Carbon dioxide in soil profiles: Production and temperature dependence

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[1] The temperature dependance of soil respiration has most commonly been addressed using surface flux data, despite the fact that surface flux measurements implicate CO_2 transport and storage effects that may preclude robust assessments of the temperature dependence of soil respiration. Here we examine whether soil respiration might be assessed using soil profile CO_2 production inferred from soil CO_2 concentration profiles. Over the 9-month study period, we observed marked similarities in the temperature response of CO_2 production across four study sites of contrasting vegetation cover and land use. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions

1. Introduction

[2] Soil CO_2 emissions comprise an important component of the global carbon cycle, and represent the largest terrestrial source of CO_2 to the atmosphere. Globally, soils emit ~75 Pg C y^{-1} *Schlesinger and Andrews* [2000] as a result of root and microbial respiration throughout, and often deep in the soil profile *Goulden et al.* [1998].

[3] Temperature is a primary control on CO_2 production in most soils *Rustad and Fernandez* [1998]; *Peterjohn et al.* [1994]; *Kirschbaum* [2000]; *Lloyd and Taylor* [1994]; *Raich and Schlesinger* [1992], but not all studies concur [*Giardina and Ryan*, 2000]. As global temperatures rise, any changes in soil CO_2 emissions will in part be determined by the temperature dependence of soil CO_2 production.

[4] Because root and microbial sources of CO_2 show increased activity as a function of temperature *Boone et al.* [1998] and since new studies suggest that global temperature increases are amplified in the ground *Huang et al.* [2000]; *Beltrami et al.* [2000], it is critical that the temperature dependence of soil CO_2 production be examined.

[5] The temperature dependance of soil respiration has generally been addressed using surface flux data (e.g., *Raich et al.*, 1990), which measures the diffusion of gas in response to a concentration gradient according to Fick's Law. In an ideal situation, surface flux should reflect CO_2 production, as only production should cause subsurface CO_2 concentrations to vary. In most soils, however, CO_2 storage is significant due to the limited diffusivity of the soil matrix, which varies mostly as a function of water filled pore space *Millington* [1959]; *McCarty et al.* [1999]. Other factors such as mass movement related to wind and atmospheric pressure changes *Renault et al.* [1998]; *Massman et al.* [1997], tradeoffs between the gas and water-filled pore volume *Hillel* [1998], or simultaneous vertical transport of heat and water *Fang and Moncrieff* [1999], along with chemical equilibrium exchanges with soil water and groundwater *Andrews and Schlesinger* [2001] can play an additional role in controlling soil profile CO_2 distribution. As a result, subsurface concentrations, and surface fluxes of CO_2 are a function of root and microbial production as well as a suite of other processes.

[6] These factors suggest that it is important to consider whether temperature controls on CO_2 releases from soils can be assessed by examining the relationships between soil profile temperature and soil profile CO_2 production. Subsurface CO_2 production can be estimated from soil CO_2 concentration profiles using Fick's Laws to calculate flux gradients between sampling intervals *DeJong and Schappert* [1972]; *Davidson and Trumbore* [1995]. The primary advantage of using this method is that CO_2 production calculations are insensitive to the quantity of CO_2 stored in the soil profile. To date however, no published studies have attempted to couple measurements of subsurface CO_2 production with detailed soil profile temperature data.

[7] Here we report the results of an investigation into the CO_2 production at four air-ground climate observatories in Eastern Canada. The objective of this study is to examine the temperature dependence of soil CO_2 production through depth across several land use types. We find that the temperature dependence of CO_2 production is strong and remarkably consistent across study sites.

2. Methods

[8] The study was conducted over a 9-month period at four sites in eastern Nova Scotia, Canada. These sites were chosen to represent a range of different land use characteristics and thermal budgets. They include a mixed hardwood stand (CCW) and adjacent field (CCF) and a spruce wood (PW) and adjacent field (PF). All soils are shallow till-derived clay loams.

[9] Each site is equipped with a meteorological station monitoring standard aboveground parameters in addition to detailed subsurface thermal and moisture budgets. Subsurface temperature probes are installed at depths of 0, 5, 10, 20, 50 and 100 cm, along with moisture probes at 5 and 35 cm (Figure 1). The stations sample all variables at 30 s intervals and store 5 minute averages. Details of the functioning of these stations are described elsewhere *Beltrami* [2001].

[10] Carbon dioxide is sampled approximately weekly, and to date, over 6000 samples have been analyzed as part of this project. Vented surface flux chambers *Hutchinson and Mosier* [1981] are used in combination with multiport gas wells *Burton and Beauchamp* [1994] for collection of CO_2 samples. Three wells are installed at each site with sampling ports at 1 (surface), 5, 10, 20, 50 and 100 cm (Figure 1). Samples were collected in 4 ml evacuated tubes and CO_2 concentrations were determined using gas chromatography. Each mean surface flux value is calculated from three chamber measurements, while at each depth, mean concentrations are calculated from the three gas wells.

[11] Variability between adjacent wells was typically on the order of 10%. Bleeding between well ports was addressed by

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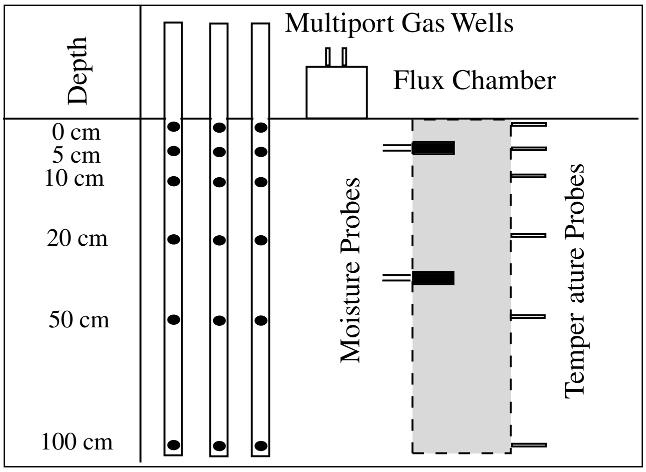

Figure 1. Site setup: Subsurface instrumentation and CO_2 sampling. Wells are located 1 m apart.

discarding post installation data, by drawing small sample volumes, and by allowing sufficient time intervals between sampling for equilibration.

3. CO_2 Production

[12] Since CO_2 production generally increases near the surface where labile carbon is readily available, production at each depth is calculated from the difference between the flux across soil layers *Davidson and Trumbore* [1995]. In other words, the outward output from layer i minus input from layer i-1 below, from the surface to maximum sampling depth,

$$p_{CO_2} = F_i - F_{i-1}, \tag{1}$$

where p_{CO_2} and F are CO_2 production and flux density ($gm^{-2}s^{-1}$) respectively, and i represents a soil layer at depth z.

[13] Interlayer flux (F) is determined from Fick's Law in one dimension,

$$F = -D\frac{\partial C}{\partial z}, \tag{2}$$

where D is the diffusivity (m^2s^{-1}), C is the CO_2 concentration (gm^{-3}) and z is depth (m).

[14] Combination of (1) and (2) *Davidson and Trumbore* [1995] yields

$$p_{CO_{2i}} = \left[D_{e_i}\left(\frac{C_i - C_{i-1}}{z}\right)\right] - \left[D_{e_{i+1}}\left(\frac{C_{i+1} - C_i}{z}\right)\right], \tag{3}$$

where D_{e_i} is effective diffusivity for layer i.

[15] Because we are using very fine sampling intervals where production is rapid and soil constituents are unevenly distributed, the soil CO_2 gradient to the surface is not always smooth. To avoid the negative production values *DeJong and Schappert* [1972] all productions in a profile were offset by the most negative value so that the lowest CO_2 production value is then zero. The magnitude of negative production values is always very small and this change has no discernable impact on production values in areas of the profile where production is rapid. Production in surface layers was calculated using atmospheric concentrations across a distance of 1 cm.

[16] Effective diffusivity is calculated using a modified Millington relationship *McCarthy and Johnson* [1995] that includes an expression for aqueous diffusion,

$$D_e = \frac{\frac{\theta_w^{\frac{10}{3}} D_{fw}}{H} + D_{fg}\,\theta_g^{\frac{10}{3}}}{\theta_T^2} \tag{4}$$

where D_{fg} is the diffusion coefficient in free air, D_{fw} is the diffusion coefficient in free water, θ_T, θ_w, and θ_g are the total, water-filled, and gas-filled volumetric soil porosity, respectively and H is the dimensionless form of Henry's solubility constant for CO_2 in water *Hillel* [1998].

4. Results and Discussion

[17] Surface CO_2 flux showed strong seasonal variation, with values falling between 0.01 to 10 g CO_2-C $m^{-2}d^{-1}$. We observed clear differences among land use types; CO_2 flux was consistently highest in the deciduous (CCW) and field sites (CCF and PF), followed by the coniferous woodland (PW), corresponding to the typical annual soil respiration for each land use type *Raich and Schlesinger* [1992].

[18] Subsurface CO_2 concentrations varied between 800 and 4000 ppm over the sampling period, and were consistent with other published results for similar land use types *Sotomayor and Rice* [1999]; *Burton and Beauchamp* [1994]. Especially during late summer, high concentrations were observed at the soil-atmosphere interface, when the concentrations measured at the surface ports were typically 5–8 times that of the atmosphere.

[19] Carbon dioxide production derived from the subsurface concentration profiles showed stronger seasonal variations than surface flux, ranging from 0.001 g CO_2-C $m^{-2}d^{-1}$ to almost 30 g CO_2-C $m^{-2}d^{-1}$. Approximately 95% of the CO_2 production at each site occurred in the very shallow subsurface (0–2.5 cm). Over winter, deeper layers became proportionately more important, but shallow CO_2 production dominates in these soils.

[20] Although cumulative totals for calculated profile CO_2 production and surface flux track one another well, weekly surface flux measurements were not a good indicator of production, as shown in Figure 2. Surface flux more closely followed changes in the shallowest subsurface concentrations (see Figure 3), which are highly influenced by surface diffusivity, profile CO_2 storage in addition to advective forces mentioned earlier.

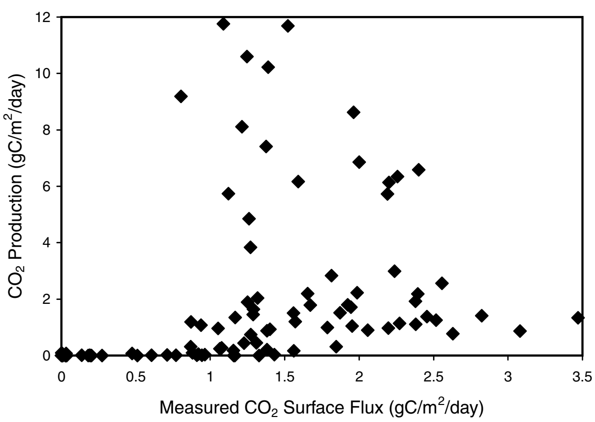

Figure 2. Weekly surface flux measurements vs. subsurface CO_2 production (all sites).

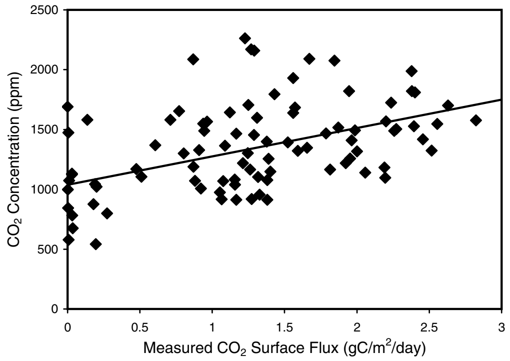

Figure 3. Weekly surface flux vs. subsurface CO_2 concentrations measured at the shallowest depth (all sites).

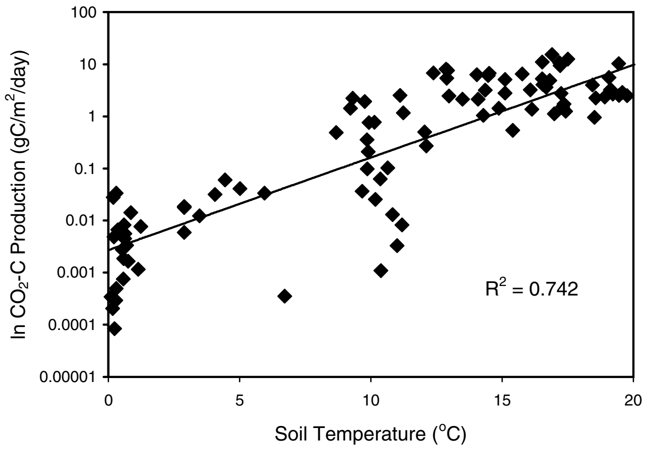

Figure 4. Scaled surface temperature dependence of calculated CO_2 surface production at all sites.

[21] As shown in Table 1, the temperature dependence of surface CO_2 flux was not consistently strong. Soil CO_2 production and temperature, on the other hand, showed good agreement and consistency among sites. Production versus temperature relationships were strongest in the shallow subsurface.

[22] Soils with higher cumulative profile production produced more CO_2 at all temperatures, but the slopes of temperature dependency regressions for each site were similar, suggesting some common response across these land use types. To test whether the temperature response of soil respiration across sites was the same, we normalized the weekly production values for each site to control for cumulative CO_2 produced under different land use cover. The surface CO_2 production vs temperature response across all sites fell along a single, strongly significant exponential regression as shown in Figure 4. This suggests that the temperature response of soil CO_2 production might be relatively stable on a regional scale, and across a range of land use types.

[23] Data from below 5 cm were used to evaluate the temperature dependence of deeper soil respiration, as all showed similar trends; a temperature dependency relation similar to that of the surface data, but with $\sim$10 times less CO_2 production at any given soil temperature. Scaling, as above, for cumulative profile CO_2 production allowed all sites to be modelled with a single, exponential temperature vs production regression, as shown in Figure 5. The overall significance of this regression is weaker than for the surface layers, but so is the signal of CO_2 production, as these deeper layers account for only about 5% of total profile value.

[24] At all sites, modelled diffusivity values ranged by 5 orders of magnitude in response to fluctuations in soil moisture. Many studies indicate the importance of moisture on rates of surface flux *Pinol et al.* [1995]; *Groffman and Tiedje* [1991]; *Davidson et al.* [2000], but in many soils, moisture controls on transport and storage may make it difficult to resolve true CO_2 production responses. In this study, moisture did appear to exert some control over CO_2 production; outliers falling far below the regression line in Figure 4 and Figure 5 coincide with soil moisture measurements within $\sim$5% of saturation. This suggests that temperature is the dominant control at these sites over the wide range of soil moisture values observed (30%–100% pore saturation), except in situations of extreme moisture which may limit CO_2 production through oxygen limitation.

Table 1. Goodness of Fit (r^2) of Exponential Regressions Between Temperature and 0 cm CO_2 Production/Surface Fluxes at All Monitored Sites. Each Sample Value is the Mean of 3 Measurements.

CO_2	# samples	CCF	CCW	PF	PW
Prod.	104	0.86	0.62	0.90	0.88
Sfc. Flux	104	0.73	0.54	0.26	0.66

5. Conclusions

[25] Calculated values of soil profile CO_2 production appeared to be strongly controlled by temperature at our study sites, and we observed a similarity in temperature response across all land use types. On the other hand, the temperature dependence of CO_2 surface flux was weaker and less consistent among our study sites.

[26] To our knowledge, there have not been other studies in which surface CO_2 flux and subsurface CO_2 concentration profile measurements have been coupled with detailed subsurface thermal and moisture data. Although surface flux measurements are invaluable for measuring annual respiration budgets, our results suggest that calculating profile production is a powerful tool for the assessment of temperature dependence, providing a direct index of biologic activity. Surface flux measurements implicate CO_2 transport and storage effects that may preclude robust assessments of temperature dependence at many sites.

[27] We observed a CO_2 production and temperature response that was regionally stable across a range of land use types. More studies using these techniques are needed in order to improve

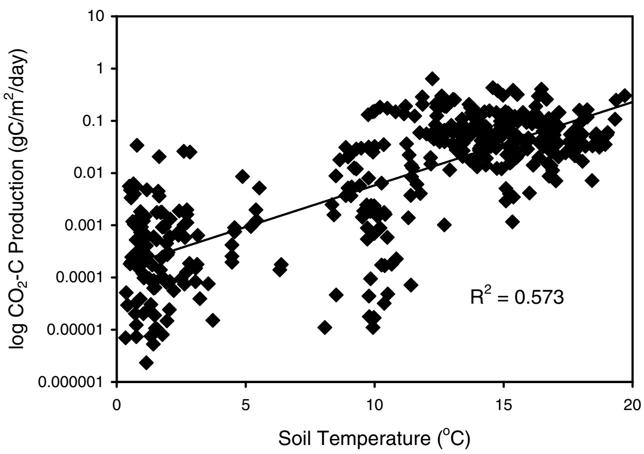

Figure 5. Normalized subsurface temperature dependence of calculated subsurface CO_2 production for 5–100 cm sampling ports at all sites.

estimates of current soil respiration, and perhaps in conjunction with well-established global ground temperature change data sets, to assess the magnitude of historical and future increases in soil CO_2 production.

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