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Soil CO_2 dynamics and fluxes as affected by tree harvest in an experimental sand ecosystem

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[1] Soil CO_2 production is a key process in ecosystem C exchange, and global change predictions require understanding of how ecosystem disturbance affects this process. We monitored CO_2 levels in soil gas and as bicarbonate in drainage from an experimental red pine ecosystem, for 1 year before and 3 years after its aboveground biomass was removed. Lack of physical disturbance, strict prevention of plant regrowth, and a comparison ecosystem without rooted plants facilitated isolation of the microclimatic and biochemical effects of instantaneous canopy removal and cessation of photosynthesis. Preharvest gas-phase CO_2 levels fluctuated with growing-season soil temperature but reached their greatest levels (up to 10,000 ppmV) during late winter beneath snow and ice cover. This pattern, and the annual CO_2 efflux of $\sim$500 g C m^{-2} yr^{-1}, continued for 2 years following harvest; the efflux declined by half in the third year. The surprising continuity of preharvest and postharvest rates of soil CO_2 production reflects the replacement of root respiration with microbial respiration of root and litter substrates of declining lability, but boosted by soil temperature increases. Mass balance is consistent with a bulk root+litter exponential decay time ($-1/k$) of 4–6 years, such that most of the subsurface biomass accumulated over 15 years of tree growth would be lost in a decade after the harvest. The preharvest bicarbonate C efflux, which was less than 0.1% of the gas-phase efflux, trebled after the harvest owing to elimination of evapotranspiration and consequent increases in drainage while soil CO_2 levels remained high. A large fraction of this "hydrospheric" sink for atmospheric CO_2 is attributed to weathering under high soil CO_2 levels before spring snowmelt and soil-water flushing. These observations suggest that disturbance may enhance long-term chemical-weathering CO_2 sinks.

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1. Introduction

[2] CO_2 levels of the ocean/atmosphere are a key feature of the habitability of Earth and of its climate regulation [*Berner*, 2001]. Soil respiration, or soil CO_2 efflux, is one of the largest global CO_2 exchanges between the continents and the ocean/atmosphere system, estimated to average approximately 70 PgC/yr. This rate is of the same order as global net primary productivity and more than ten times the rate of fossil-fuel burning [*Raich and Schlesinger*, 1992]. Thus small perturbations to global soil respiration may exert relatively large effects on atmospheric CO_2 loading; understanding of subsurface/soil CO_2 levels and the processes driving their dynamics has broad implications for studies of global change.

[3] Coordinated efforts are being directed at characterizing the global spatial and temporal distributions of terrestrial ecosystem CO_2 uptake and loss by the eddy covariance technique [e.g., *Running*, 1998]. These studies have identified large-scale relationships between ecosystem respiration and environmental variables, which complement findings of many other studies of soil respiration at smaller scales. A key concern of this work is to understand the response of soil respiration to disturbance, particularly forest clearing and climate change. It is generally agreed that advances on this front will require both large-scale monitoring [e.g., *Valentini et al.*, 2000] and studies of soil processes on the ground [e.g., *Rayment and Jarvis*, 2000].

[4] Disturbance associated with forest clearing and removal can reduce or eliminate photosynthetic C fixation whereupon soil respiration becomes a key pathway for ecosystem C loss to the atmosphere. Reported responses of soil CO_2 production to forest clearing have varied [e.g., *Gordon et al.*, 1987; *Marra and Edmonds*, 1996; *Striegl and Wickland*, 1998] and the process drivers are not well understood due to the complex interactions of changes in

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physical conditions (soil structure and texture, T, moisture, etc.) with disturbance and subsequent regrowth. Little work has been done on the efflux of dissolved CO_2 from disturbed systems in runoff.

[5] This paper reports a multiyear study of soil CO_2 dynamics in an experimental sand ecosystem in which red pine trees were grown for fifteen years before aboveground biomass was harvested. The harvest was controlled in that it was performed without physical disturbance of the ground surface or soil, and no plant regrowth was allowed for 3 years afterward. This allowed us to isolate and observe the microclimatic effects of canopy removal and the biochemical effects of instantaneous and total elimination of photosynthate delivery to the subsurface. The experimental design facilitated monitoring of the ecosystem responses to tree removal in both gas-phase and aqueous CO_2 concentrations and fluxes.

[6] Given this simple system and disturbance, we posed the following research question: How do subsurface CO_2 dynamics and fluxes change in response to a controlled tree harvest? We hypothesized that elimination of root respiration, rapid (<1 year) decay of fine roots, and low soil organic matter content of the sand would lead to declines in CO_2 levels in the harvested sandbox. We predicted immediate and large drops in CO_2 concentrations and fluxes, in both aqueous and gas phases, immediately after harvest; thereafter substantive but more gradual declines would follow.

2. Methods

2.1. Site Description

[7] The Hubbard Brook Experimental Forest (HBEF) is located in the White Mountains of north-central New Hampshire. In May 1982, large outdoor "sandbox" lysimeters, 7.5 m × 7.5 m × 1.5 m deep, were constructed at HBEF. The sandboxes were constructed to minimize heterogeneity so ecosystem inputs, outputs and changes in storage could be carefully monitored while maintaining a vigorous, stand-scale plant cover [*Bormann et al.*, 1987, 1993, 1998, 2002]. The lysimeters were lined with Hypalon and filled with a 1.3-m-thick layer of 0.95-cm screened sand. The locally derived granitic sand had known N and soil organic matter content [*Bormann et al.*, 1993] and an average grain-size distribution of 94% sand, 4.5% silt, and 1.5% clay-sized particles [*O'Brien et al.*, 2004]. Plastic drainage pipes were installed in a 15-cm-thick layer of 1.9- to 3.8-cm-diameter gravel underlying the sand. The drainage pipes for the sandboxes were connected to an all-weather subsurface monitoring gallery where drainage flow rate and flow-weighted chemistry were measured with tipping buckets and fraction collectors. The sandboxes are located 200 m east of a weather station that monitors daily temperature, precipitation, solar radiation, wind speed, and vapor pressure. Mean air temperature at Hubbard Brook in July is about 19°C and in January is about −8°C [*Federer*, 1973] (see also http://hbr.lternet.edu/research/data/wea/tdm/tdmi.htm). Nearly 1,200 mm/yr of precipitation falls on the Hubbard Brook area (http://hbr.lternet.edu/research/data/atmos/psd/psdi.htm), 70% as rain and 30% as snow [*Bormann and Likens*, 1979].

[8] Between 0.048 and 0.05 m^3 of local topsoil per m^2 was tilled into the upper 20 cm of sand in each box, yielding initial average sandbox organic C concentration of 0.2% by weight. In May 1983 the "red pine" sandbox was planted with 196 seedlings (*Pinus resinosa* Ait.) in a 0.5 m nodal grid, giving each tree 0.25 m^2 of growing space. The "nonvascular" sandbox was initially kept free of rooted plants by active weeding, until it was eventually colonized by a lichen (*Cladonia cristatella* Tuck.) and a moss (*Polytricum spp.*). In general, both boxes have been kept as undisturbed as possible, with the only intrusions being occasional weeding, soil sampling, installation of small sampling equipment and replanting of failed seedlings in the red pine box [*Ingersoll et al.*, 1987].

[9] On 1 May 1998 the trees were carefully harvested from the red pine sandbox by hand and all living aboveground biomass was removed. Physical disturbance of the ground surface was minimized by placing wood planking on the stumps. The cut trees were separated into foliage, stems, and branches for biomass analysis. The only biomass left at the surface of the box after tree harvest were the tree stumps, twigs that had fallen prior to the harvest, and a 5- to 8-cm-thick blanket of needles referred to as the leaf litter layer. Soil cores for soil organic matter (SOM) analysis, litter and root samples were taken in the red pine box at the time of tree harvest [*Havig*, 2002]. SOM was measured on soil samples cored from 12 randomly selected locations from beneath the litter layer after roots were removed from the samples. Litter was also sampled from 12 randomly selected locations. The carbon contents of these materials were determined by elemental analyzer [*Havig*, 2002].

2.2. Field Measurements

[10] CO_2 concentrations in the vadose zone were monitored using stainless steel soil gas samplers in one central location in the each of the sandboxes, at three depths: 15, 35 and 95 cm [*White*, 2001]. Soil temperature was measured by thermocouples at the same depths and also at 5 cm. Gas samples were collected approximately every three weeks beginning in fall 1996. Samples were extracted using 60-mL syringes, then injected for analysis into a benchtop Shimadzu GC-8A gas chromatograph with thermal conductivity detector. Grab samples of drainage water samples were collected biweekly for determination of field pH and total dissolved inorganic carbon. Bicarbonate concentrations were estimated using the latter two parameters and the carbonate equilibrium-constant values for the measured temperature of the drainage water [*Drever*, 1997].

2.3. CO_2 Fluxes

[11] CO_2 fluxes out of the red pine sandbox (moles C m^{-2} s^{-1}) were calculated using measured CO_2 concentrations and Fick's First Law,

$$CO_2\,flux = -D_e \frac{dC}{dz}, \tag{1}$$

where D_e is the effective diffusion coefficient in soil (m^2 s^{-1}), C is the CO_2 concentration in the soil (moles C m_{air}^{-3}) at depth z = 15 cm [e.g., *DeJong and Schappert*, 1972; *Wood and Petraitis*, 1984; *Wood et al.*, 1993]. The effective

diffusion coefficient was obtained by correcting for soil moisture and porosity by

$$D_e = \frac{\theta_g^{10/3}}{\eta^2} D_g, \quad (2)$$

where θ_g is the volumetric gas content ($\eta - \theta_{water}$), η is the porosity ($m^3_{air}\, m^{-3}_{soil}$), and D_g is the free-air CO_2 diffusion coefficient ($m^2\ s^{-1}$) [*Millington and Quirk*, 1961]. A mean porosity value of 0.48 from *Bormann et al.* [1993] and soil moisture content θ_{water} ranges from *Strobridge* [1998] were used. Soil moisture content values measured in the red pine box were used before tree harvest and preharvest values measured in the nonvascular box were projected, based on measured discharge rates, after tree harvest. Postharvest moisture conditions in the red pine box were assumed to mimic the nonvascular box because transpiration by the trees was eliminated and the discharge from the red pine sandbox increased to become similar to the nonvascular system (see below). Because of the high porosity and very low moisture content of the sandbox sand (typically about 2.5% and never exceeding 10% even during the heaviest precipitation events [*Strobridge*, 1998]), error in the soil moisture content was a small source of uncertainty. The flux uncertainty, due to effects of both moisture-content projection and porosity error, was estimated by sensitivity analysis on θ_g (equation (2)) to be approximately ±20%.

[12] The CO_2 diffusion coefficient was corrected for soil temperature by

$$D_g = D_{g25}\left(\frac{T}{T^o}\right)^b, \quad (3)$$

where $D_{g\ 25}$ is the CO_2 diffusion coefficient at 25°C [*Lide and Frederikse*, 1995], T is the soil temperature at 15 cm depth (K), T^o is the reference temperature (298.15 K) and b = 1.823 [*Bird et al.*, 1960].

[13] CO_2 fluxes calculated by this method pertained to the location of the single depth array of gas samplers, but their representation of the whole sandbox was poorly known due in part to spatial heterogeneity and in part to errors typically associated with physical simplifications assumed by diffusion calculations [e.g., *Norman et al.*, 1997]. Therefore the diffusion-based fluxes were independently checked during summer 2000 using a Li-Cor Li-6250 infrared gas analyzer (IRGA) with closed dynamic flux chamber [e.g., *Nay et al.*, 1994; *Rayment and Jarvis*, 2000; *Norman et al.*, 1997] which was deployed to each of 20 permanent collars placed into the mineral soil at random locations in the harvested red pine sandbox. This chamber setup was used in a null balance mode, in which a metered portion of the gas circulating through the chamber was scrubbed of CO_2 to maintain approximately steady ambient atmospheric CO_2 level in the bulk gas [*White*, 2001]. This setup introduced a minor error in the determination of the bulk gas CO_2 concentration; therefore some null-balance flux results were checked by conventional transient mode flux measurements [e.g., *Nay et al.*, 1994]. Comparison of the two techniques at given collar and time yielded flux result agreement within 15%. Averaging of the spatially distributed chamber results yielded whole-box flux estimates which consistently fell within the ±20% error envelope, dominated by uncertainty in porosity and water-content estimates, of the results of the diffusion calculations (equation (1)) for the same times [*White*, 2001]. Given the well-documented biases associated with diffusion- and chamber-based methods [e.g., *Nay et al.*, 1994; *Healy et al.*, 1996; *Norman et al.*, 1997], this agreement, which was obtained without tuning the effective diffusivity (equation (2)) in the diffusion calculations, was somewhat surprising. It may be due in part to the physically simple and relatively homogeneous nature of the sand and the soil-air interfaces in our systems.

3. Results

3.1. Concentration and T Fluctuations

[14] Red pine (RP) and nonvascular (NV) CO_2 levels exhibited the same temporal trends (Figure 1), but CO_2 levels were several times larger in the red pine sandbox (both before and after harvest) than those in the nonvascular sandbox. CO_2 concentrations and concentration gradients increased and decreased in close concert with temperature during the growing season; the effect was much larger in the red pine sandbox, where it declined after harvest.

[15] Large gas concentration "spikes" occurred during winter. In the nonvascular box these spikes were of similar magnitude to the growing-season peaks, whereas in the red pine box the spikes were typically about twice as large as the growing-season peaks both before and after harvest. The wintertime CO_2 buildups were apparently triggered by a combination of snow cover and shallow soil freezing suggested by the temperature records (Figure 1). Minor sampling and equipment-installation excavations, conducted in late winter and early spring of 1998 in the red pine sandbox, revealed layers of ice several cm thick beneath the leaf-litter layer. This is consistent with observations by *Federer* [1973] that wintertime soil heat flow should cause slow melting and water redistribution near a soil-snow interface. *Dudziak and Halas* [1996] and *Mast et al.* [1998] inferred a similar process and effects on soil CO_2. *Federer* [1973] also reported HBEF wintertime soil T depth profiles which were much like the profiles observed in the sandboxes [*White*, 2001].

[16] Concentrations of dissolved CO_2 in the form of bicarbonate (HCO_3^-) generally followed the trends of gas-phase CO_2 fluctuations (Figure 2a), with modest increases during the growing seasons and sharper but more irregular increases during winter CO_2 spikes. The pH of drainage, by contrast, was relatively constant both seasonally and over the entire period of record (Figure 2b). Drainage concentration data were spotty in time before the harvest, owing to evapotranspirative elimination of drainage flow during growing seasons [*O'Brien et al.*, 2004].

3.2. CO_2 Fluxes in the Red Pine Sandbox

[17] Time series of CO_2 effluxes from the red pine sandbox are shown in Figure 3. Mean annual CO_2 flux and cumulative annual flux estimates for each of the years are shown in Table 1. For these purposes, we conservatively assign zero flux values when snowpack existed on the sandbox. This is consistent with the buildup of concentrations and decline of concentration gradients during these periods (Figure 1) due to inhibition of the efflux by soil

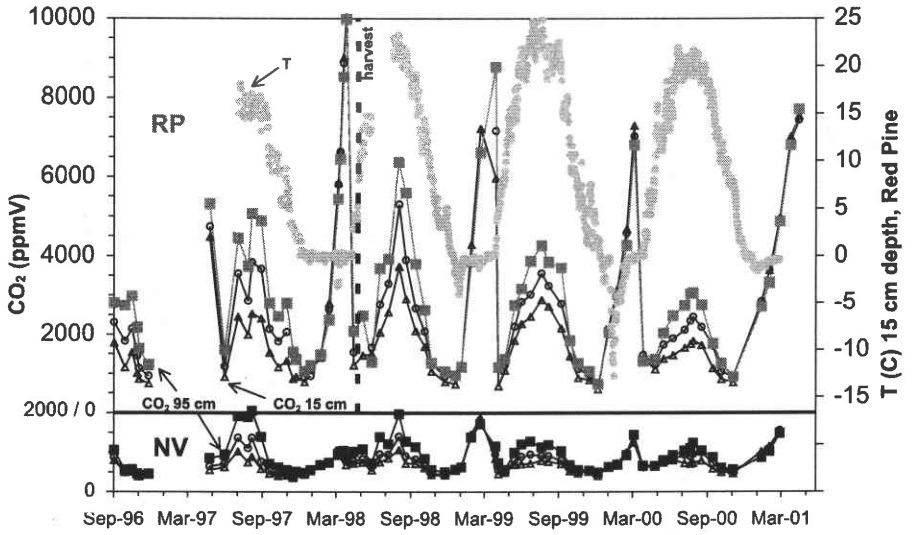

Figure 1. Gas-phase CO_2 concentrations at 15 (triangles), 35 (circles), and 95 (heavy squares) cm depths in the red pine (RP, top plot) and nonvascular (NV, bottom plot) sandboxes. Peak nonvascular concentrations are one-fifth of peak RP concentrations (note split *y* axis scale).

freezing and/or ice layers at the soil surface [*White*, 2001]. However, wintertime CO_2 losses through snow cover could be substantial. *McDowell et al.* [2000] estimated these losses to be as much as 10% of growing-season values, while *Mast et al.* [1998] estimated losses through snow to be as much as one fourth of total annual respiration.

[18] The preharvest pattern of seasonal fluctuation was preserved after harvest, with a slightly lower but broader peak the second year after harvest, and definite decline in amplitude by the third postharvest year. The preharvest annual flux (Table 1) was about 5 times the average rate of SOM loss, and 3–5 times the average rate of net soil C gain which was due to about 160–200 $gC/m^2/yr$ of accumulating roots and litter over the 15 years of red pine growth in the sandbox (Table 2).

3.3. Bicarbonate Fluxes in the Red Pine Sandbox

[19] The bicarbonate flux was very small relative to the gas flux at all times (Figure 4). In the first year after harvest, the cumulative gas CO_2 flux was indistinguishable from the previous year, but the bicarbonate flux increased by a factor of approximately 3, owing to elimination of ET and

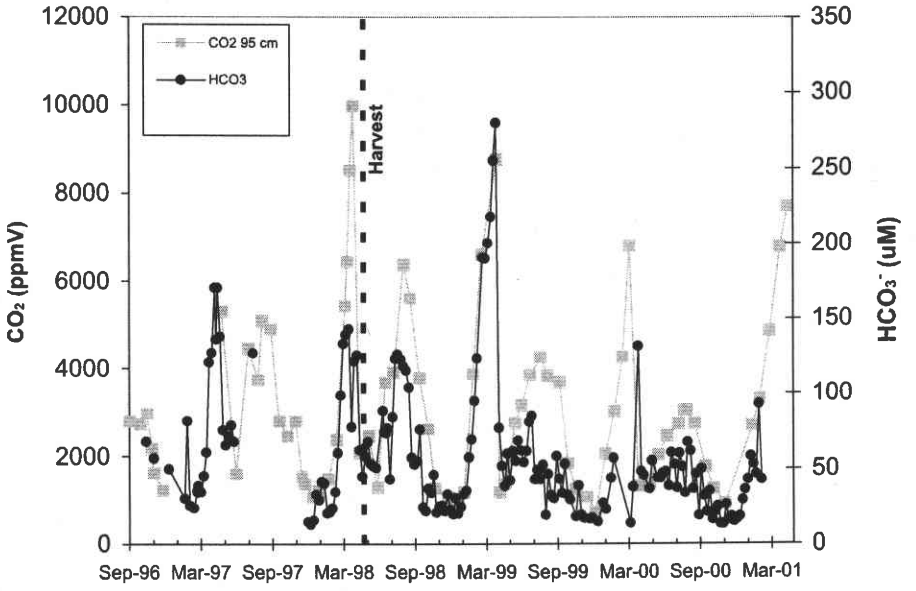

Figure 2a. Red pine CO_2 concentration at 95 cm depth (from Figure 1) plotted with bicarbonate concentrations in drainage.

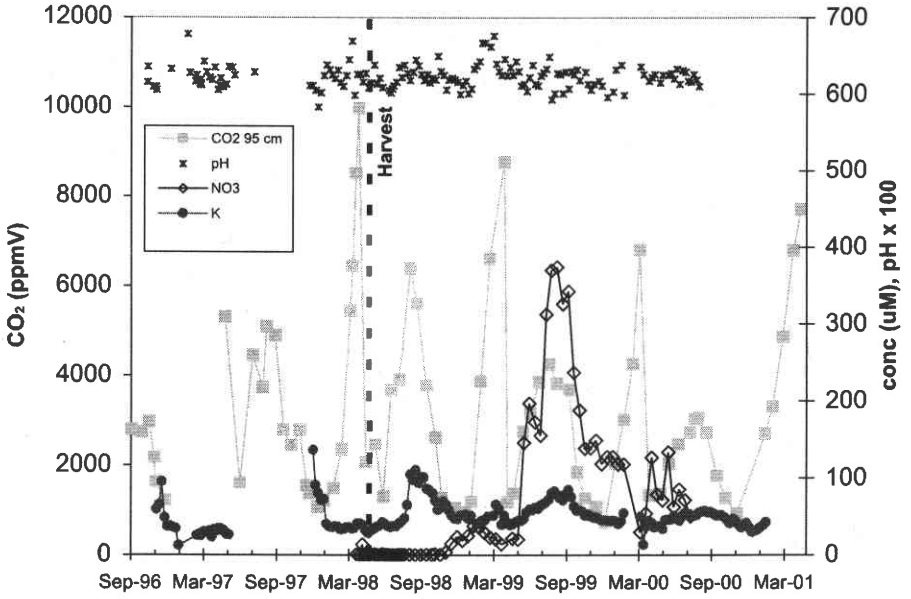

Figure 2b. Red pine CO_2 concentration at 95 cm depth (from Figure 1) plotted with pH, nitrate, and potassium concentrations in drainage (adapted from *Keller et al.* [2006]. Mean pH was 1.5–2 units greater than runoff in nearby HBEF streams and >2 units greater than mean precipitation pH [*Likens and Bormann*, 1995].

increased water throughput [*O'Brien et al.*, 2004; *Keller et al.*, 2006] while preharvest concentration levels were maintained (Figure 2a). The bicarbonate flux then followed the decreasing trend of the gas flux, which was particularly evident in the third year after harvest (Figure 4).

4. Discussion

4.1. Subsurface CO_2 Production

[20] The range of growing-season gas-phase CO_2 flux estimates before harvest was 0.5–3E-6 μM m^{-2} s^{-1} (Figure 3). This range is very similar to ranges reported in several studies of temperate hardwood and mixed-hardwood forests [e.g., *Baldocchi and Vogel*, 1996; *Gaudinski et al.*, 2000; *Boone et al.*, 1998; *Hanson et al.*, 1993] and perhaps slightly larger than ranges reported for boreal pine forests [e.g., *Striegl and Wickland*, 1998; *Baldocchi and Vogel*, 1996]; it is one half or less of ranges reported for some mixed coniferous and fir forests [e.g., *Widen*, 2002; *Drewitt et al.*, 2002]. While the shapes and heights of the seasonal respiration peaks varied (Figure 3), the average annual fluxes did not appreciably change for 2 years after the

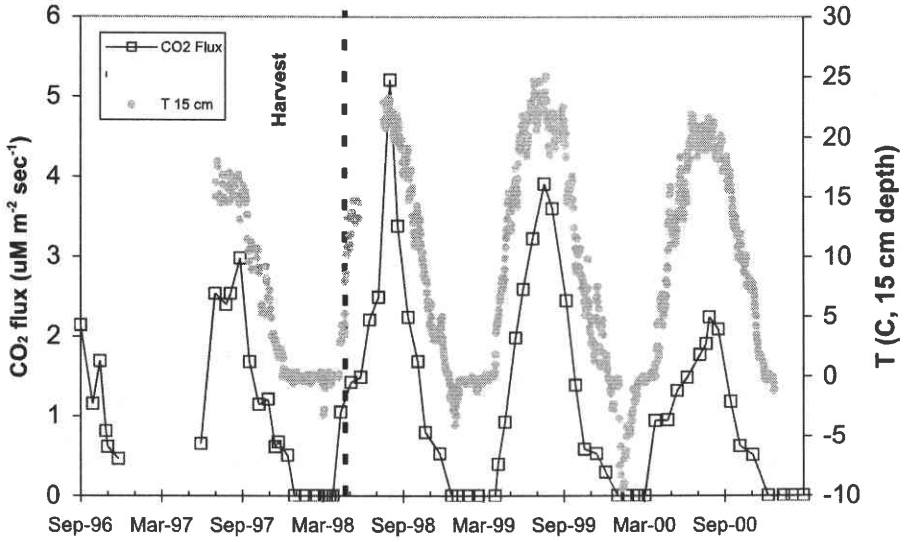

Figure 3. CO_2 effluxes from the red pine sandbox, shown with synoptic soil T. Fluxes during periods of snow cover are conservatively plotted as zero. Means and seasonal cumulations are summarized in Table 1.

Table 1. Fluxes From the Red Pine Sandbox Reported by Water Year[a]

		Postharvest		
	Preharvest 1997	1998	1999	2000
Mean annual flux, moles C m^{-2} s^{-1} (±)	1.15 E-6 (0.3)	1.37 E-6 (0.4)	1.27 E-6 (0.4)	0.72 E-6 (0.2)
Cumulative flux, g C m^{-2} yr^{-1} (±)	435 (113)	518 (151)	481 (151)	272 (76)

[a]See Figure 3. Error is based on uncertainty ranges in porosity and water content estimates used to calculate the fluxes (equations (1) and (2)). These errors predominate over CO_2 sampling and measurement error [*White*, 2001].

harvest (Table 1), contrary to our prediction and to observed respiration decreases from other clear-cut field experiments [*Striegl and Wickland*, 2001; *Weber*, 1990].

[21] We explored the effect of the postharvest increase in seasonal soil temperature variation on the CO_2 fluxes by plotting each flux estimate against mean soil T on that day, for the entire study period (Figure 5). The exponential trends are similar to those reported in many previous studies where data are fitted to an expression of the form

$$F = F_0 \exp(kT), \quad (4)$$

where F and F_0 are the flux at the temperature T (°C) of interest and at 0°C, respectively, and the magnitude of k quantifies the degree of upward curvature of the T-flux plots, i.e., the responsiveness of production to temperature change. The results of our year-by-year fits of the fluxes to equation (4) show constant k values for the three seasons preceding 2000 (Figure 5, inset). This corresponds to the period of sustained mean annual flux. The k values for this period are similar to those previously reported for shorter-term temperature-change responses of conifer systems [e.g., *Rayment and Jarvis*, 2000; *Drewitt et al.*, 2002; *Widen*, 2002]. However, the consistent rightward progression of the T-flux plots over the whole study period (Figure 5) indicates change in the production regime. This is described by decline of the intercept term in equation (4) which is commonly recast in the literature as F_{10}, the "baseline" CO_2 flux at 10°C. Figure 5 (inset) shows that even while k remains constant, F_{10} drops smoothly. The approximate constancy of the seasonal average flux through 1999, in the face of dropping F_{10}, seems likely to be due to progressively higher soil temperatures (Figure 3). This is supported by analysis of temperature profiles by *Keller et al.* [2006] which shows that mean maximum T for the upper 35 cm increased by 5°C from 1997–1998 and by another 2°C from 1998–1999. The first increase can be attributed to canopy removal, while the second increase may have been in response to warmer and/or sunnier weather in 1999. Evolving insulating properties of the litter layer may have also played a role during both years.

[22] The exponential decline of F_{10}, and the abrupt drop of k after 1999, indicate non-temperature-driven shifts in the postharvest decomposition regime. The red pine sandbox was left physically undisturbed during this period, so we have no direct observations of roots nor microbes to document these shifts. Photosynthate stores in the root systems could have sustained mycorrhizal respiration for some part of the 1998 season. Hydrochemical monitoring showed a large 1998 pulse of dissolved K in soil water and in drainage (Figure 2b). This K, pulses of which reappeared with declining amplitude in subsequent seasons, was presumably released from labile tissue, particularly leaf and root litter, and lost via drainage due to lack of plant uptake. The decline of F_{10} may, then, reflect the combined effects of rapid loss of root/mycorrhizal respiration and a more gradual decrease of substrate quality in the litter pools. This idea is consistent with hydrochemical data showing NO_3 remaining at or below detection until nearly a year after the harvest, whereupon its levels soared in 1999 to nearly 400 μM in drainage (Figure 2b). The 1999 NO_3 surge was charge-balanced by Ca and presaged by declines in DOC and the DOC/DON ratio in drainage, all of which are consistent with onset of nitrification and a shift in decomposition from N to C limitation, i.e., from labile to more structural substrates [*Keller et al.*, 2006]. It is notable that k, the temperature sensitivity of decomposition, did not change during this period, but fell distinctly a year later in the 2000 growing season (Figure 5). The cause of this delay is unknown but it may reflect the collapse of part of the decomposer community in the aftermath of the large nutrient losses of 1999 (Figure 2b).

Table 2. Carbon Distribution (SOM, Roots, and Litter) at Planting and at Tree Harvest, Compared to Cumulative Postharvest C Efflux Three Seasons After Harvest[a]

	C Content Planting, June 1983	C Content Harvest, 1 May 1998	ΔC Cumulative, 15 Years	Postharvest Respired C
SOM	3996[b]	2772	−1224	...
Roots	11[c]	876	865	...
Litter	0	1584	1584	...
Roots+Litter	11	2460	**2449**	...
Total	**4007**	**5232**	**1225**	**1272**

[a]Unit is g C m^{-2}. Cumulative postharvest C efflux three seasons after harvest is shown in last column. Note that the efflux is about half the roots+litter accumulation (Figure 4). However, reported root accumulation is a minimum; actual may be as much as 50% larger. See text for additional discussion of uncertainties.

[b]OM is from site, initially tilled into box; assumes negligible SOM in sand. Value is estimated from *Bormann et al.* [1993].

[c]Value is estimated from *Bormann et al.* [1993].

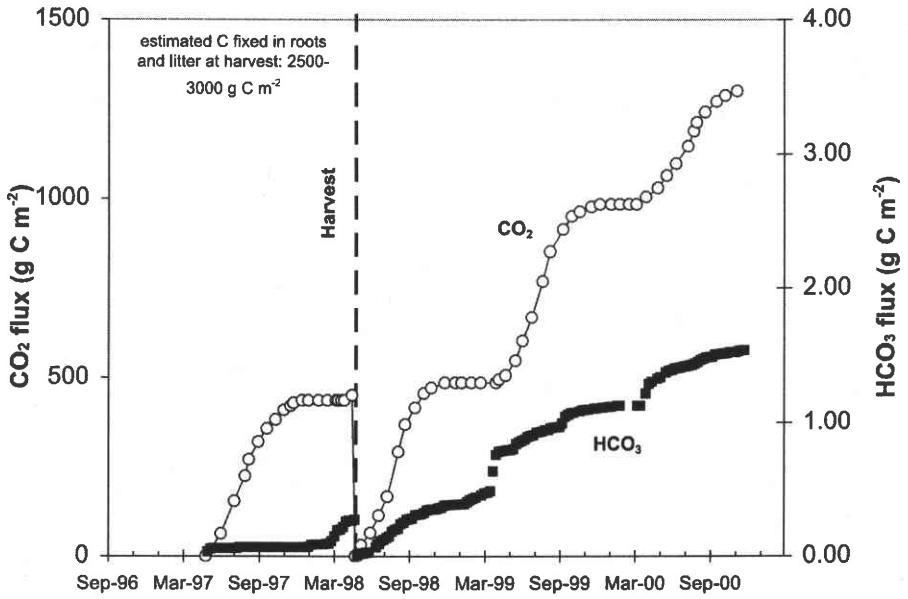

Figure 4. Cumulative gas-phase (left axis) and dissolved (HCO_3^-, right axis) CO_2 effluxes from the red pine sandbox, for 1 year before and 3 years after harvest. Note 10^3 factor difference between gas-phase and dissolved fluxes. Steep dissolved cumulations in late winter were due to rapid snowmelt and soil-water flushing, while steepest gas cumulations occurred during summer.

4.2. Sources and Rates of Soil C Loss

[23] Cumulated over three years, the postharvest CO_2 efflux equaled about half of root+leaf litter C at harvest (Figure 4), or about one fourth of all belowground C at harvest (Table 2). The C sources of postharvest CO_2 are constrained to some extent by the mass balance in Table 2. The roots could have supplied just enough C to generate all of the postharvest CO_2 if they completely decomposed. This scenario is probably unreasonable: Estimates of decomposition of woody roots indicate a 45–63% dry weight loss

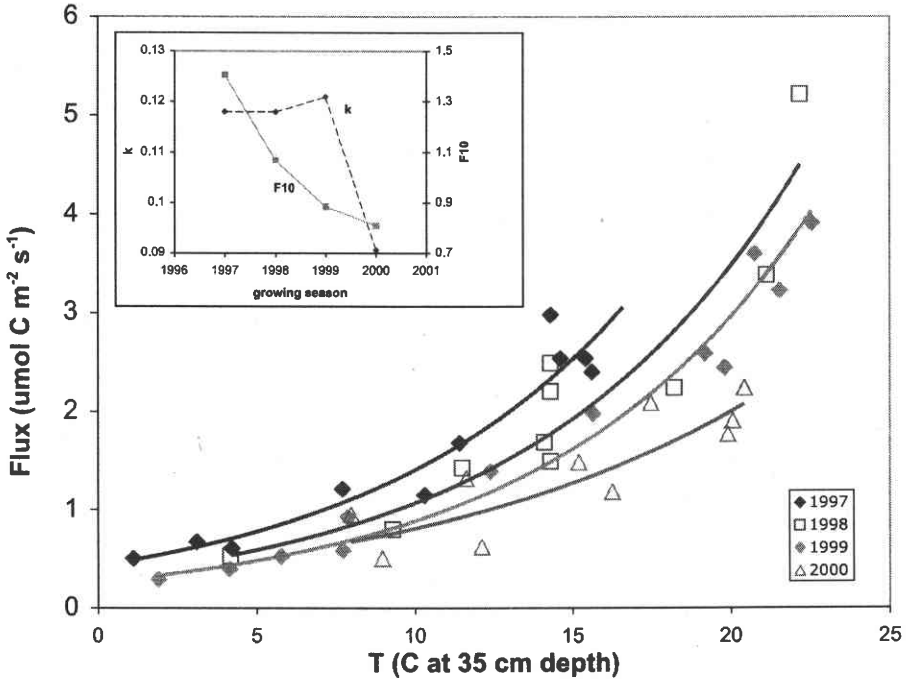

Figure 5. Flux data shown in Figure 3, plotted season-by-season against synoptic soil T, with best-fit exponential parameterizations of equation (4) shown as smooth curves. Inset shows smooth decline throughout the study in best-fit flux at 10°C (F_{10}), and persistence of best-fit response to temperature change (k) through 1999.

4 years following harvest of a northern hardwood forest [*Fahey and Arthur*, 1994]. Decomposition of the leaf litter layer could have supplied all of the C for the postharvest CO_2 flux, but this cannot be the case because some litter persisted as an identifiable layer at the ground surface through summer 2000. Sufficient C in SOM, initially incorporated as topsoil in both sandboxes, was present to supply the postharvest flux. However, CO_2 levels in the nonvascular sandbox (Figure 1), where SOM was essentially the only decomposition substrate, indicate this type of decomposition can account for only a small fraction of CO_2 production in the red pine sandbox during this time. Furthermore the average preharvest rate of C loss in red pine SOM, about 80 g C m^{-2} yr^{-1} (see Table 2) was less than one fifth the rate of postharvest CO_2 efflux in 1998 and 1999 (Table 1). These observations strongly suggest that postharvest C losses were dominantly from the root and leaf litter pools.

[24] Exponential fits to the rate of C loss in CO_2, expressed as fraction root+litter C remaining versus time, yields a $-1/k$ (decay time) parameter of 4 years. This decay-time estimate is low to the extent we have underestimated fine root biomass; that is, it could be as much as 50% larger. It is not the same as the turnover time of these pools in the living system, but it probably gives a lower limit. The similarity of the 1997–1999 fluxes suggests that the decay rate of root and leaf litter increased after the harvest. If, for example, preharvest root respiration were approximately equal to decay [e.g., *Schlesinger*, 1998], the decay (turnover) rate would have been about half the postharvest rate. This would give a preharvest turnover time of 8–12 years. This range lumps all litter from roots plus aboveground sources and so is not applicable to any one of these pools; furthermore, it relies on a guess of the preharvest ratio of root to microbial respiration. *Gaudinski et al.* [2000] estimated 2- to 10-year lumped turnover times for these pools in Harvard forest. The apparent similarity is interesting given that the Harvard forest study found annual CO_2 fluxes about twice the preharvest red pine values, and annual net soil C gain only one tenth to one fifth of the preharvest red pine rate.

[25] The CO_2 concentration and flux history of the red pine sandbox, viewed over the entire study period (Figures 1 and 3), records a macroscopically smooth transition from a photosynthetically driven to a decomposition-only system. It is not possible, on the basis of our measurements, to know the relative importance of root and microbial respiration before the harvest (as noted above), nor to estimate how the respiration components changed in time after the harvest. While our experiment was not designed for these purposes, it nonetheless highlights the difficulties attending such work [e.g., *Bowden et al.*, 1993; *Trumbore et al.*, 2006].

4.3. Carbonate Hydrochemistry and Partitioning of CO_2 Efflux

[26] Red pine sandbox drainage bicarbonate levels (Figure 2a) and consistently high pHs (Figure 2b), indicate that acid neutralization occurred by rapid carbonic-acid weathering along downward vadose flowpaths in the red pine sandbox [*Berner and Rao*, 1997; *Bormann et al.*, 1998; *O'Brien et al.*, 2004]. Furthermore, the indistinguishable response of pH to the harvest (Figure 2b) indicates that this weathering regime was sustained throughout the study period. Relatively fresh mineral surfaces in the sandboxes allowed rapid weathering reaction progress, and the coarse texture of the sand supported large water throughflow rates with the elimination of ET following the harvest; thus bicarbonate loss following harvest, or at least the increase in the bicarbonate loss after harvest, may be large relative to what would occur in better-developed soils. Concentrations of bicarbonate and major cations in red pine sandbox drainage water were substantially larger, throughout the study period, than in stream runoff from neighboring Hubbard Brook experimental watersheds [*Keller et al.*, 2006]. Our observations may be pertinent to understanding hydrochemical responses of primary-successional systems to disturbance [*Keller et al.*, 2006], but this issue requires further study.

[27] Bicarbonate generated by weathering and leaving the sandbox in drainage, represents translocation of atmospheric CO_2 to the hydrosphere, i.e., groundwaters, streams [e.g., *Worrall and Lancaster*, 2005], and the oceans. This hydrospheric sink is potentially important in long-term regulation of atmospheric CO_2 because of the 10^3 years bulk turnover time of Earth's terrestrial and ocean waters. The phenomenon is analogous to similar rates of lithospheric sequestration of CO_2 in carbonate rocks by silicate-weathered Ca and Mg, which control atmospheric CO_2 levels over the geologic timescale of the turnover of that reservoir [*Berner*, 1999]. The effect of the harvest on the hydrospheric sink was to increase it substantially by 3X in the first postharvest year. The trigger was the immediate cessation of water uptake by the trees at harvest. *Raymond and Cole* [2002] suggested that the Mississippi river basin has responded similarly to land-use disturbances over the past century, although in that case the disturbance effect was difficult to distinguish from that of a long term increase in precipitation in the basin. Nonetheless this all suggests that certain kinds of ecosystem disturbance, extrapolated globally, could enhance weathering CO_2 sinks.

[28] Irrespective of the harvest, a large fraction of the hydrospheric sink is attributable to wintertime CO_2 buildup beneath frozen cover and the flushing of large volumes of high-HCO_3^- water during snowmelt. Nearly one half of the 1998–1999 bicarbonate efflux occurred during this brief period (Figure 4). *Berner and Rao* [1997] called attention to this phenomenon; we do not know how globally important it is. We are presently studying the effect of the harvest on overall sequestration of atmospheric CO_2 by chemical weathering in the sandboxes.

5. Conclusions

[29] Throughout the study period, growing-season CO_2 production and its gas-phase and dissolved concentrations in the sandboxes were strong functions of soil temperature. Contrary to our expectation and to other field studies, the overall CO_2 efflux from the red pine sandbox changed insignificantly for 2 years after harvest, even though regrowth was strictly prevented, root respiration was eliminated, and there was no physical disturbance of the soil. Large postharvest soil CO_2 fluxes were due to increased soil temperatures driving increased microbial decomposition, even through a shift to carbon-limited, structural-tissue

decomposition in the second year. The decline in CO_2 levels and production-rate response to T occurred after this shift and the associated loss of NO_3-N in drainage, in the third year.

[30] Mass balance indicates that postharvest CO_2 came dominantly from the root+litter pools, and that the decay time of these pools in aggregate was about 4–6 years. This implies a turnover time of these pools consistent with those obtained in previous studies of living forests. Our decay-time result suggests that subsurface C fixed by the red pine trees in 15 years of growth would be essentially gone a decade after harvest, under the conditions of this study. The no-regrowth condition is clearly not applicable to many real systems, but the result nevertheless underscores the vulnerability of young, pioneering forests to soil C loss associated with disturbance.

[31] Export of CO_2 as HCO_3^- in drainage was <0.1% of the gas-phase efflux from the red pine sandbox, even after its postharvest trebling due to increased water throughput. Late-winter buildup of CO_2 levels beneath snow and ice cover substantially boosted the drainage efflux, but not the gas-phase efflux. While insignificant in the context of ecosystem C exchange, the dissolved C export pathway is a hydrospheric sink for atmospheric CO_2 and its increase could be an important long-term consequence of disturbance.

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