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Below ground CO_2 efflux from cut blocks of varying ages in sub-boreal British Columbia

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Abstract

Instantaneous measures of below ground CO_2 fluxes were made in a mature stand and seven vegetated cut blocks 0, 2, 3, 5, 6, 9 and 10 years after harvest in sub-boreal forests of Central British Columbia, Canada from May to October, 2000. All cut blocks were replanted to hybrid spruce (*Picea glauca* × *engelmannii*) within 2 years of harvest and the natural vegetation on site was unmanaged. Instantaneous measures of soil temperature and moisture (each cut block) and continuous measures of soil temperature (one cut block) were made and later used in regression equations to predict below ground CO_2 fluxes from 24 May to 20 September 2000. Instantaneous below ground CO_2 fluxes ranged from between 2 μmol C m^{-2} s^{-1} in the Spring and highs of 10 μmol C m^{-2} s^{-1} during mid-Summer. Cumulative seasonal below ground CO_2 flux totals ranged between 695 and 785 g C m^{-2} for the cut blocks aged 3 years or older, while the 0- and 2-year-old and cut blocks produced the low (560 g C m^{-2}) and high (861 g C m^{-2}) CO_2 flux totals, respectively. Below ground CO_2 fluxes in all cut blocks were 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 instantaneous below ground CO_2 fluxes. Conversely, a positive correlation was not found between mean soil temperature and cumulative below ground CO_2 flux at all sites. The lack of correlation may indicate that soil temperature is not the main factor controlling below ground CO_2 flux as cut blocks age.

Keywords: Soil respiration; Carbon dioxide; Sub-boreal forest; Managed stand

1. Introduction

Since the 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 1980s (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 forested land to pasture (Tans et al., 1990). Boreal/sub-boreal regions in Canada are estimated to hold 65–104 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 future of atmospheric CO_2 levels. Individual studies comparing a cut block against a mature forest's below ground CO_2 flux have

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found conflicting results: some studies indicate a decrease in CO_2 fluxes (Edwards and Ross-Todd, 1983; Weber, 1990; Chang and Trofymow, 1996; Striegl and Wickland, 1998), others demonstrate an increase (Ewel et al., 1987a; Gordon et al., 1987; Lytle and Cronan, 1998) and still others show no change in below ground CO_2 fluxes (Fernandez et al., 1993; Toland and 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- 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 and Apps, 1994).

Below ground CO_2 flux has widely been found to correlate with soil temperature and soil moisture (Kucera and Kirkham, 1971; Fernandez et al., 1993; Striegl and 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 in soil moisture (McCaughey, 1989; Londo et al., 1999). The soil moisture in a clearcut 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 depend on the relative reduction in transpiration to increases in evaporation.

Below ground CO_2 fluxes result from two main sources: root respiration and the decomposition of organic matter and associated respiration of soil fauna. Harvesting the forest 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). Thus, removal of the trees will result in at least a temporary decrease in root respiration and decreased fine root turnover. However, this could be offset by a 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 and Hu, 1997). Burning slash may remove much of the soil organic layer, and if severe enough, kill the soil microorganisms (Pietikainen and Fritze, 1993; Chang and Trofymow, 1996). Other impacts of timber harvesting, such as soil compaction due to machinery, may result in reduced soil microbial activity and/or root growth and respiration (Chang et al., 1995).

Most studies investigating 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 and Ross-Todd, 1983; Gordon et al., 1987; Toland and Zak, 1994; Mallik and Hu, 1997; Striegl and 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. Furthermore, increasing harvesting pressures on northern forests and the large below ground carbon stores associated with boreal and sub-boreal forests, demonstrates the need to understand the source/sink relationships for CO_2 in cut blocks following forest removal. Thus, it is the intent of this paper to demonstrate the changes in below ground CO_2 flux and biomass accumulation in the 10-year period following forest harvesting and reestablishment of sites in sub-boreal British Columbia.

2. Material and methods

2.1. 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 different ages and one mature stand in sub-boreal British Columbia. The cut blocks and mature stand were all located within a 10 km radius of each other in, or immediately adjacent to, the University of Northern British Columbia/University British Columbia Aleza Lake Research Forest (54°01′N, 122°07′W). All cut blocks were located within the wk1 variant of the sub-boreal spruce (SBS) biogeoclimatic zone as described by the Ecosystem Classification System of British Columbia (Meidinger and Pojar, 1991). The wk1 variant is cool; mean air temperature = 1.7–5 °C, and wet; snowfall relatively high compared to other regions within the central plateau of sub-boreal British

Columbia. Snowfall in this region typically accumulates by November and has melted 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. Cut blocks were selected for uniformity in soils; all were clay rich and classified as Ortho Luvic Gleysols (Arocena and Sanborn, 1999). Prior to harvest, forests within the cut blocks were dominated by hybrid spruce (*Picea glauca* × *engelmannii*), paper birch (*Betula papyrifera*), and sub-alpine fir (*Abies lasiocarpa*).

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 as it was most representative of mature SBS wk1 forests from within the research forest. Each cut block was planted with hybrid white spruce (*P. glauca* × *engelmannii*), but there was some variation in the planting densities: cut blocks aged 3- and 9 years were planted at 1600 stems ha^{-1}, 5- and 10-year-old cut blocks were planted at 1400 stems ha^{-1}, and 2- and 6-year-old cut blocks were planted at 1200 stems ha^{-1}. The cut blocks were classified as sub-hygric (high water tables) and high in nutrients (SBS wk1 07-08) (Meidinger and Pojar, 1991). The 0- and 9-year-old cut blocks were classified as drier and of a lower nutrient status (SBS wk1-01). However, both 0- and 9-year-old cut blocks were quite moist in the Summer of 2000. The cut blocks had only one notable difference with respect to post-harvest treatment. Slash was piled but not burned at the newest cut block (harvested February, 2000), piled and burned at the 2-year-old cut block, and broadcast burned in all other cut blocks. Locations within the cut blocks with concentrated ash, particularly in the 2-year-old cut block were avoided.

2.2. 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 m east–west transect at 10 m intervals. In the 6-year-old cut block, collars were randomly placed throughout a 1 ha measurement area. All collars located within cut blocks were a minimum of 20 m away from wildlife trees or tree patches and all collars were a minimum of 30 m away from the edge of the cut block or forested stand. Below ground CO_2 flux measurements were made between 800 and 1800 h using a portable infrared gas exchange system (LI-6200, LI-Cor Inc., Lincoln, NE, USA) with soil chamber attachment (6000-09, LI-Cor Inc.) as in Norman et al. (1992). Soil temperature (6000-09TC, LI-Cor Inc.) 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.

2.3. Biomass sampling

On 5–10 May and 6–14 August 2000, a total of 40 randomly placed 0.5 m^2 quadrats in each 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 ±1 S.D. of the mean seedling height at each cut block. All biomass samples were dried for 72 h at 65 °C and weighed to obtain oven-dry weights.

2.4. Soil temperature measurement instrumentation

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

2.5. Cumulative seasonal below ground CO_2 efflux

Seasonal below ground CO_2 fluxes for each cut block were estimated for a period extending from 24 May to 20 September 2000. Multiple linear regression equations were established relating instantaneous estimates of soil temperature and soil moisture to below ground CO_2 flux. For the purpose of interpolating CO_2 fluxes to all dates, a second set of regressions were established between continuous soil temperature measurements at the 6-year-old cut block with the instantaneous soil temperature measurements at each cut block to provide a continuous estimate of soil temperatures for each cut block. Finally, cumulative seasonal below ground CO_2 fluxes were estimated based on regression equations using the continuous soil temperatures at each cut block and instantaneous soil moisture measurements taken approximately every 2 weeks. The variables used for each cut block were selected using the best subset method and the R^2 difference test ($P = 0.05$). Following ecosystem CO_2 flux convention, a positive value was used to indicate CO_2 gain by the atmosphere, while a negative value was used to indicate CO_2 removal from the atmosphere.

2.6. Error analysis

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

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

where x is the total S.E. for each biweekly period.

3. Results

3.1. 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 measured instantaneous CO_2 fluxes ranged from approximately 2 μmol C m^{-2} s^{-1} in October to highs of between 7 and 10 μmol C m^{-2} s^{-1} in July for cut blocks aged 2–10 years and the mature forest (Fig. 1a–h). The newest cut block was the only exception with maximum measured instantaneous below ground CO_2 fluxes that did not exceed 6 μmol C m^{-2} s^{-1} in July (Fig. 1a).

3.2. Soil temperature

Cut blocks had similar seasonal soil temperature trends, with soil temperature maxima approaching or exceeding 15 °C in July (Fig. 2a–g). Soil temperatures in the mature stand (Fig. 2h) were uniformly cooler than the cut blocks, with the exception of the 0-year-old cut block. 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-year-old cut block to 13.2 °C in the newest cut block. The slightly lower soil temperatures found in the 0-year-old cut block may have resulted from a thick layer of slash on the soil surface that insulated the ground from the sun.

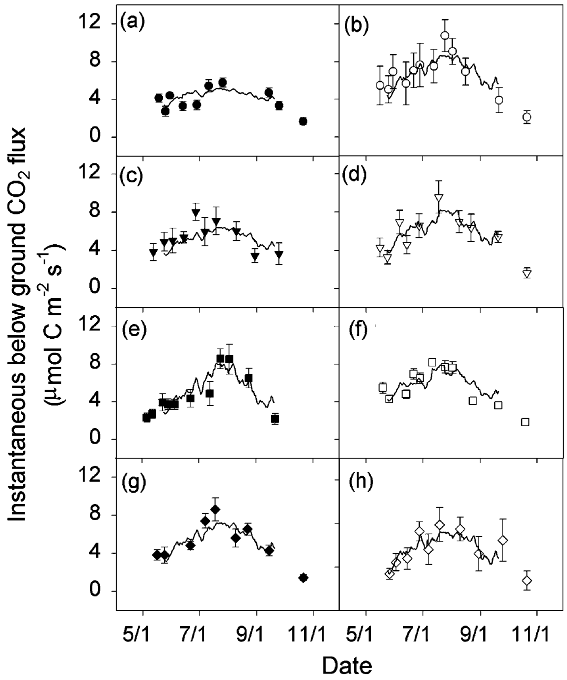

Fig. 1. The instantaneous below ground CO_2 flux for a mature stand and seven cut blocks aged (a) 0 year, (b) 2 years, (c) 3 years, (d) 5 years, (e) 6 years, (f) 9 years and (g) 10 years since harvest and a mature stand (h) from May until the end of October 2000 in the Aleza Lake Research Forest, British Columbia. The symbols and lines represent the measured instantaneous and modelled below ground CO_2 fluxes, respectively. The error lines on the symbols represent the 95% confidence interval (CI).

3.3. Below ground CO_2 flux and soil temperature

Below ground CO_2 efflux at each cut block correlated well with soil temperature at 10 cm depth (Fig. 3a–h). Linear regressions were marginally but significantly ($P = 0.05$) improved for some cut blocks by introducing soil moisture (Table 1). With the exception of the newest cut block ($R^2 = 0.24$), regression equations explained from 40 to 67% of the

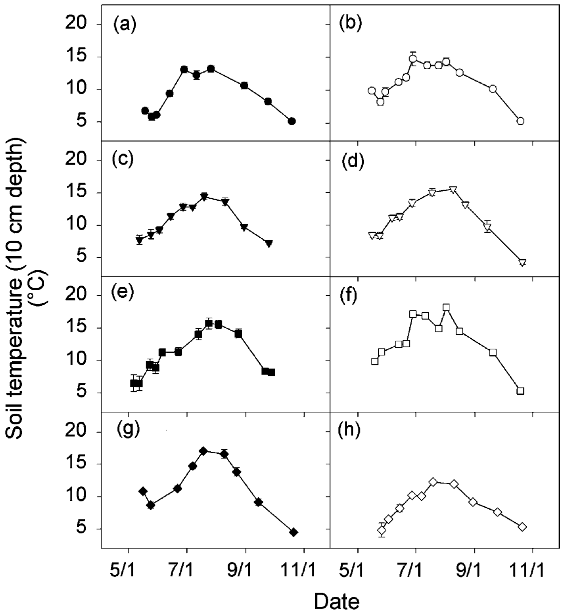

Fig. 2. In situ soil temperature (10 cm depth) for seven cut blocks aged (a) 0 year, (b) 2 years, (c) 3 years, (d) 5 years, (e) 6 years, (f) 9 years and (g) 10 years since harvest and a mature stand (h) from May until the end of October in the Aleza Lake Research Forest, British Columbia. The error bars represent the 95% CI.

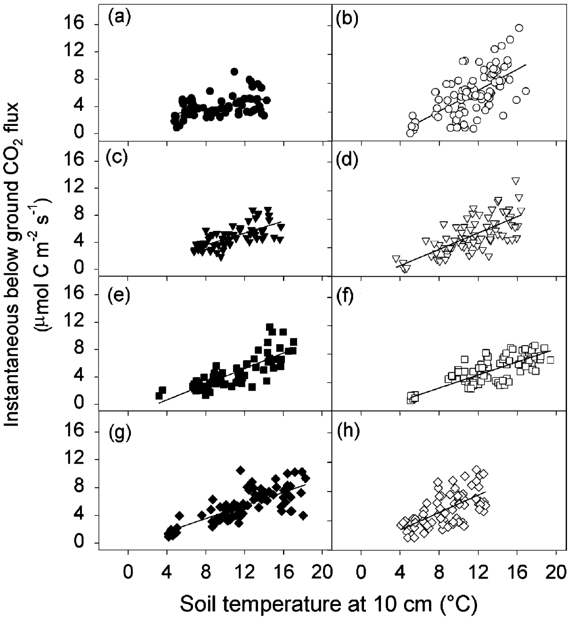

Fig. 3. Relationship between in situ soil temperature (10 cm depth) and below ground CO_2 flux for seven cut blocks aged (a) 0 year, (b) 2 years, (c) 3 years, (d) 5 years, (e) 6 years, (f) 9 years and (g) 10 years and a mature stand (h) since harvest in the Aleza Lake Research Forest from May until October, 2000. The solid line represents the linear regression line relating soil temperature (10 cm depth) to below ground CO_2 flux.

variation in below ground CO_2 flux for cut blocks and mature forest.

3.4. Soil water content

The cut blocks and the mature stand had gravimetric soil moisture (kg H_2O/kg dry soil) values ranging from between 98% in the 3-year-old cut block to 41% in the newest cut block (Fig. 4a–h). Soil moisture was reasonably 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

Table 1
Multiple and single linear 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-year-old and one mature stand[a]

Site age (years)	Measurement dates	n	Regression	R^2	Regression	R^2
0	18 May–19 October	72	$1.84 + 0.235T$	0.19	$0.443 + 0.216T + 0.0293M$	0.24
2	16 May–19 October	87	$-1.66 + 0.727T$	0.40	$-1.66 + 0.727T$	0.40
3	12 May–25 September	60	$0.091 + 0.441T$	0.46	$0.091 + 0.441T$	0.46
5	16 May–21 October	77	$-0.719 + 0.573T$	0.50	$-4.67 + 0.592T + 0.0583M$	0.54
6	6 May–28 September	69	$-1.631 + 0.571T$	0.67	$-1.631 + 0.571T$	0.67
9	19 May–19 October	95	$-0.308 + 0.469T$	0.54	$-2.67 + 0.459T + 0.0447M$	0.59
10	16 May–21 October	78	$-0.229 + 0.473T$	0.58	$-0.233 + 0.474T$	0.58
Mature	26 May–21 October	75	$0.402 + 0.545T$	0.41	$2.05 + 0.653T - 0.0397M$	0.43

[a] All measurements for the regressions were made in the Aleza Lake Research Forest, May–October, 2000. T: soil temperature (°C); M: gravimetric soil moisture (%).

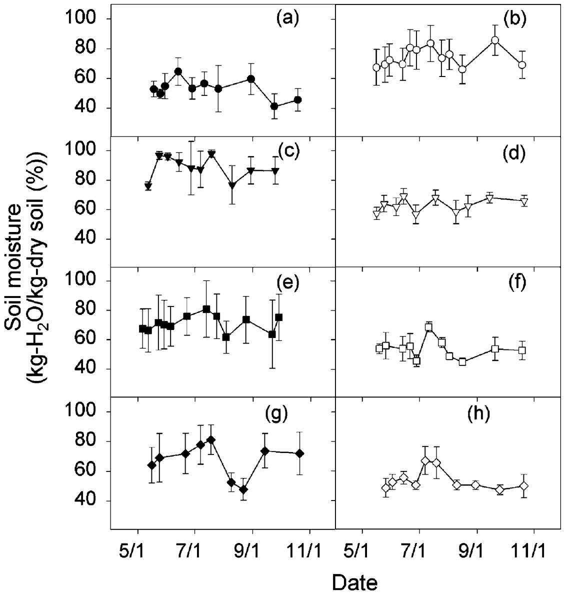

Fig. 4. In situ soil moisture for seven cut blocks aged (a) 0 year, (b) 2 years, (c) 3 years, (d) 5 years, (e) 6 years, (f) 9 years and (g) 10 years since harvest and a mature stand (h) from May until the end of October in the Aleza Lake Research Forest. The error bars represent the 95% CI.

moisture. However, lower relative soil moisture in the 0- and 9-year-old cut blocks was consistent with their drier biogeoclimatic classification.

3.5. 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 woody shrub and herbaceous species while the older cut blocks (9- and 10-year-old), not surprisingly, had a greater proportion of their biomass in conifer seedling. The newest cut block had very little biomass present on site as it was logged in the previous Winter. The total biomass in 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 blocks had significantly different biomass, lesser and greater, respectively, than that of other cut blocks ($P = 0.05$).

Increases in above ground biomass between May and mid-August ranged from 28 g biomass per square

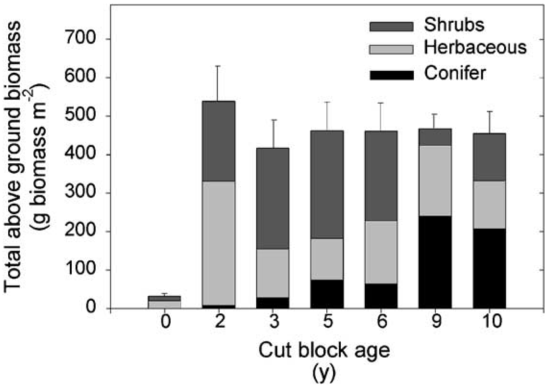

Fig. 5. The total above ground biomass partitioned into conifer, herbaceous plant, and shrub in each of the cut blocks measured within the Aleza Lake Research Forest. The error bars represent the 95% CI.

Table 2
Above ground conifer, herbaceous plants, woody shrub and total biomass in Spring (5–10 May) and late Summer (6–14 August), and the change in biomass from Spring to Summer for seven cut blocks in the Aleza Lake Research Forest

Cut block age (years)	Spring biomass (g m^{-2})				Late Summer biomass (g m^{-2})				Biomass change (g m^{-2})
	Conifer	Herbaceous[a]	Woody shrub	Total biomass	Conifer	Herbaceous	Woody shrub	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

[a] No herbaceous plants were 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 (years)	Correlation to tower measurement		
	R^2	Slope	y-Intercept
0	0.93	1.16	−3.09
2	0.83	0.944	0.837
3	0.77	1.00	−0.262
5	0.88	1.07	−1.26
6	0.89	1.22	−2.22
9	0.77	1.06	1.51
10	0.87	1.31	−2.68
Mature	0.94	1.01	−2.70

metre in the newest cut block to a high of 442 g biomass per square metre 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 of over 164 g per square metre across the season. The lower conifer biomass in the 10-year-old cut block, relative to the 9-year-old cut block, likely resulted from heavy leader weevil attack (*Pissodes strobi* (*Peck*)) on seedlings in the oldest cut block.

3.6. Cumulative seasonal below ground CO_2 flux

Instantaneous soil temperatures for each site were well correlated with continuous soil temperature measurement at the 6-year-old cut block (Table 3). Estimates of cumulative seasonal below ground CO_2 fluxes for all cut blocks, using regression equations, ranged from 560 g C m^{-2} at the newest cut block to 861 g C m^{-2} at the 2-year-old cut block (from 24 May to 20 September 2000) (Fig. 6). While these represent the extremes, cumulative below ground CO_2 flux estimates for the 3–10-year-old cut blocks were surprisingly consistent, with a mean of 726 g C m^{-2}. There was a good correlation between total above ground biomass on each cut block and the cumulative seasonal below ground CO_2 flux estimates (Fig. 7a). As the biomass increased, there was an increase in the cumulative seasonal below ground CO_2 flux ($R^2 = 0.87$). Interestingly, the cumulative below ground CO_2 flux (from 24 May to 20 September 2000) for all the cut blocks exhibited a weak negative

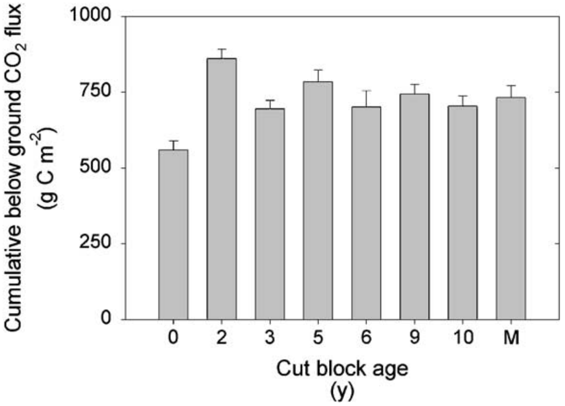

Fig. 6. The estimated cumulative below ground CO_2 efflux from a mature stand (M) and seven cut blocks aged 0, 2, 3, 5, 6, 9 and 10 years since harvest from 24 May to 20 September 2000 in the Aleza Lake Research Forest. The error bars represent the 95% CI.

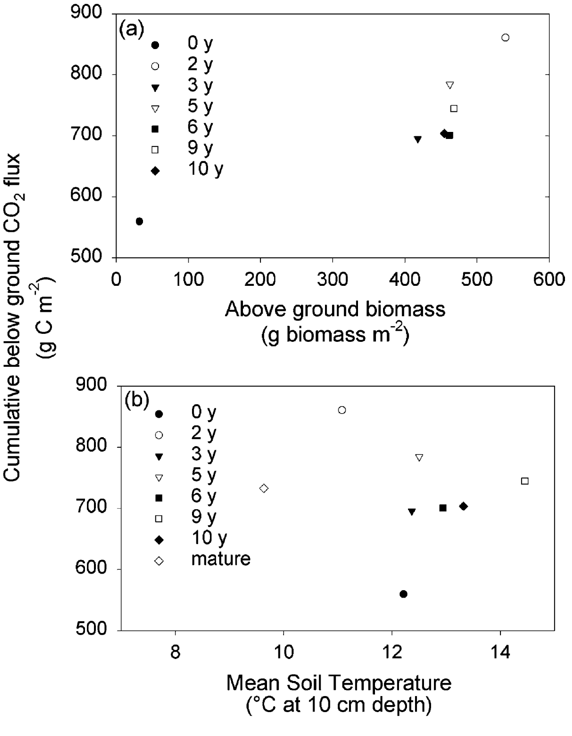

Fig. 7. The relationship of (a) the net above ground biomass and (b) the mean soil temperature at each cut block with the cumulative seasonal below ground CO_2 flux (from 24 May to 20 September 2000) in seven cut blocks aged 0, 2, 3, 5, 6, 9, and 10 years since harvest and a mature stand (b only) in the Aleza Lake Research Forest.

relationship to mean soil temperature at 10 cm depth ($R^2 = 0.18$) (Fig. 7b).

4. Discussion

4.1. Effect of soil temperature and moisture on below ground respiration

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

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 and Kirkham, 1971; de Jong 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 not significant statistically or weakly linear. The range of soil moisture values was low for all cut blocks and never approached 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 variance of soil moisture contents observed and/or the relatively high soil moisture observed for most cut blocks.

4.2. Effect of cut block age, site preparation, root respiration and mean soil temperature on below ground CO_2 fluxes

Apart from the newest cut block, all cut blocks had fairly similar cumulative below ground CO_2 fluxes for the season (Fig. 6). 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-year-old in Florida where below ground CO_2 fluxes were higher in the older plantation. However, the cut blocks in our study were much slower growing and younger than the plantations in Ewel et al. (1987a). They suggest that the increase in below ground CO_2 flux in the older plantation in their study was due to greater root activity. Although root activity was not directly assessed in our study, we did observe that as biomass increased in our cut blocks, so did cumulative seasonal below ground CO_2 flux (Fig. 7a). 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, soil temperatures in the mature stand rose more slowly in the Spring, and with the possible exception of the newest cut block, were consistently lower than those in all cut blocks. Had the soil temperatures risen sooner and to the same extent as in the cut blocks, the mature forest's below ground CO_2 efflux may have been greater. 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 and 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.

The respectively lower and greater below ground CO_2 fluxes observed for the 0- and 2-year-old cut blocks, relative to the other cut blocks (Figs. 3 and 6), could be due in part to their different cut block treatments. The 0-year cut block was recently harvested (2 months prior to the commencement of field measurements) and presumably tree roots from the felled trees died throughout the Summer. It is possible, however, that roots in the Spring buoyed the earlier below ground CO_2 fluxes, but became less important later in the Summer. Thus, the invariable below ground CO_2 from the 0-year cut block may be the result of decreasing CO_2 fluxes from dying tree roots combined with increasing soil temperatures as the Summer progressed. Unlike the other cut blocks, the 0- and 2-year-old cut blocks were not broadcast burned. Presumably, this allowed some of the existing shrubs and herbaceous plants to remain after harvest. Therefore, it is likely that the higher below ground CO_2 fluxes at the 2-year site may be due, at least in part, to the greater initial biomass present after harvest.

While soil temperature was a good predictor of seasonal CO_2 fluxes from one site, mean soil temperature (10 cm depth) for each cut block did not correlate well with the cumulative below ground CO_2 flux from each cut block (Fig. 7b). The lack of a correlation between mean soil temperature and cumulative below ground CO_2 flux was not expected because the cut blocks were of a similar soil type. Results of others have demonstrated a positive relationship between decomposition of organic carbon contained within the mineral soil of 82 forested sites and soil temperature (Giardina and Ryan, 2000). However, the authors further demonstrated that while soil temperature is well correlated with the below ground CO_2 flux on a short-term basis, the inter-annual variation in the below ground CO_2 flux was not dependent solely upon the mean soil temperature. In this, our work concurs and supports the notion that soil temperature alone may not be useful for predicting below ground CO_2 fluxes in cut blocks of different ages.

4.3. Cumulative seasonal below ground respiration

Cumulative seasonal below ground CO_2 flux, from 25 May to 20 September 2000, totalled between 560 g C m^{-2} in the youngest cut block and 853 g C m^{-2} in the 2-year-old cut block (Fig. 7a), with daily CO_2 fluxes ranging from 2.78 to 8.97 g C m^{-2} per day. These values are consistent with below ground CO_2 fluxes reported for boreal forest (Russell and Voroney, 1998), a Florida slash pine plantation (Ewel et al., 1987a) and an 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 and Cronan, 1998) and a jack-pine lichen woodland (Striegl and Wickland, 1998) have measured CO_2 fluxes that were lower than those found in this study. The greater below ground CO_2 fluxes observed in this study may have been due to the nutrient rich, moist soils found in the research forest. Valentini et al. (2000), 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 higher latitude even though the northern forests typically had lower soil temperatures. It is postulated that the greater below ground respiration rates may be the result of higher soil moisture levels with increasing latitude (Grace and Rayment, 2000).

5. Conclusions

Seasonal trends in below ground CO_2 efflux from harvested sub-boreal cut blocks in this study appeared to correlate most strongly with soil temperature as opposed to soil moisture, which was relatively invariant within cut blocks. The biomass present at each cut block was correlated positively with the below ground CO_2 efflux. However, when the mean soil temperatures and cumulative below ground CO_2 effluxes are compared between cut blocks, higher mean soil temperatures did not result in greater losses of CO_2 from below ground. In these cut blocks, soil temperature may be a good predictor over the short-term, but it may not be the main controlling factor of the below ground CO_2 efflux over the long-term. Therefore, it appears that up to 10 years after harvest, plant biomass, rather than cut block age, soil temperature or soil moisture, has the greatest influence on the relative magnitude of below ground CO_2 efflux from cut blocks in sub-boreal British Columbia.

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