

Soil CO₂ production and surface flux at four climate observatories in eastern Canada

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[1] Soils constitute the largest terrestrial source of carbon dioxide to the atmosphere, and in the context of changing global temperature and moisture patterns, it is critical that we understand the climatic controls on soil respiration. We use subsurface CO₂ concentrations, surface CO₂ flux and detailed physical monitoring of the subsurface regime to examine physical controls on soil CO₂ production. Results indicate that subsurface CO₂ production is very sensitive to the subsurface thermal regime, where relationships were robust and also stable across all land use types studied. In contrast, the thermal dependence of surface CO₂ flux was much weaker. We found that soil heat content, rather than soil temperature, was the most descriptive index of the biological processes contributing to soil profile CO₂ production at our study sites. Soil moisture was also found to have an important influence on subsurface CO₂ production, particularly because of the relationship between moisture and soil profile diffusivity. Nondiffusive profile CO₂ transport also appears to be important at these sites where the subsurface controls on transport change regularly and markedly. *INDEX TERMS*: 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1610 Global Change: Atmosphere (0315, 0325); 1615 Global Change: Biogeochemical processes (4805); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); *KEYWORDS*: carbon dioxide in soil profile, soil CO₂, physical controls of soil respiration, soil respiration, CO₂ and soil temperature, CO₂ fluxes

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1. Introduction

[2] Soils are the largest terrestrial source of carbon dioxide to the atmosphere, globally, emitting ~75 Pg C yr⁻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] In light of rising global temperatures and shifting moisture patterns [Houghton et al., 1990; Mann et al., 1998], it is critical that we understand the climatic controls on soil CO₂ production, since small changes in soil-atmosphere CO₂ flux could potentially match the current annual CO₂ surplus of 6 Pg C yr⁻¹ [Schlesinger and Andrews, 2000] released by fossil fuel burning. This may further contribute to CO₂ radiative forcing if not balanced by a concomitant increase in terrestrial gross primary production (GPP).

[4] Temperature is a primary control on CO₂ production in most soils, according to site-specific studies of experimental soil warming [Rustad and Fernandez, 1998; Peterjohn et al., 1993; Peterjohn et al., 1994; McHale et al., 1998; Luo et al., 2001] and in recent reviews of soil respiration data [Kirschbaum, 2000; Lloyd and Taylor, 1994; Raich and Schlesinger, 1992]. Both root and microbial sources of CO₂ show an exponential increase in activity as a function of temperature [Boone et al., 1998].

[5] The influence of moisture on CO₂ production in the soil is generally less pronounced than that of temperature [Groffman and Tiedje, 1991; Pastor and Post, 1986; Pinol et al., 1995; Schlentner and Van Cleve, 1985]. The optima for soil CO₂ flux appears to be at intermediate water contents [Clark and Gilmour, 1983; Davidson et al., 2000], but it is difficult to make accurate predictions of respiratory increases attributable to shifting moisture regimes because changes will be less well distributed spatially than increases in temperature [Clair et al., 1998]. In addition, moisture has important effects on the transport and storage of soil CO₂ in and from the soil profile [McCarthy and Johnson, 1995; McCarty et al., 1999; Millington, 1959].

[6] To date, most soil respiration research has been based on surface flux data [e.g., Raich et al., 1990], which measures the diffusion of gas in response to a concentration gradient as described by Fick's Law. Many studies assume that surface flux should reflect CO₂ production, as only production should cause subsurface CO₂ concentrations to vary. In most soils, however, the limited diffusivity of the soil matrix stores CO₂, varying mostly as a function of water filled pore space [Millington, 1959; Washington et al., 1994]. 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 additional roles in controlling soil profile CO₂ patterns. As a result, surface fluxes of CO₂ are a function of root/microbial production as well as the diffusive, advective, thermal and geochemical controls on CO₂ transport and storage. Given the potential complications associated with coupling surface flux measurements to physical variables, it is important to consider whether physical controls on CO₂ releases from soils would be better assessed by examining the relationships to soil profile CO₂ production.

[7] A relatively small number of subsurface studies have addressed respiration by measuring CO₂ production within the soil profile [Burton and Beauchamp, 1994; Buyanovsky and Wagner, 1983; Davidson and Trumbore, 1995]. Using sampling of the subsurface CO₂ concentrations at several depth intervals, rates of production are estimated using a multilayered Fickian soil model, with production being the difference between fluxes into, and out from, each layer [DeJong and Schappert, 1972; Davidson and Trumbore, 1995]. The primary advantage of using this method is that, unlike surface flux measurements, CO₂ production calculations account for the quantity of CO₂ stored in the soil profile. To date, however, no published studies have attempted to integrate detailed information on the subsurface physical environment with subsurface CO₂ production data, so relatively little is known about subsurface relationships between temperature, moisture and CO₂ production.

[8] This paper summarizes the first year of data collected as part of a project studying subsurface CO₂ concentrations, production, surface flux, and detailed subsurface meteorology at several land use types. This study aims to satisfy three main objectives; to document subsurface temperature, moisture, CO₂ concentrations, production and variability through an annual cycle; to examine subsurface production and surface flux relationships; and to examine the use of total soil profile heat rather than temperature as a variable controlling CO₂ production. This paper offers information about the nature, distribution and variability of CO₂ production in response to the physical environment at these sites.

2. Methods

[9] The study is being conducted at four sites in eastern Nova Scotia, Canada, where data have been collected for nearly 400 days. 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, located within 1 km of the coast. A schematic of site locations is shown in Figure 1.

[10] Each site is equipped with a meteorological station monitoring typical 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; these moisture data follow one another closely. The stations sample all instrumentation at 30-s intervals and store 5-min averages. Figure 2 shows a diagram of the typical subsurface instrumentation. The functioning of these stations is described elsewhere [Beltrami, 2001] in more detail. For the

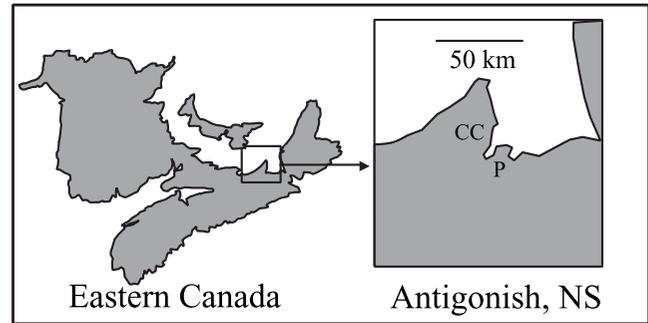


Figure 1. Plan of study locations. The Crystal Cliffs (CC) and Pomquet (P) locations each have two contrasting study sites: field and deciduous forest at CC and field and coniferous forest at P.

duration of the study period, soil moisture at the PW site has been inferred from instrumentation at the adjacent PF site, which shares identical soil type characteristics.

[11] Carbon dioxide is sampled approximately weekly, and to date, over 6000 samples have been analyzed as part of this project including measurements of near-surface free atmosphere CO₂ concentrations. Vented surface flux chambers [Hutchinson and Mosier, 1981] are used for collection of CO₂ samples in combination with multiport gas wells and methodologies developed by Burton and Beauchamp [1994]. Three wells are installed at each site with sampling ports at 0, 5, 10, 20, 50 and 100 cm. Samples are collected in 4-ml evacuated tubes after purging one volume of soil air from the well sampling port, and CO₂ concentrations are then determined using gas chromatography. A mean surface flux value is calculated from three chamber measurements, and subsurface concentrations are calculated from an average of up to three subsurface samples at each depth. Between wells, and between surface flux chambers, the range in concentrations is typically small, falling between 10% and 20%.

3. CO₂ Production

[12] Carbon dioxide production at each depth is calculated as the difference between the flux across soil layers, in other words, the outward output from layer *i* minus input from layer *i-1* below, from the surface to maximum sampling depth,

$$p_{CO_2} = F_i - F_{i-1}, \quad (1)$$

where p_{CO_2} is production of CO₂, F is CO₂ flux density ($g\ m^{-2}\ s^{-1}$) and *i* represents a certain soil layer at depth *z*.

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

$$F = -D \frac{\partial C}{\partial z}, \quad (2)$$

where D is the diffusivity ($m^2\ s^{-1}$), C is the CO₂ concentration ($g\ m^{-3}$) and z is depth (m).

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

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

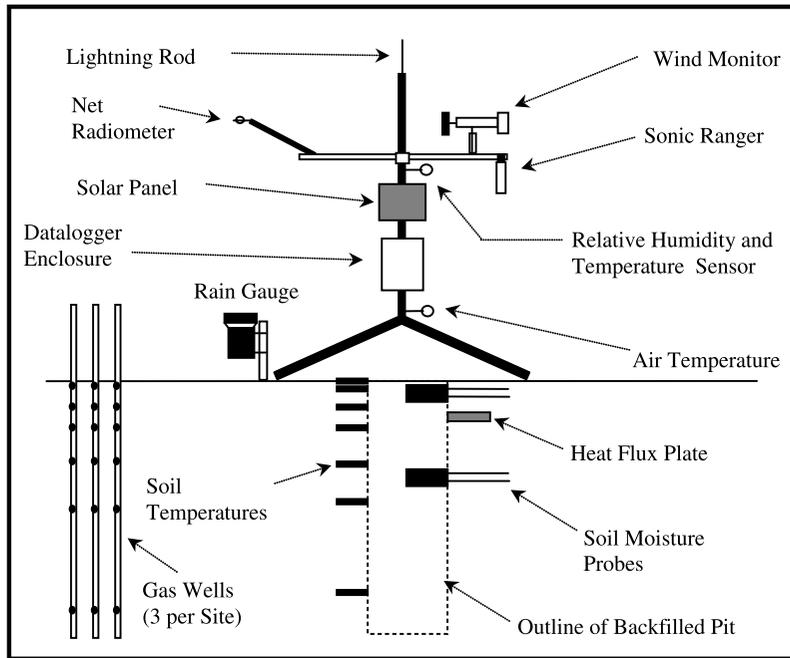


Figure 2. Schematic of site instrumentation. There are four stations instrumented in this fashion, two at each of the locations marked in Figure 1.

where C_i and D_{e_i} are the concentration and effective diffusivity for layer i , respectively.

[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 variable. To cope with the unlikely negative production values encountered by other researchers [DeJong and Schappert, 1972], which also occasionally appear in this data set, we offset all production values in a profile by the most negative value so that the lowest CO_2 production value in each profile is then zero. The magnitude of negative production values is always very small and this change has no discernible impact on production values in areas of the profile where production is rapid. Production in surface layers was calculated using

atmospheric concentrations in the place of C_{i-1} across a distance of 1 cm, because the center lines of the surface well sampling ports are actually 1 cm below the surface.

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

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

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 values,

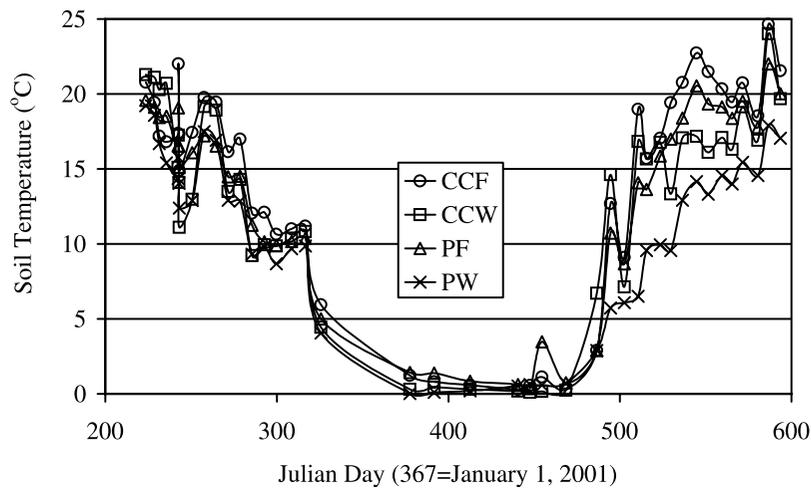


Figure 3. Plot of soil surface temperatures over the 380-day study period. As a result of heavy and persistent snow cover, soils remained unfrozen all winter.

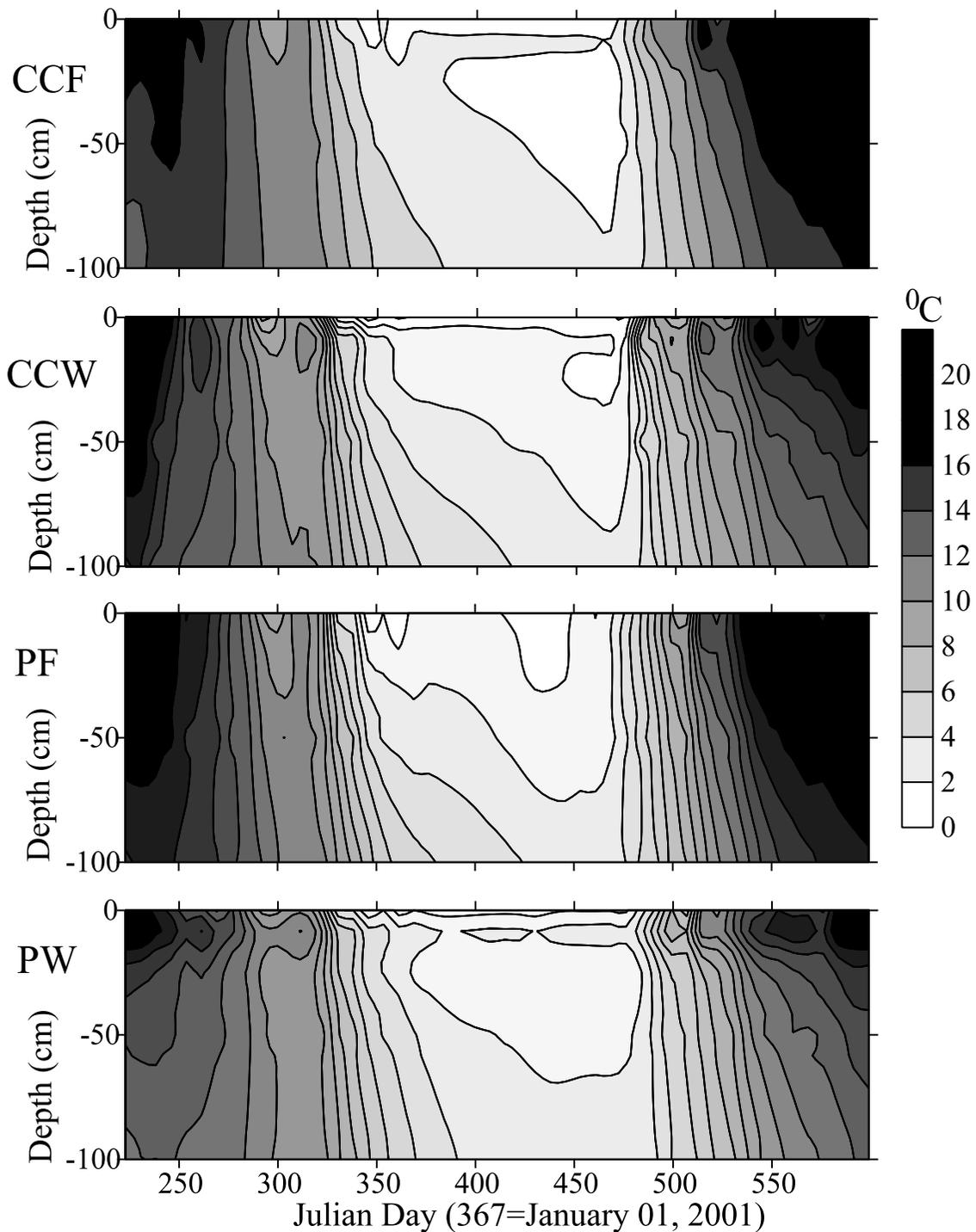


Figure 4. Plot of annual soil temperature through depth at all study sites. As expected, deeper soils displayed greater thermal stability with respect to surface soils.

respectively, and H is the dimensionless form of Henry's solubility constant for CO_2 in water [Hillel, 1998].

4. Results and Discussion

4.1. Subsurface Environment

[17] Soil surface temperatures ranged from 0°C to 25°C during the sampling period as shown in Figure 3. Early and

persistent winter snow prevented freezing of soils altogether, which is unusual for this region. At depth, temperatures were more stable seasonally but followed surface temperature patterns as shown in Figure 4. Precipitation events and corresponding soil moisture variations caused notable changes in shallow subsurface temperatures, which are particularly evident during the dry summer sampling period in the latter part of the data series.

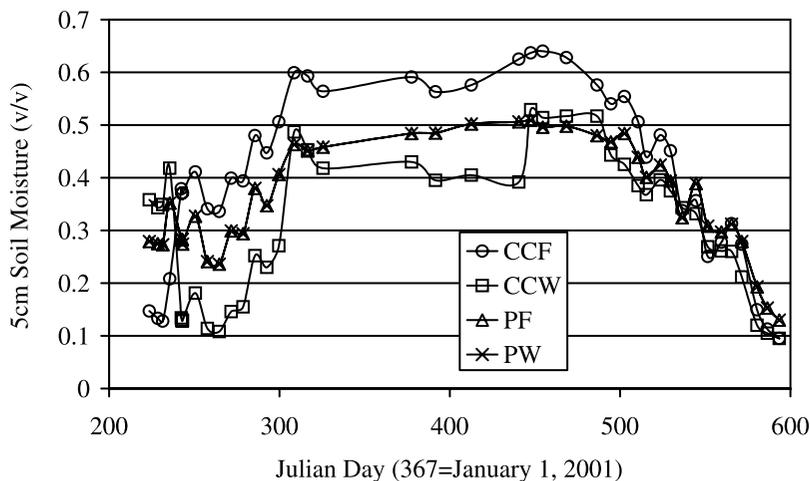


Figure 5. Near-surface soil moisture at all sites. The data series for the PF and PW sites are identical because the PW site does not currently have a functioning moisture probe; values are inferred from the adjacent PF site.

[18] Soil moisture also showed strong seasonal patterns, with very dry summers and extremely wet winters as shown in Figure 5. Soils were nearly saturated all winter, and consistently high groundwater levels were noted. Drainage characteristics in all soils were slightly different. Soils at each site are till derived clay loams with the exception of the CCW site, which has a larger fraction of sand. During the winter, this site shows high maximum water content and therefore peak porosity, but displays better drainage characteristics than the others which stayed closer to saturation.

4.2. CO₂ Surface Flux

[19] Surface CO₂ flux showed strong seasonal variation, with values falling between 0.01 and 10 g CO₂-Cm⁻² d⁻¹. Figure 6 shows annual surface flux patterns for each site. We observed clear differences in total annual surface flux

among land use types; CO₂ flux was highest in the deciduous (CCW) and field sites (CCF and PF), followed by the coniferous woodland (PW). Cumulative surface flux calculated by extrapolating surface flux values between sampling intervals, is shown in Figure 7. These values ranged from 200 to 350 g C m⁻² annually, which corresponds to the typical annual soil respiration for each land use/vegetation type at this latitude [Raich and Schlesinger, 1992].

4.3. Subsurface CO₂ Concentrations and Production

[20] Subsurface CO₂ concentrations varied between 800 and 4000 ppm over the sampling period, and are shown in Figure 8. These concentrations are 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

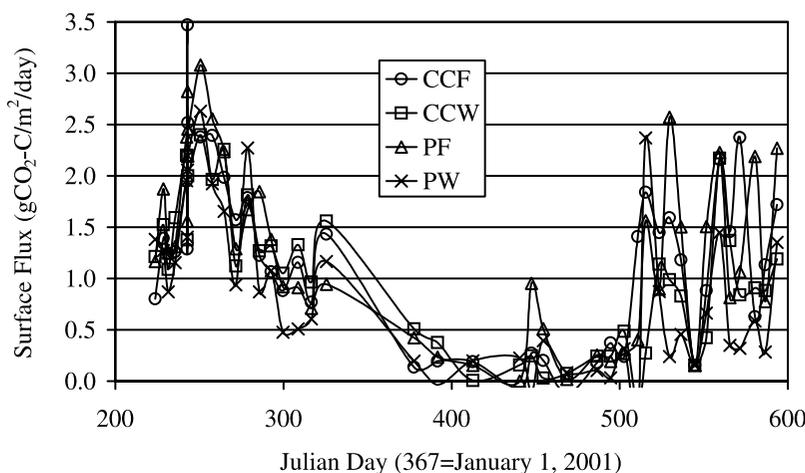


Figure 6. Plot of measured surface fluxes over the sampling period. There is very large variability in surface fluxes, particularly in the latter part of the sampling period when soils were extremely dry. Between wells, the range in subsurface concentrations is typically small, falling within 10% to 20%.

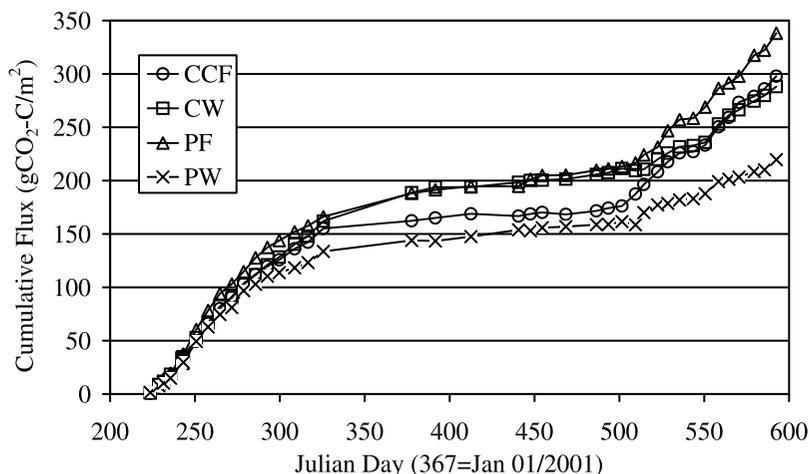


Figure 7. Cumulative flux for the study period. Total cumulative fluxes at the end of the sampling period fell within a published range of values for each land use type.

the soil-atmosphere interface, when the concentration measured at the 0-cm ports was typically 5–8 times that of the atmosphere. High concentrations deep in the soil profile in the earlier part of the sampling period are likely the result not of high rates of production, but storage of soil CO_2 under a low porosity, compact soil layer near 50 cm. Occasionally, a temporary perched groundwater table is evident atop this layer after precipitation events. During the wetter summer of 2000, when moderate rates of production were combined with regular rain, the poorly diffusive characteristics of this hardpan became most evident as CO_2 accumulated underneath. It is interesting to note that patterns in subsurface CO_2 concentrations do not show distinct seasonality, a function of the tradeoff between the dominance of production and storage processes during the year.

[21] Carbon dioxide production derived from the subsurface concentration profiles showed stronger seasonal variations than surface flux, and much stronger seasonal patterns than the concentration profiles alone would indicate. Subsurface production of CO_2 ranged from $0.001 \text{ g CO}_2\text{-C m}^{-2} \text{ d}^{-1}$ to almost $30 \text{ g CO}_2\text{-C m}^{-2} \text{ d}^{-1}$. As would be inferred from the high concentration gradient across the soil surface, $\sim 95\%$ of the CO_2 production at each site occurred in the very shallow subsurface (0–2.5 cm). Figure 9 shows the annual subsurface distributions of CO_2 production for each site. Over winter, deeper layers became proportionately more important, but shallow CO_2 production overwhelmingly dominates in these soils. This contrasts sharply with the findings of *Goulden et al.* [1998], who found deep sources of CO_2 in permafrost regions of the boreal forest. It is interesting to note that the distribution of subsurface production in Figure 9 bears resemblance to the temperature contour plot in Figure 4.

4.4. Thermal Dependence of CO_2 Production

[22] While the temperature dependence of surface CO_2 flux was not consistently strong, CO_2 production and temperature showed good agreement and consistency among sites. Production-temperature relationships were strongest in the shallow subsurface, which is the zone responsible for at

least 90% of production at each site. Exponential regressions best fit the data, and values of r^2 were typically near 0.90 for each site except CCW, where the data appear to divide into two periods; pre- and post-February. At this site, autumn production remained unusually high following leaf senescence. Once the winter production minima was reached in February, production was sluggish and followed a different temperature-production regression line. This is possibly related to the strong seasonality of litter deposition and C cycling at this deciduous site. A summary of r^2 values for surface flux and near-surface production vs soil temperature is provided in Table 1.

[23] Deeper soil temperature-production regressions had similar slopes to those of the surface, but production was ~ 10 times lower at all temperatures. The overall significance of deeper regressions were weaker than for the surface layers, but these areas are also only responsible for only 5–10% of total profile production.

[24] In general, production-temperature relationships are strong, but most interestingly, the surface CO_2 production-temperature values (including all CCW data) fall along a single, significant ($r^2 = 0.73$) exponential regression. This suggests a regionally stable temperature dependence of soil CO_2 production, even across the range of land use types in this study.

[25] The temperature- CO_2 production relationships across these sites is further strengthened when temperature is expressed as profile heat content using a weighted average of the six profile temperatures. The total heat content per unit mass of the soil profile was estimated [*DeGaetano et al.*, 1996] by

$$\frac{Q}{C} = \int_{z=0}^{z_{\max}} T(z) dz, \quad (5)$$

where Q is heat per unit mass, C is the heat capacity of the soil, T is the temperature and z is the depth of the soil (positive downwards). Soil heat exchanges occur at all depths and this energy is readily available to all areas of the

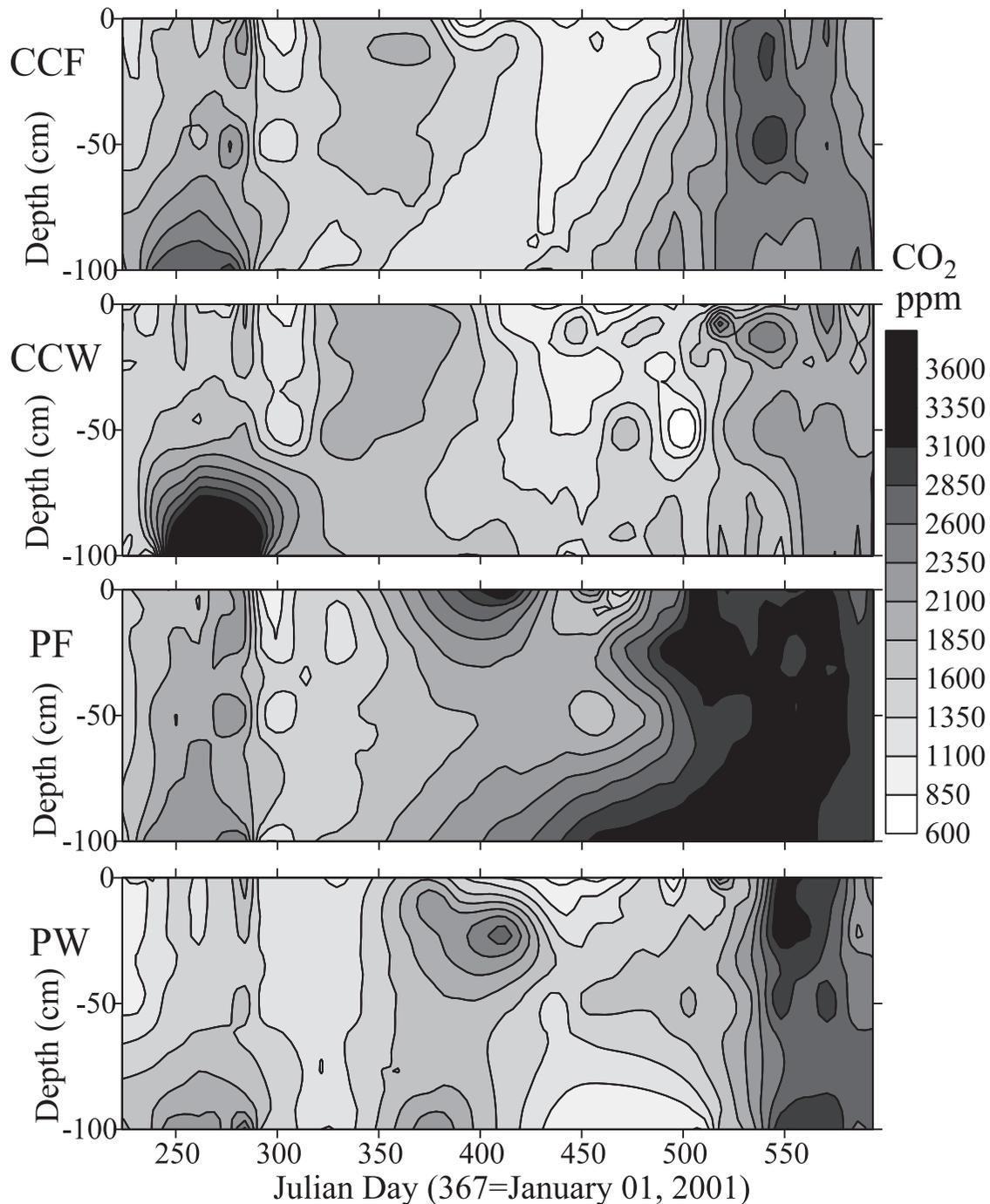


Figure 8. Carbon dioxide concentrations generally fell between 1000–2000 ppm except during periods of intense production. As described in the text, high CO₂ concentrations accumulated underneath a dense, semiconfining layer near the start of the study period at the CCW site.

profile, and also to soil organisms that depend on this heat for metabolic regulation. Soil profile heat is a function of thermal fluctuations over a relatively long interval, and is a good integration of the daily energy budget at the soil surface. Using the heat content expression significantly improves the agreement between surface CO₂ production and total profile heat at all sites. As shown in Figure 10, these production-heat relationships ($r^2 = 0.83$) are very

strong, especially since the regression describes a full annual cycle across four sites and three land use types. Surface flux relationships rarely display this consistency.

4.5. Moisture, CO₂ Production and Diffusivity Values

[26] Many researchers have found correspondence between soil moisture and CO₂ surface flux [Pinol *et al.*, 1995; Groffman and Tiedje, 1991; Davidson *et al.*, 2000],

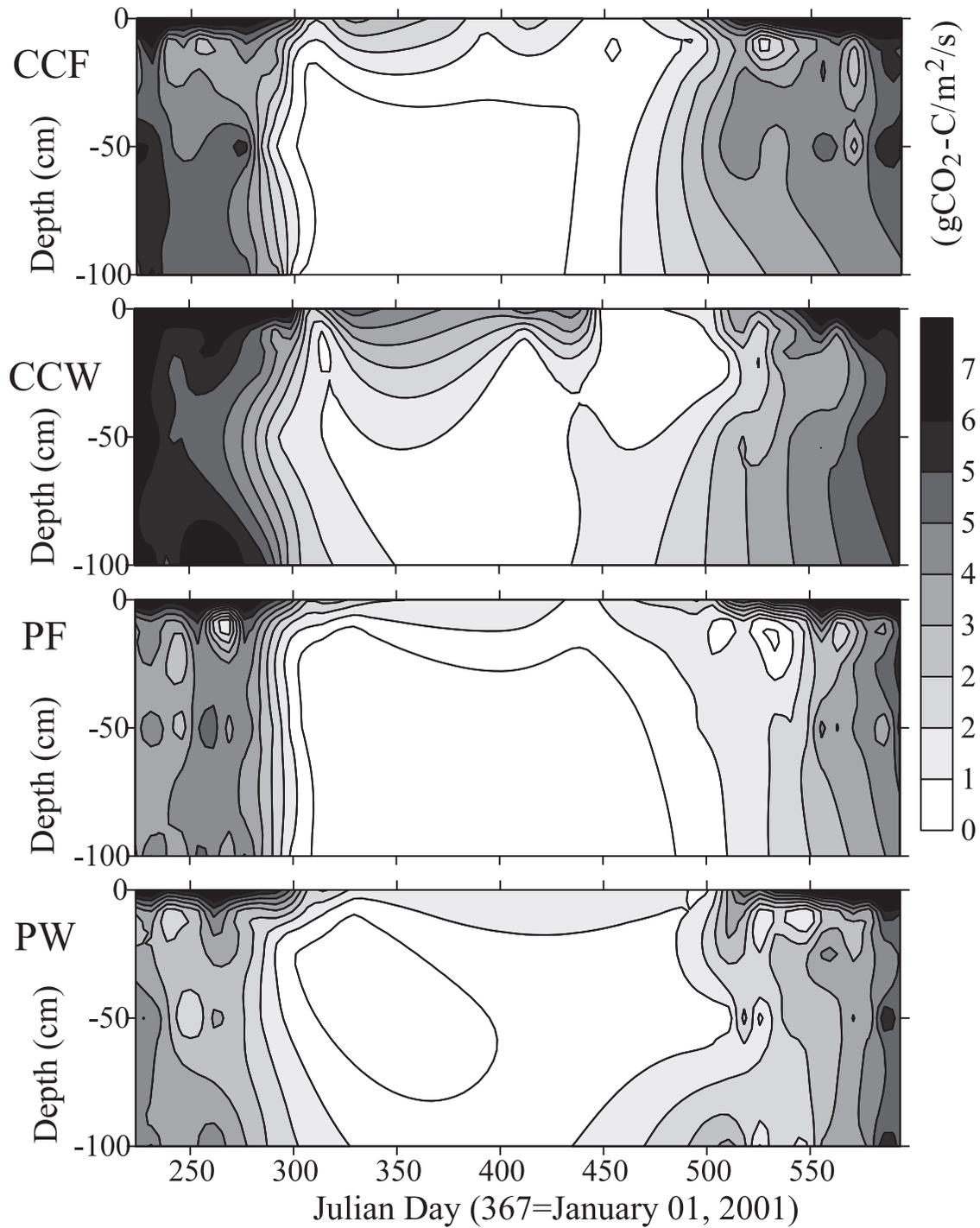


Figure 9. Calculated subsurface CO_2 production values for all depths. The distribution of production is similar to that of temperature, shown in Figure 4. High rates of wintertime production were noted for surface soils at the CCW site, probably due to the strong seasonality of carbon cycling in this deciduous forest.

but the relationship has not been tested using subsurface production methods. Changes in soil diffusivity regulate rates of gas transport to and away from sites of production, and availability of oxygen to aerobic soil microorganisms. In addition, moisture controls on transport/storage and flux may make it difficult to isolate a biological response in

many soils. This data set offers the possibility to more closely examine moisture-diffusivity relationships in the field, and its influence on CO_2 production and surface flux measurements.

[27] As shown in Figure 11, modeled values of effective diffusivity (D_e) showed a seasonal pattern opposite to that

Table 1. Goodness of Fit (r^2) of Exponential Regressions Between Temperature and 0-cm CO_2 Production/Surface Fluxes at All Monitored Sites^a

CO_2	Number of Samples per Site	CCF	CCW	PF	PW
Production	164	0.86	0.62	0.90	0.88
Surface Flux	164	0.73	0.54	0.26	0.66

^aEach sample value is the mean of three measurements.

of soil moisture (Figure 5); low diffusivity in winter accompanying high volumetric water content and high diffusivity in the dry summers. Maximum diffusivity in these soils is high, owing to the high porosity/low compaction, and during the dry summers, diffusivity values approached that of CO_2 through free air. Winter diffusivity values were extremely low, closer to the value for molecular diffusion of CO_2 through water. Typically, site-specific annual diffusivity values varied by 4 orders of magnitude in response to soil moisture.

[28] To a great extent, diffusivity determines the magnitude of the production values when calculated from soil profile concentration gradients. Diffusivity fluctuates widely compared with the profile concentration gradients and a glance back to equation (3) suggests that the wide swings in the magnitude of diffusivity relative to other input values makes it the dominant control on soil CO_2 production. Over this annual cycle, diffusivity has changed by up to 10^4 times in response to moisture shifts, while subsurface concentrations were relatively constant, having varied only by a factor of 4. Further analysis of diffusivity values can provide insights into relationships between surface flux, subsurface production and subsurface concentrations.

4.6. Diffusion Mechanics

[29] To investigate the mechanics of diffusion across the soil surface, and the accuracy of modeled values, we attempted to calculate flux across the soil surface using equation (2). Modeled and measured values of CO_2 surface flux were typically in the right order of magnitude and manifested the same seasonal trends. The calculated values, however, tended to overestimate fluxes in the summer and underestimate slightly in the winter. The best agreement between measured and predicted flux was at the PF site, which was somewhat surprising since this windy location is likely prone to advective transport effects such as wind pumping [Massman *et al.*, 1997]. As there is relatively little error associated with the measurement of subsurface CO_2 concentrations, and we assume the diffusivity model to be correct, we can use the calculated flux values as a theoretical reference to find the 'missing' surface flux (calculated - measured values). The calculated surface flux represents the potential flux if only diffusive mechanisms were involved in transport across the soil surface. When measured fluxes are different from the calculated potential flux, nondiffusive processes are driving part of the CO_2 emissions.

[30] Measured fluxes were smaller than calculated fluxes, but only during the summer periods, as shown in Figure 12. This "missing" flux lags significantly behind soil temper-

ature, but varies closely with soil moisture, as shown in Figure 13. In light of other published studies documenting the response of subsurface CO_2 concentrations to changes in wind speed and other advective forces [Hirsch *et al.*, 2002; Massman *et al.*, 1997; Jones *et al.*, 1999], a missing flux scenario is reasonable. Periods of low soil moisture and high permeability would likely exaggerate advective transport of CO_2 across the soil surface [Washington *et al.*, 1994], which would go unquantified by surface chambers measuring only diffusive fluxes.

[31] Earlier studies at the same sites [Risk *et al.*, 2002] identified a poor coupling between subsurface CO_2 production and surface flux. We had previously identified better correlation between flux and concentration, consistent with diffusive transport, but this relationship broke down this summer when extremely dry soils ($\sim 9\%$ volumetric water content) likely promoted larger advective influences. This study further sheds light on the processes involved; CO_2 production and surface flux are, in practice, twice separated by mechanisms of transport, once with respect to diffusive controls on storage and CO_2 concentrations, and once again by diffusive/advective movement across the soil surface. We find stronger correlations in the heat- CO_2 production relationship when transport is likely dominated by diffusion. Overall, surface flux at these sites is a poor indicator of both near-surface and deep soil CO_2 production; in relative terms, subsurface CO_2 production appears to provide a more direct index of biological activity, which explains the robust measures of thermal dependence that fit better with our theoretical understanding of biologic metabolism.

5. Conclusions

[32] The body of CO_2 research literature contains few studies in which subsurface CO_2 concentration sampling has been used to estimate profile CO_2 production. We aren't aware of any other studies that integrate this approach with surface flux measurements and detailed subsurface thermal

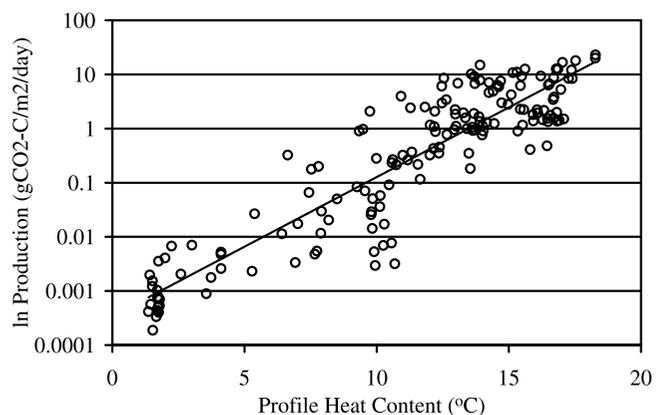


Figure 10. Relationship between soil profile heat content (Q/C) and shallow CO_2 production. Data from all sites plot along a single exponential regression. Using profile heat content as opposed to soil temperature improves the overall r^2 value from 0.73 to 0.83.

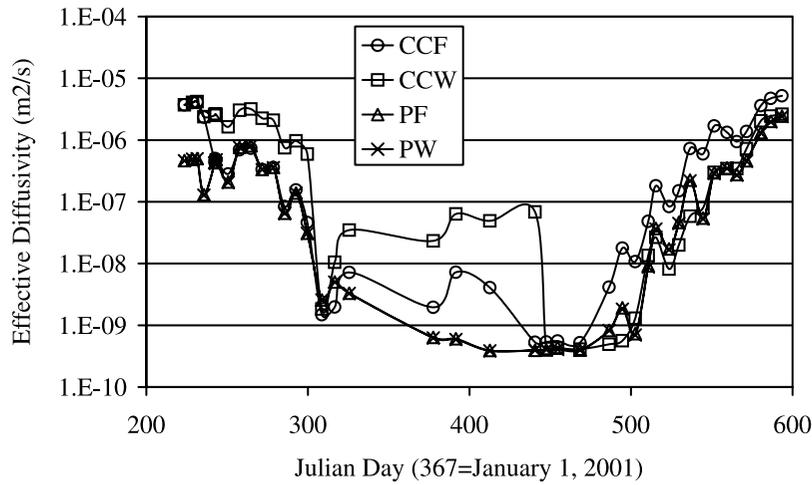


Figure 11. Modeled diffusivity for the study period. Diffusivity values showed a pattern opposite to that of soil moisture (Figure 5).

and moisture data. This combination permits analysis of the physical controls on soil respiration, but also of CO₂ transport, a neglected but critical component of soil respiration studies.

[33] Analysis of transport in this study supports diffusion theory, in particular the fact that surface CO₂ emissions and soil CO₂ production are not directly related, but are separated by the mechanics of diffusive transport. Also, we have indirectly identified the importance of nondiffusive transport that may go unquantified by surface flux measurements. As a result, surface flux analysis alone may not be suited for the assessment of physical controls on soil respiration at sites where the controls on transport change regularly and markedly. In other words, undocumented transport mechanisms could easily masquerade as metabolic variability in some surface flux studies, which may explain the wide scope of findings in the literature.

[34] We found that soil heat content, as opposed to temperature, was a more descriptive index of the biological processes contributing to soil respiration at our study sites. Calculated values of soil profile CO₂ production were strongly controlled by soil heat, and we observed a similarity in thermal response across all land use types. This contrasted with the thermal dependence of CO₂ surface flux, which was not as strongly tied to soil temperature. Moisture was found to be an important control on subsurface CO₂ production, particularly because of the relationship between moisture and diffusivity.

[35] More studies using these multidisciplinary techniques are sorely needed in order to improve estimates of current soil respiration and to attack issues of thermal, hydrologic and transport controls on soil CO₂ production. In conjunction with well-established global ground temperature data sets, these techniques should provide important tools to

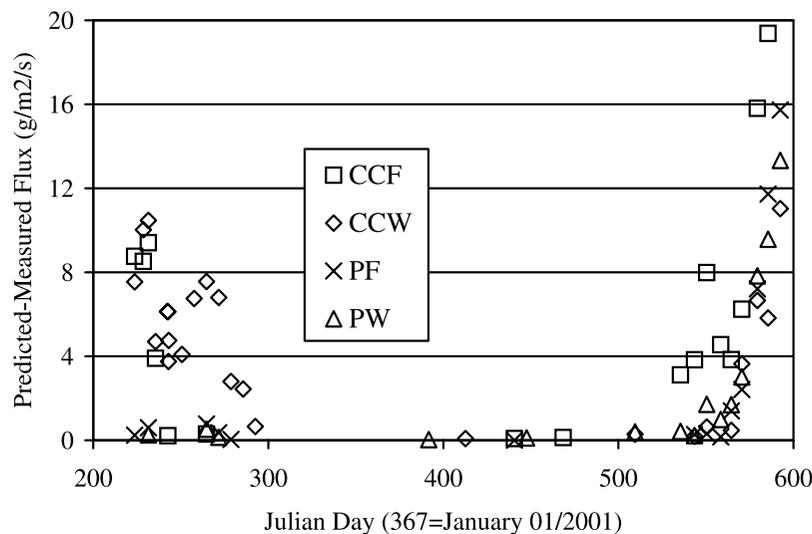


Figure 12. Missing (theoretical-measured) surface fluxes for all sites. Results suggest that low summer soil moisture values promoted nondiffusive transport, which accounts for the large seasonal discrepancy between potential and measured values.

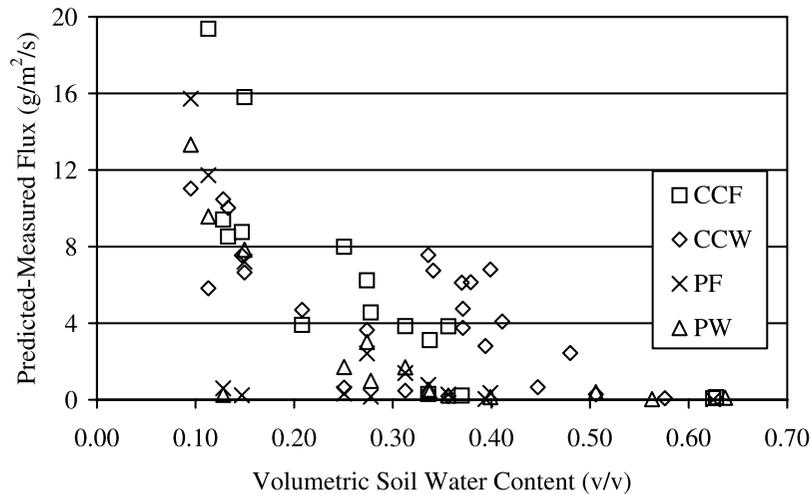


Figure 13. Relationship between missing surface fluxes and soil moisture. Reconciliation of predicted and measured fluxes is only possible when soil moisture is high, and transport is solely the result of diffusive mechanisms.

assess the magnitude of historical and future increases in soil CO₂ production.

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