal and sub-Boreal forests. How clearing of forests impacts the below ground respiration may well determine when sites convert 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 litter from the canopy (Covington 1981; Federer 1984; Kawaguchi & Yoda 1989; Yarie 1993; Olsson et al. 1996; Pennock & 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). Studies differ on the effect tree harvesting has on below ground respiration; some indicate an increase in respiration (Ewel et al. 1987a; Gordon et al. 1987; Lytle & Cronan 1998), while others indicate no change in respiration (Fernandez et al. 1993; Toland & Zak 1994) and still others note a reduction in respiration (Edwards & Ross-

Todd 1983; Weber 1990; Chang & Trofymow 1996; Striegl & Wickland 1998). The varying responses indicate that forest soils do not respond to clearcutting in a simplistic manner. Site-specific conditions may well control how an area's carbon budget responds to disturbance.

The main microclimate controls on the below ground CO_2 flux are moisture and temperature (Kucera & Kirkham 1971; Fernandez et al. 1993; Striegl & Wickland 1998). The microorganisms responsible for decomposition of organic matter generally demonstrate a positive relationship to moisture and temperature. However, if temperature or moisture becomes excessive respiraton may decrease. Therefore, the microclimate changes resulting from forest harvesting will influence how belowground respiration responds. The removal of trees lowers evapotranspiration and may increase solar radiation at the soil surface (Lewis 1998). The change in the soil's microclimate may increase and or decrease soil moisture and temperature, depending on factors such as time of year, slope, aspect and vegetation.

The harvesting of trees may lower below ground respiration because root respiration can constitute over 50% of the predisturbance below ground respiration rates (Ewel et al. 1987b; Fernandez et al. 1993; Londo et al. 1999). Furthermore, silvicultural practices employed may influence the respiration rates of the soil. Burning slash may remove much of the soil organic layer, and if severe enough, kill the soil microorganisms (Pietikainen & Fritze 1993; Chang & Trofymow 1996). Other impacts of timber harvesting, such as soil compaction due to machinery, may result in reduced aeration of the site leading to a decrease in soil microorganisms and/or aerobic respiration (Chang et al. 1995). Hence, it is not surprising that previous studies have not demonstrated a consistant response of soil respiration to timber harvesting.

How vegetation and soils are affected by climatic change and forest management will influence the carbon budget of a regenerating clearcut. Rapid regrowth of vegetation following forest harvesting may mitigate the efflux of CO_2 from below ground respiration. However, if management, climate change or microclimate factors negatively impact revegetation of a clearcut, the CO_2 budget could be dominated by below ground respiration, thus delaying a site's transition from source to sink for carbon.

In this chapter, I attempt to quantify the growing season net CO_2 flux for a sub-Boreal clearcut 5 and 6 years after harvesting 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 chapter to not only establish whether sub-Boreal clearcut sites in the SBS wk1 08 are likely to be a source or a sink for CO_2, but also to determine the relative importance of the component fluxes from soil and plants on the overall carbon budget of such sites.

Methodology

The site characteristics

CO_2 flux measurements were from 27 June to 3 September 1999 and 24 May to 20 Sept. 2000, in a clearcut in the University of Northern British Columbia/University of British Columbia Aleza Lake Research Forest (54°01'30" N and 122°07'30" W). An 84.15 ha stand, in the sub-Boreal spruce wet cool sub-zone that was sub-hygric and nutrient rich (SBS wk1 08), was harvested in 1994. Prior to harvesting the clearcut contained a combination of hybrid white spruce and subalpine fir (*Abies lasiocarpa*) with an understory of *Ribes lacustre, Lonicera involucrata, Viburnum edule, Oplopanax horridus,* and *Rubus idaeus.* After mounding, the cut block was planted with two year-old hybrid spruce (*Picea glauca x Picea engelmannii*) with a smaller component of lodgepole pine (*Pinus contorta* var. *latifolia*) in spring, 1995. The soil is classified as an Orthic Luvic Gleysol (Arocena & Sanborn 1999). Based on the site prescription and a vegetation survey conducted in 1999, the cut block contained 1200 spruce seedlings ha^{-1} along with a variety of natural deciduous plants dominated by *Epilobium angustifolium, Spiraea douglasii* spp. *menziesii, R. idaeus, R. lacustre, Cornus canadensis, L. involucrata, Equisetum arvense* and a variety of grasses dominated by *Calamagrostis canadensis.* The site is cool and wet and has a relatively high snowfall when compared to other areas in the central plateau region of sub-Boreal British Columbia (mean annual air temperature - 1.7 to 5°C) (Meidinger & Pojar 1991).

The site was well suited for the BREB approach. The regenerating canopy was short, with vegetation rarely exceeding 1.2 m in height. 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, satisfying the recommended 100 m of fetch for every meter in height suggested by others (Horst & Weil 1992; Stannard 1997). In addition, the site was relatively flat with a slope of approximately 1% overall. The 100 x 100 m measurement area was subdivided into a 20 x 20 m grid network and the BREB tripod placed in the center grid square in 1999 and in the adjacent grid square to the south in 2000. 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, Alberta) and Bowen ratio energy balance (BREB) approach. The CO_2 gradient was measured by means of a closed path CO_2/H_2O infra-red gas analyzer (IRGA) (Li-6262, LI-COR, Lincoln, Nebraska) connected to intake tubes situated in arms off the instrument tripod. In 1999, the top arm of the Bowen ratio system was 2.5 m above ground level and the bottom arm 1.4 m directly beneath it. During the 2000 field season the top arm was increased to 2.8 m and the bottom arm 1.48 m directly beneath it. It is recognized that the arms are within the roughness layer of the canopy, but if the arms had been placed above the roughness layer, the fetch would have been inadequate in several directions. However, while not ideal, others have successfully measured CO_2 and H_2O fluxes within the roughness layer above the canopy (Raupach & Legg 1984; Denmead & Bradley 1985; Price & Black 1990).

Flow rates through the system tubing were maintained at 700 to 800 ml min^{-1}. Every two minutes the air drawn in through the intake tubes was reversed between the reference and sample cells of the IRGA and 40 seconds was allowed for the pump to purge the IRGA between measurements. Average CO_2 gradients were calculated every 20 minutes. At the beginning of every hour, one cell of the IRGA was scrubbed to establish the absolute concentrations of CO_2 and H_2O. 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 10s with a tripod mounted Q7 REBS net radiometer (Campbell-Scientific) and averaged over a 20 minute interval. To establish the temperature gradient (sensible heat flux), two chromel-constantan fine wire thermocouples (75 μm) were placed at the end of each of the two arms. 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, soil heat flux (G) was calculated in three steps. First, soil characteristics were used to calculate the heat capacity of the moist soil (C_S):

$$C_S = \rho_b(c_d + \theta_m c_W) \quad (1)$$

where ρ_b is the bulk density of the soil, c_d is the specific heat of a dry mineral soil, θ_m is the water content on a percent mass basis and c_W is the specific heat of water. Second, the amount of energy stored between the thermocouples (K m^2 s^{-1}) below ground (S) over each 20 minute interval was then calculated:

$$S = \frac{\Delta T_S C_S d}{t} \quad (2)$$

where ΔT_S is the change in soil temperature, d is the depth of the sensors and t is time. G was then calculated by summing the energy stored below ground (S) with the heat flux values provided by the heat flux plates (G_g).

$$G = G_g + S \quad (3)$$

The movement of latent heat (LE), sensible heat (H), and CO_2 (F_C), through the atmosphere above the clearcut were calculated based on the following equations:

$$\begin{aligned} LE &= -L_V K_E \partial \rho_V / \partial z \\ H &= -\rho C_P K_H \partial T / \partial z \quad (4\text{-}6) \\ F_C &= -K_C \partial \rho_C / \partial z \end{aligned}$$

Where K_E, K_H and K_C are the eddy diffusivities for water vapour, heat and CO_2 respectively, ρ_V is water vapour density, ρ_C is CO_2 density, ρ is air density, C_P is the specific heat of air, T is the absolute air temperature and z is height.

Using the universal gas law equations 4 and 6 can be transformed to:

$$\begin{aligned} LE &= -L_V K_E \frac{P M_V \partial w}{T R \partial z} \\ F &= K_C \frac{P M_C \partial c}{T R \partial z} \end{aligned} \quad (7\text{-}8)$$

where P is pressure, M_V is the molecular weight of water, w is the mole fraction of water to air, R is the universal gas constant and M_C is the molecular weight of CO_2.

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

$$Q^* = H + LE + G \quad (9)$$

the similarity assumption ($K_H = K_E = K_C$) and the Bowen ratio. The Bowen ratio, defined as sensible heat divided by latent heat, was calculated by:

$$\beta = H / LE = C_P \partial T / L_V \varepsilon \partial_w \quad (10)$$

where ∂T is the temperature gradient L_V is the latent heat of vaporization of water, ε is the ratio of molecular weight of water vapour to dry air and $\partial \rho_V$ is the water density gradient. Sensible heat was substituted in the energy balance equation with βLE solving for LE:

$$LE = (Q^* - G)/(1 + \beta) \quad (11)$$

The eddy diffusivity coefficient for the CO_2 flux (K_C) was calculated using the following equation:

$$K_C = K_H = (z_1 - z_2)H / (T_1 - T_2)\rho C_P \quad (12)$$

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 indicate movement away from the surface and negative toward the surface.

Other meteorological measurements

Further meteorological conditions were measured at the site. Wind speed and direction were estimated using a wind sensor placed at the top of the tower (at 2.8 m in 1999 and 3.0 m in 2000) (R.M. Young 03002-10 Wind Sentry, Campbell Scientific). Light levels were taken using a quantum sensor (Li-Cor quantum sensor, Li-Cor). In 1999, 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. In 2000, the four thermocouples were placed at 10 cm beneath the surface to improve soil temperature sampling at that depth. The soil and light measurements were taken every minute and then averaged over 20 minutes. Air temperature and relative humidity were measured with a single probe (HMP35C, Campbell Scientific) every 10 seconds and then averaged over 20 minutes. In 2000, a rain gauge was added to the site (TE-525M, Campbell-Scientific) to continuously measure rainfall. During the 1999 field season rainfall values were taken from a meteorological tower located approximately 7.5 km away. All the data were stored on two data loggers (21X, Campbell Scientific) and transfered to a field-portable laptop computer as required. The meteorological data was compared to historical data provided by the Ministry of Forests, from 1952 to 1980 and 1993 to 1998.

Conifer photosynthesis

At the beginning of each field season, the average heights of the spruce seedlings were calculated and 20 seedlings that were within ± one standard deviation of the mean were randomly selected. A one-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 northern or southern side of the seedlings in 1999. After finding the bulk of the biomass was in the needles less than or equal to 1 year of age (See Appendix I), and that there was little difference in the photosynthetic rates between those needles, only 1 year-old needles were selected in 2000 for sampling.

Photosynthesis and respiration measurements were made using a portable closed gas-exchange system (LI-6200, Li-Cor) on a weekly basis. Respiration measurements were conducted during the day by placing the branchlet in the dark and measuring the corresponding respiration rates. Microclimate variables of light (μmol PAR m^{-2} s^{-1}) (Li-Cor quantum sensor, Li-Cor), relative humidity, air temperature and atmospheric water vapour content were measured by the LI-6200 while soil temperature (Reotemp instruments, San Diego, California) and soil moisture (Nie-Co-Product Nieuwkoop B.V., Aalsmeer, Holland) were made independently but simultaneous with gas-exchange measurements. These microclimate variables were later used in regression models to establish relationships that were used to predict carbon uptake (see below).

Deciduous plant photosynthesis and respiration

The deciduous plants on site leafed out around 31 May in both 1999 and 2000. Throughout the field season photosynthetic and respiration rates of *E. angustifolium*, *S. douglasii* spp. *menziesii*, and *L. involucrata*, were measured with the LI-6200 (as above) under varying microclimate conditions. The plants were randomly selected on each measuring day within the study area. Area-based photosynthesis and respiration were 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 PVC collars (9.55 cm in diameter) were placed in randomly selected grid squares throughout the measurement area. Measurements were taken using a Li-6200 with the soil chamber attachment (6000-09, Li-Cor) as in Norman et al. (1992). During the soil measurements both soil temperature (6000-09TC, Li-Cor) and moisture (as above) were taken at a depth of 10 cm.

Biomass

On July 7-8 and August 17-18 1999, the above ground living biomass for the deciduous plants was destructively sampled in 24 randomly selected 1 m^2 plots within the measurement grid. During the 2000 field season, 12 randomly selected 0.5 m^2 plots of above ground living biomass were destructively sampled six times across the growing season. The increase from two sampling dates in 1999 to six in 2000 was an attempt to better characterize the changes in leaf biomass throughout the growing season.

On 25 September 1999, 20 randomly selected *P. glauca x P. engelmannii* seedlings were destructively sampled. The seedling branchlets were further divided up by individual needle age classes. In early May and late September of 2000, a further 20 seedlings were destructively sampled. All the biomass samples were dried at 65 °C for 72 h and weighed to the nearest 0.01 g.

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 divided into four components: conifer, herbaceous deciduous plant, woody deciduous plant (shrub) and below ground respiration. Multiple regressions were established using the best subset method. The significant variables ($p=0.05$) found using this method were used in the models to predict fluxes. The regressions provided estimates of the CO_2 fluxes in $\mu mol\ CO_2\ m^{-2}\ s^{-1}$. The rates were given in m^2 of leaf surface area or soil surface area.

The component model required four steps to scale from the leaf to the clearcut. First, the leaf area for each component was correlated to biomass (conifer, herbaceous, and woody plant). Second, the relationship between leaf area and biomass was used in conjunction with the estimates of leaf biomass of the clearcut ($g\ m^{-2}$) taken throughout the study period to estimate the leaf area index for each plant biomass component. Third, the estimate of CO_2 uptake was made using the regressions and the data from the micometeorological tower for each component. Finally, the estimates from the regressions were multiplied by the leaf area calculated in the second step, producing the CO_2 flux estimates for the different plant components. When modeling the plant photosynthetic and respiration rates it was assumed that 15% of net primary production (NPP) of the leaves was lost to stem respiration (Ryan et al. 1994; Levy & Jarvis 1998). The below ground CO_2 flux estimates were already in m^2, hence, the CO_2 flux was estimated based on the regressions and the micrometeorological values given by the tower. Upon completing the flux estimates for each component, the overall flux of the site was estimated for every 20 minutes using:

$$F_c = F_{conifers} + F_{herbaceousplants} + F_{woodyplants} + F_{belowground}$$

Corrections of BREB data

In order to predict a continuous CO_2 flux for the cut block various corrections of the BREB data were necessary. The clearcut 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, some 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 & Knapp 1998). In contrast, during longer periods of equipment failure or extended rain events, a regression between light and the CO_2 fluxes for the days adjacent to the problem period were created and used as a predictor of the CO_2 fluxes. The regression was then used to fill in the gaps in the data (Ham & Knapp 1998). Of the total measurement days, 30% and 9% required the use of regressions to fill problem or lost data in 1999 and 2000, respectively.

Nighttime CO_2 fluxes were occasionally over estimated 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 & Watts 1984). In addition, the small Q^* value associated with nighttime flux predictions can further exacerbate the problem by inaccurately predicting the eddy diffusivity coefficient resulting in an exaggeration of the CO_2

flux (Price & Black 1990). The Component model estimates of ecosystem flux were used in place of BREB nighttime estimates when stratification occurred.

Error analysis

The insturment errors were used in conjuction with the standard errors of nighttime component model estimates and the daytime regression estimates to produce 95% confidence limits for the BREB method. Error analysis for the BREB method was based on the instrument errors with the exception of the soil heat flux plates. Due to the spatial variablility of the soil, the error was assumed to be 20%.

Results

Physical environment

The summers of 1999 and 2000 were cool with few episodes of warm weather (Fig. 1). The mean daily air temperatures for each month ranged between 7.5 °C (May) to 15 °C (August) in 1999 and 8.5°C (September) to 14.5 °C (July) in 2000. The monthly mean temperatures were significantly cooler than the historical record (1952-1980) in May 1999, August 2000 and July and September in both 1999 and 2000 ($p=0.005$). The rainfall in 2000 was significantly greater than the historical record (1952-1980) in July and significantly greater than the record from 1993-1998 in July, August and September ($p=0.05$). The rainfall data for 1999 could not be compared because of damage to the rain gauge from late June to August 14, 1999. However, when the 2000 meteorological data is compared to that of 1999 there was no statistical difference in air temperature (Fig. 1). The rainfall for the months of May and September were similar for 1999 and 2000, but the rainfall in the months of June and August may have been greater in 2000. While not statistically significant, the greater rainfall in 2000 may have translated into higher soil moisture levels (Fig. 2).

Microclimate variables and the ecosystem component CO_2 flux

The component fluxes correlated well with microclimate variables for 1999 and 2000 (Table 1a,b). Conifer net photosynthesis correlated well with the microclimate variables of light, soil temperature and air temperature in 1999 ($R^2 = 0.76$) and microclimate variables of light, soil temperatures and relative humidity in 2000 ($R^2 = 0.72$) (Table 1a,b). In 1999, predictions of photosynthesis in herbaceous plants, based on photosynthetic measurements on *E. angustifolium*, required two separate regressions. Light, soil moisture and soil temperature were used to predict daytime CO_2 fluxes. A second equation for the herbaceous plants was created for estimations subsequent to 7 August 1999 following a marked decrease in photosynthesis at that time. In 2000 a single equation adequately represented daytime CO_2 uptake by herbaceous plants. Woody shrubs were represented by *S. douglasii* spp. *menziesii* in 1999 and *L. involucrata* in 2000. Unlike the other plants, the regression for S. *douglasii* spp. *menziesii* represented the CO_2 flux for both day and night.

Instantaneous measurements of dark respiration for the plant species in 1999 and 2000 correlated significantly with air temperature alone in three of the four plant species (*P. glauca x P. engelmannii* , *E. angustifolium* and , *L. involucrata*) (Fig. 3 a-e). The relationship was hyperbolic or linear with maximum respiration rates ranging from 2.5 μmol C m^{-2} s^{-1} for *L. involucrata* to 4.5 μmol C m^{-2} s^{-1} for *P. glauca x P. engelmannii* and *E. angustifolium.*

In contrast to 1999, the net photosynthesis in, *P. glauca x P. engelmannii, L. involucrata* and *E. angustifolium* appeared to correlate more strongly with light level in 2000 (Fig. 4). The 2000 instantaneous CO_2 flux for *P. glauca x P. engelmannii* and *E. angustifolium* saturated at approximately 500 μmol PAR $m^{-2} s^{-1}$ and had compensation points of about 70 μmol PAR $m^{-2}s^{-1}$. Photosynthesis of *L. involucrata* exhibited a parabolic relationship to light with maximum rates at approximately 1000 μmol PAR $m^{-2} s^{-1}$ and compensation point below 40 μmol PAR $m^{-2} s^{-1}$. The maximum instantaneous CO_2 flux typically resided at 13 μmol C $m^{-2}s^{-1}$ for *P. glauca x P. engelmannii*, 16 μmol C $m^{-2}s^{-1}$ for *E. angustifolium* and 12 μmol C $m^{-2}s^{-1}$ for *L. involucrata.*

The instantaneous below ground CO_2 fluxes correlated with soil temperature at 10 cm depth in 1999 and 2000 (Fig. 5 a,b). A correlation between instantaneous below ground CO_2 flux and soil moisture was significant in 1999 only ($p=0.05$). Instantaneous below ground CO_2 flux ranged from 1.2 μmol C $m^{-2} s^{-1}$ at 3.2 °C to 9.2 μmol C $m^{-2} s^{-1}$ at 15.9 °C. The relationship was essentially linear in 1999 and exponential in 2000 with R^2 values of 0.66 and 0.7, respectively (Table 1a,b).

Biomass

Based on biomasss, the deciduous plants were a more important sink for CO_2 than the coniferous plants for both 1999 and 2000. The deciduous plants began to leaf out on approximately June 1 and by the middle of August all the plants had accumulated over 189 g C m^{-2} (not including allocation to stem biomass of woody shrubs in 1999) of aboveground biomass in 1999 and 276 g C m^{-2} in 2000(Table 2a,b). By the end of the growing season the conifers had only allocated 10.6 and 18.6 g C m^{-2} of new growth to stems and needles in 1999 and 2000, respectively. Of total carbon allocated to above ground plant parts, >90% was resident in deciduous plant above ground biomass both years.

The BREB method and component model estimates of ecosystem CO_2 fluxes

The component model agrees with the BREB method during the day, but their estimates frequently diverged at night. Typical CO_2 flux estimates for the clearcut from the component model and BREB methods are shown for 4 July and 29 July 1999 and 15 June and 17 August 2000 (Fig. 6a-d). For sake of contrast, and to illustrate the 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 predicted CO_2 efflux from the site is much diminished resulting in both approaches predicting similar daily CO_2 losses/gains for the clearcut (Fig. 7,8).

After making nighttime corrections to the BREB data, both the component model and BREB approaches predicted the clearcut to be a sink from 27 June to 3 September 1999 (Table 3) and a source from 24 May to 20 September 2000 (Table 4). Component CO_2 fluxes indicated that herbaceous and woody plants absorbed the bulk of the carbon removing -212 and -165 g C m^{-2} respectively during the 1999 study period and –315 and –172 g C m^{-2} respectively in the 2000 study. In comparison, the conifers only removed an estimated -47 and –96 g C m^{-2} in 1999 and 2000 respectively. Below ground respiration acted as a constant CO_2 source throughout the season. From 27 June to 3 September 1999 and 24 May to 20 September 2000 the roots and soil flora and fauna released 338 and 686 g C m^{-2} respectively, thereby counteracting most or all of the carbon sink generated via plant photosynthesis.

Below ground CO_2 flux

Below ground CO_2 efflux was sizable both during both growing seasons (between 4 to 8.2 g C m^{-2} d^{-1}) (Table 3-4) and for measurement dates following the the last BREB measurement in 1999 (between 3.2 to 4.2 g C m^{-2} d^{-1}) (Fig. 9). Following the 1999 BREB measurement period, below ground respiration for Sept. 4 through 23, 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. 9), enough to convert the site into an overall source for CO_2.

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

The clearcut experienced a divergence between the BREB and component model estimates of daily ecosystem CO_2 flux in early August for both growing seasons (Fig. 7,8). Prior to the down turn in photosynthetic uptake of CO_2 in 1999, the BREB approach predicted mean daytime CO_2 fluxes (mean = -0.07 mg C m^{-2} s^{-1}) that were only 0.01 mg C m^{-2} s^{-1} greater (more positive) than the component model (mean = -0.08 mg C m^{-2} s^{-1}). After 7 August 1999 the mean daytime CO_2 fluxes were –0.046 and –0.079 mg C m^{-2} s^{-1} for the BREB and component model, respectively. This resulted in a significant change in mean difference between the two approaches of 0.033 mg C m^{-2} s^{-1}. Hence, a new equation was created with a negative relationship to day of year and time of day was created to estimate the daytime CO_2 flux of the herbaceous plants after 7 August 1999. Similarly, a weaker divergence occurred in 2000. Prior to 10 August 2000, the BREB method and component model averaged -0.09 and –0.074 mg C

m^{-2} s^{-1}, respectively. This resulted in a mean difference of -0.016 mg C m^{-2} s^{-1}. Following 10 August 2000 the BREB method averaged –0.033 mg C m^{-2} s^{-1} and the component model averaged –0.049 mg C m^{-2} s^{-1} resulting in a mean difference of 0.016 mg C m^{-2} s^{-1}. The change in early August is significant for both 1999 and 2000 at $p < 0.001$ at a 99% confidence level.

Comparison of Ecosystem CO_2 Flux estimates from 1999 and 2000

Because of the extended measurement period in 2000, a direct contrast of growing seasons between years 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 5). The size of the sink for the summer of 1999 was calculated at -86 g C m^{-2} using the component model and –20 ±43 g C m^{-2} using the BREB method. In contrast, the 2000 data indicates the clearcut to be a source of 43 g C m^{-2} using the component model and 65 g C m^{-2} with the BREB method. The BREB daily CO_2 flux estimates for 1999 were generally lower (greater sink) than those in 2000 (Fig. 10).

Both years had similar daily photosynthetic rates for the season (Fig. 11) and cumulative CO_2 uptake for the individual plant components (Table 5). The seasonal totals of photosynthetic CO_2 uptake were -424 C m^{-2} in 1999 and –422 g C m^{-2} in 2000. Herbaceous plants and conifers fixed more total CO_2 (increase of 21 and 9.3 g C respectively) in 2000 than 1999, while the woody shrubs had a slight drop in CO_2 uptake (decrease of 31.6 g C m^{-2}). In both 1999 and 2000, the deciduous plant contribution to ecosystem photosynthesis was much larger than the contribution from the conifers seedlings (Table 5).

The difference in the seasonal ecosystem CO_2 flux appeared to be driven largely by the below ground CO_2 fluxes to the atmosphere in the summer of 2000 (Fig. 12). From 27 June to 3 September 1999, the cumulative below ground CO_2 flux was estimated at 338 g C m^{-2} while over the same interval in 2000 the estimate was 466 g C m^{-2}, a 38% increase. There was no statistical difference between the soil temperatures at 10-cm depth for the same periods for 1999 and 2000 ($p=0.05$, data not shown).

Discussion

BREB flux estimates

The component model and BREB method compared well. Both methods predicted the clearcut to be a sink in 1999 and a source of CO_2 in 2000. The daytime estimates were similar (Fig 6a-d) and the daily fluxes were very comparable for both 1999 and 2000 (Fig. 7,8). The two approaches diverged in early August during both 1999 and 2000, with the BREB method predicting the site to be a larger source for CO_2 than the component model. In 1999, the model for the herbaceous plants was adjusted by incorporating day as a negative influence on CO_2 uptake, but it was unable to immediately bring the two approaches into agreement. The problem associated with the component model is its reliance on measured leaf level CO_2 flux that were only measured once or twice every two weeks. A rapid change in photosynthetic uptake due to senescence, flowering and seed set, heat stress or frost damage cannot be accommodated by 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 predict the site to be a sink for CO_2 for the 1999 growing season (Table 3). The component model's estimate is likely too large because of its inability to interpolate fluxes during the two weeks subsequent to Aug. 7. Prior to Aug. 7, the difference between the BREB method and the component model was only 0.011 mg C m^{-2} s^{-1}, but after Aug. 7 the difference increased to 0.033 mg C m^{-2} s^{-1}. While this appears to be a small difference, it was significant enough to change the site from a sink of -20 ±43 g C m^{-2} with the BREB method to -86 g C m^{-2} using the component model.

Though it was necessary to dismantle BREB instrumentation prior to the onset of winter, components of the ecosystem flux, such as below ground respiration, would have undoubtedly continued and thus, contributed to the annual carbon budget of the cut block. For example below ground respiration emitted an estimated 68 g C m^{-2} between Sept. 3 and Sept. 23 in 1999 (Fig. 9) and this loss of CO_2 would continue at a reduced rate under the snowpack (Coxson & Parkinson 1987; Sommerfeld et al. 1993; Clein & Schimel 1995; Evans et al. 1998). The snow insulates the soil, buffering it against the colder air temperatures thereby allowing for greater below ground respiration than would be generally indicated by air temperature (Bleak 1970; Moore 1983). A study conducted during the winters of 97/98 by Evans et al. (1998) within the Aleza Lake Research Forest at a site with an identical site series (SBS wk1-8) observed winter flux that ranged between 0.603 to 0.772 g C m^{-2} d^{-1}. Others have found similar winter CO_2 flux that ranged between 0.409 to 0.736 g C m^{-2} d^{-1} (Sommerfield et al. 1993) and 0.204 to 0.818 g C m^{-2} day^{-1} (Coxson and Parkinson 1987) in southeastern Wyoming and southwestern Alberta respectively. Using the values from Evans et al. (1998) the modest sink from 27 June to 3 September results in loss of CO_2 from the site, roughly be estimated to be between 83 to

121 g C m^{-2} yr^{-1}. The 1999 estimate contains four specific assumptions: CO_2 losses range between 0.603 to 0.772 g C d^{-1} under the snowpack (Nov. 1 to April 30); fluxes linearly decreased to the winter flux in the fall (Sept.4 to Oct 31); fluxes decreased from the winter flux to a net uptake of –1.41 g C d^{-1} in the Spring (May 1 to June 1) when the site flushed (-1.41 g C d^{-1} is the average daily CO_2 flux from June 27 to July 5); after June 1 the flux remained at –1.41 g C d^{-1} until June 27 when the BREB flux estimates resumed. The loss of CO_2 in 2000 is only exacerbated by the winter CO_2 flux. The winter losses of CO_2 alone would raise the flux to approximately 229 to 265 g C m^{-2} yr^{-1}. The estimates demonstrate that the loss of CO_2 during the winter months is enough to surmount any gain by the plants during the summer months for this clearcut at this age.

The component flux

The conifer CO_2 uptake was similar to rates measured by others under a variety of conditions (Watts & Neilson 1978; Bassman 1989; Man & Lieffers 1997), typically ranging between 8 and 12 μmol C m^{-2} s^{-1} depending on the microclimate. The deciduous plants had much higher leaf area specific photosynthetic rates than the conifers, with rates typically ranging from 6 and 16 μmol C m^{-2} s^{-1} depending on the species and the micrometeorological conditions. Instantaneous below ground CO_2 fluxes were similar to those found by some researchers (Edwards & Sollins 1973; Ewel et al. 1987; Gordon et al. 1987; Russell & Voroney 1998), but higher than seen by others (Weber 1990; Fernandez et al. 1993; Lytle & Cronan 1998; Striegl & Wickland 1998) for various types of forests and cut blocks. The higher below ground CO_2 flux observed in this study may have been the result of a trend of higher respiration rates with increasing latitude (Valentini et al. 2000). In a study of European forests, Valentini et al. (2000)

found northern areas to have a greater ecosystem respiration rate, even though their soil temperatures were much lower.

The Overall CO_2 flux in comparison to other northern forests

The observed BREB method fluxes of 0.0545 to 0.213 mg C m^{-2} s^{-1} in this study, are similar to those found in the literature for young clearcuts and some mature stands. For example, Price & Black (1990), found daily CO_2 fluxes to be between 0.0545 to 0.136 mg C m^{-2} s^{-1} for a young juvenile Douglas-fir stand. The main difference between the Douglas-fir stand (Price and Black, 1990) and the planted spruce clearcu studied here was that the former was a source for CO_2 for a longer period of the day. This may be the result of the shorter day length and and drier conditions at the lower latitude Douglas-fir site. Another study on a 12 year-old Boreal cut block in Siberia during July 1996, averaged -0.104 g C m^{-2} d^{-1} over a 14 day measurement period (Valentini et al. 2000). In contrast, during the month of July at the Aleza Lake clearcut, ecosystem CO_2 flux in 1999 averaged –1.23 and –1.72 g C m^{-2} d^{-1} and in 2000 averaged 0.142 g C m^{-2} d^{-1} and 0.439 g C m^{-2} d^{-1} using the BREB method and component model, respectively. Therefore, the Aleza Lake cut block differed from the 12 year-old Siberian forest in both summers, being a greater sink in 1999 and a greater source in 2000.

The maximum BREB CO_2 uptake rates in the clearcut were ≈-0.218 mg C m^{-2} s^{-1} but it averaged approximately -0.114 and -0.12 mg C m^{-2} s^{-1} at midday (27 June to 3 September) for 1999 and 2000 respectively. Mature stands in the Boreal forest tend to have equivalent or lower flux of CO_2 when compared to the clearcut in this study. Values of fluxes in high latitude forests range from maximum values of -0.155 mg C m^{-2} s^{-1} in an ecotonal Boreal forest

(Hollinger et al. 1999) to a minimum of -0.049 mg C m^{-2} s^{-1} in a Siberian larch forest (Hollinger et al. 1998). Maximum CO_2 uptake for Canadian Boreal forests average between ≈-0.084 mg C m^{-2} s^{-1} (Jarvis et al. 1997) at a southern Saskatchewan black spruce site to ≈-0.095 mg C $m^{-2}s^{-1}$ in a black spruce-lichen woodland near Scheferville, Quebec (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.

Many northern forests often have a negative carbon budget. Studies indicate that northern forests are often tenuously balanced between being 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 one year (≈70 g C m^{-2} October 1994 to October 1995 and ≈20 g C m^{-2} between October 1995 to October 1996), but a sink over a 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 June 1, 1994 and May 31, 1995 and ≈60 g C m^{-2} during the same period in 1995-96.

The Seasonal Ecosystem Flux for 1999 and 2000

The estimated ecosystem CO_2 flux for 27 June to 3 September 1999 and 2000, demonstrated a switch from source to sink for CO_2 then back to source again over the growing seasons. The variation demonstrated in the two years is not uncommon as illustrated by Goulden et al. (1998) above. Clearly, shifts in climatic conditions can impact the size of the ecosystem CO_2 flux. For example, changes in the length of the growing season (Goulden et al. 1998) rainfall (Grieu et al. 1988; Baldocchi 1997; Cienciala et al. 1997), and soil/air temperature (Vapaavuori et al. 1992; Harrington et al. 1994) can alter the photosynthetic CO_2 uptake and/or the below ground CO_2 efflux from year to year.

The difference in the overall ecosystem CO_2 flux, between 1999 and 2000, is not the result of reduced photosynthetic uptake. The modeled photosynthetic CO_2 uptake was remarkably uniform for 1999 and 2000 (Fig. 11). Furthermore, the biomass present on the site was very similar between the two years. The biomass values from 1999 totaled 235 g C m^{-2} in aboveground biomass compared to 276 g C m^{-2} in aboveground biomass in 2000 (woody shrub values for leaf biomass only). The main difference was an 18.6 g C m^{-2} increase in the aboveground conifer biomass and a 38 g C m^{-2} increase in herbaceous plants biomass. In contrast, the component models estimated a decrease in photosynthetic uptake of CO_2 of only 1.91 g C m^{-2} from 1999 to 2000 (27 June to 3 September). While there are discrepancies between the biomass and component model CO_2 flux estimates, the results do indicate that there was little change in the photosynthetic CO_2 uptake over the two growing seasons.

The below ground CO_2 flux increased greatly from 1999 to 2000 (Fig. 12). The component model, based on instantaneous measurements across the growing season, estimated the below ground CO_2 flux to be 338 g C m^{-2} in 1999 and 466 g C m^{-2} in 2000 (27 June to 3 September); an increase of 128 g C m^{-2}. There were no distinguishable differences between the soil temperatures and an increase in root respiration seems unlikely given that there was only a small difference in aboveground biomass between years. While not statistically different, the soil moisture levels in 1999 were consistently lower in the mid summer months when compared to 2000 (Fig. 2b). Soil moisture was a significant variable in predicting below ground CO_2 fluxes in 1999. When soil moisture becomes limited its influence on the below ground CO_2 flux becomes greater (Londo et al. 1999), and in extreme situations soil moisture, demonstrates a greater importance than soil temperature (Parker et al. 1983).

Summary

Over the two study periods that roughly coincided with the growing season, the clearcut in this study acted as a small sink for CO_2 in1999 and source of CO_2 in 2000. However, if estimates for below ground fluxes for the entire year are considered, losses of CO_2 from the soil would easily exceed that taken up through photosynthesis at the site for both growing seasons. 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 and 5 years of conifer growth in the field. Hence, if our goal is to minimize the accumulation of greenhouse gases in the atmosphere in the years immediately after harvest, mechanical (brushing) or herbicidal removal of deciduous ("non-crop") vegetation should avoided.

References

Angus, D. & Watts, P. 1984: Evapotranspiration – How good is the bowen ratio method? Agricultural Water Management **8**, 133-150.

Arocena, J. & Sanborn, P. 1999: Mineralogy and genesis of selected soils and their implications for forest management in central and northeastern British Columbia. Canadian Journal of Soil Science **79**, 571-592.

Baldocchi, D., Vogel, C. & Hall, C. 1997: Seasonal variation of carbon dioxide exchange rates above and below a Boreal forest. Agricultural and Forest Meteorology **83**, 147-170.

Bassman, J. 1989: Influence of two site preparation treatments on ecophysiology of planted *Picea engelmannii* X *glauca* seedlings. Canadian Journal of Forest Research **19**, 1359-1370.

Birdsey, R. A., Planinga, A. J. & Heath, L. S. 1993: Past and prospective carbon storage in United States forests. Forest Ecology and Management **58**, 33-40.

Black, T., Hartog, G. d. & Neumann, H. 1996: Annual cycles of water vapour and carbon dioxide fluxes in and above a Boreal aspen forest. Global Change Biology **2**, 219-230.

Bleak, A. 1970: Disappearance of plant material under a winter snow cover. Ecology **51**, 915-917.

Broderick, D. 1990: The biology of Canadian weeds. 93. *Epilobium angustifolium* L. (Onagraceae). Canadian Journal of Plant Science **70**, 247-259.

Burschel, P., Korsten, E., Larson, B. & Weber, M. 1993: Present role of the German forests and forestry in the national carbon budget and options to its increase. Water, Air, Soil Pollution **70**, 325-340.

Chang, S., Preston, C. & Weetman, G. 1995: Soil microbial biomass and microbial and mineralizable N in a clear-cut chronosequence on northern Vancouver Island, British Columbia. Canadian Journal of Forest Research **25**, 1597-1607.

Chang, S. X. & Trofymow, J. A. 1996: Microbial respiration and biomass (substrate-induced respiration) in soils of old-growth and regenerating forests on northern Vancouver Island, British Columbia. Biology and Fertilility of Soils. **23**, 145-152.

Ciais, P., Tans, P. P., Trolier, M., White, J. W. C. & Francey, R. J. 1995: A large northern hemisphere terrestrial CO_2 sink indicated by the $^{13}C/^{12}C$ ratio of the atmospheric CO_2. Science **269**, 1098-1102.

Clein, J. & Schimel, J. 1995: Microbial activity of tundra and taiga soils at sub-zero temperatures. Soil Biology and Biochemistry **27**, 1231-1234.

Cohen, W. B., Harmon, M. E., Wallin, D. & Fiorella, M. 1996: Two Decades of Carbon Flux from Forests of the Pacific Northwest. Bioscience **46**, 836-844.

Covington, W. W. 1981: Changes in forest floor organic matter and nutrient content following clear cutting in northern hardwoods. Ecology **62**, 41-48.

Coxson, D. S. & Parkinson, O. 1987: Winter respiratory activity in aspen woodland forest floor litter and soils. Soil Biology and Biochemistry **19**, 49-59.

Dale, V., Houghton, R. & Hall, C. 1991: Estimating the effects of land-use change on global atmospheric CO_2 concentrations. Canadian Journal of Forest Research **21**, 87-90.

Dixon, R. K., Brown, S., Houghton, R. A., Solomon, A. M., Trexier, M. C. & Wisniewski, J. 1994: Carbon pools and flux of global forest ecosystems. Science **263**, 185-190.

Edwards, N. T. & Ross-Todd, B. M. 1983: Soil carbon dynamics in a mixed deciduous forest following clear-cutting with and without residual removal. Soil Science Society of America Journal 47.

Edwards, N. T. & Sollins, P. (1973): Continuous measurement of carbon dioxide evolution from partitioned forest floor components., pp. 406, Environmental Sciences Division. Oak Ridge National Laboratory, Oak Ridge, Tenn.

Evans, R., Lousier, J., Massicotte, H. & Coxson, D. 1998: Winter carbon dioxide evolution and soil temperatures in sub-Boreal spruce forests in central British Columbia. Paper pres. Ecology & Management of Northern Forest Soils Proceedings, University of Northern British Columbia.

Ewel, K. C., Cropper, W. P. J. & Gholz, H. L. 1987a: Soil CO_2 evolution in Florida slash pine plantations. I. Changes through time. Canadian Journal of Forest Research 17, 325-329.

Ewel, K. C., Cropper, W. P. J. & Gholz, H. L. 1987b: Soil CO_2 evolution in Florida slash pine plantations. II. Importance of root respiration. Canadian Journal of Forest Research 17, 330-333.

Fan, S.-M., Goulden, M., Munger, J., Danube, B., Bakwin, P., Wofsy, S., Amthor, J., Fitzjarrald, D., Moore, K. & Moore, T. 1995: Environmental controls on the photosynthesis and respiration of a Boreal lichen woodland: a growing season of whole-ecosystem exchange measurements by eddy correlation. Oecologia 102, 443-452.

Federer, C. A. 1984: Organic matter and nitrogen content of the forest floor in even-aged northern hardwoods. Canadian Journal of Forest Research 14, 763-767.

Fernandez, I. J., Son, Y., Kraske, C. R., Rustad, L. E. & David, M. B. 1993: Soil carbon dioxide characteristics under different forest types and after harvest. Soil Science Society of America Journal **57**, 1115-1121.

Gordon, A. M., Schlentner, R. E. & Van Cleve, K 1987: Seasonal patterns of soil respiration and CO2 evolution following harvesting in the white spruce forests of interior Alaska.Canadian Journal of Forest Research **17**, 304-310.

Goulden, M., Wofsy, S. & Harden, J. 1998: Sensitivity of Boreal forest carbon balance to soil thaw. Science **279**, 214-217.

Ham, J. & Knapp, A. 1998: Fluxes of CO_2, water vapor, and energy from a prairie ecosystem during the seasonal transition from a carbon sink to a carbon source. Agricultural and Forest Meteorology **89**, 1-14.

Heath, L., Kauppi, P., Burschel, P., Gregor, H.-D., Guderian, R., Kohlmaier, G., Lorenz, S., Overdieck, D., Scholz, F., Thomasius, H. & Webger, M. 1993: Contribution of the temperate forests to the world's carbon budget. Water, Air, Soil Pollution 70, 55-69.

Hollinger, D., Goltz, S., Davidson, E., Lee, J., Tu, K. & Valentine, H. 1999: Seasonal patterns and environmental control of carbon dioxide and water vapour exchange in an ecotonal Boreal forest. Global Change Biology **5**, 891-902.

Hollinger, D., Kelliher, F., Schulze, D.-E., Bauer, G., Arneth, A., Byers, J., Hunt, J., McSeveny, T., Kobak, K., Milukova, I., Sogatchev, A., Tatarinov, F., Varlargin, A., Ziegler, W. & Vygodskaya, N. 1998: Forest-atmosphere carbon dioxide exchange in eastern Siberia. Agricultural and Forest Meteorology **90**, 291-306.

Horst, T. & Weil, J. 1992: Footprint estimation for scalar flux measurements in the atmospheric surface layer. Boundary Layer Meteorology **59**, 279-296.

Jarvis, P., Massheder, J., Hale, S., Moncieff, J., Rayment, M. & Scott, S. 1997: Seasonal variation of carbon dioxide, water vapor, and energy exchanges of a Boreal black spruce forest. Journal of Geophysical Research **102**, 28953-28966.

Johnson, D. 1992: Effects of forest management on soil carbon stores. Water, Air and Soil Pollution **64**, 83-120.

Kawaguchi, H. & Yoda, K. 1989: Carbon-Cycling Changes during Regeneration of a Deciduous Broadleaf Forest after Clear-Cutting II. Aboveground Net Production. Ecological Research **4**, 271-286.

Keeling, R. F., Piper, S. C. & Heimannt, M. 1996: Global and hemispheric CO_2 sinks deduced from changes in atmospheric O_2 concentrations. Nature **381**, 218-221.

Kolochugina, T. & Vinson, T. 1993a: Comparison of two methods to assess the carbon budget of forest biomes in the former Soviet Union. Water, Air, and Soil Pollution **70**, 207-221.

Kolochugina, T. & Vinson, T. 1993b: Equilibrium analysis of carbon pools and fluxes of forest biomes in the former Soviet Union. Canadian Journal of Forest Research **23**, 81-88.

Kucera, C. L. & Kirkham, D. R. 1971: Soil respiration studies in tallgrass prairie in Missouri. Ecology **52**, 912-915.

Kurz, W. & Apps, M. 1994: The carbon budget of Canadian forests: A sensitivity analysis of changes in disturbance regimes, growth rates, and decomposition rates. Environmental Pollution **83**, 55-61.

Kurz, W., Apps, M., Comeau, P. & Trofymow, J. (1996): The carbon budget of British Columbia's forests 1920-1989: Preliminary analysis and recommendations for refinements., pp. 62, Canadian Forest Service and BC Ministry of Forests.

Levy, P. & Jarvis, P. 1998: Stem CO_2 fluxes in two sahelian shrub species (*Guiera senegalensis* and *Combretum micranthum*). Functional Ecology **12**, 107-116.

Lewis, T. 1998: The effect of deforestation on ground surface temperatures. Global and Planetary Change **18**, 1-13.

Lindroth, A., Grelle, A. & Morén, A.-S. 1998: Long-term measurements of Boreal forest carbon balance reveal large temperature sensitivity. Global Change Biology **4**, 443-450.

Lytle, D. E. & Cronan, C. S. 1998: Comparative soil CO_2 evolution, litter decay, and root dynamics in clear-cut and uncut spruce-fir forest. Forest Ecology and Management **103**, 121-128.

Man, R. & Lieffers, V. 1997: Seasonal variations of photosynthetic capacities of white spruce (*Picea glauca*) and jack pine (*Pinus banksiana*) saplings. Canadian Journal of Botany **75**, 1766-1771.

Meidinger, D. & Pojar, J. (1991): Ecosystems of British Columbia, pp. 1-330, BC Ministry of Forest.

Melillio, J. M., McGuire, A. D., Kicklighter, D. W., III, B. M., Vorosmarty, C. J. & Schioss, A. L. 1993: Global climate change and terrestrial net primary production. Nature **363**, 234-240.

Moore, T. 1983: Winter-time litter decomposition in a subarctic woodland. Arctic Alpine Research **15**, 413-418.

Norman, J., Garcia, R. & Verma, S. 1992: Soil surface CO_2 fluxes and the carbon budget of a grassland. Journal of Geophysical Research **97**, 18,845-18,853.

Olsson, B. A., Staaf, H., Lundkvist, H., Bengtsson, J. & Rosen, K. 1996: Carbon and nitrogen in coniferous forest soils after clear-felling and harvests of different intensity. Forest Ecology and Management. **82**, 19-32.

Pennock, D. J. & van Kessel, C. 1997: Effect of agriculture and clear-cut forest harvest on landscape-scale soil organic carbon storage in Saskatchewan. Canadian Journal of Soil Science **77**, 211-218.

Pietikainen, J. & Fritze, H. 1993: Microbial biomass and activity in the humus layer following burning: Short-term effects of two different fires. Canadian Journal of Forest Research **23**, 1275-1285.

Post, W. M., Emanuel, W. R., Zinke, P. J. & Stangenberger, A. G. 1982: Soil carbon pools and world life zones. Nature **298**, 156-159.

Post, W. M., Peng, T.-H., Emanuel, W. R., Anthony W. Kin, Dale, V. H. & DeAngelis, D. L. 1990: The Global Carbon Cycle. Amercian Scientist **78**, 310-326.

Price, D. & Black, T. 1990: Effects of short-term variation in weather on diurnal canopy CO_2 flux and evapotranspiration of a juvenile Douglas-fir stand. Canadian Journal of Forest Research **23**, 139-158.

Raich, J. & Nadelhoffer, K. 1989: Belowground carbon allocation in forest ecosystems: Global trends. Ecology 70, 1346-1354.

Ryan, M., Hubbard, R., Clark, D. & Sanford, R. 1994: Woody tissue respiration for *Simarouba amara* and *Minquartia guianensis*, two tropical wet forest trees with different growth habits. Oecologia 100, 213-220.

Sarmiento, J. L. 1993: Atmospheric CO_2 stalled. Nature **365**, 697-698.

Schimel, D. 1995: Terrestrial ecosystems and the carbon cycle. Global Change Biology **1**, 77-91.

Sommerfeld, R., Mosier, A. & Musselman, R. 1993: CO_2, CH_4 and N_2O flux through a Wyoming snowpack and implications for global budgets. Nature **361**, 140-142.

Stannard, D. 1997: A theoretically based determination of Bowen-ratio fetch requirements. Boundary Layer Meteorology **83**, 375-406.

Striegl, R. G. & Wickland, K. P. 1998: Effects of a clear-cut harvest on respiration in a jack pine-lichen woodland. Canadian Journal of Forest Research **28**, 534-539.

Tanner, C. 1960: Energy balance approach to evapotranspiration from crops. Soil Science Society of America Proceedings **24**, 1-9.

Tans, P., Fung, I. & Takahashi, T. 1990: Observational constraints on the global atmospheric CO_2 budget. Science **247**, 1431-1438.

Toland, D. E. & Zak, D. R. 1994: Seasonal patterns of soil respiration in intact and clear-cut northern hardwood forests. Canadian Journal of Forest Research **24**, 1711-1716.

Turner, D., Koerper, G., Harmon, M. & Lee, J. 1995: A carbon budget for forests of the conterminous United States. Ecological Applications **5**, 421-436.

Verma, S., Rosenberg, N. & Blad, B. 1978: Turbulent exchange coefficients for sensible heat and water vapor under advective conditions. Journal of Applied Meteorology **17**, 330-338.

Waring, R., Landsberg, J. & Williams, M. 1998: Net primary production of forests: a constant fraction of gross primary production? Tree Physiology **18**, 129-134.

Watts, W. & Neilson, R. 1978: Photosynthesis in Sitka spruce (*Picea sitchensis*)(Bong.)Carr.) VIII. Measurements of stomatal conductance and $^{14}CO_2$ uptake in controlled environments. Journal of Applied Ecology **15**, 245-255.

Webb, E., Pearman, G. & Leuning, R. 1980: Correction of flux measurement for density effect due to heat and water vapour transfer. Quarterly Journal of the Royal Meteorlogical Society **106**, 85-100.

Weber, M. G. 1990: Forest soil respiration after cutting and burning in immature aspen ecosystems. For. Ecol. Manage **31**, 1-14.

Woodwell, G., Hobbie, J., Houghton, R., Melillo, J., Moore, B., Peterson, B. & Shaver, G. 1983: Global deforestation: Contribution to atmospheric carbon dioxide. Science **222**, 1081-1086.

Yarie, J. 1993: Effects of selected forest management practices on environmental parameters related to successional development on the Tanana River floodplain, interior Alaska. Canadian Journal of Forest Research **23**, 1001-1014.

Zinke, P., Stangenberger, A., Post, W., Emanuel, W. & Olson, J. (1984): Worldwide organic carbon and nitrogen data, Oak Ridge National Laboratory.

Table 1a – Multiple regression equations for prediction of component CO_2 fluxes below ground respiration and photosynthesis by plant type, day of year and time of day) in a 5 year-old clearcut in the Aleza Lake Research Forest, British Columbia Multiple linear regressions were established using the best subset method. Standard error of the estimate respresented by (SE).

Component Flux	Time of Year	Regression Equation (μmol C $m^{-2}s^{-1}$)	R^2	SE
Below ground	Jun. 27 to Sept. 23	$R = -0.953-0.354*A+0.0198*D$	0.66	0.978
Conifer (Day)	Jun. 27 to Sept. 3	$P_n = 1.61+0.22*A+1.8*\ln(B)-0.323*C$	0.76	2.74
Conifer (Night)	Jun. 27 to Sept. 3	$R = -0.056*C/(1-0.0191*C)$	0.72	0.915
Herbaceous Plants (Day)	Jun. 27 to Aug. 7	$P_n = 7.89+0.666*A+1.88*\ln(B)+0.0247*C-0.0416*E-0.007291*F$	0.53	3.30
Herbaceous Plants (Night)	Jun. 27 to Sept. 3	$R = 0.534+0.137*A-0.161*C-0.0202*G$	0.81	0.465
Herbaceous Plants (Day)	Aug. 7 to Sept. 3	$P_n = 70.4+2.48*\ln(B)+0.496*C-0.406*E+0.161G$	0.78	2.87
Woody Plants	Jun. 27 to Sept. 3	P_n and $R = 4.72+1.26*\ln(B)-0.239*C$	0.77	1.77

Key: A – soil temperature

B – Light (μmol PAR m^{-2} s^{-1})

C – air temperature (°C)

D – soil moisture (%)

E-day of year

F- time of day

G – relative humidity (%)

*all regression equation variables significant at the 0.95 level

Table 1b – The relationship between microclimate variables and the below ground CO_2 flux and photosynthesis and respiration in conifer, herbaceous plant and woody shrub components of a 6 year-old clear-cut within the Aleza Lake Research Forest, British Columbia. Multiple regressions were established using the best subset method. Standard error of the estimate respresented by (SE).

Component	Equation (μmol C $m^{-2}s^{-1}$)	R^2	SE
Below ground	$R = -0.092\text{-}3.647^{(A/10)}$	0.70	1.33
Conifer (Day)	$P_n = 0.613-0.0776A-0.019275B+0.2438C-17.12D-0.00000763(B)^2$	0.54	3.04
Conifer (Night)	$R = -(0.0912C)/(1-0.0089C)$	0.48	0.777
Herbaceous Plants (Day)	$P_n = 3.23-3.88\ln(B)+0.0524E$	0.72	2.79
Herbaceous Plants (Night)	$R = -(0.912C)/(1-0.0155C)$	0.51	0.900
Woody Shrubs (Day)	$P_n = -10.9-0.0141B+0.000005(B)^2+0.553C-0.459F+0.0162G$	0.78	1.57
Woody Shrubs (Night)	$R = -(0.0576C)/(1-0.0069C)$	0.45	0.362

A – Soil Temperature (10 cm depth)

B – Light (μmol PAR m^{-2} s^{-1})

C – Air Temperature (°C)

D – Relative Humidity (%)

E – Day of Year

F – Absolute Humidity (0.1kPa H_2O)

G – Soil Moisture (%)

* - all regressions significant at the 0.95 level

Table 2a – Herbaceous and woody biomass for deciduous vegetation early (July 7-8/99) and late (Aug. 17-18/99) in the growing season in a 5 year-old clearcut in the Aleza Lake Research Forest, British Columbia. The woody shrub estimates represent leaf biomass only.

Component	July 7-8 $g\ m^{-2}$	August 17-18 $g\ m^{-2}$	Biomass Change $g\ m^{-2}$
Conifer*	34.9	45.5	10.6
Herbaceous Plants	95	125	30
Woody Shrubs	48	64	16
Total	178	234	56.6

*estimated by subtracting the weight of the new growth from the total weight in September

Table 2b – The amount of aboveground biomass present on May 10 and August 6, 2000, and the change in biomass between these dates, for a 6 year-old clearcut within the Aleza Lake Research Forest, British Columbia

Component	May 10 $g\ m^{-2}$	August 6 $g\ m^{-2}$	Biomass Change $g\ m^{-2}$
Conifer	45.5	64.1	18.6
Herbaceous Plants	-*	163	163
Woody Shrubs	140	234	94
Total	186	461	276

*No biomass present in the spring

Table 3.- Comparison of growing season estimates of CO_2 flux from primary components using the component model from 27 June to 3 September 1999 with the BREB estimates in a 5 year-old clearcut at the Aleza Lake Research Forest, British Columbia.

Components	Component Model g C m^{-2}	BREB Method g C m^{-2}
Below ground	338	-
Conifers	-47	-
Herbaceous Plants	-212	-
Woody Plants	-165	-
TOTAL	-86	-20 ±43

Table 4- Comparison of growing season estimates of CO_2 flux from primary components using the component model from 24 May to 20 September 2000 with the BREB estimates in a 6 year-old clearcut at the Aleza Lake Research Forest, British Columbia

Components	Component Model $g\ C\ m^{-2}$	BREB Method $g\ C\ m^{-2}$
Below ground	686	-
Conifers	-96	-
Herbaceous Plants	-315	-
Woody Shrubs	-172	-
Total	103	143 ± 57

Table 5 – The BREB method and component model estimates of the growing season CO_2 flux in a 5 to 6 year-old clearcut, over a comparable interval, from June 27 to September 3, in the Aleza Lake Research Forest, British Columbia

Component	1999 $g\ C\ m^{-2}$		2000 $g\ C\ m^{-2}$	
	Component Model	*BREB*	Component Model	BREB
Below ground	338	-	466	-
Conifers	-47	-	-58	-
Herbaceous Plants	-212	-	-232	-
Woody Shrubs	-165	-	-133	-
Total	-86	-20 ±43	43	66 ±44

Figures and Legends

Figure 1 – The 1999 and 2000 growing season mean daily air temperature and rainfall contrasted with the historical mean daily air temperature and rainfall (1952-1980) for a 5-6 year-old clearcut located in the Aleza Lake Research Forest, British Columbia.

Figure 2 a,b - The measured mean soil temperature (a) and moisture (b) in 1999 and 2000 for a 5-6 year-old clearcut located in the Aleza Lake Research Forest, British Columbia.

Figure 3 a-e – The daytime respiration rates for coniferous and deciduous plant species in 1999 (Fig 3 a-b) and 2000 (Fig. c-e) for a 5 and 6 year-old clearcut located in the Aleza Lake Research Forest, British Columbia.

Figure 4 a-f – The net instantaneous net photosynthetic CO_2 uptake in *P. glauca* x *P. engelmannii*, *S. douglasii* spp. *menesizii*, *L. involucrata* and *E. angustifolium* versus light for the growing seasons of 1999 (Fig. 4 a-c) and 2000 (Fig. d-f) for a clearcut located in the Aleza Lake Research Forest, British Columbia.

Figure 5 a-b – Instantaneous measures of below ground efflux of CO_2 for the growing seasons of 2000 (a) and 1999 (b). Measurements were taken in a 5-6 year-old clearcut located in the Aleza Lake Research Forest, British Columbia.

Figure 6 a-d – A comparison of CO_2 flux estimates of the BREB method and component model for selected days in 1999 (Fig. 6 a-b) and 2000 (Fig. 6 c-d) for a 5-6 year-old clearcut located in the Aleza Lake Research Forest, British Columbia.

Figure 7 – A comparison between the BREB method and component model estimates of CO_2 flux for 27 June to 3 September 1999. Measurements from a 5 year-old clearcut located in the Aleza Lake Research Forest, British Columbia.

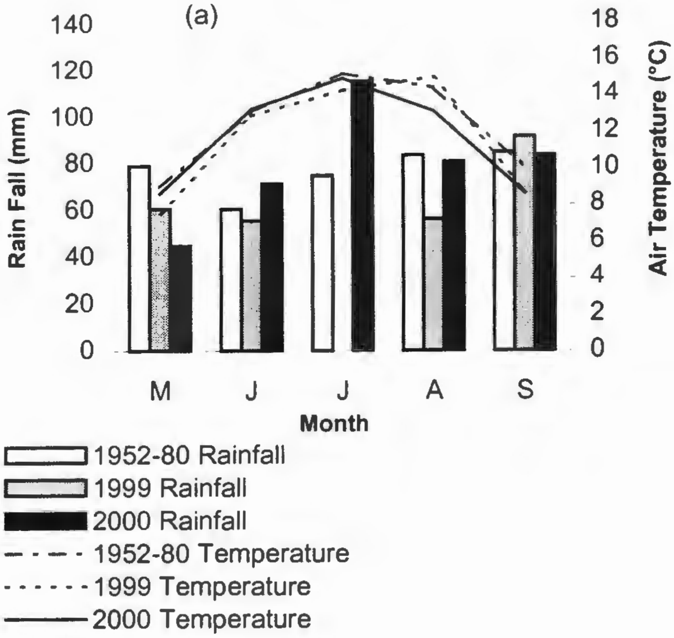
Figure 8 - A comparison between the BREB method and component model estimates of the CO_2 flux for 24 May to 20 September 2000. Measurements were made in a 6 year-old clearcut located in the Aleza Lake Research Forest, British Columbia.

Figure 9 – The estimated below ground CO_2 flux for 27 June to 23 September 1999. In the 20 days following the last BREB measurement the site was estimated to lose a further 68 g C m^{-2}. Estimated flux for a 5 year-old clearcut located in the Aleza Lake Research Forests, British Columbia.

Figure 10 – The BREB ecosystem CO_2 flux estimates for a young clearcut (age 5/6 years since harvest) during the 1999 and 2000 growing seasons in the Aleza Lake Research Forest, British Columbia.

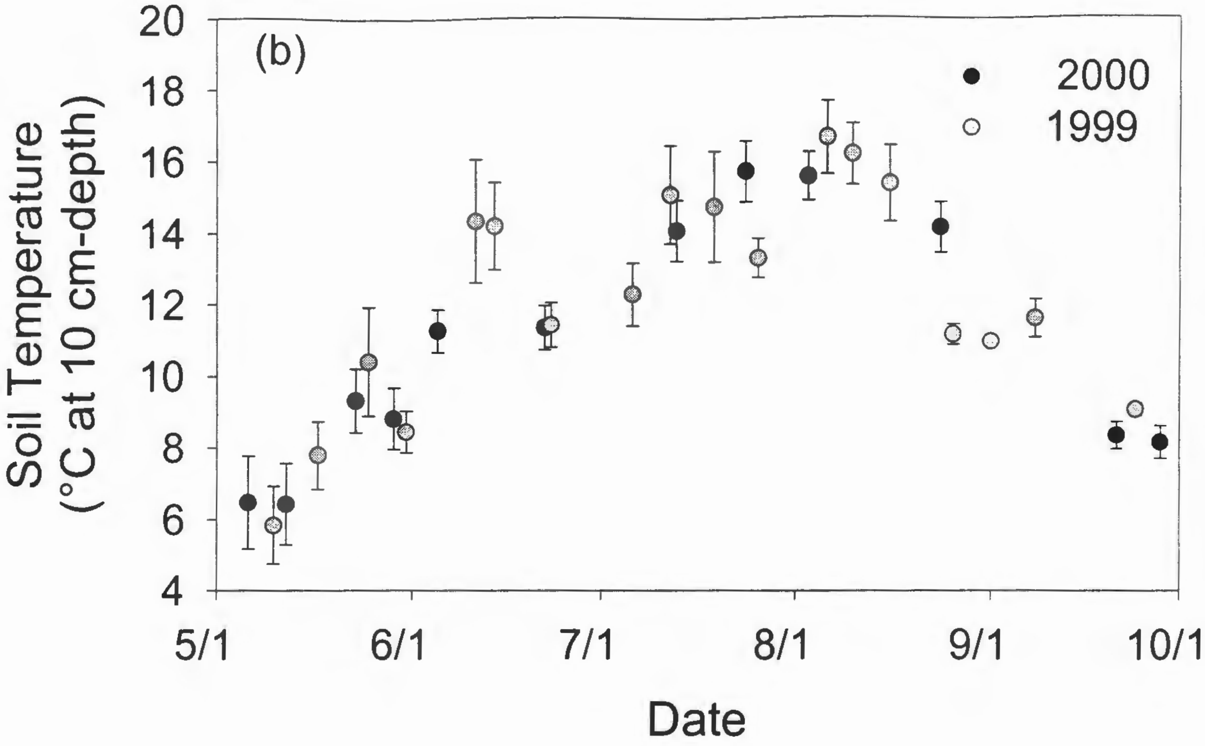
Figure 11 -The component model estimates of daily photosynthetic CO_2 uptake for the 1999 and 2000 growing seasons (June 27 to September 3) in a 5-6 year-old clearcut located in the Aleza Lake Research Forest, British Columbia.

Figure 12 - The daily below ground CO_2 flux during the 1999 and 2000 growing seasons (June 27 to September 3) in a 5 to 6 year-old clearcut located in the Aleza Lake Research Forest, British Columbia.



* data missing for July 1999

Figure 1


(b)
2000
1999
Soil Temperature
(°C at 10 cm-depth)
20
18
16
14
12
10
8
6
4
5/1
6/1
7/1
8/1
9/1
10/1
Date

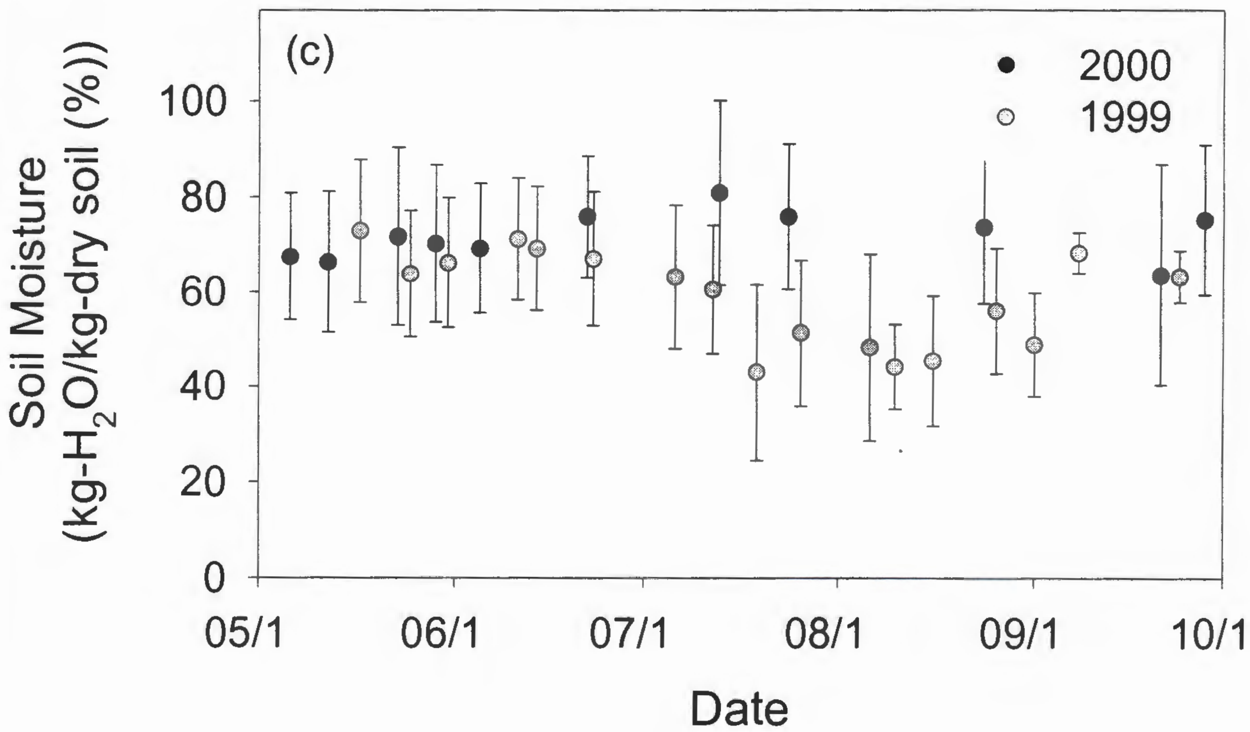
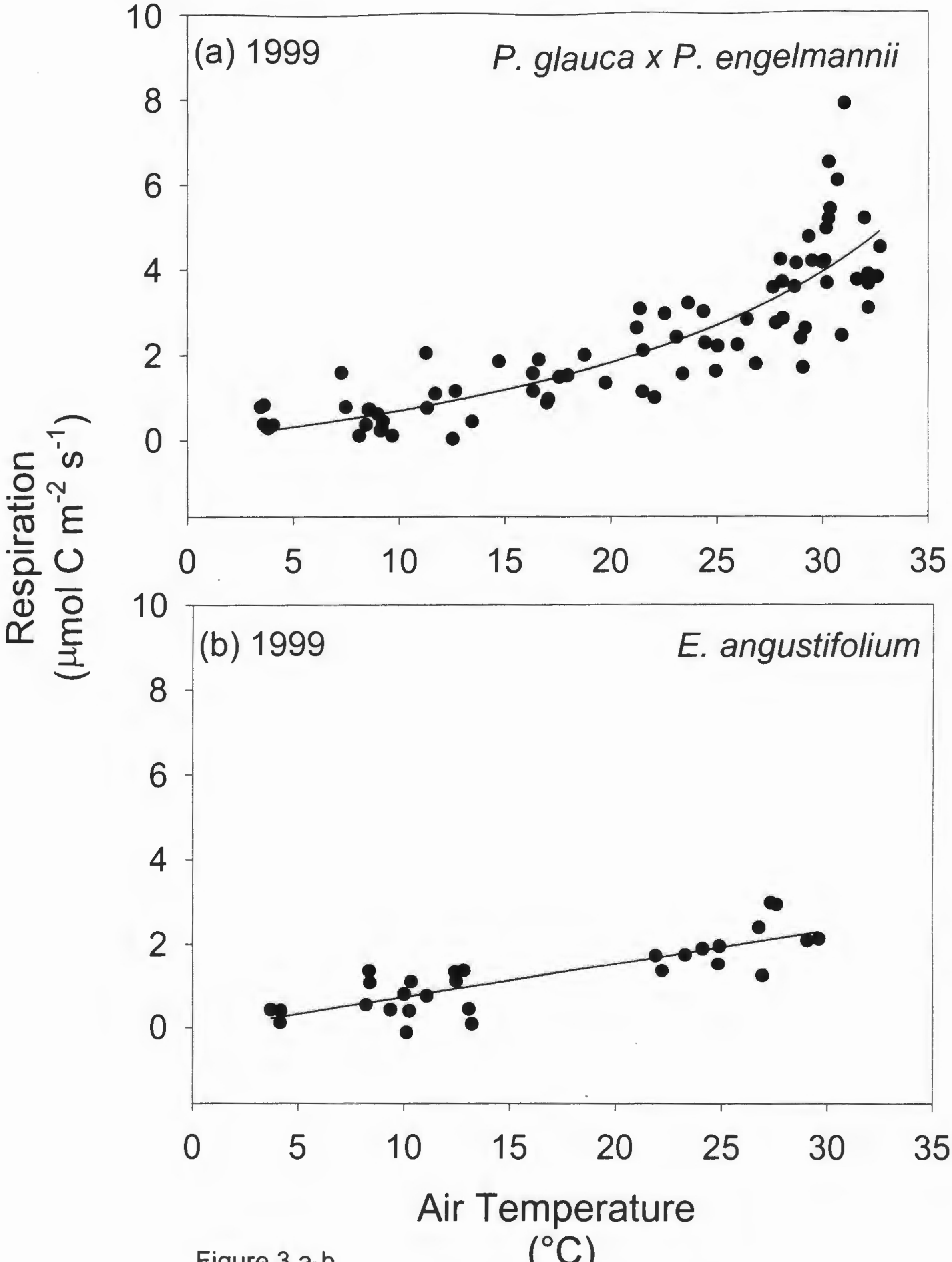
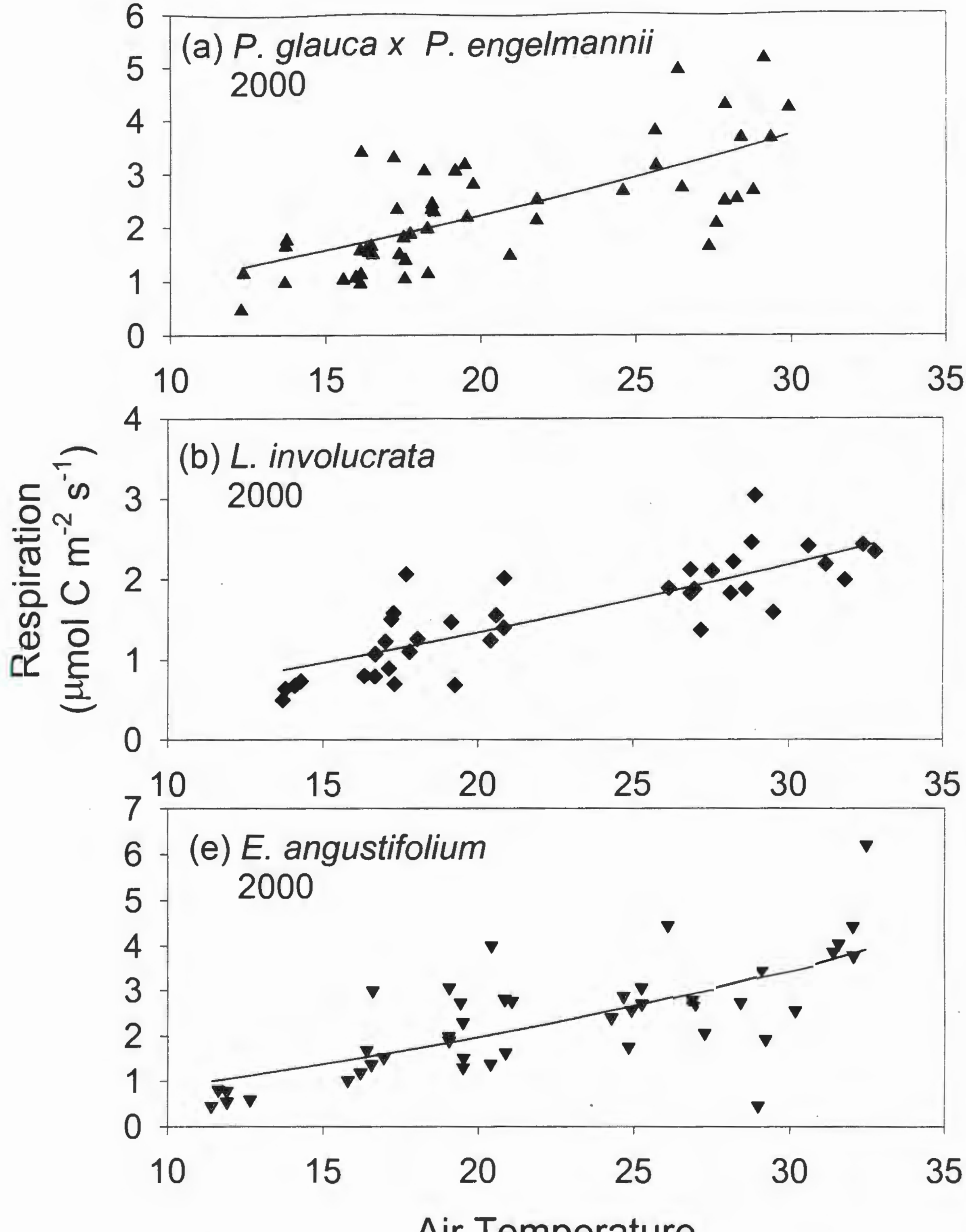

(c)
2000
1999
Soil Moisture
(kg-H2O/kg-dry soil (%))
100
80
60
40
20
0
05/1
06/1
07/1
08/1
09/1
10/1
Date

Figure 2 a,b



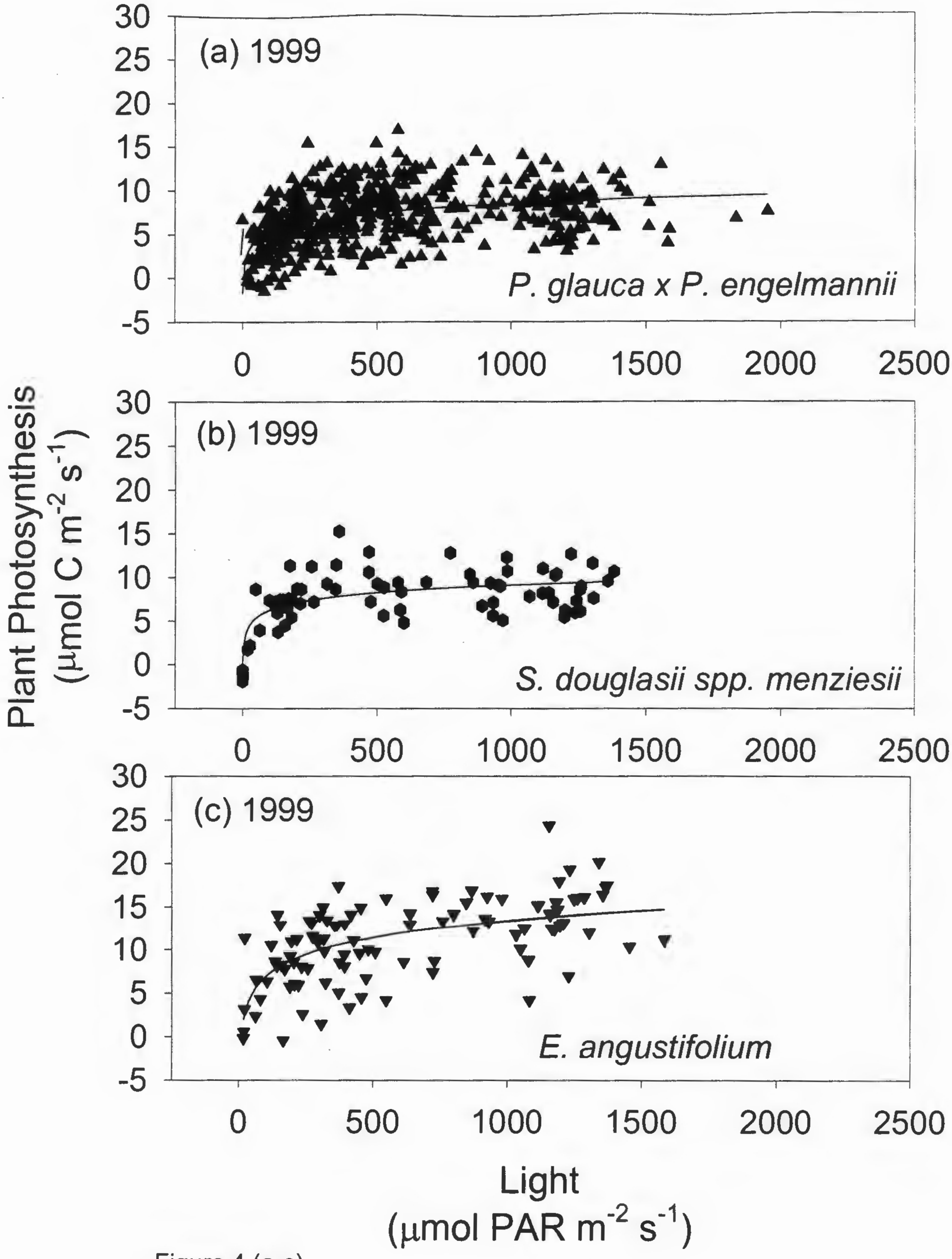
(a) 1999
P. glauca x P. engelmannii
(b) 1999
E. angustifolium
Respiration
(µmol C m-2 s-1)
Air Temperature
(°C)
0
2
4
6
8
10
0
5
10
15
20
25
30
35

Figure 3 a-b



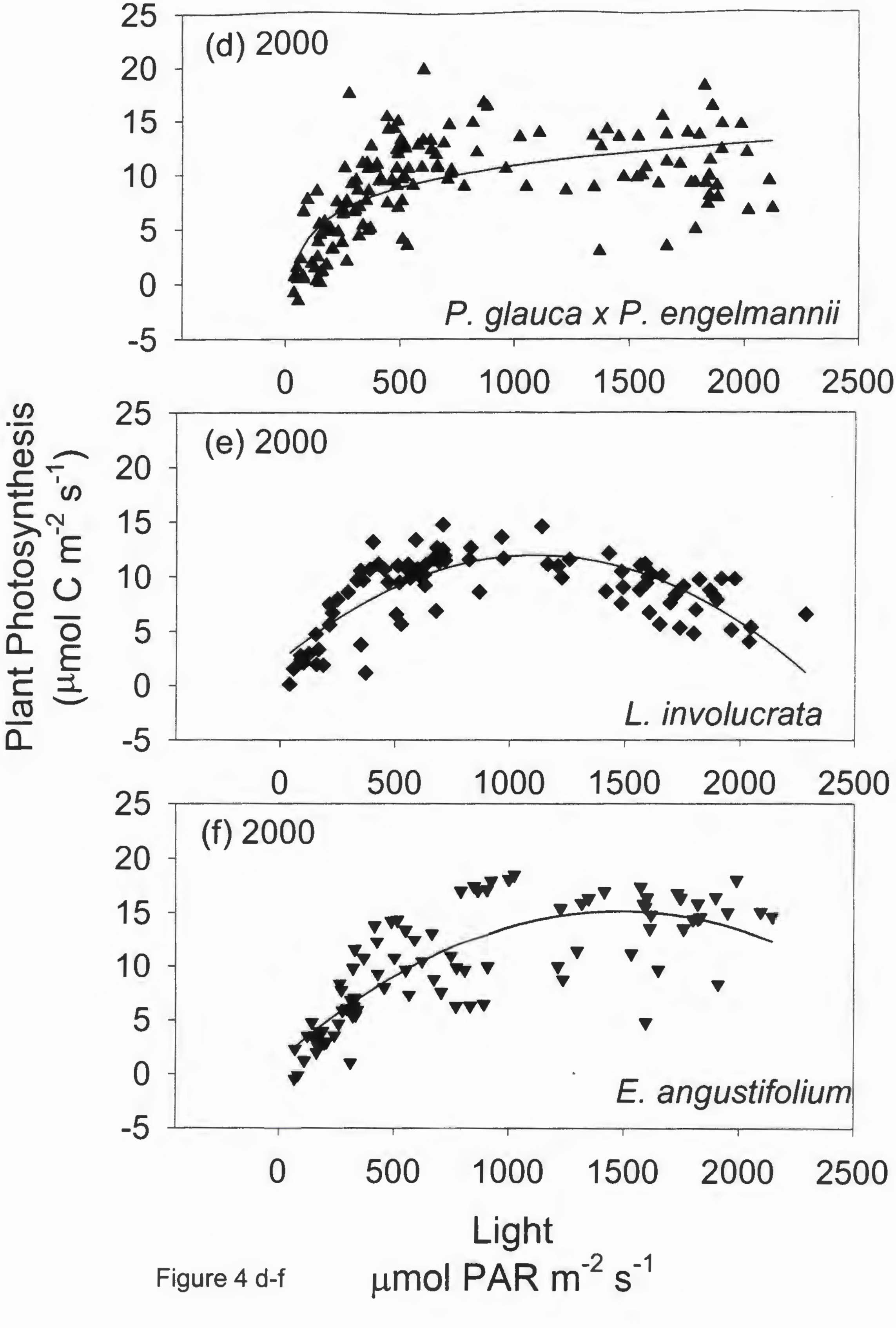
(a) P. glauca x P. engelmannii
2000
(b) L. involucrata
2000
(e) E. angustifolium
2000
Respiration
(μmol C m-2 s-1)
Air Temperature
(°C)
0
1
2
3
4
5
6
7
10
15
20
25
30
35

Figure 3 c-e



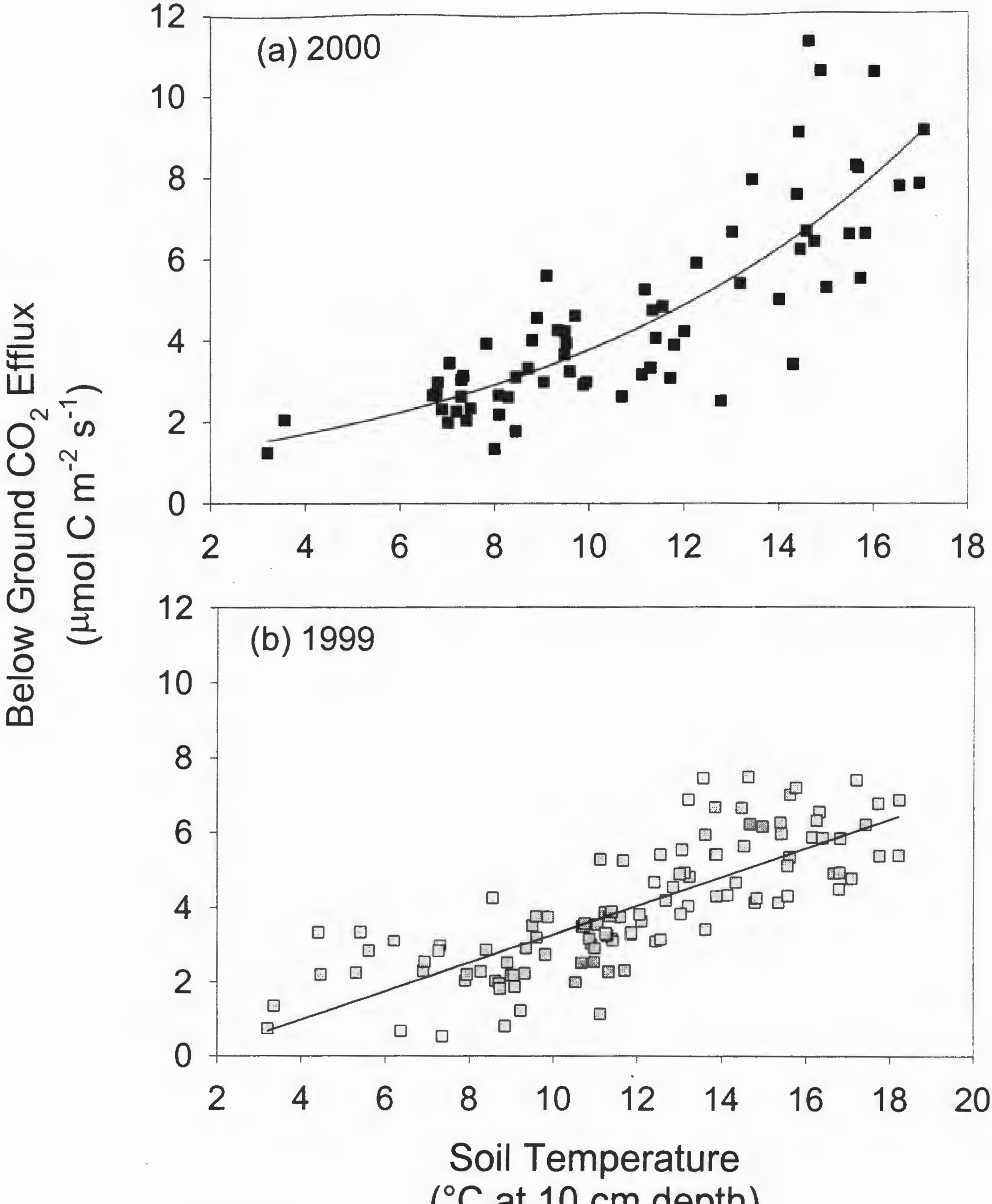
(a) 1999
P. glauca x P. engelmannii
(b) 1999
S. douglasii spp. menziesii
(c) 1999
E. angustifolium
Plant Photosynthesis
(μmol C m-2 s-1)
Light
(μmol PAR m-2 s-1)
30
25
20
15
10
5
0
-5
0
500
1000
1500
2000
2500

Figure 4 (a-c)



(d) 2000
P. glauca x P. engelmannii
(e) 2000
L. involucrata
(f) 2000
E. angustifolium
Plant Photosynthesis
(μmol C m-2 s-1)
Light
μmol PAR m-2 s-1

Figure 4 d-f



(a) 2000
(b) 1999
Below Ground CO_2 Efflux
(μmol C m^{-2} s^{-1})
Soil Temperature
(°C at 10 cm depth)

Figure 5 a-b

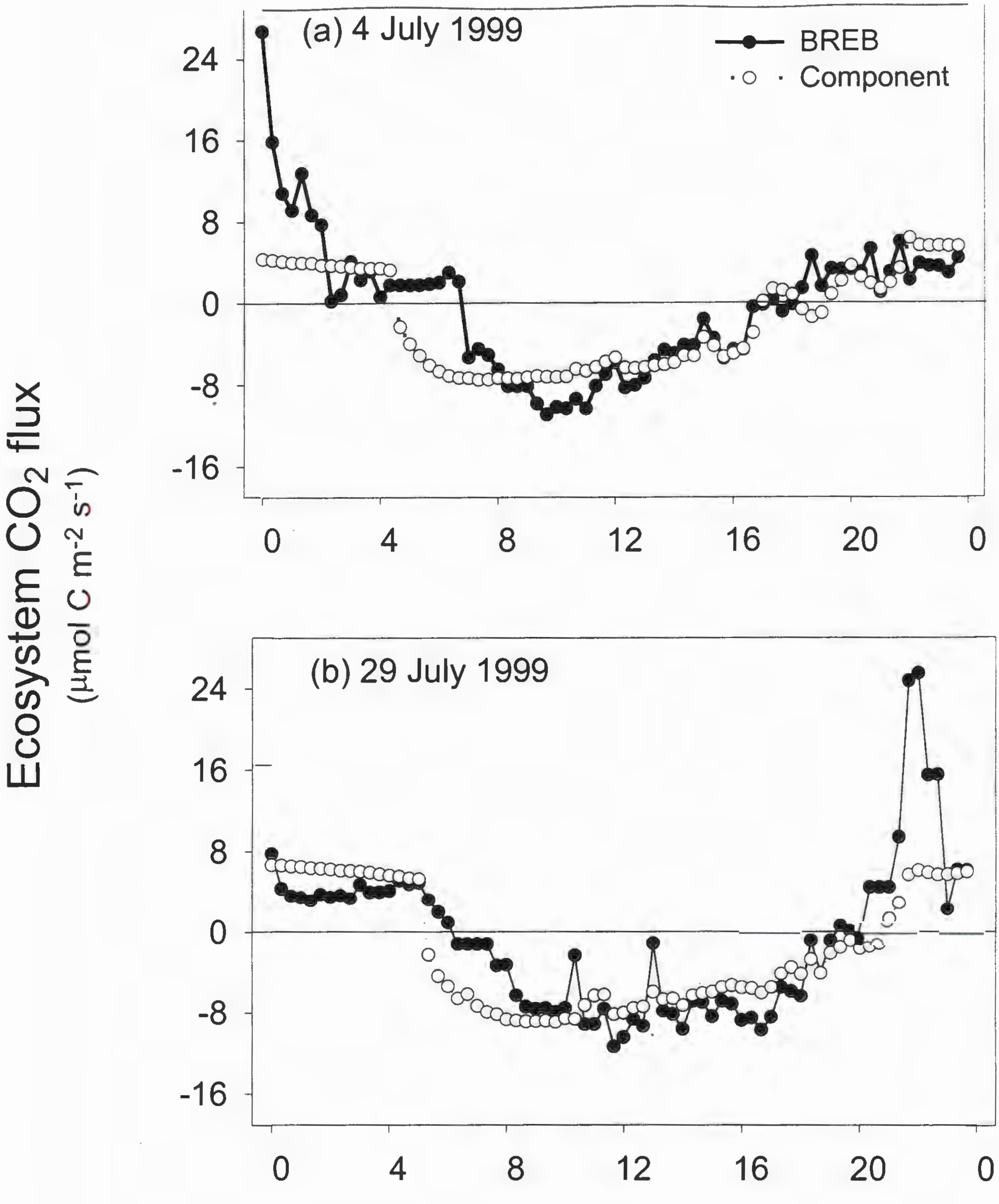
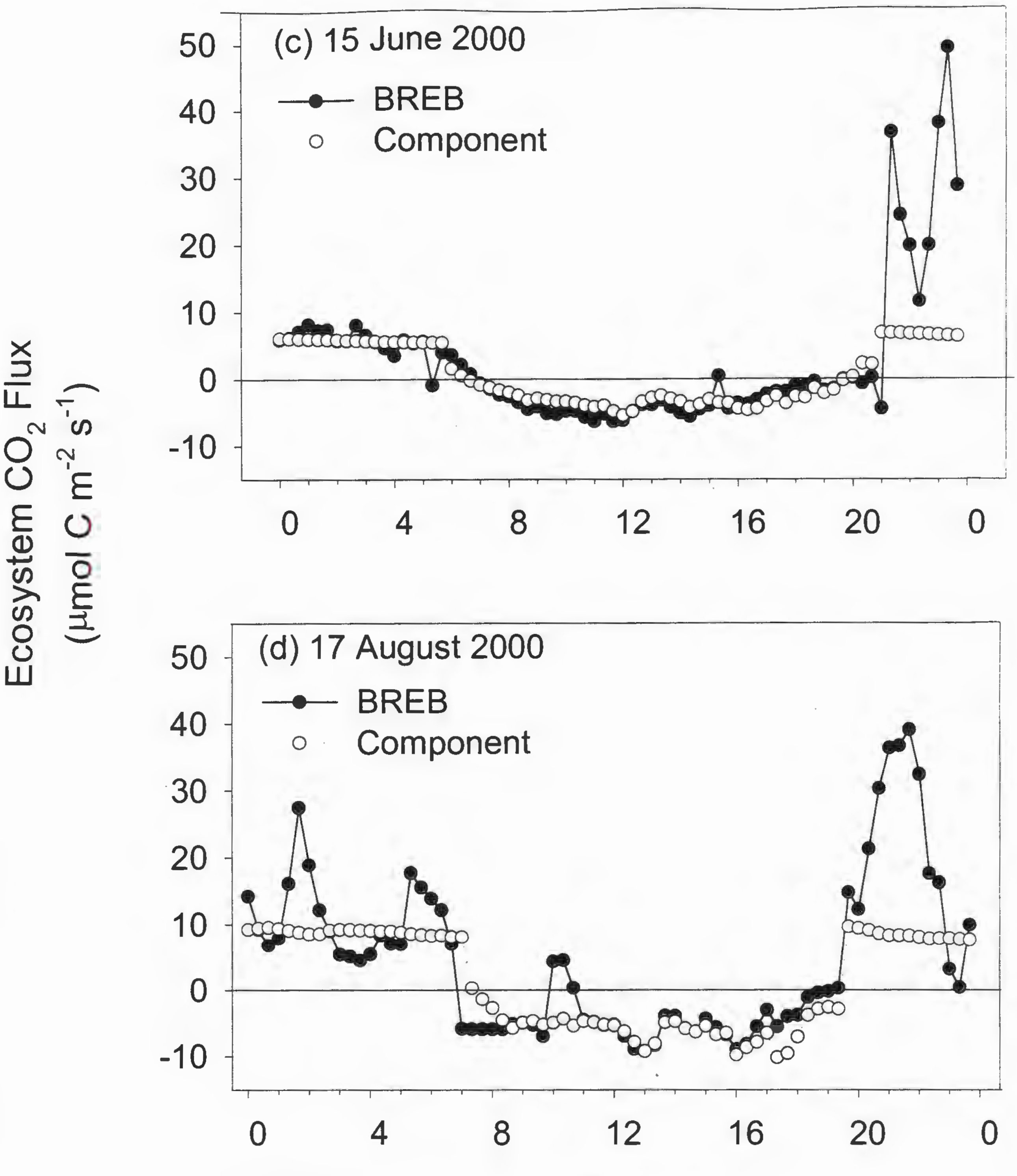

(a) 4 July 1999
BREB
Component
(b) 29 July 1999
Ecosystem CO_2 flux
(μmol C m^{-2} s^{-1})
24
16
8
0
-8
-16
0
4
8
12
16
20
0
Time of day (h)

Figure 6 (a-b)



(c) 15 June 2000
BREB
Component
(d) 17 August 2000
BREB
Component
Ecosystem CO_2 Flux
(μmol C m^{-2} s^{-1})
Hour
50
40
30
20
10
0
-10
0
4
8
12
16
20
0

Figure 6 c-d

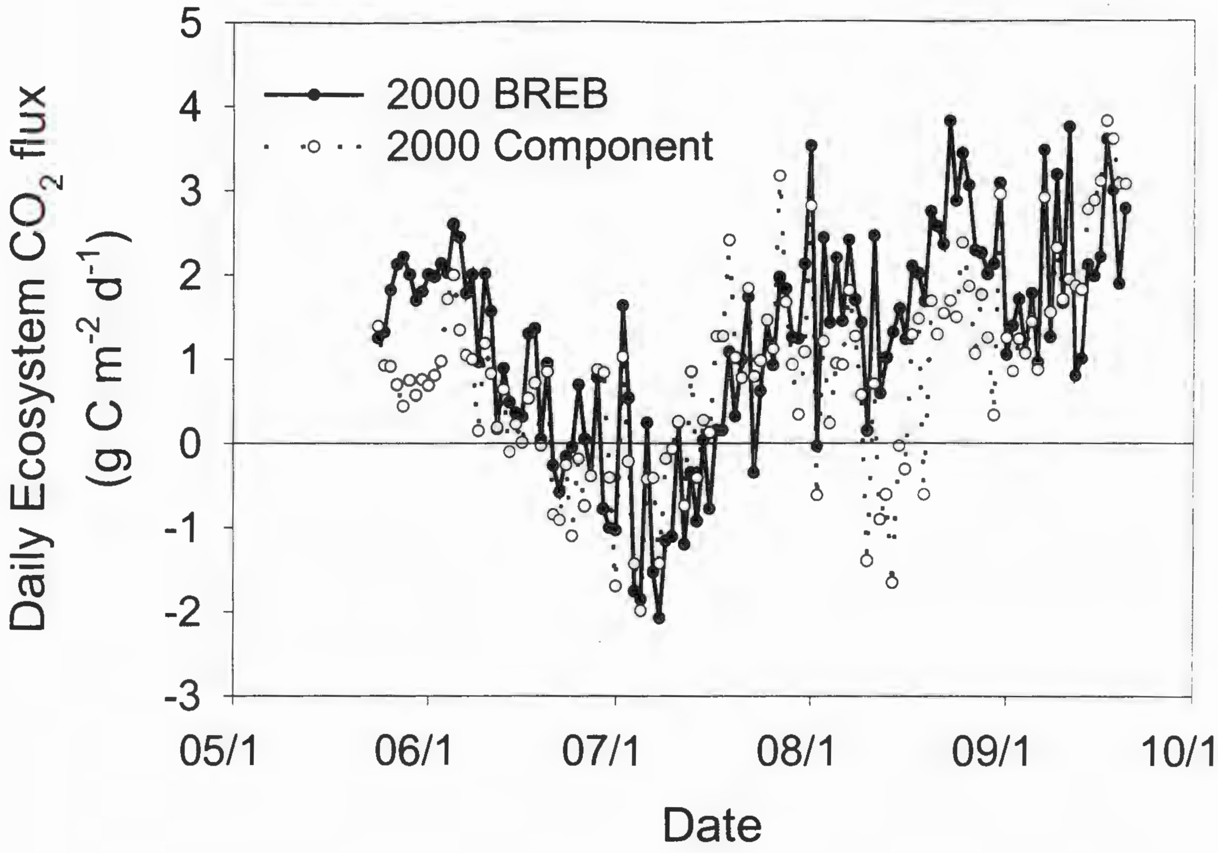

2000 BREB
2000 Component
Daily Ecosystem CO_2 flux
($g\ C\ m^{-2}\ d^{-1}$)
5
4
3
2
1
0
-1
-2
-3
05/1
06/1
07/1
08/1
09/1
10/1
Date

Figure 8

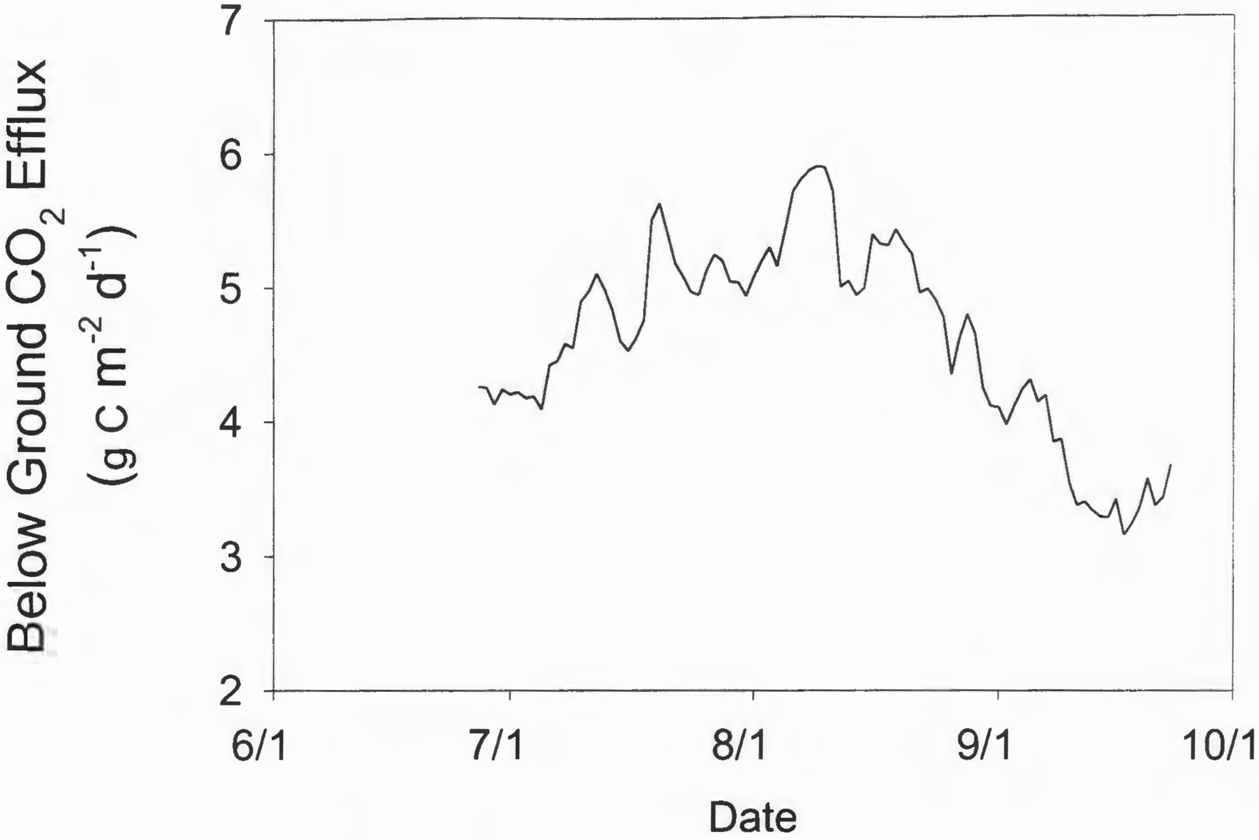


Figure 9

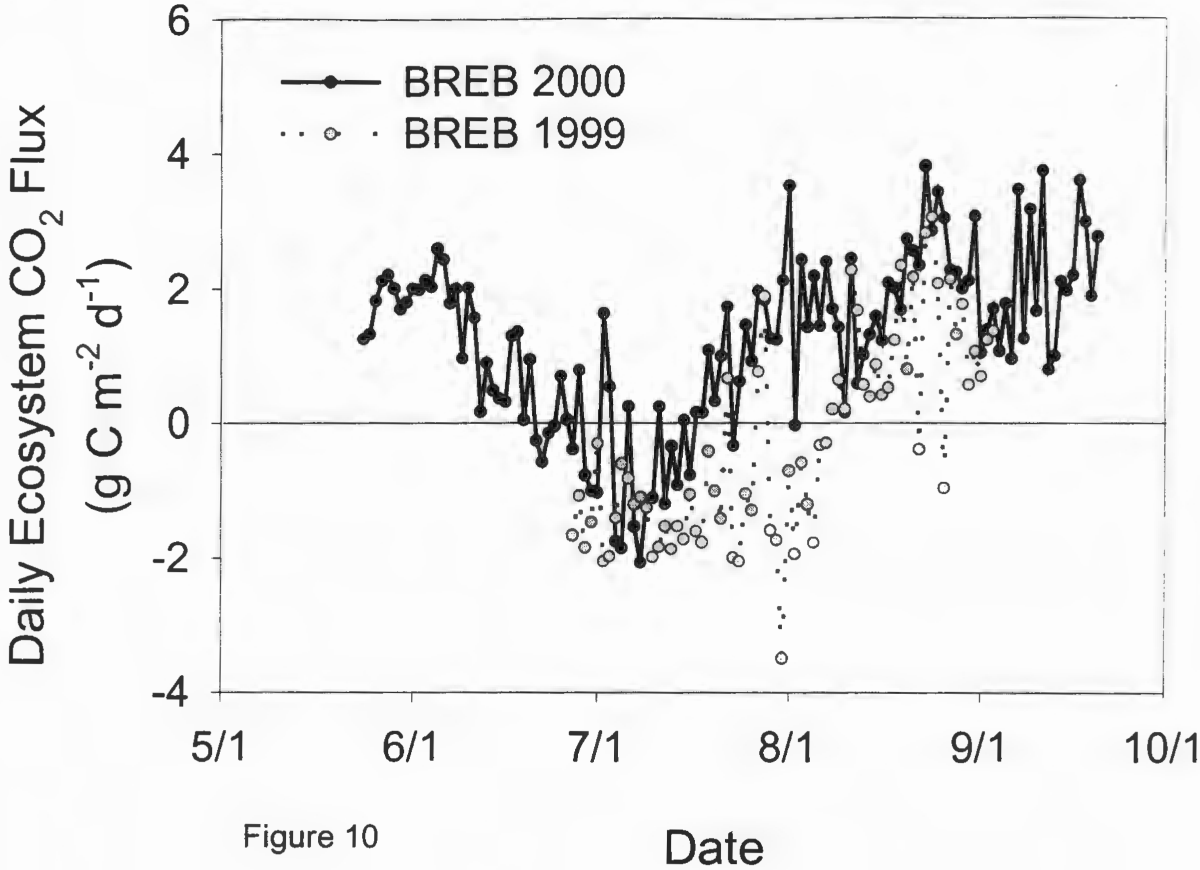

BREB 2000
BREB 1999
Daily Ecosystem CO_2 Flux
($g\ C\ m^{-2}\ d^{-1}$)
6
4
2
0
-2
-4
5/1
6/1
7/1
8/1
9/1
10/1
Date

Figure 10

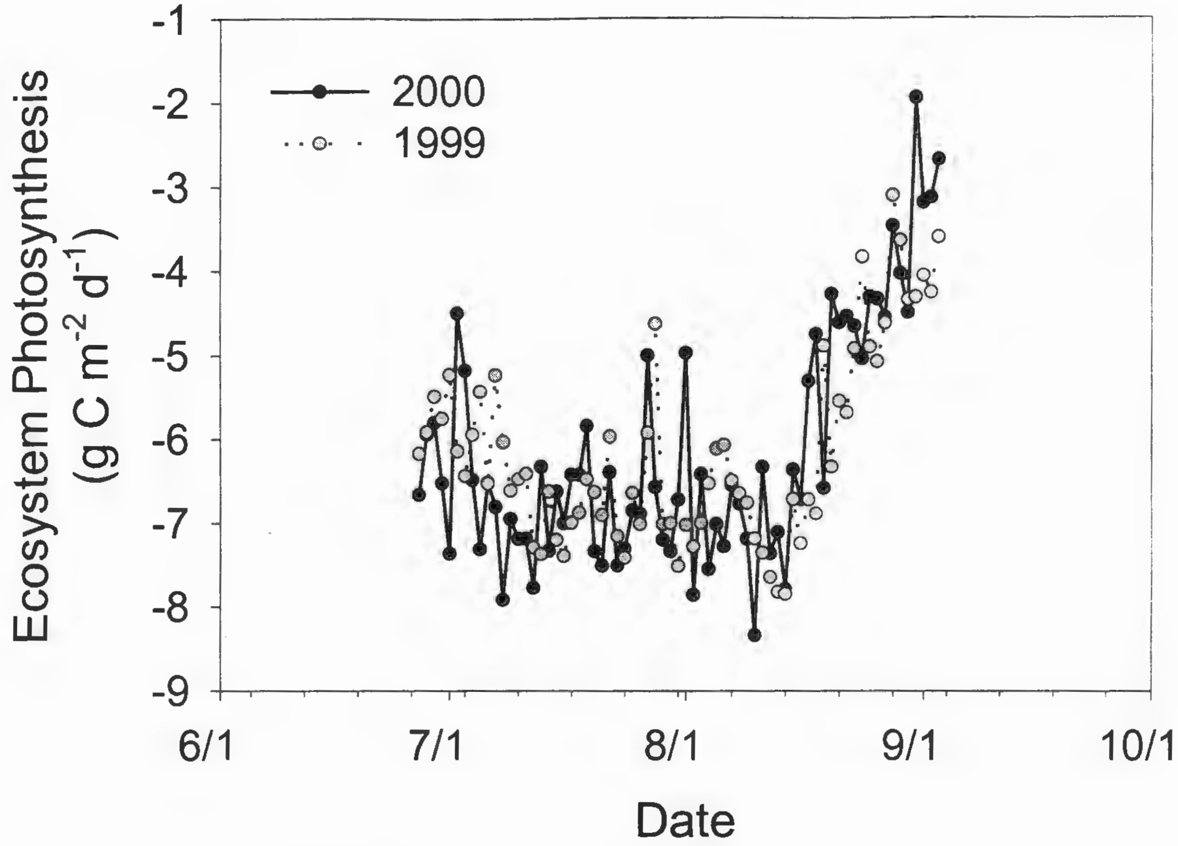

Ecosystem Photosynthesis
(g C m-2 d-1)
2000
1999
-1
-2
-3
-4
-5
-6
-7
-8
-9
6/1
7/1
8/1
9/1
10/1
Date

Figure 11

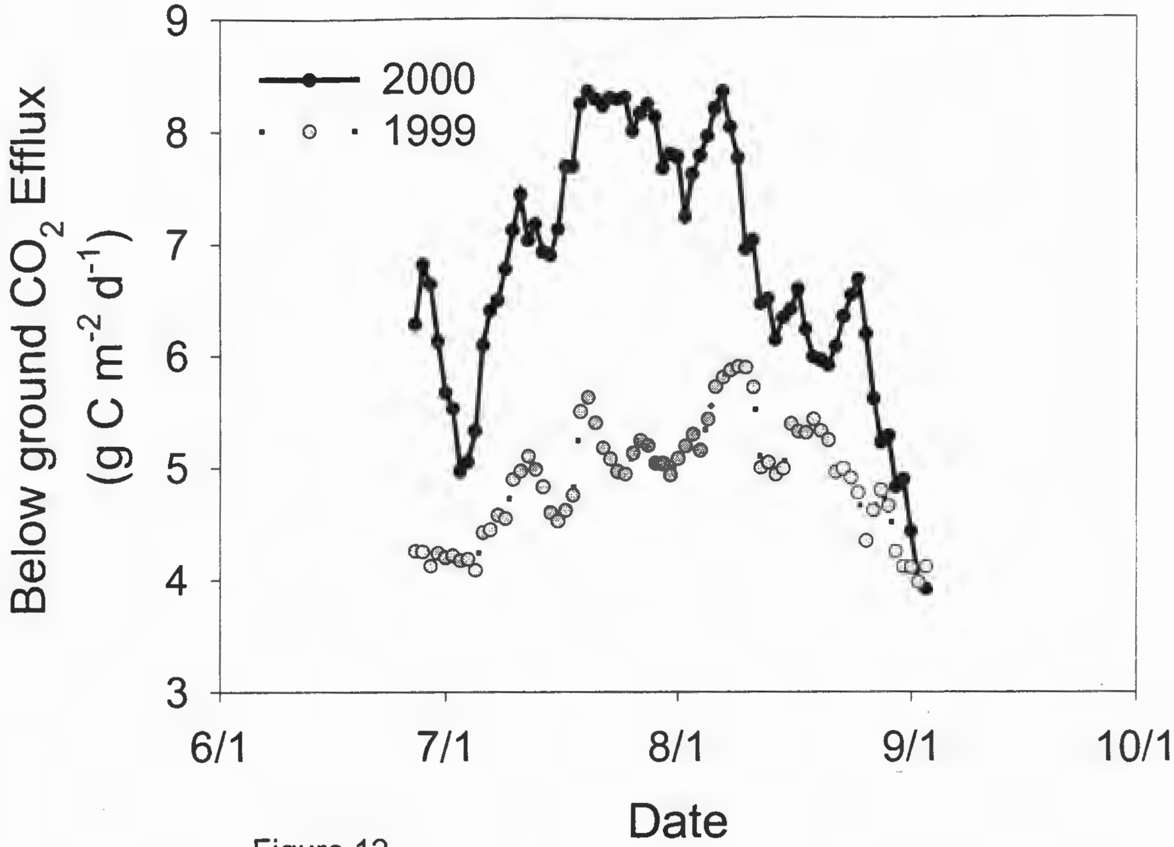

2000
1999
9
8
7
6
5
4
3
Below ground CO_2 Efflux
(g C m^{-2} d^{-1})
6/1
7/1
8/1
9/1
10/1
Date

Figure 12

BELOW GROUND CO_2 FLUX FROM CUT BLOCKS OF VARYING AGES IN SUB-BOREAL BRITISH COLUMBIA

Abstract

Instantaneous measures of below ground CO_2 fluxes were made in a mature stand and seven cut blocks aged 0, 2, 3, 5, 6, 9 and 10 years after harvest in sub-Boreal forest of Central British Columbia (SBS wk1), Canada from May to October, 2000. The cut blocks aged 3, 5, 6, and 10 were located in the 08 variant (very nutrient rich, sub-hygric), the 2 year-old cut block was in the 07 variant (nutrient rich, sub-hygric) and the 0 and 9 year-old cut blocks were in the 01 variant (poor to nutrient rich, sub-mesic to sub-hygric). All cut blocks were replanted to hybrid spruce (*Picea glauca x Picea engelmannii*) within two years of harvest and the deciduous vegetation was never herbicided or brushed. Instantaneous (each cut block) and continuous (one cut block) measures of soil temperature and moisture were made and later used to predict below ground CO_2 flux from 24 May to 20 September 2000. Instantaneous below ground CO_2 flux ranged from between 2 μmol C m^{-2} s^{-1} in the spring to highs of 10 μmol C m^{-2} s^{-1} during mid-summer. Cumulative seasonal below ground CO_2 flux ranged from between 658 and785 g C m^{-2} for the cut blocks aged 3 years or older, while the 2 year-old and new cut block produced the high (861 g C m^{-2}) and low CO_2 fluxes (560 g C m^{-2}) respectively. Below ground CO_2 flux in the cut blocks positively correlated with soil temperature and the amount of

biomass present on site. Only a few cut blocks demonstrated a significant relationship between soil moisture and the instantaneous below ground CO_2 flux.

The estimated net ecosystem CO_2 fluxes for the cut blocks were calculated by subtracting the biomass gained on each cut block from the cumulative seasonal below ground CO_2 flux. All the cut blocks were net sources of CO_2 with values ranging between 372 g C m^{-2} at the 3 year-old cut block to 540 g C m^{-2} at the 10 year-old cut block. There was no correlation between below ground CO_2 flux or the estimates of net ecosystem CO_2 flux and cut block age.

Introduction

Since pre-industrial times, land-use change has been associated with approximately 50% of the rise in atmospheric CO_2 prior to 1980 (Woodwell et al. 1983) and 23% of the rise during the 1980's (Schimel 1995). The increase of CO_2 from land-use change has been largely associated with timber harvesting (Harmon et al. 1990) and conversion of forestlands to pasture (Tans et al. 1990).

Boreal/sub-Boreal regions in Canada are estimated to hold 65 to 104 Gt of carbon within the soil or eight times the amount stored in the plant biomass (Post et al. 1982; Apps et al. 1993). Hence, the impact timber harvesting has on below ground carbon stores in sub-Boreal/Boreal forest may have a great impact on the current levels of atmospheric CO_2. Individual studies comparing a cut block against a mature forest's below ground CO_2 flux have found conflicting results: some studies indicate a decrease in CO_2 fluxes (Edwards & Ross-Todd 1983; Weber 1990; Chang & Trofymow 1996; Striegl & Wickland 1998), others demonstrate an increase

(Ewel et al. 1987a; Gordon et al. 1987; Lytle & Cronan 1998) and still others show no change in below ground CO_2 fluxes (Fernandez et al. 1993; Toland & Zak 1994). However, few studies have investigated the below ground CO_2 flux from a series of cut blocks that vary in age. Ewel et al. (1987a) found an increase in the below ground CO_2 flux from a 9 year-old to 29 year-old slash pine plantation in Florida. In British Columbia, it is assumed that cut blocks remain a source for CO_2 for at least 10 years after harvest (Kurz & Apps 1994).

Below ground CO_2 flux is positively correlated to soil temperature and soil moisture (Kucera & Kirkham 1971; Fernandez et al. 1993; Striegl & Wickland 1998). Impacts on these microclimate variables from disturbance may result in higher or lower below ground CO_2 flux. Timber harvesting typically results in higher soil temperatures (Lewis 1998; Londo et al. 1999) and often a decrease soil moisture (McCaughey 1989; Londo et al. 1999). The soil moisture in a clear-cut is frequently reduced because of higher surface temperatures, but the loss can be partially offset by reduced transpiration from plants because of lower plant biomass. Hence, the amount of soil moisture at each cut block will be depend on the relative reduction in transpiration to increased evaporation.

Below ground CO_2 fluxes result from two main sources: root respiration, and the decomposition of organic matter and associated respiration of soil flora and fauna. Timber harvesting has the potential to impact both of the above sources. Root respiration is assumed to represent up to 55% of the below ground CO_2 production in a forested site (Ewel et al. 1987b; Fernandez et al. 1993; Andrews et al. 1999). The removal of the trees results in the death of the tree roots and at least a temporary decrease in root respiration. Furthermore, the reduction in roots results in a decrease in fine root turnover and the subsequent release of CO_2 from root decomposition. The silvicultural practices employed may influence the below ground CO_2 flux through the modification of the moisture or organic matter content of the soil(Mallik & Hu 1997). Burning slash may remove much of the soil organic layer, and if severe enough, kill the soil microorganisms (Pietikainen & Fritze 1993; Chang & Trofymow 1996). Other impacts of timber harvesting, such as soil compaction due to machinery, may result in reduced soil aeration of the cut block leading to a decrease in soil microorganisms and/or aerobic respiration (Chang et al. 1995).

It is the intention of this paper to investigate the effect of time since harvesting of sub-Boreal forest on below ground CO_2 evolution. Most studies researching the impact of timber harvesting on below ground CO_2 fluxes have focused on a single or few clearcut(s) of the same age in the few years initially following harvest (e.g. Edwards & Ross-Todd 1983; Gordon et al. 1987; Toland & Zak 1994; Mallik & Hu 1997; Striegl & Wickland 1998). While they provide information on the initial effects of harvesting and the impacts of different types of site preparation, they do not provide insight into how below ground CO_2 fluxes change over the complete forest reestablishment period. When one couples this lack of information with the increasing pressure to harvest northern areas and the large below ground carbon stores in Boreal and sub/Boreal forests, the need to understand the source/sink relationships of CO_2 in clearcuts becomes vital. Thus, it is the intent of this paper to demonstrate the changes in below ground CO_2 flux and biomass accumulation in the 10 years following forest harvesting and reestablishment of sites in sub-Boreal British Columbia.

Material and Methods

Study Site

We made instantaneous below ground CO_2 flux measurements and sampled above ground biomass from May to October 2000, in seven cut blocks of various ages and one mature stand. The cut blocks were all located within a 10 km radius of each other, and resided in, or immediately adjacent to the University of British Columbia and University of Northern British Columbia Aleza Lake Research Forest (54°01' N and 122°07' W). All cut blocks were located within the sub-Boreal Spruce zone (SBS wk1) as described by the Ecosystem Classification of British Columbia, and classified as both cool: mean air temperature = 1.7 to 5 °C, and wet: relatively high snowfall compared to other regions within the central plateau region of sub-Boreal BC (Meidinger & Pojar 1991). The snowfall typically accumulates by November and melts by the end of April/early May. During the winter of 1999/2000 the cut blocks were covered in snow by November and soils did not freeze. Soils at the cut blocks were all clay rich and classified as Ortho Luvic Gleysols (Arocena & Sanborn 1999).

The cut blocks were winter logged and of varying ages since harvest (0, 2, 3 5, 6, 9, and 10 years). A non-harvested mature stand, adjacent to the 3 year-old cut block, was selected to represent mature forest within the research forest area. Each of the cut blocks were planted with hybrid white spruce (*Picea glauca x Picea engelmannii*) with the exception of the 5 and 6 year-old cut blocks which had some inclusions of lodgepole pine (*Pinus contorta* var. *latifolia*). There was some variation in the planting density of the cut blocks: the cut blocks aged 3 and 9 had planting densities of 1600 stems ha^{-1}, the 5 and 10 year-old cut blocks had a planting density of 1400 stems ha^{-1} and the 2 and 6 year-old cut blocks had a planting density of 1200 stems ha^{-2}.

The cut blocks aged 2, 3, 5, 6 and 10 years were of the site series 07 and 08 (nutrient rich to very nutrient rich, sub-hygric). The 0 and 9 year-old cut blocks was located in sites series 01 (poor to nutrient rich, sub-mesic to sub-hygric). The cut blocks experienced some differences in harvest and post harvest treatments: 0, 2, and 3 year-old cut blocks had single wildlife trees retained throughout the cut block, the 5 year-old cut block had several wildlife tree patches, and the remainder of the cut blocks were clearcut. Slash was piled but not burned at the 0 year-old cut block (harvested February, 2000), piled and burned at the 2 yr-old cut block and broadcast burned at all the older cut blocks. Prior to harvest, the cut blocks were composed mainly of hybrid spruce (*P. glauca x P. engelmannii*), paper birch (*Betula papyrifera*), and sub-alpine fir (*Abies lasiocarpa*).

Below ground CO_2 Flux Measurement

In seven of the eight cut blocks, eight pairs of PVC collars (9.55 cm in diameter) were placed along a 70 metre east-west transect at 10 meter intervals. In the 6 year-old cut block collars were randomly placed throughout a measurement area of 1 ha as in Chapter 2. All collars located within cut blocks were a minimum of 20 meters away from wildlife trees or tree patches and all collars were a minimum of 30 meters way from the edge of the cut block or forested stand. Below ground CO_2 flux measurements were made using a portable infra-red gas exchange system (Li-6200, Lincoln, Nebraska, USA) with soil chamber attachment (6000-09, Li-Cor) as in Norman et al. (1992). Soil temperature (6000-09TC, Li-Cor) and moisture (kg H_2O/kg dry soil) (Nie-Co-Product Nieuwkoop B.V., Aalsmeer, Holland) were taken simultaneously with the instantaneous CO_2 flux measurements at a depth of 10 cm.

Biomass Sampling

On May 5 -10 and August 6 – 14, 2000, a total of 40 randomly placed 0.5 m^2 samples per cut block were sampled for total above ground deciduous biomass and separated into woody shrub and herbaceous plant. Conifer biomass was sampled by destructively harvesting 20 randomly selected seedlings within ± one standard deviation of the mean seedling height at each cut block. All biomass samples were dried for 72 h at 65 °C and weighed.

Soil temperature measurement instrumentation

Continuous soil temperature was monitored with a data logger (21X, Campbell-Scientific, Edmonton, Alberta) and four thermocouples (chromel-constantan) inserted at 10 cm depth at the 6 year-old cut block. Soil temperatures were recorded every 1 minute and averaged over 20 minute intervals.

Total Below ground and Ecosystem CO_2 Flux Estimates

The below ground CO_2 flux was estimated for the growing season from 24 May to 20 September 2000 for all cut blocks. For each cut block, multiple regressions were established relating the measured soil temperature and soil moisture to the instantaneous below ground CO_2 flux. A second set of regressions were established between the recorded soil temperatures at the 6 year-old cut block and the instantaneous soil temperature measurements at each cut block to provide a continuous estimate of soil temperatures for each cut block. Using the estimated soil temperatures at each cut block and the soil moisture measurements taken approximately every two weeks, the cumulative seasonal below ground fluxes were estimated for each cut block.

The estimated seasonal ecosystem CO_2 flux accounted for growth of vegetation. The biomass sampled in early May was subtracted from the early August measurement to allow for a prediction of above ground biomass gains. It was assumed that there was an equivalent amount of biomass stored below ground as there was above ground(Broderick 1990). Of the total biomass sampled 50% was assumed to be carbon (e.g. Kawaguchi & Yoda 1989; Gower et al. 1997; Steele et al. 1997; Slaughter et al. 1998). Finally, total gain in biomass carbon was subtracted from the cumulative seasonal below ground CO_2 flux to determine if the cut blocks were sources or sinks of CO_2. Following the convention of ecosystem CO_2 flux papers, a positive value indicates CO_2 loss to the atmosphere while a negative value indicates the uptake of CO_2 from the atmosphere.

Error analysis

Error analysis for the cumulative below ground CO_2 flux and the estimated ecosystem CO_2 flux were based on 95% confidence limits produced from the standard error of the estimate (SE) for the the regressions and the standard deviations for the biomass samples. To produce a more accurate estimate of the error associated with the below ground CO_2 flux, the SE was totaled on a biweekly basis and the error was estimated as follows:

$$Error = 1.96 * \sqrt{\sum x^2}$$

Where x is the total SE for each biweekly period

Results

Growing season below ground CO_2 fluxes

The below ground CO_2 flux peaked in July for all cut blocks with the lowest values corresponding to measurements taken in May and October. The flux ranged from approximately 2 μmol C $m^{-2}s^{-1}$ in October to highs between 8 and 10 μmol C $m^{-2}s^{-1}$ in July for cut blocks aged 2 yrs to mature (Fig. 1 a-h). The newest cut block was the only exception with maximum below ground flux reaching only 6 μmol C $m^{-2}s^{-1}$ in July.

Soil Temperature

All cut blocks had similar soil temperatures, which were different to those in the mature stand (Fig. 2 a-h). The mature stand had soil temperatures similar to those in the cut blocks earlier in the growing season, but as the summer progressed the cut block soil temperatures rose a greater amount. For example, the mature stand had soil temperatures of only 12.27 °C in early August, while the cut blocks had temperatures ranging from 18.2°C in the 9 yr-old cut block to 13.2°C in the newest cut block.

Below ground CO_2 flux and soil temperature

Below ground CO_2 efflux correlated well with linear relationships to soil temperature (10 cm depth) (Fig 3 a-h). The relationships were marginally but significantly ($p=0.05$) improved for some cut blocks by adding a linear relationship to soil moisture (Table 1). The relationships appear to be fairly strong for the cut blocks aged 2 years to Mature, but the newest cut block had a low R^2 of only 0.24. Fluxes followed the seasonal change in soil temperature for all cut blocks except the new cut block.

Soil Water Content

The cut blocks and the mature stand had soil moisture (kg H_2O/kg dry soil) values ranging between 98% at the 3 year-old cut block to 41% at the newest cut block (Fig. 4). The values were fairly consistent for each individual cut block throughout the summer, with none of the cut blocks experiencing severe drought or flooding. There was no obvious relationship between cut block age and soil moisture.

Above ground biomass

Age of the cut block had a significant effect on the relative proportion of above ground biomass found in conifer, woody shrubs and herbaceous species (Fig. 5). The younger cut blocks had a higher proportion of the biomass allocated to deciduous species while the older cut blocks (9 and 10 year-old), not surprisingly, had a greater proportion of the biomass in conifer biomass. The newest cut block had very little biomass present on site. The cut blocks aged 3, 5, 6, 9, and 10 year-old were not significantly different from one another. However, the 0 and 2 year-old cut block were significantly different from the others ($p=0.05$).

Above ground biomass from spring to mid-August increased by 28 g C m^{-2} at the newest cut block to a high of 446 g C m^{-2} in the 2 year-old cut block (Table 2). With the exception of the newest cut block, all the sites had above ground biomass gains over 165 g C m^{-2} across the season.

Cumulative seasonal below ground CO_2 flux

Using the modeled soil temperature for each site (Table 3), the cumulative seasonal below ground CO_2 flux for all cut blocks ranged from 560 g C m^{-2} at the newest cut block to 861 g C m^{-2} at the 2 yr-old cut block (May 24 to September 20, 2000) (Fig. 6). While these represent the extremes, the bulk of the cut blocks and the mature stand had cumulative seasonal below ground CO_2 flux of approximately 709 g C m^{-2}. There was a correlation between total above ground biomass on each cut block and the cumulative seasonal below ground CO_2 flux (Fig. 7). As the biomass increases, there was a positive increase in the cumulative seasonal below ground CO_2 flux (R^2 = 0.87).

Estimated net ecosystem CO_2 flux for each cut block

The estimated net ecosystem CO_2 efflux varies from cut block to cut block (Fig. 8). The 10 year-old cut block had the greatest net ecosystem CO_2 loss (538 g C m^{-2}) while the 3 year-old cut block had the lowest (372 g C m^{-2}). The magnitude of the estimated ecosystem CO_2 loss from each cut block was in the order of 5 > 10 > 0 > 9 > 6 > 2 > 3.

Discussion

Effect of soil temperature and moisture on below ground respiration

The positive correlation between soil temperature and in some cases soil moisture (Table 1) has been demonstrated by others (Kucera & Kirkham 1971; Fernandez et al. 1993; Striegl & Wickland 1998). The relationship between soil temperature and the instantaneous below ground CO_2 flux appeared largely linear in all cases. Researchers in the past have used either non-linear (Toland & Zak 1994; Striegl & Wickland 1998; Londo et al. 1999) or linear (Mathes & Schriefer 1985; Mallik & Hu 1997) equations to explain below ground CO_2 fluxes, but in this case the linear equations fit best.

The effect soil moisture has on the below ground CO_2 flux is generally believed to be parabolic (Londo et al. 1999). As soils approach saturation or drought conditions, the below ground CO_2 flux generally decreases (Kucera & Kirkham 1971; deJong et al. 1974; Londo et al. 1999). However, the relationship between soil moisture and instantaneous below ground CO_2 flux in our study was either statistically insignificant or weakly linear. The range of soil moisture values is low for all cut blocks and never approaches the extremes of drought or saturation. Had the cut blocks been moisture limited, the impact of soil moisture on the below ground CO_2 flux may have been more evident. Parker et al. (1983) in a study on soil respiration in the Chihuahuan Desert, found soil moisture to have a greater impact on below ground CO_2 flux than soil temperature. The greater dependence of below ground CO_2 flux on soil moisture in the Chihuahuan Desert is believed to have been the result of moisture being more limiting to roots or soil organisms. Therefore, the weak or lack of a dependence of below ground CO_2 flux on soil moisture at cut blocks in the Aleza Lake Research Forest may have been due to the limited range of soil moisture content present, or the relatively high wetness of the subzone.

Effect of cut block age and root respiration on below ground CO_2 flux

Apart from the newest cut block, all the cut blocks have fairly similar cumulative below ground CO_2 flux for the season (Fig. 6). However, the 0, 2 and 5 year-old cut blocks were statistically different. Initially, this seems to contradict results from Ewel et al. (1987a), in a study involving two slash pine (*Pinus ellottii*) plantations aged 9 and 29-years-old in Florida where below ground CO_2 flux was higher in the older plantation. The cut blocks in this study are much slower growing and are younger than the plantation in Ewel et al. (1987a). It is suggested by Ewel et al. (1987a), that the increase in below ground CO_2 flux in their study was due to greater root activity in the older stand. This relationship is weakly supported by the data in this study. As the biomass present on the cut blocks increased, so did the cumulative seasonal below ground CO_2 flux (Fig. 7). The new cut block had the lowest cumulative seasonal below ground CO_2 flux and above ground biomass and the 2 and 5 year-old cut blocks had the greatest cumulative seasonal below ground CO_2 flux and above ground biomass. Following this reasoning the mature stand with its greater biomass should have had the greatest cumulative seasonal below ground CO_2 flux. However, the mature stand also had much cooler soils. Had the soil temperatures been higher, the mature forest's below ground CO_2 rates may have been much higher due to greater root activity. While the sample size is too small to confidently draw a strong conclusion, the importance of roots on below ground CO_2 production is well noted by other researchers (Ewel et al. 1987b; Bowden et al. 1993; Fernandez et al. 1993; Thierron & Laudelout 1996; Boone et al. 1998). Therefore, assuming increases in above ground biomass result in a proportional increase in below ground biomass, the difference in biomass present on the cut blocks likely contributed to the below ground CO_2 flux.

Cumulative seasonal below ground respiration

Cumulative seasonal below ground CO_2 flux, between May 25 and September 20, totaled between 560 g C m^{-2} in the new cut block to 853 g C m^{-2} in the 2 year-old cut block (Fig. 7), with values ranging from 2.78 to 8.97 g C m^{-2} d^{-1}. These value are similar to a study by Russell & Voroney (1998) of the below ground CO_2 flux in a Boreal aspen forest (values ranged between 0.61 to 9.34 μmol C m^{-2} s^{-1}) and others in an oak forest (Edwards & Sollins 1973) slash pine plantation (Ewel et al. 1987a) and Alaskan white spruce forest and clearcut (Gordon et al. 1987). However, other studies in an Eastern Ontario aspen forest (Weber 1990), a coniferous and deciduous forest in Maine (Fernandez et al. 1993), a spruce-fir forest in Maine (Lytle & Cronan 1998) and a jack-pine lichen woodland (Striegl & Wickland 1998) have predicted CO_2 flux that were lower than those found in this study. The greater below ground CO_2 flux may be due to the nutrient rich, moist soils found in the sub zones. Valentini et al. (2000), in a study of ecosystem CO_2 flux found that northern European forest ecosystems are dominated by respiration. They found that northern coniferous, deciduous and mixed forests in Europe have similar photosynthetic CO_2 uptakes to their southern counterparts, but respiration rates increased with latitude even though the forests typically had lower soil temperatures. It is postulated that this may be the result of higher soil moisture values (Grace & Rayment 2000).

The estimated net ecosystem CO_2 flux

The increase in above ground biomass may have promoted below ground CO_2 flux, but the biomass accumulation helped counteract the increased CO_2 flux from the cut blocks. The estimated net ecosystem CO_2 flux ranged from 371 C m^{-2} to 538 g C m^{-2} in the 3 year-old and

10 year-old cut blocks respectively. The cut blocks with high cumulative seasonal below ground CO_2 flux also had greater above ground biomass (2 and 3 year-old cut blocks). The size of the sink provided by the above ground biomass acted to augment the increase in below ground CO_2 flux, but the greater biomass acted as a larger sink. The increase in carbon sequestration by the plants appears to counter act the increase in below ground respiration, frequently reducing the loss of CO_2 from the cut block.

Northern harvested cut blocks have slow regrowth and appear to be sources of CO_2 even ten years after harvest. The conifers are still not of sufficient size to balance the CO_2 lost from below ground. Deciduous plants may contribute to the below ground CO_2 flux through root respiration, but they also increase the amount of carbon absorbed on young regenerating cut blocks, thereby reducing the size of the net ecosystem CO_2 loss. It appears that up to 10 years after harvest, plant biomass and soil temperature, not the cut block age, dictate the size of the below ground and ecosystem CO_2 flux. Therefore, it may be important to support the deciduous plants in cut blocks in the years after harvest to reduce the amount of CO_2 lost to the atmosphere.

References

Andrews, J., Harrison, K., Matamala, R. & Schlesinger, W. 1999: Separation of root respiration from total soil respiration using carbon-13 labeling during free-air carbon dioxide enrichment (FACE). Soil Science Society of America Journal **63**, 1429-1435.

Apps, M., Kurz, W., Luxmore, R., Nilsson, L., Sedjo, R., Schmidt, R., Simpson, L. & Vinson, T. 1993: Boreal forests and tundra. Water, Air , and Soil Pollution **70**, 39-53.

Arocena, J. & Sanborn, P. 1999: Mineralogy and genesis of selected soils and their implications for forest management in central and northeastern British Columbia. Canadian Journal of Soil Science **79**, 571-592.

Boone, R., Nadelhoffer, K., Canary, J. & Kaye, D. 1998: Roots exert a strong influence on the temperature sensitivity of soil respiration. Nature **396**, 570-572.

Bowden, R., Nadelhoffer, K., Boone, R., Melillo, J. & Garrison, J. 1993: Contributions of above ground litter, below ground litter and root respiration to total soil respiration in a temperate hardwood forest. Canadian Journal of Forest Research **23**, 1402-1407.

Broderick, D. 1990: The biology of Canadian weeds. 93. *Epilobium angustifolium* L. (Onagraceae). Canadian Journal of Plant Science **70**, 247-259.

Chang, S., Preston, C. & Weetman, G. 1995: Soil microbial biomass and microbial and mineralizable N in a clear-cut chronosequence on northern Vancouver Island, British Columbia. Canadian Journal of Forest Research **25**, 1597-1607.

Chang, S. X. & Trofymow, J. A. 1996: Microbial respiration and biomass (substrate-induced respiration) in soils of old-growth and regenerating forests on northern Vancouver Island, British Columbia. Biology and Fertility of Soils. **23**, 145-152.

deJong, H., Schappert, V. & MacDonald, K. 1974: Carbon dioxide evolution from virgin and cultivated soil as affected by management practices and climate. Canadian Journal of Soil Science **54**, 299-307.

Edwards, N. T. & Ross-Todd, B. M. 1983: Soil carbon dynamics in a mixed deciduous forest following clear-cutting with and without residual removal. Soil Science Society of America Journal **47**, 1014-1021.

Edwards, N. T. & Sollins, P. (1973): Continuous measurement of carbon dioxide evolution from partitioned forest floor components., pp. 406, Environmental Sciences Division. Oak Ridge National Laboratory, Oak Ridge, Tenn.

Ewel, K. C., Cropper, W. P. J. & Gholz, H. L. 1987a: Soil CO2 evolution in Florida slash pine plantations. I. Changes through time. Canadian Journal of Forest Research **17**, 325-329.

Ewel, K. C., Cropper, W. P. J. & Gholz, H. L. 1987b: Soil CO2 evolution in Florida slash pine plantations. II. Importance of root respiration. Canadian Journal of Forest Research **17**, 330-333.

Fernandez, I. J., Son, Y., Kraske, C. R., Rustad, L. E. & David, M. B. 1993: Soil carbon dioxide characteristics under different forest types and after harvest. Soil Science Society of Amercia Journal **57**, 1115-1121.

Gordon, A. M., Schlentner, R. E. & K., V. C. 1987: Seasonal patterns of soil respiration and CO2 evolution following harvesting in the white spruce forests of interior Alaska. Canadian Journal of Forest Research **17**, 304-310.

Gower, T., Vogel, J. G., Norman, J. M., Kucharik, C. J. & Steele, S. J. 1997: Carbon distribution and aboveground net primary production in aspen, jack pine, and black spruce stands in Saskatchewan and Manitoba, Canada. Journal of Geophysical Research **102**, 29,029-29,041.

Grace, J. & Rayment, M. 2000: Respiration in balance. Nature **404**, 819-820.

Harmon, M., Ferrel, W. K. & Franklin, J. 1990: Effects of carbon storage on conversion of old-growth forests to young forests. Science **247**, 699-702.

Kawaguchi, H. & Yoda, K. 1989: Carbon-Cycling Changes during Regeneration of a Deciduous Broadleaf Forest after Clear-Cutting II. Aboveground Net Production. Ecological Research **4**, 271-286.

Kucera, C. L. & Kirkham, D. R. 1971: Soil respiration studies in tallgrass prairie in Missouri. Ecology **52**, 912-915.

Kurz, W. & Apps, M. 1994: The carbon budget of Canadian forests: A sensitivity analysis of changes in disturbance regimes, growth rates, and decomposition rates. Environmental Pollution **83**, 55-61.

Lewis, T. 1998: The effect of deforestation on ground surface temperatures. Global and Planetary Change **18**, 1-13.

Londo, A., Messina, M. & Schoenholtz, S. 1999: Forest harvesting effects on soil temperature, moisture, and respiration in a bottomland hardwood forest. Journal of the Soil Science Society of America **63**, 637-644.

Lytle, D. E. & Cronan, C. S. 1998: Comparative soil CO2 evolution, litter decay, and root dynamics in clear-cut and uncut spruce-fir forest. Forest Ecology and Management **103**, 121-128.

Mallik, A. & Hu, D. 1997: Soil respiration following site preparation treatments in Boreal mixedwood forest. Forest Ecology and Management **97**, 265-275.

Mathes, K. & Schriefer, T. 1985: Soil respiration during secondary succession: Influence of temperature and moisture. Soil Biology and Biochemistry **17**, 205-211.

McCaughey, H. 1989: Energy exchange for a forest site and a clear-cut site at chalk river, Ontario. The Canadian Geographer **33**, 299-311.

Meidinger, D. & Pojar, J. (1991): Ecosystems of British Columbia, pp. 1-330, BC Ministry of Forest.

Norman, J., Garcia, R. & Verma, S. 1992: Soil surface CO_2 fluxes and the carbon budget of a grassland. Journal of Geophysical Research **97**, 18,845-18,853.

Parker, L., Miller, J., Steenberg, Y. & Whitford, W. 1983: Soil Respiration in a ChihuahuanDesert rangeland. Soil Biology and Biochemistry **15**, 303-309.

Pietikainen, J. & Fritze, H. 1993: Microbial biomass and activity in the humus layer following burning: Short-term effects of two different fires. Canadian Journal of Forest Research **23**, 1275-1285.

Post, W. M., Emanuel, W. R., Zinke, P. J. & Stangenberger, A. G. 1982: Soil carbon pools and world life zones. Nature **298**, 156-159.

Russell, C. A. & Voroney, R. P. 1998: Carbon dioxide efflux from the floor of a Boreal aspen forest. I. Relationship to environmental variables and estimates of C respired. Canadian Journal of Soil Sciene **78**, 301-310.

Schimel, D. 1995: Terrestrial ecosystems and the carbon cycle. Global Change Biology **1**, 77-91.

Slaughter, K., Grigal, D. & Ohmann, L. 1998: Carbon storage in southern Boreal forests following fire. Scandinavian Journal of Forest Research **13**, 119-127.

Steele, S., Gower, S., Vogel, J. & Norman, J. 1997: Root mass, net primary productiong and turnover in aspen, jack pine and black spruce forests in Saskatchewan and Manitioba, Canada. Tree Physiology **17**, 577-587.

Striegl, R. G. & Wickland, K. P. 1998: Effects of a clear-cut harvest on respiration in a jack pine-lichen woodland. Canadian Journal of Forest Research **28**, 534-539.

Tans, P., Fung, I. & Takahashi, T. 1990: Observational constraints on the global atmospheric CO_2 budget. Science **247**, 1431-1438.

Thierron, V. & Laudelout, H. 1996: Contribution of root respiration to total efflux from the soil of a deciduous forest. Canadian Journal of Forest Research **26**, 1142-1148.

Toland, D. E. & Zak, D. R. 1994: Seasonal patterns of soil respiration in intact and clear-cut northern hardwood forests. Canadian Journal of Forest Research **24**, 1711-1716.

Valentini, R., Matteucci, G., Dolman, A., Schulze, E.-D., Rebmann, C., Moors, E., Granier, A., Gross, P., Jensen, N., Pilegaard, K., Lindroth, A., Arelle, A., Bernhofer, C., Grünwald, T., Aubinet, M., Ceulemans, R., Kowalski, A., Vesala, T., Rannik, Ü., Berbigier, P., Loustau, D., Guõmundsson, J., Thorgeirsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrief, J., Montagnani, L. & Jarvis, P. 2000: Respiration as the main determinant of carbon balance in European forests. Nature **404**, 861-864.

Weber, M. G. 1990: Forest soil respiration after cutting and burning in immature aspen ecosystems. Forest Ecology and Management**31**, 1-14.

Woodwell, G. M., Hobbie, J. E., Houghton, R. A., Meliilo, J. M., Moore, B., Peterson, B. J. & Shaver, G. R. 1983: Global Deforestation: Contribution to Atmospheric Carbon Dioxide. Science **222**, 1081-1086.

Table 1 – Multiple and single regression equations for instantaneous below ground CO_2 flux using soil temperature with or without moisture for cut blocks aged 0, 2, 3, 5, 6, 9, 10 and mature. Measurements of soil temperature, moisture and instantaneous below ground CO_2 flux for the regressions were taken in the Aleza Lake Research Forest, May to October, 2000.

Site Age	Regression	R^2	Regression	R^2
0	1.837+0.235T	0.19	0.443+0.216T+0.0293M	0.24
2	-1.66+0.727T	0.40	-1.66+0.727T	0.40
3	0.091+0.441T	0.46	0.091+0.441T	0.46
5	-0.719+0.573T	0.50	-4.67+0.592T+0.0583M	0.54
6	-1.631+0.571T	0.67	-1.631+0.571T	0.67
9	-0.398+0.459T	0.62	-2.67+0.459T+0.0447M	0.58
10	-0.229+0.473T	0.58	-0.233+0.474T	0.58
Mature	0.4019+0.545T	0.41	2.05+0.653T-0.0397M	0.43

T – temperature (°C)

M – moisture (%)

Table 2 – Above ground conifer, herbaceous, woody shrub and total biomass in spring (May 5-10) and late summer (August 6-14), and the change in biomass from spring to summer, at 7 cut blocks in the Aleza Lake Research Forest.

Cut Block Age	*Spring Biomass (g m^{-2})*				*Late Summer Biomass (g m^{-2})*				*Biomass Change g m^{-2}*
	Conifer	Herbaceous*	Woody Shrubs	Total Biomass	Conifer	Herbaceou	Woody Shrubs	Total Biomass	
0	0	-	3.73	3.73	0	20.3	12.1	32.4	28.6
2	4.99	-	91.9	96.9	8.07	323	208	539	442
3	14	-	86.8	101	28	127	262	418	317
5	49	-	158	208	74	108	280	452	254
6	45.5	-	140	185.5	64	163	234	462	277
9	185	-	33.8	219	240	184	43.3	468	249
10	205	-	85.7	290	207	126	122	455	164

*No herbaceous plants present in spring

Table 3 – Correlation of soil temperature at a meteorological tower in the 6 year-old cut block with instantaneous soil temperatures measurements made at each cut block coincident with below ground CO_2 flux determinations.

Site Age	Correlation to Tower Measurement R^2
0	0.93
2	0.83
3	0.77
5	0.88
6	0.89
9	0.77
10	0.87
Mature	0.94

Figures and Legends

Figure 1 – The instantaneous below ground CO_2 flux for a mature stand and 7 cut blocks aged 0, 2, 3, 5, 6, 9 and 10 years since harvest from May until the end of October, 2000 in the Aleza Lake Research Forest. The symbols and lines represent the measured instantaneous and modeled below ground CO_2 fluxes, respectively. The bars on the symbols represent a 95% confidence interval

Figure 2 – *In situ* soil temperature (10 cm depth) for a mature stand and 7 cut blocks aged 0, 2, 3, 5, 6, 9 and 10 years since harvest from May until the end of October in the Aleza Lake Research forest. Vertical lines represent a 95% confidence interval.

Figure 3 – Relationship between *in situ* soil temperature (10 cm depth) and below ground CO_2 flux for a mature stand and 7 cut blocks aged 0, 2, 3, 5, 6, 9 and 10 years since harvest in the Aleza Lake Research Forest from May until October, 2000. The solid line (-) represents the modeled below ground CO_2 flux.

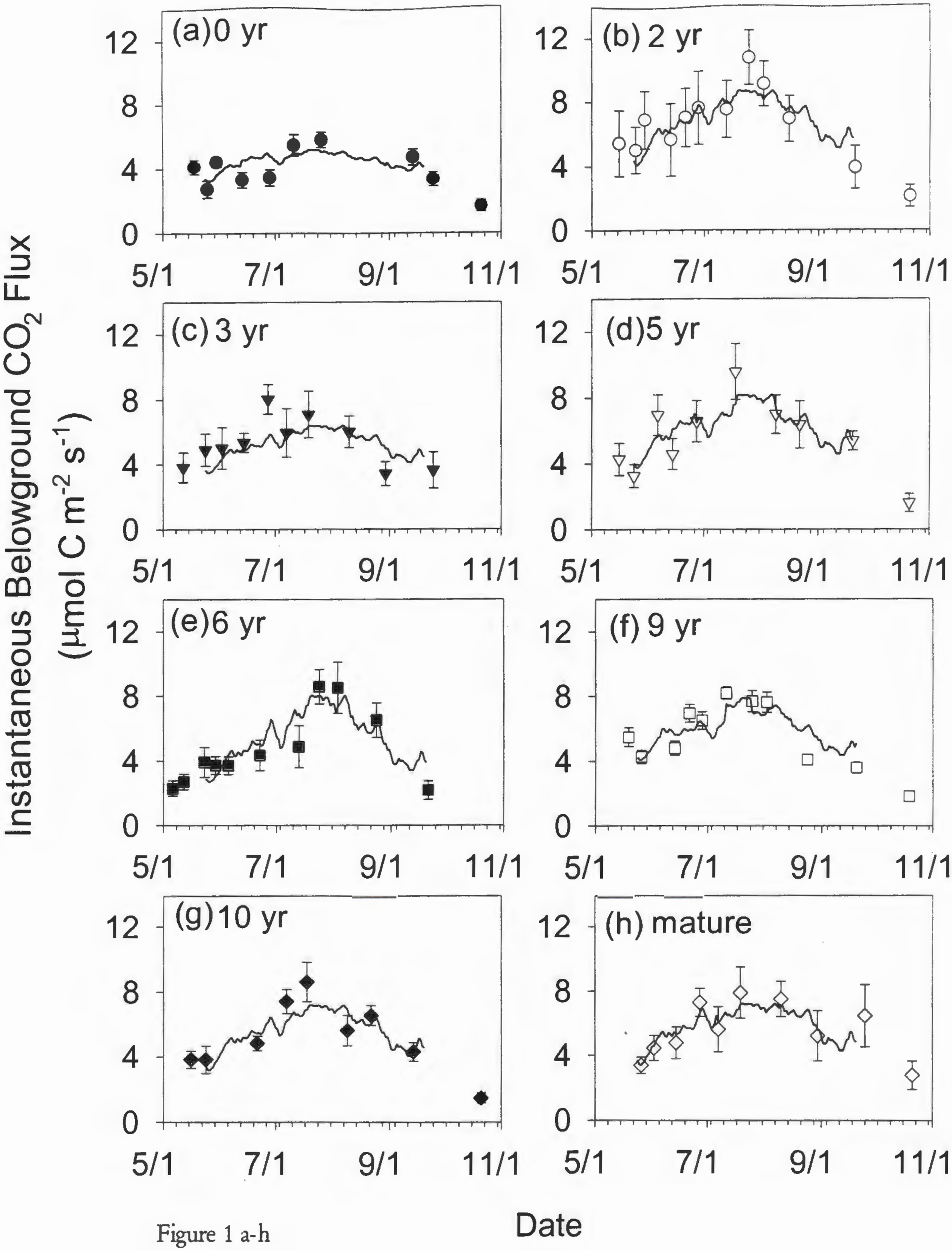
Figure 4 – *In situ* soil moisture for a mature stand and 7 cut blocks aged 0, 2, 3, 5, 6, 9 and 10 years since harvest from May until the end of October in the Aleza Lake Research forest. Vertical lines represent a 95% confidence interval.

Figure 5 – The total above ground biomass partitioned into conifer, herbaceous and shrubs in each of the cut blocks measured within the Aleza Lake Research forest.

Figure 6 – The estimated net below ground CO_2 efflux from a mature stand and seven cut blocks aged 0, 2, 3, 5, 6, 9 and10 years since harvest from May 24 to September 20, 2000 in the Aleza Lake Research Forest.

Figure 7 – The relationship between the net above ground biomass and cumulative seasonal below ground CO_2 flux (May 24 to September 20, 2000) at 7 cut blocks aged 0, 2, 3, 5, 6, 9, and 10 years since harvest in the Aleza Lake Research Forest.

Figure 8 – The estimated net efflux of CO_2 from May 24 to September 20, 2000, in 7 cut blocks aged 0, 2, 3, 5, 6, 9 and 10 years since harvest in the Aleza Lake Research Forest.



(a)0 yr
(b) 2 yr
(c) 3 yr
(d)5 yr
(e)6 yr
(f) 9 yr
(g)10 yr
(h) mature
Instantaneous Belowground CO_2 Flux (μmol C m^{-2} s^{-1})
Date

Figure 1 a-h

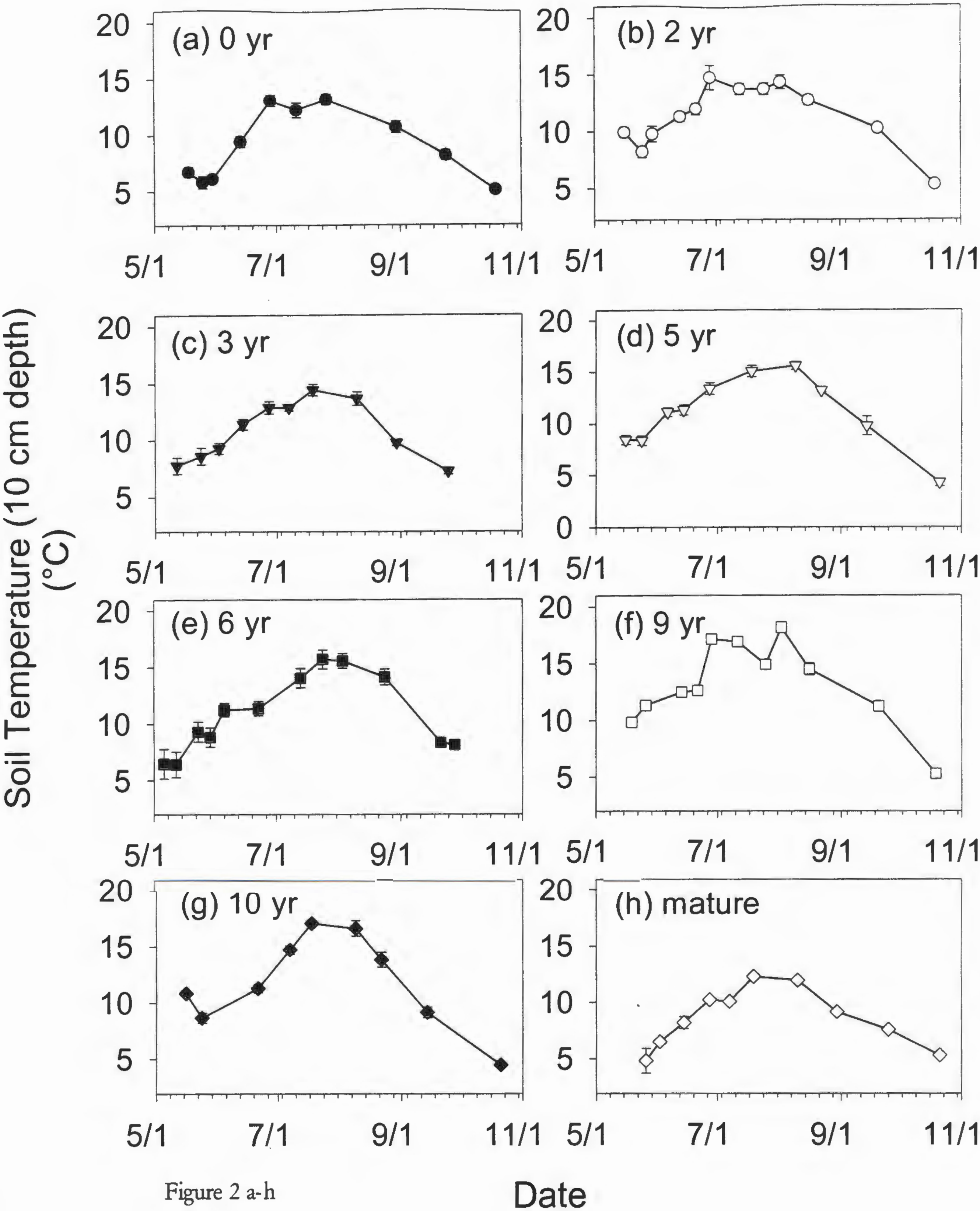

(a) 0 yr
(b) 2 yr
(c) 3 yr
(d) 5 yr
(e) 6 yr
(f) 9 yr
(g) 10 yr
(h) mature
Soil Temperature (10 cm depth) (°C)
Date
5/1
7/1
9/1
11/1
0
5
10
15
20

Figure 2 a-h

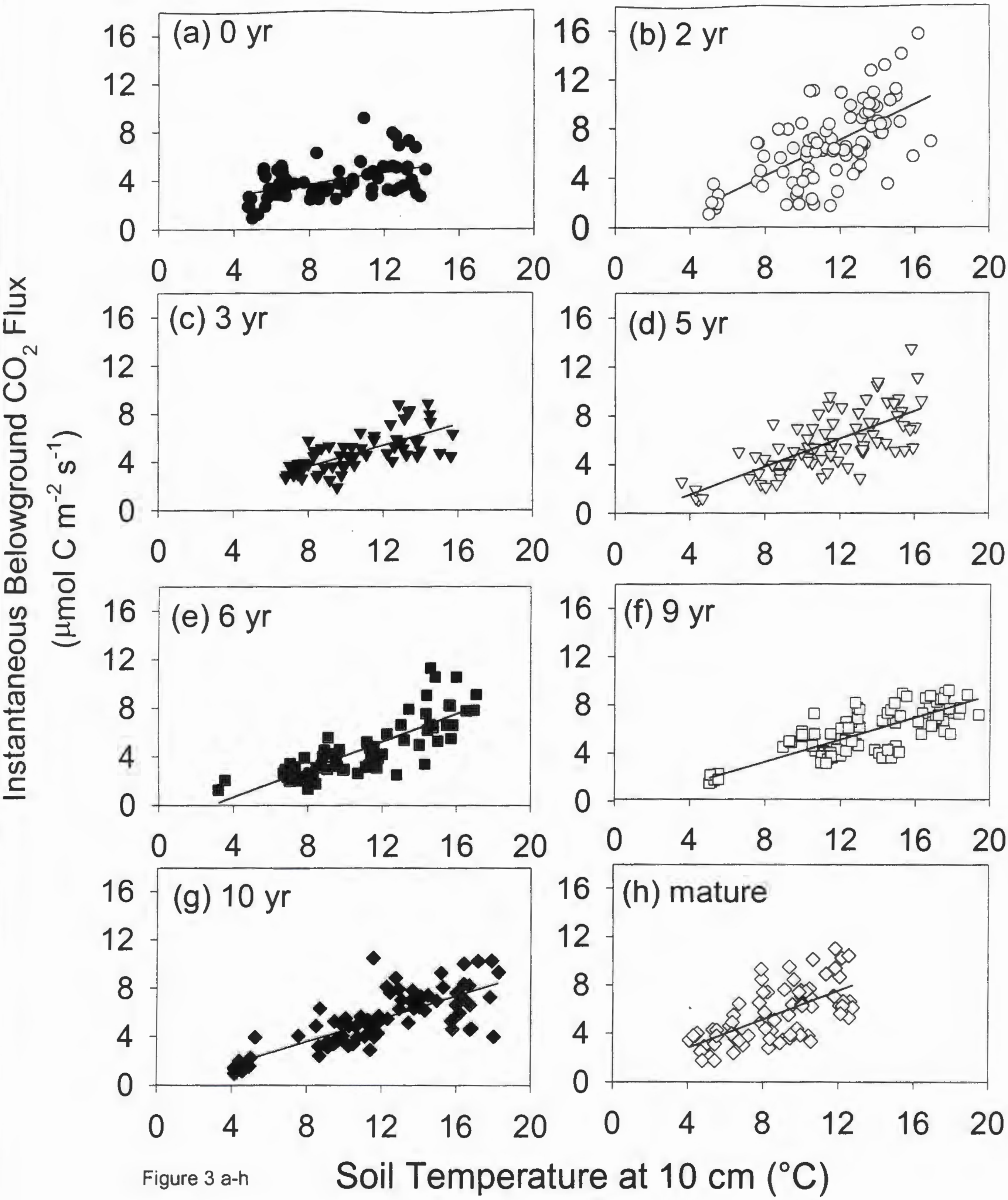

(a) 0 yr
(b) 2 yr
(c) 3 yr
(d) 5 yr
(e) 6 yr
(f) 9 yr
(g) 10 yr
(h) mature
Instantaneous Belowground CO_2 Flux ($\mu mol\ C\ m^{-2}\ s^{-1}$)
Soil Temperature at 10 cm (°C)

Figure 3 a-h

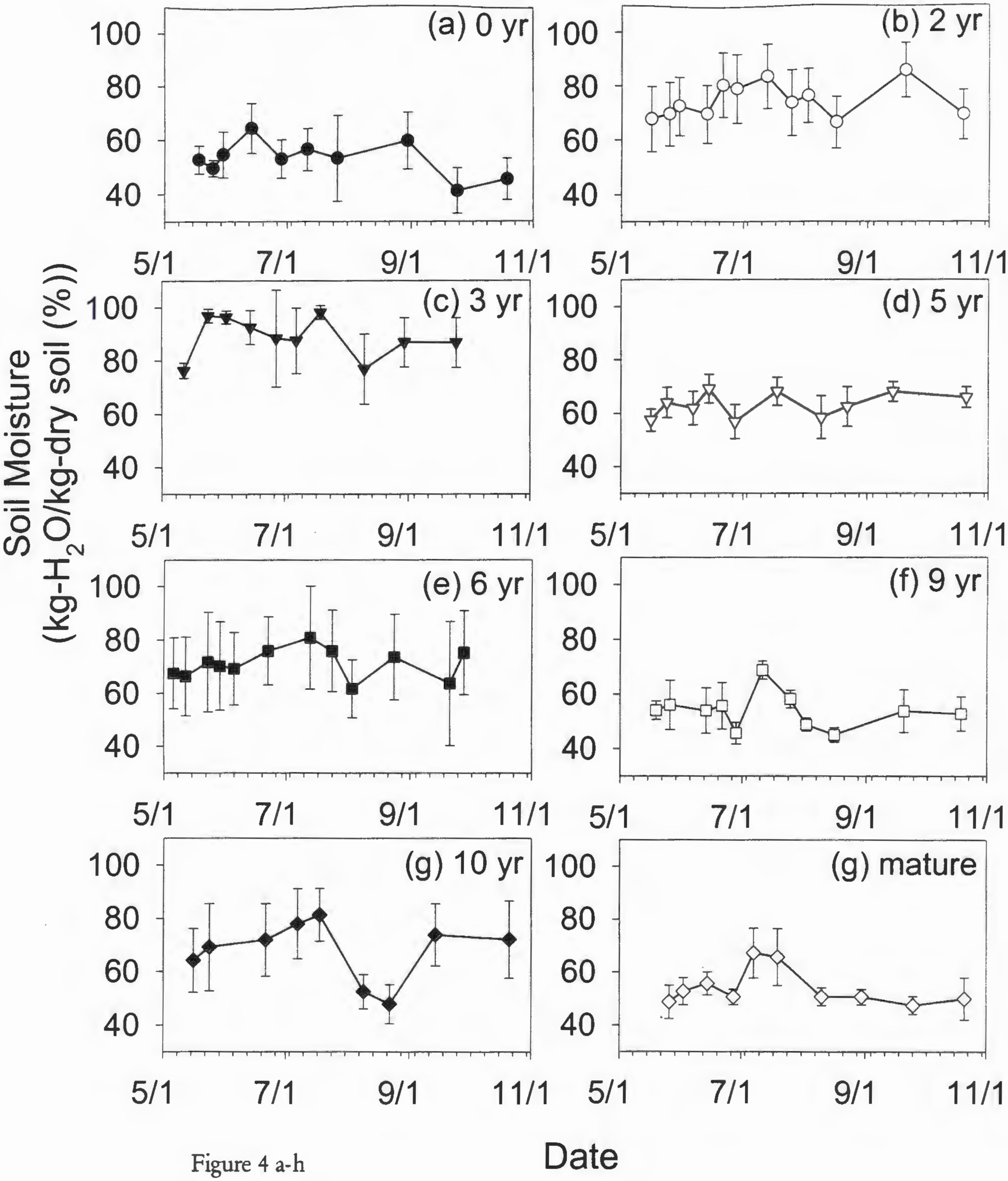
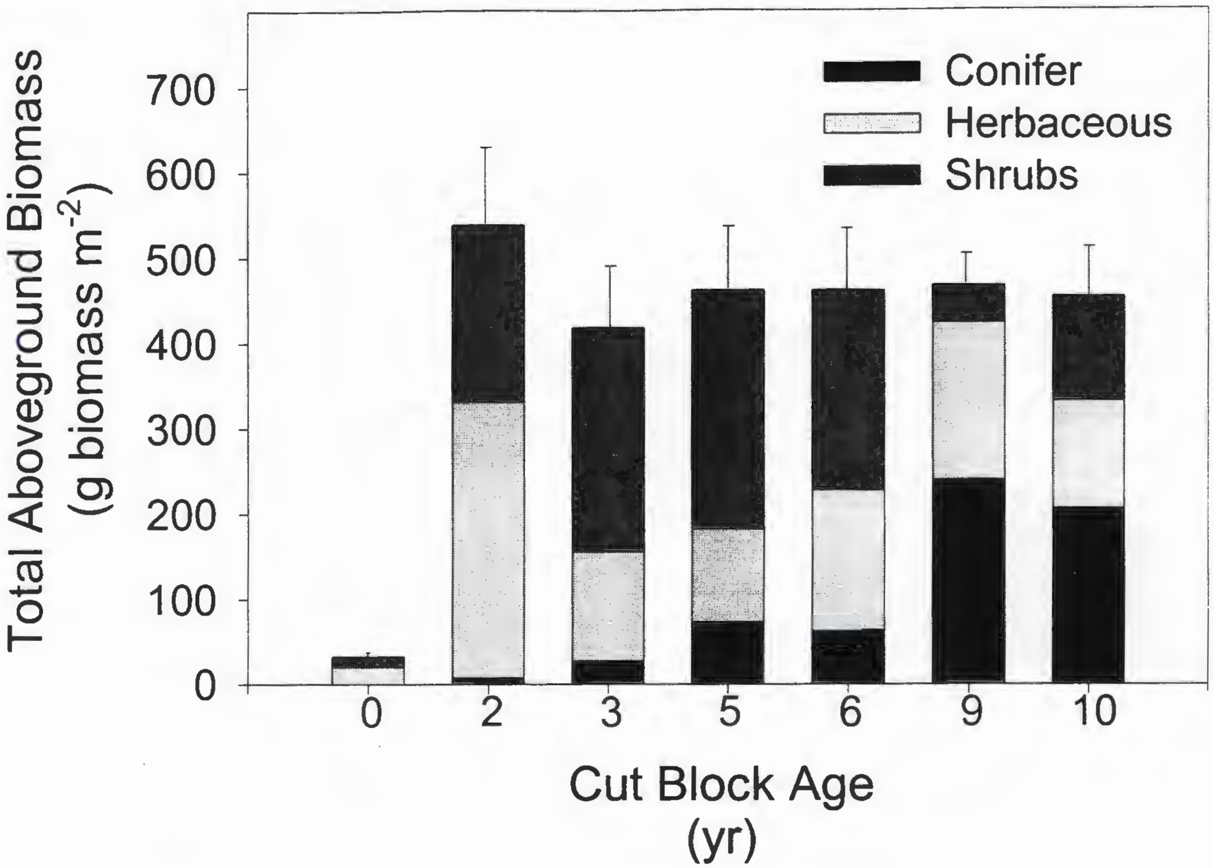

(a) 0 yr
(b) 2 yr
(c) 3 yr
(d) 5 yr
(e) 6 yr
(f) 9 yr
(g) 10 yr
(g) mature
100
80
60
40
5/1
7/1
9/1
11/1
Soil Moisture
(kg-H_2O/kg-dry soil (%))
Date

Figure 4 a-h



Total Aboveground Biomass
(g biomass m-2)
700
600
500
400
300
200
100
0
Conifer
Herbaceous
Shrubs
0
2
3
5
6
9
10
Cut Block Age
(yr)

Figure 5

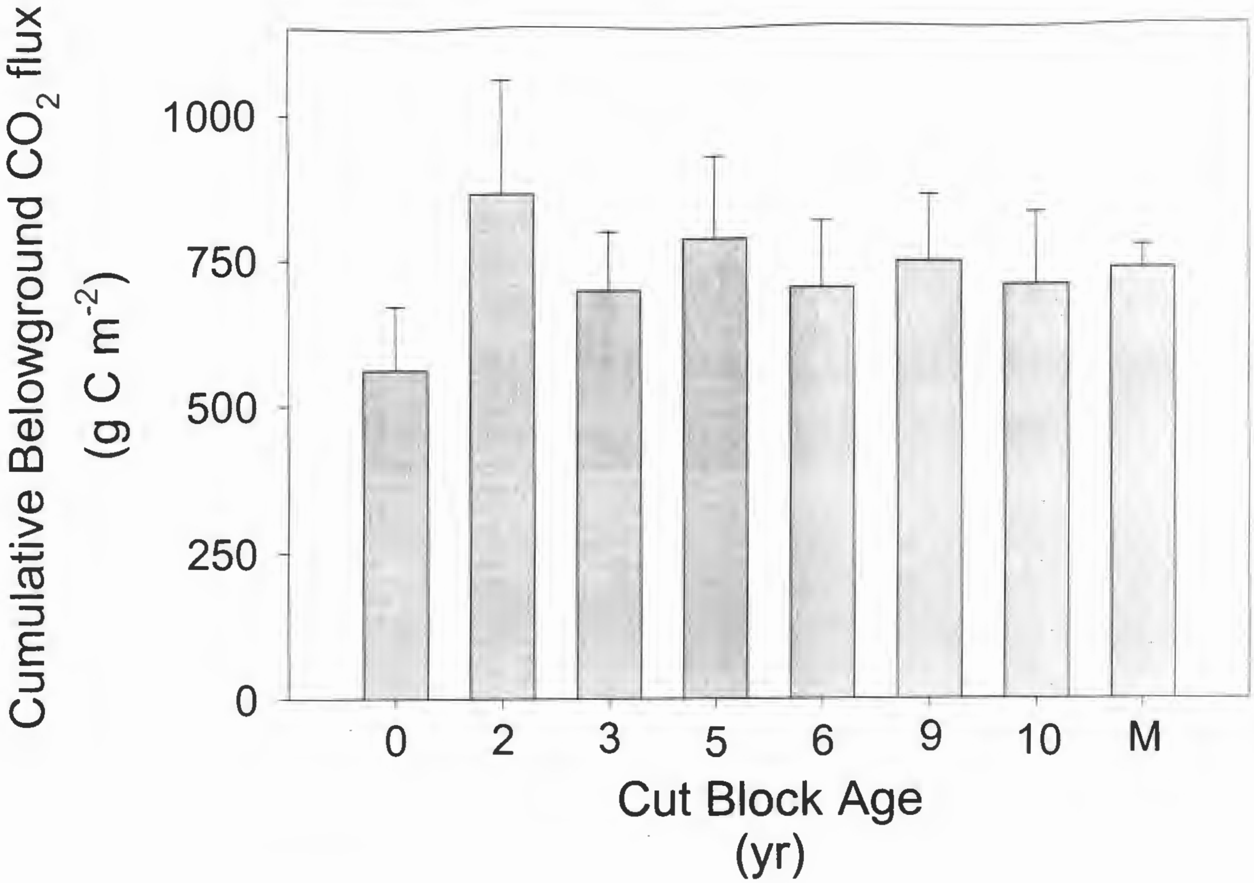
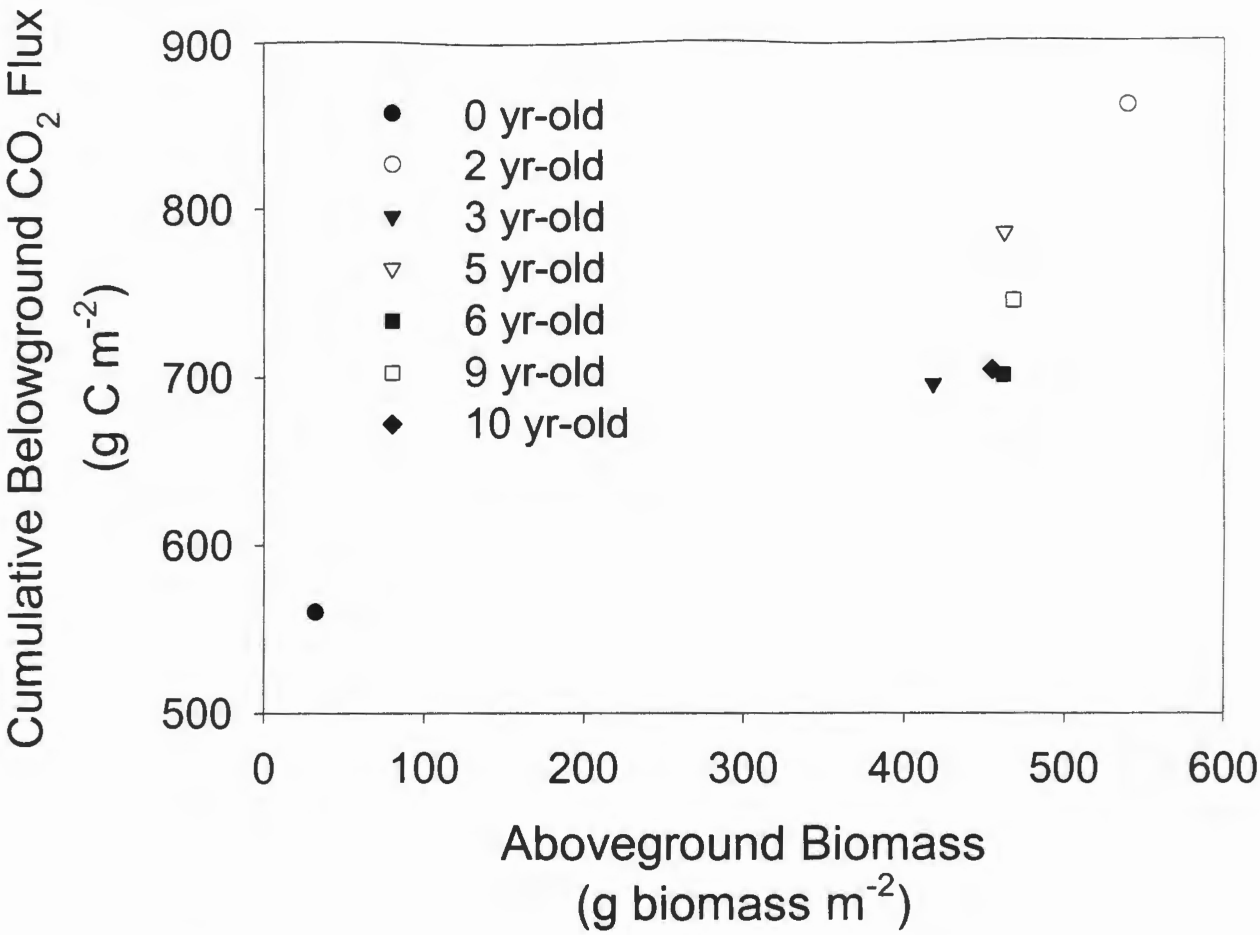

Cumulative Belowground CO_2 flux
($g\ C\ m^{-2}$)
1000
750
500
250
0
0
2
3
5
6
9
10
M
Cut Block Age
(yr)

Figure 6



Cumulative Belowground CO_2 Flux
($g\ C\ m^{-2}$)
900
800
700
600
500
0
100
200
300
400
500
600
0 yr-old
2 yr-old
3 yr-old
5 yr-old
6 yr-old
9 yr-old
10 yr-old
Aboveground Biomass
(g biomass m^{-2})

Figure 7

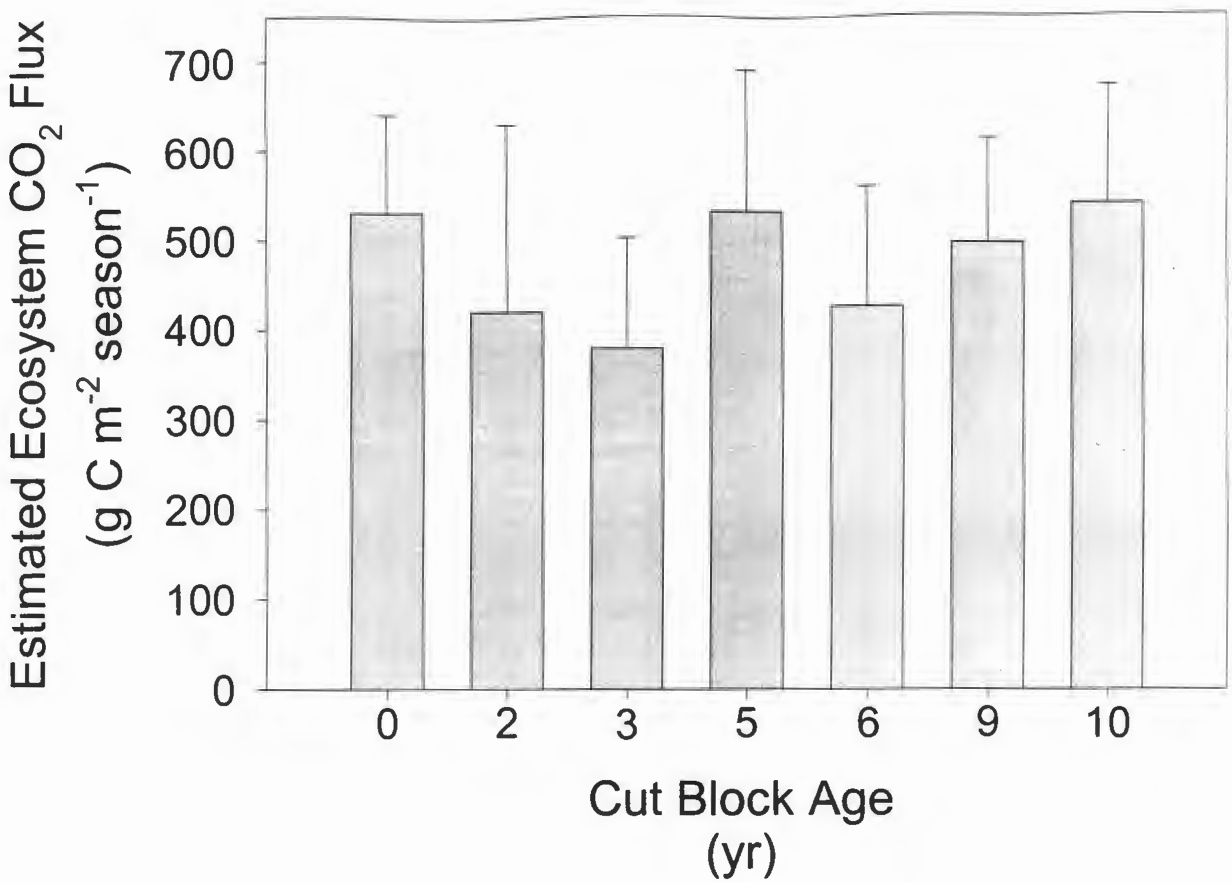

Estimated Ecosystem CO2 Flux
(g C m-2 season-1)
700
600
500
400
300
200
100
0
0
2
3
5
6
9
10
Cut Block Age
(yr)

Figure 8

SUMMARY AND CONCLUSIONS

The CO_2 budget of young regenerating sub-Boreal forests of varying ages since harvest

The common assumption that young regenerating forests only remain a source of CO_2 for approximately 10 years after harvest may not be applicable for sites in the SBS wk1 that are sub-hygric. The Bowen ratio data and the component model demonstrate that a clearcut of 5 to 6 years in the SBS wk1 08 is a source of CO_2 over the course of a year. Similar results from a Boreal forest study in Siberia found that a 12 year-old forest was only weakly a sink of CO_2 in July (Valentini et al. 2000a). Therefore, if the young Siberian forest is only a weak sink during the middle of summer, it is likely to be a source of CO_2 over the course of a year. Seedlings in sub-Boreal and Boreal forests are slow growing because of a shorter growing season and harsher winters as compared to cut blocks in the south. The assumption that seedlings enter their exponential growth phase after 10 years (Kurz & Apps 1994) appears to be false when considering SBS wk1 08 cut blocks. In the 9 and 10 year-old cut blocks observed in chapter 3, the conifers still are not the dominant contributor to the overall CO_2 uptake.

The photosynthesis of deciduous plants dominate the CO_2 uptake component of ecosystem flux in regenerating stands at Aleza Lake on the sites studied for at least 10 years. For all cut blocks aged 0 to 10 years, the bulk of the biomass was found in the herbaceous and woody shrubs. The photosynthetic CO_2 uptake using the component model for the 5 to 6 year-old clearcut found the herbaceous plants and woody shrubs to take up 376 and 365 g C m^{-2} for

1999 and 2000, respectively (27 June to 3 September). The deciduous plant photosynthesis dwarfs the conifer CO_2 uptake of only 47 and 58 g C m^{-2} during 1999 and 2000 respectively. The conifers became more important as the cut blocks aged, but the increase in conifer biomass appeared to come at the expense of deciduous plants. The older cut blocks did not have a greater accumulation in above ground biomass when compared to the younger cut blocks. Hence, in young clearcuts, biomass sequestration did not appear to improve as the cut blocks aged. However, no measurements of change in below ground biomass with clearcut age were made.

Below ground respiration was the dominant CO_2 flux in the cut blocks at Aleza Lake. In all cut blocks the below ground carbon loss exceeded any carbon gains by the plants. The dominance of the respiration in northern areas has recently been reported by Valentini et al. (2000) for a latitudinal series of European forests. Hence, even though northern regions have cooler temperatures, the respiration rates increased. This may be the result of increased soil moisture or available organic matter (Grace & Rayment 2000) or greater below ground soil flora or fauna.

Timber harvesting did not result in greater below ground losses of CO_2 when compared to the mature forest. The below ground CO_2 flux for the mature harvest was similar to all cut blocks even though its soil temperatures were slightly lower. The mature stand would have the greater root biomass relative to the cut blocks. Therefore, it is possible that the increase in root respiration in the mature stand was offset by the negative impact of lower temperatures on the below ground CO_2 flux.

Discrepancies between the ecosystem CO_2 method results

The results indicate that sub-hygric SBS wk1 cut blocks that are < 10 years of age in the Aleza Lake region are likely sources of CO_2 annually. However, there were discrepancies between the result of the BREB method, component model and the estimated ecosystem CO_2 fluxes found in chapter 3. The BREB method and the component model for 2000 estimated growing season ecosystem CO_2 flux to be 143 ±57 and 103 g C m^{-2}, respectively. In contrast, the estimated ecosystem CO_2 flux predicted a loss of 424 g C m^{-2}. The component model and the estimated ecosystem CO_2 flux both used similar cumulative below ground CO_2 flux equations. Therefore, the discrepancy is the result of Component model and the biomass based net ecosystem estimtes in Chapter 3. The component model estimated the CO_2 uptake to be 583 g C m^{-2} while the net ecosystem CO_2 flux estimated a gain of 276 g C m^{-2} based on the biomass values. The discrepancy is not surprising as the two methods use two fundamentally different approaches to estimating plant carbon sequestration.

Discrepancies between different techniques are not uncommon when attempting to quantify the CO_2 flux from a forest. Norman et al. (1997), examined the differences in below ground CO_2 flux using five different soil chambers and a sonic anemometer. They found that multipliers ranging from 0.93 (sonic anemometer) to 1.45 were needed to bring the different methods in agreement, thus demonstrating a large variance in the results from process based instruments. At an old aspen stand within the Canadian Boreal forest, two research groups set out to measure the net ecosystem exchange of CO_2. Yang (1998), using an eddy covariance system, estimated the net primary productivity (NPP) to be -708 g C m^{-2} . In contrast, two studies in the same old aspen stand that used allometric equations to estimate NPP and net ecosystem exchange (NEE) of carbon found lower CO_2 fluxes: Gower et al. (1997), estimated above ground components to sequester -352 g C m^{-2} y^{-1} and Steele et al. (1997) estimated the carbon allocation to roots to be -52 g C m^{-2} y^{-1} for a total of –404 g C m^{-2} y^{-1}. As with the results of our study, the biomass based estimates are lower than the modeled or tower based estimates of NPP of CO_2. Biomass estimates of CO_2 uptake may have lower NPP values because the carbon lost to leaf turnover, flowers, seed production and root exudates are not accounted for. However, the BREB method and component model CO_2 flux estimates have their inherent flaws as well. The BREB method is susceptible to a variety of measurement errors and is hampered in non-homogenous stands. The component model has errors associated with the CO_2 uptake of each of the components that would be compounded when scaled up to the ecosystem level. It is difficult to predict the exact size of the CO_2 flux, and the size of the error for each method, because all methods have relatively large errors associated with them (Kimball et al. 1997). However, while the various estimates for the CO_2 flux for cut block at Aleza Lake varied, they all indicate the cut block was a source of CO_2 for at least six years.

Implications for timber harvesting and the Kyoto Protocol

Young regenerating forests in the Aleza Lake region slowly recover resulting in a prolonged period of CO_2 losses to the atmosphere. If losses of CO_2 from young regenerating sub-Boreal forests are to be avoided, silvicultural practices must consider the important components of the CO_2 flux. In the years immediately after harvest the presence of deciduous plants should not be discouraged (e.g. removal through brushing) except in the extreme situations where conifer seedlings would otherwise be greatly suppressed. If overall productivity of the cut blocks is suppressed, the flux of CO_2 from below ground will dominate, providing an even larger source of CO_2 to the atmosphere. However, planted spruce seedlings are slow growing in the cut blocks studied, and are consequently incapable of providing the sink required to switch cut blocks from sources to sinks of CO_2 10 years after harvest.

The implication for reforestation and afforestation carbon credits to industrialized nations such as Canada and the USA are weakened by the slower recovery of forests found in the SBS wk1 08. If forests in sub-Boreal British Columbia are cut on set rotation times then the time available for carbon sequestration will be shortened. The results from this study indicate that harvested stands in the SBS wk1 08 are sources for CO_2 for at least 10 years and likely more. The longer time it takes to change from source to sink casts doubt on the assumption that clearcuts require only ten years to become change from a source to a sink of CO_2. For forestry related activities to be used as carbon credits, the total sinks and sources must be accounted for. The longer a cut block remains a carbon source, the greater the impact of forest harvesting on the size of the source of CO_2 related to forestry activities. This will weaken the argument for taking credits for carbon sequestration in northern forests.

Potential implications of global warming on cut block carbon budgets

If global warming occurs as predicted, the greatest impacts will likely be seen at higher latitudes (Melillio et al. 1993). It has been demonstrated that northern forest CO_2 budgets are sensitive to length of growing season and rising temperatures (Lindroth et al. 1998). The seedlings would benefit from increased temperature, as they will be photosynthetically active for a longer period of the year, but with increasing air temperatures comes greater evaporation and soil moisture loss. However, because Aleza Lake forests are located in a wet ecosystem (wk1), the impact may be smaller than for more xeric northern sites. While there is no concrete evidence that cut blocks in the Aleza Lake region would benefit under global warming, it is likely that the longer growing season and sufficient water supply would promote plant CO_2 uptake and possibly a earlier change from source to sink of CO_2 for cut blocks in the SBS wk1 08.

A more rapid change from source to sink for CO_2 for young regenerating forests is not certain. There is a fear among scientists that global warming will enhance decomposition of organic matter resulting in an uncontrollable feedback system of runaway greenhouse gases and global warming. Below ground CO_2 fluxes are closely linked to temperature (Kucera & Kirkham 1971; Fernandez et al. 1993; Striegl & Wickland 1998) and if the relationship is maintained over time, the losses of below ground carbon may dwarf any gains by improved plant CO_2 uptake. However, there is some doubt that the below ground CO_2 flux will cause unrestrained CO_2 losses from decomposition and root respiraton to the atmosphere with increasing temperatures. Giradina & Ryan (2000) demonstrated that long-term below ground CO_2 fluxes are not limited by soil temperature. They suggest below ground CO_2 fluxes will not rapidly increase with rising global temperatures alone, postulating there may be other limiting factors such as nutrient quality. This would be of tremendous importance in northern soils, as they tend to have a greater portion of their carbon stored below ground. However, if the below ground CO_2 flux is enhanced, carbon uptake that results from more favourable temperatures and longer growing season and may be counteracted by increased respiration.

Summary

The results of the two field seasons indicate that a spruce-dominated clearcuts in sub-hygric areas of the Aleza Lake Research Forest are sources of CO_2 for longer than the 10 years assumed by models (Kurz & Apps 1994). However, the size of the CO_2 source appears to vary from year to year in accordance with large inter-annual variability in the below ground CO_2. Deciduous plants contribute the bulk of photosynthetic CO_2 uptake on young regenerating cut blocks at Aleza Lake, with conifers, even at 10 years, contributing a lesser share.

Future Research

To better understand how harvesting sub-Boreal forest affects atmospheric CO_2 concentrations, the full breadth of impacts must be investigated. First, research is needed to understand when cut blocks in northern areas convert from sources to sinks of CO_2. The longer a cut block remains a source for CO_2 the greater the impact rotation time has on the size of the sink generated by the new forest over time. A larger span of years after harvest, ranging from 0 to 30, is needed to establish the time in which cut blocks change from source to sink. Ideally this would be repeated at multiple sites of the same age using different independent measurement techniques (e.g. eddy covariance) to confirm the results. Second, the full range of impacts, positive or negative, from road building, harvesting, transportation and storage time of carbon in the wood products must be considered. Third, the influx of people into northern areas results in forested areas being cleared for agricultural, commercial (ie. sesmic lines) or residential uses. How the conversion of forested lands to other uses proceeds, will increasingly be of importance in northern regions. Lastly, it is necessary to understand what controls the CO_2 flux within a regenerating forest. The imminent effects of global climate change may drastically change the source/sink status of many forests. We need to understand if northern forests are going to become stronger or weaker sinks/sources if we are to attempt to control the rising levels of atmospheric CO_2.

References

Fernandez, I. J., Son, Y., Kraske, C. R., Rustad, L. E. & David, M. B. 1993: Soil carbon dioxide characteristics under different forest types and after harvest. Soil Science Society of America Journal **57**, 1115-1121.

Giradina, C. & Ryan, M. 2000: Evidence that deomposition rates of organic carbon in mineral soil do not vary with temperature. Nature **404**, 858-861.

Gower, T., Vogel, J. G., Norman, J. M., Kucharik, C. J. & Steele, S. J. 1997: Carbon distribution and above ground net primary production in aspen, jack pine, and black spruce stands in Saskatchewan and Manitoba, Canada. Journal of Geophysical Research **102**, 29,029-29,041.

Grace, J. & Rayment, M. 2000: Respiration in balance. Nature **404**, 819-820.

Kimball, J., Thornton, P., White, M. & Running, S. 1997: Simulating forest productivity and surface-atmospheric carbon exchange in the BOREAS study region. Tree Physiology **17**, 589-599.

Kucera, C. L. & Kirkham, D. R. 1971: Soil respiration studies in tallgrass prairie in Missouri. Ecology **52**, 912-915.

Kurz, W. & Apps, M. 1994: The carbon budget of Canadian forests: A sensitivity analysis of changes in disturbance regimes, growth rates, and decomposition rates. Environmental Pollution **83**, 55-61.

Lindroth, A., Grelle, A. & Morén, A.-S. 1998: Long-term measurements of Boreal forest carbon balance reveal large temperature sensitivity. Global Change Biology **4**, 443-450.

Melillio, J. M., McGuire, A. D., Kicklighter, D. W., III, B. M., Vorosmarty, C. J. & Schioss, A. L. 1993: Global climate change and terrestrial net primary production. Nature **363**, 234-240.

Norman, J. M., Kucharik, C. J., Gower, S. T., Baldocchi, D. D., Crill, P. M., Rayment, M., Savage, K. & Striegl, R. G. 1997: A comparison of six methods for measuring soil-surface carbondioxide fluxes. Journal of Geophyisical Research **102**, 28,771-28,777.

Steele, S., Gower, S., Vogel, J. & Norman, J. 1997: Root mass, net primary productiong and turnover in aspen, jack pine and black spruce forests in Saskatchewan and Manitioba, Canada. Tree Physiology **17**, 577-587.

Striegl, R. G. & Wickland, K. P. 1998: Effects of a clear-cut harvest on respiration in a jack pine-lichen woodland. Canadian Journal of Forest Research **28**, 534-539.

Valentini, R., Dore, S., Marchi, G., Mollicone, D., Panfyorov, M., Rebmann, C., Kolle, O. & Schulze, E.-D. 2000a: Carbon and water exchanges of two contrasting central Siberia landscape types: regenerating forest and bog. Functional Ecology **14**, 87-96.

Valentini, R., Matteucci, G., Dolman, A., Schulze, E.-D., Rebmann, C., Moors, E., Granier, A., Gross, P., Jensen, N., Pilegaard, K., Lindroth, A., Arelle, A., Bernhofer, C., Grünwald, T., Aubinet, M., Ceulemans, R., Kowalski, A., Vesala, T., Rannik, Ü., Berbigier, P., Loustau, D., Guõmundsson, J., Thorgeirsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrief, J., Montagnani, L. & Jarvis, P. 2000b: Respiration as the main determinant of carbon balance in European forests. Nature **404**, 861-864.

Yang, P. 1998: Carbon dioxide flux within and above a Boreal aspen forest. PhD, University of British Columbia, Vancouver.

APPENDIX I

Carbon allocation in the stems and needles of interior spruce seedlings from a 5 year-old clearcut in the Aleza Lake Research Forest, BC in 1999. The biomass was sorted according to the age of the needles.

Needle Age-class	Stems (g)	Needles (g)
1 yr-old ≥	67.3	137
1 yr-old <	135	40.2
TOTAL	202	177

APPENDIX II

21X program for the Bowen ratio system

```
Program: Bowen-ratio C02 program entered directly from the 023/C02 system
              manual.


*      1 Table 1 Programs
01:    1             Sec. Execution Interval

Make measurements.

01:    P17           Panel Temperature

01:    35:           [RefTemp C]

02:    P13           Thermocouple Temp (SE)
       01: 1         Rep
       02: 1         5 mV slow Range
       03: 8         IN Chan
       04: 2         Type E (Chromel-Constantan)
       05: 35        Ref Temp Loc
       06: 33        Loc : [:TC lower]
       07: 1         Mult
       08: 0.0000    Offset

03:   P14           Thermocouple Temp (DIFF)
       01: 1         Rep
       02: 1         5 mV slow Range
       03: 4         IN Chan
       04: 2         Type E (Chromel-Constantan)
       05: 33        Ref Temp Loc
       06: 32        Loc : [:del air TC]
       07: 1         Mult
       08: 0.0000    Offset

04:    P35           Z=X-Y
       01: 33        X Loc
       02: 32        Y Loc
       03: 34        Z Loc :

05:    P91           If Flag/Inchan
       01: 24        Flag 4 is reset
       02: 30        Then Do

06:   P2            Volt (DIFF)
       01: 2         Reps
       02: 4         500 mV slow Range
       03: 6         IN Chan
       04: 10        Loc :
       05: 1         Mult
       06: 0.0000    Offset

07:    P89           If X<=>F
```

```
      01: 10        X Loc
      02: 4         <
      03: -500      F
      04: 30        Then Do

08:   P2            Volt (DIFF)
      01: 1         Rep
      02: 5         5000 mV slow Range
      03: 6         IN Chan
      04: 10        Loc :
      05: 1         Mult
      06: 0.0000    Offset

09:   P95           End
```

Compute differential C02 and H20

```
10:   P86           Do
      01: 3         Call Subroutine 3

11:   P86           Do
      01: 27        Set low Flag 7

12:   P87           Beginning of Loop
      01: 0         Delay
      02: 2         Loop Count

13:   P36           Z=X*Y
      01: 10--      X Loc
      02: 26--      Y Loc
      03: 41--      Z Loc :

14:   P33           Z=X+Y
      01: 41--      X Loc
      02: 24--      Y Loc
      03: 41--      Z Loc :

15:   P86           Do
      01: 7         Call Subroutine 7

16:   P35           Z=X-Y
      01: 28--      X Loc
      02: 21--      Y Loc
      03 : 30--     Z Loc :

17:    P36          Z=X*Y
      01: 30--      X Loc
      02: 18--      Y Loc
      03: 30--      Z Loc :

18:   P86           Do
      01: 17        Set high Flag 7

19:   P95           End

20:   P86           Do
      01: 8         Call Subroutine 8

21:   P94           Else
```

```
22:  P86          Do
     01: 1        Call Subroutine I

23:  P95          End
```

If valves just switched or the system is in manual control (FLAG 5 high) setFLAG 9 high.

```
24:  P91          If Flag/INchan
     01: 11       Flag 1 is set
     02: 30       Then Do

25:  P86          Do
     01: 19       Set high Flag 9

26:  P94          Else

27:  P91          If Flag/INchan
     01: 13       Flag 3 is set
     02: 19       Set high Flag 9

28:  P95          End
```

Generate Output Array every 20 minutes

```
29:  P92          If time is
     01: 0        minutes into a
     02: 20       minute interval
     03: 10       Set high Flag 0 (output)

30:  P80          Set Active Storage Area
     01: 1        Final Storage Area
     02: 21       Array ID or location

31:  P77          Real Time
     01: 110      Day/Hour-Minute

32:  P78          Resolution
     01: 1        High Resolution

33:  P71          Average
     01: 5        Reps
     02: 36       Loc

34:  P70          Sample
     01: 7        Reps
     02: 21       Loc

35:  P86          Do
     01: 29       Set low Flag 9

36:  P71          Average
     01: 3        Reps
     02: 32       Loc [AVG TC upper]
```

```
37:  P71          Average
     01: 3        Reps
     02: 33       Loc [AVG TC lower]

38:  P91          If Flag/INchan
     01: 15       Flag 5 is set
     02: 30       Then Do

39:  P86          Do
     01: 2        Call Subroutine 2

40:  P94          Else

Perform an automatic scrub at the top of the hour

41:  P92          If time is
     01: 0        minutes into a
     02: 60       minute interval
     03: 14       Set high Flag 4

42:  P91          If Flag/INchan
     01: 18       Flag 8 is set
     02: 14       Set high Flag 4

43:  P18          Time
     01: 0        Tenths of seconds into minute (maximum 600)
     02: 600      Mod/by
     03: 45       Loc :

Valve switching is synchronized every 4 minutes

44:  P92          If time is
     01: 0        minutes into a
     02: 4        minute interval
     03: 30       Then Do

45:  P86          Do
     01: 21       Set low Flag 1

46:  P86          Do
     01: 42       Set high Port 2

47:  P86          Do
     01: 22       Set low Flag 2

48:  P86          Do
     01: 13       Set high Flag 3

49:  P86          Do
     01: 9        Call Subroutine 9

50:  P95          End

51:  P92          If time is
     01: 2        minutes into a
     02: 4        minute interval
     03: 30       Then Do

52:  P86          Do
     01: 41       Set high Port 1

53:  P86          Do
```

```
      01: 12        Set high Flag 2

54:   P86           Do
      01: 13        Set high Flag 3

55:   P86           Do
      01: 9         Call Subroutine 9

56:   P95           End

57:   P89           If X<=>F
      01: 45        X Loc
      02: 3         >=
      03: 400       F
      04: 23        Set low Flag 3

58:   P95           End

59:   P96           Serial Output
01:   30            SM192/SM716/CSM1

60: P               End Table I

* 2   Table 2 Programs
      01: 10        Sec. Execution Interval

01:   P30           Z=F
      01: 5000      F
      02: 44        Z Loc :

02:   P21           Analog Out
      01: 1         CAO Chan
      02 : 44       mV Loc

03:   P10           Battery Voltage
      01: 9         Loc : [BATT VOLTAGE]

04:   P11           Temp 107 Probe
      01 1          Rep
      02 1          IN Chan
      03 1          Excite all reps w/EXchan 1
      04 1          Loc : [SE T amb C]
      05 1          Mult
      06 0.0000     Offset

05:   P4            Excite/Delay/Volt(SE)
      01 1          Rep
      02 5          5000 mV slow Range
      03 2          IN Chan
      04 3          Excite all reps w/EXchan 3
      05 15         Delay (units .01sec)
      06 5000       mV Excitation
      07 8          Loc : [RH fraction]
      08 .001       Mult
      09 0.0000     Offset

06:   P56           Saturation Vapor Pressure
      01: 1         Temperature Loc
      02: 2         Loc : [SVP kPa]

07:   P36           Z=X*Y
      01: 8         X Loc
      02: 2         Y Loc
```

```
      03:2          Z Loc : [e amb kPa]

08:   P38           Z=X/Y
      01: 2         X Loc
      02: 23        Y Loc
      03: 3         Z Loc : [:H20 mM/M]

09:   P37           Z=X*F
      01: 3         X Loc
      02: 1000      F
      03: 3         Z Loc : [:H20 mM/M]

10:   PI            Volt (SE)
      01 1          Rep
      02 4          500 mV slow Range
      03 3          IN Chan
      04 4          Loc : [:Rn ]
      05 1          Mult
      06 0.0000     Offset

11:   P89           If X<=>F
      01: 4         X Loc Rn
      02: 3         >=
      03:0          F
      04: 30        Then Do

net radiometer (positive)

12:   P37           Z=X*F
      01: 4         X Loc
      02: 8.96      F
      03: 4         Z Loc :

13: P94             Else

net radiometer (negative)

14:   P37           Z=X*F
      01: 4         X Loc
      02: 11.21     F
      03: 4         Z Loc :

15:   P95           End

16:   PI            Volt (SE)
      01 2          Reps
      02 3          50 mV slow Range
      03 9          IN Chan
      04 5          Loc :
      05 1          Mult
      06 0.0000 Offset

Soil heat flux #1
17:   P37           Z=X*F
      01: 5         X Loc
      02: 43.7      F
      03: 5         Z Loc :

Soil heat flux #2

18:   PI            Volt (SE)
      01 2          Reps
      02 3          50 mV slow Range
```

```
      03 10         IN Chan
      04 6          Loc :
      05 1          Mult
      06 0          Offset

19:   P37           Z=X*F
      01: 6         X Loc
      02: 42.6      F
      03:6          Z Loc :

measure soil temperature

20:   P14           Thermocouple Temp (DIFF)
      01 1          Rep
      02 1          5 mV slow Range
      03 3          IN Chan
      04 2          Type E (Chromel-Constantan)
      05 35         Ref Temp Loc
      06 7          Loc : [:Tsoil ]
      07 1          Mult
      08 0.0000     Offset

21:   P3            Pulse
      01 1          Rep
      02 1          Pulse Input Chan
      03 21         Low level AC; Output Hz.
      04 16         Loc : [:Wind speed ]
      05 .75        Mult
      06 .2         Offset

22:   P5            AC Half Bridge
      01 1          Rep
      02 5          5000 mV slow Range
      03 4          IN Chan
      04 2          Excite all reps w/EXchan 2
      05 5000       mV Excitation
      06 17         Loc : [:Wind dir ]
      07 355        Mult
      08 0.0000 Offset

23:   P92           If time is
      01: 0         minutes into a
      02: 20        minute interval
      03: 10        Set high Flag 0 (output)

24:   P80           Set Active Storage Area
      01: 3         Input Storage Area
      02: 13        Array ID or location

25:   P71           Average
      01: 1         Rep
      02: 7         Loc Tsoil

26:   P31           Z=X
      01: 7         X Loc
      02: 13        Z Loc :

27:   P35           Z=X-Y
      01: 13        X Loc
      02 : 12       Y Loc
      03: 14        Z Loc :

28:   P31           Z=X
```

```
      01: 13        X Loc
      02: 12        Z Loc :

29:   P80           Set Active Storage Area
      01: 1         Final Storage Area
      02: 22        Array ID or location

30:   P77           Real Time
      01: 110       Day/Hour-Minute

31:   P71           Average
      01: 6         Reps
      02: 1         Loc

32:   P70           Sample
      01: 2         Reps
      02: 13        Loc

33:   P70           Sample
      01: 2         Reps
      02: 8         Loc

34:   P69           Wind Vector
      01: 1         Rep
      02: 60        Samples per sub-interval
      03: 00        Polar Sensor/(S, D1, SD1)
      04: 16        Wind Speed/East Loc
      05: 17        Wind Direction/North Loc

35:   P             End Table 2

* 3   Table 3 Subroutines

Scrub subroutine for IRGA zero

01:   P85           Beginning of Subroutine

01:   1             Subroutine Number
      02: P91       If Flag/INchan
      01: 21        Flag 1 is reset
      02: 30        Then Do
      03: P30       Z=F
      01: 36.7      F
      02: 54        Z Loc :
      04: P30       Z=F
      01: 42        F
      02: 55        Z Loc :

05:   P30           Z=F
      01: 17835     F
      02: 56        Z Loc :

06:   P30           Z=F
      01: 14724     F
      02: 57        Z Loc :

******Enter local pressure in kPa for F below

07:   P30           Z=F
      01: 98        F
      02: 23        Z Loc :

08:   P30           Z=F
```

```
      01: .10132    F
      02 : 43       Z Loc :

09:   P38           Z=X/Y
      01: 43        X Loc
      02: 23        Y Loc
      03: 43        Z Loc :

10:   P86           Do
      01: 11        Set high Flag 1

During first pass switch upper arm into reference cell,
lower arm into sample cell, and set scrub valve on

11:   P86           Do
      01: 42        Set high Port 2

12:   P86           Do
      01: 44        Set high Port 4

13:   P86           Do
      01: 22        Set low Flag 2

14:   P86           Do
      01: 9         Call Subroutine 9

15:   P95           End

16:   P32           Z=Z+1
      01: 46        Z Loc :

17:   P2            Volt (DIFF)
      01 2          Reps
      02 5          5000 mV slow Range
      03 6          IN Chan
      04 10         Loc :
      05 1          Mult
      06 0.0000     Offset

18:   P86           Do
      01: 3         Call Subroutine 3

19:   P89           If X<=>F
      01: 46        X Loc
      02: 3         >=
      03: 50        F
      04: 10        Set high Flag 0 (output)

20:   P80           Set Active Storage Area
      01: 3         Input Storage Area
      02: 10        Array ID or location

21:   P89           If X<=>F
      01: 46        X Loc
      02: 4         <
      03: 40        F
      04: 19        Set high Flag 9

22:   P71           Average
      01: 2         Reps
      02: 10        Loc

23:   P86           Do
```

```
      01: 27        Set low Flag 7

24:   P87           Beginning of Loop
      01: 0         Delay
      02: 2         Loop Count

25:   P35           Z=X-Y
      01: 56--      X Loc
      02: 10--      Y Loc

03:   26--          Z Loc :
26:   P38           Z=X/Y
      01: 56--      X Loc
      02: 26--      Y Loc
      03: 26--      Z Loc :

27:   P36           Z=X*Y
      01: 26--      X Loc
      02: 10--      Y Loc
      03: 24--      Z Loc :

28:   P37           Z=X*F
      01: 24--      X Loc
      02: -1        P
      03 : 24--     Z Loc :

29:   P31           Z=X
      01: 24--      X Loc
      02: 41--      Z Loc :

30:   P86           Do
      01: 7         Call Subroutine 7

31:   P31           Z=X
      01: 28--      X Loc
      02: 21--      Z Loc :

32:    P86          Do
      01: 17        Set high Flag 7

33:   P95           End

34:   P91           If Flag/INchan
      01: 28        Flag 8 is reset
      02: 30        Then Do

35:   P91           If Flag/INchan
      01: 10        Flag 0 (output) is set
      02: 30        Then Do

36:   P86           Do
      01: 24        Set low Flag 4

37:   P30           Z=F
      01: 0         F
      02: 46        Z Loc :

38:   P86           Do
      01: 43        Set high Port 3

39:   P86           Do
      01: 9         Call Subroutine 9
```

```
40:   P95          End

41:   P95          End

42:   P95          End

Manual valve control

43:   P85          Beginning of Subroutine
      01: 2        Subroutine Number

44:   P86          Do
      01: 11       Set high Flag 1

45:   P91          If Flag/INchan
      01: 12       Flag 2 is set
      02: 41       Set high Port 1

46:   P91          If Flag/INchan
      01: 22       Flag 2 is reset
      02: 42       Set high Port 2

47:   P91          If Flag/INchan
      01: 16       Flag 6 is set
      02: 45       Set high Port 5

48:   P91          If Flag/INchan
      01: 26       Flag 6 is reset
      02: 46       Set high Port 6

49:   P86          Do
      01: 9        Call Subroutine 9

50:   P95          End

51:   P85          Beginning of Subroutine

01:   3 Subroutine Number

52:   P2           Volt (DIFF)
      01: 1        Rep
      02: 5        5000 mV slow Range
      03: 8        IN Chan
      04: 40       Loc :
      05:.01221 Mult
      06: 0.0000 Offset

53:   P34          Z=X+F
      01: 40       X
      02: 273.15 F
      03: 53       Z Loc :

54:   P38          Z=X/Y
      01: 53       X Loc
      02: 54       Y Loc
      03: 18       Z Loc :

55:   P38          Z=X/Y
      01: 53       X Loc
      02: 55       Y Loc
      03: 19       Z Loc :
```

```
56:   P95          End

Apply LI-COR coefficients to C02 and H20

57:   P85          Beginning of Subroutine

01: 7 Subroutine Number

58:   P36          Z=X*Y
      01: 41--     X Loc
      02: 43       Y Loc
      03: 41--     Z Loc :

59:   P91          If Flag/INchan
      01: 27       Flag 7 is reset
      02: 30       Then Do

****LI-COR C02 polynomial****

60:   P55          Polynomial
      01 1         Rep
      02 41        X Loc
      03 28        F(X) Loc :
      04 0         CO
      05 150.94    C1
      06 7.6016    C2
      07 7.7366    C3
      08 -1.0380   C4
      09 0.0669    C5

61:   P94          Else

****LI-COR H20 polynomial****

62:   P55          Polynomial
      01 1         Rep
      02 42        X Loc
      03 29        F(X) Loc :
      04 0         CO
      05 6.275     C1
      06 3.0456    C2
      07 -0.0038   C3
      08 0.0000    C4
      09 0.0000    C5

63:   P95          End

64:   P95          End

65:   P85          Beginning of Subroutine

01: 8 Subroutine Number

66:   P31          Z=X
      01: 30       X Loc
      02: 38       Z Loc :

67:   P31          Z=X
      01: 31       X Loc
      02: 39       Z Loc :

68:   P31          Z=X
      01: 10       X Loc
```

```
      02: 36       Z Loc :

69:   P31          Z=X
      01: 11       X Loc
      02: 37       Z Loc :

70:   P91          If Flag/INchan
      01: 12       Flag 2 is set
      02: 30       Then Do

71:   P87          Beginning of Loop
      01: 0        Delay
      02: 4        Loop Count

72:   P37          Z=X*F
      01: 36--     X Loc
      02: -1       F
      03 : 36--    Z Loc :

73:   P95          End

74:   P94          Else

75:   P95          End

76:   P95          End

77:   P85          Beginning of Subroutine

01: 9 Subroutine Number

78:   P22          Excitation with Delay
      01: 3        EX Chan
      02: 0        Delay w/EX (units=.Olsec)
      03: 2        Delay after EX (units=.Olsec;
      04:0         mV Excitation

79:   P86          Do
      01: 51       Set low Port 1

80:   P86          Do
      01: 52       Set low Port 2

81:   P86          Do
      01: 53       Set low Port 3

82:   P86          Do

Set low Port 4

83:   P86          Do 0155 Set low Port 5

84:   P86          Do
      01: 56      Set low Port 6

85:   P95          End

86:   P            End Table 3

*     4
Mode 4 Output Options
01:   00           Tape/Printer Option
02:   00           Printer Baud Option
```

```
A Mode 10 Memory Allocation

01:   69           Input Locations

02:   75           Intermediate Locations

Mode 12 Security  (OSX-0)
01:   00           Security Option
02:   0000         Security Code

Input Location Assignments (with comments)
Key:
T=Table    Number    E=Entry
Number L=Location Number
      E    L
      4    1      Loc : [SE T amb C]
      6    2      Loc : [SVP kPa]
      7    2      Z Loc [e amb kPa]
      8    3      Z Loc [:H20 mM/M]
      9    3      Z Loc [:H20 mM/M]
      10   4      Loc : [:Rn ]
      12   4      Z Loc
      14   4      Z Loc
      16   5      Loc
      17   5      Z Loc
      18   6      Loc
      19   6      Z Loc
      20   7      Loc [:Tsoil ]
      5    8      Loc [RH fraction]
      3    9      Loc [BATT VOLTAGE]
      6    10     Loc
      8    10     Loc
      17   10     Loc
      28   12     Z Loc :
      26   13     Z Loc :
      27   14     Z Loc :
      21   16     Loc : [:Wind speed ]
      22   17     Loc : [:Wind dir ]
      54   18     Z Loc
      55   19     Z Loc
      31   21     Z Loc
      7    23     Z Loc
      9    23     Z Loc
      27   24     Z Loc
      28   24     Z Loc
      25   26     Z Loc
      26   26     Z Loc
      60   28     F(X) Loc :
      3    32 ' Loc : [:del air TC]
```