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Soil respiration from four aggrading forested watersheds measured over a quarter century

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Abstract

Soil respiration was measured in four aggrading, forested second-growth watersheds in the southern Appalachians using an identical method (alkali absorption) at intervals 23 and 24 years apart. Seasonal trends were similar, with mid-summer maxima and winter minima. Amounts of carbon dioxide evolved were higher in the recent measurements (1995) compared to the earlier ones (1971–1972), despite similar soil water and temperature regimes. The overall trend across all four watersheds may reflect changes in organic matter levels and subsequent root growth. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

CO_2 evolution from soils has been measured by ecologists for more than a century (Pettenkofer, 1871). The processes controlling soil carbon (C) cycling are of particular interest because, on a global basis, soils contain twice as much C as the atmosphere (Adams et al., 1990). In situ soil respiration (CO_2 evolution) is a useful measure of relative biological activity (microbial, roots, and fauna) of contrasting sites or contrasting treatments applied to the same site (Lieth and Ouellette, 1962; Schlentner and Van Cleve, 1985; Weber, 1985, 1990). In fact, annual carbon balances are considered a principal concern for measurement of net sources or sinks in forests in entire regions. For example, Valentini et al. (2000), measuring net exchanges of atmospheric carbon, determined that 15 forests in nine European countries serve as net sinks of atmospheric carbon.

Many techniques, both static and dynamic, have been developed in order to obtain more accurate measurements of CO_2 evolution. Comparative studies have found wide disparities among techniques, such that comparing soil CO_2 evolution estimates among studies or extrapolating estimates to construct C budgets requires caution (Schlentner and Van Cleve, 1985; Bekku et al., 1997, Knoepp and Vose unpublished data).

We used an identical technique, static trap with alkali absorption, to replicate the study done by Coleman and Pomeroy (unpublished data) in 1971 and 1972 to measure changes in soil respiration 23–24 years later. Similar locations were sampled to examine the current trends of four watersheds, which have been undergoing regeneration and maturation after various

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management practices. Our principal questions are: have changes occurred in CO_2 evolution in four aggrading, second-growth forested ecosystems in the southern Appalachians after nearly a quarter century? If the differences are real, are they biologically or abiotically driven?

2. Materials and methods

2.1. Site description

The Coweeta Hydrologic Laboratory (US Forest Service) is located in the southern Appalachians near Otto, NC, and encompasses a 1626 ha basin, which drains into Coweeta Creek, a tributary of the Little Tennessee River (Swank and Crossley, 1988). Annual precipitation is 1900 mm with a mean annual air temperature of 12.6 °C. Our study was carried out in four low-elevation (700–780 m) watersheds (WS): WS 6 (formerly grassland, grass herbicided 1966, now deciduous regrowth); WS 13 (coppiced deciduous forest, treated in 1962); WS 17 (white pine plantation established in 1956) and WS 18 ("control" mixed hardwood, undisturbed since 1927). These same sites were studied by Coleman and Pomeroy (unpublished) in 1971–72. All are on Typic Hapludults, in the Cowee–Evard gravelly loam series (Swank and Crossley, 1988), on east or northeast-facing slopes.

2.2. Methods

The CO_2–C output in all four watersheds was determined using an alkali absorption technique (Coleman, 1973a,b). At each site 10 aluminum cylinders, of the same diameter (10 cm), as used by Coleman and Pomeroy (unpublished), were installed to 5 cm depth. In 1971–1972, 24 h measurements were made monthly for 16 months. In 1995, measurements were made for 24 h once each in July, August, and in December. Excess alkali (2 M NaOH) remaining after the 24 h absorption was titrated with 2N HCl to the thymolphthalein endpoint, after precipitating the carbonate with $BaCl_2$. We used jars with 25% of the surface area of the cylinders, to optimize the rate of CO_2 absorption (Kirita and Hozumi, 1966).

After titrating, CO_2 evolution rates were calculated as follows: CO_2–C (mg) $= (B - V)NE$; where B is the HCl (ml) needed to titrate the NaOH solution from the control, V is the HCl (ml) needed to titrate the NaOH solution in the jars exposed to the soil atmosphere, $N = 2.0$ (HCl molarity) and E is the equivalent weight (6 for C; 22 for CO_2) (Alef, 1995). These values were corrected to a 24 h basis. All values were converted to g CO_2–C/m^2/24 h.

2.3. Climate data

Climate measurements from nearby weather stations were used for temperature and moisture. Temperature and precipitation information was obtained from long-term monthly records, in the Coweeta LTER data base (www.coweeta.ecology.uga.edu). Soil gravimetric moisture values were estimated using the equation of Helvey et al. (1972) (for 0–30 cm depth, low elevation sites) extrapolating from the 21-day cumulative mean precipitation preceding the actual date of soil respiration measurement.

2.4. Statistical analyses

Analyses of variance (ANOVA) (Proc glm, SAS Inst., 1996) followed by Tukey's multiple range test were used initially to compare rates of soil respiration among the four watersheds within years. Subsequent ANOVA compared respiration rates among months and years. A "global" analysis of covariance (ANCOVA) was performed in order to partition the variance in soil respiration among effects of watershed, year, month, temperature, and soil moisture. Multiple regression analyses (Proc glm, SAS Inst., 1996) were used to further define the relationships among soil respiration, temperature, and soil moisture. Finally, any changes in temperature or moisture that might drive yearly differences in soil respiration were assessed using ANOVA.

3. Results

3.1. Abiotic data (temperature and soil moisture)

Temperature values ranged from lows of 2.9 in midwinter to highs of 21 and 22 °C in late summer (Fig. 1A). Overall, temperatures did not vary between identical dates in 1971 and 1995 ($F = 0.04$, d.f. $= 1, 22$, $P = 0.843$) and 1971 temperatures were, on

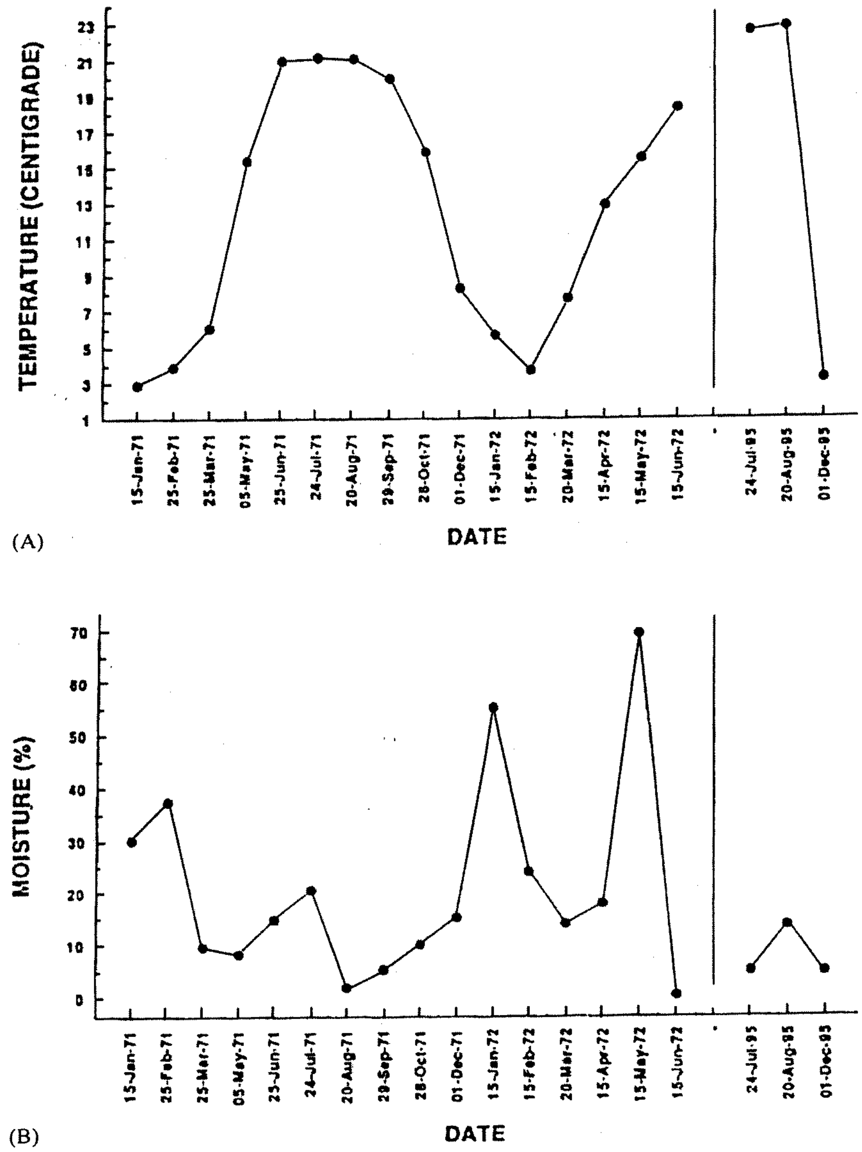

Fig. 1. Temporal changes in (A) temperature and (B) soil moisture during 1971, 1972, and 1995 at the Coweeta Hydrologic Laboratory, NC. Neither temperature nor moisture vary among years.

average, about 0.6 °C warmer than those in 1995. Moisture values ranged from 0.4 up to 69 wt.% across seasons and years (Fig. 1B). All determinations were for the upper 10 cm in the soil profile. As before, moisture values did not vary between 1971 and 1995 ($F = 3.23$, d.f. $= 1, 22$, $P = 0.086$) and were, on average, 5% higher in 1971 than 1995.

3.2. 1971–1972 Soil respiration data

The 1971–72 data (Fig. 2) showed seasonal trends in soil respiration with maximum rates occurring June through August. Watersheds 17 (pine plantation) and 18 (deciduous forest) had soil respiration rates marginally lower than WS 6 (deciduous regrowth)

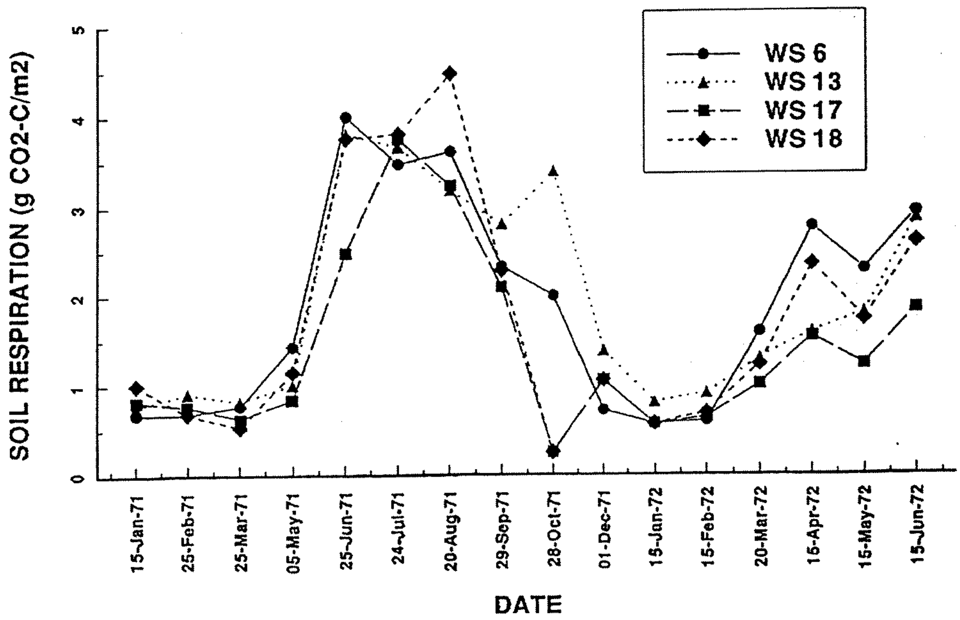

Fig. 2. Soil respiration (g CO_2–C/m^2 per day) during 1972/1973 in four watersheds (WS) at the Coweeta Hydrologic Laboratory, NC. Each point is the mean of 10 replicates per site. WS 6 = former grassland, WS 13 = coppiced, WS 17 = pine plantation, WS 18 = mixed hardwood.

and 13 (previously coppiced woodland) ($P = 0.0523$). However, differences among watersheds were minimal (Fig. 2). In both years, the summertime maxima were between 3 and 5 g CO_2–C/m^2/24 h.

3.3. 1995 Soil respiration data

In 1995, CO_2–C efflux showed a marked but consistent fluctuation both among watersheds and over

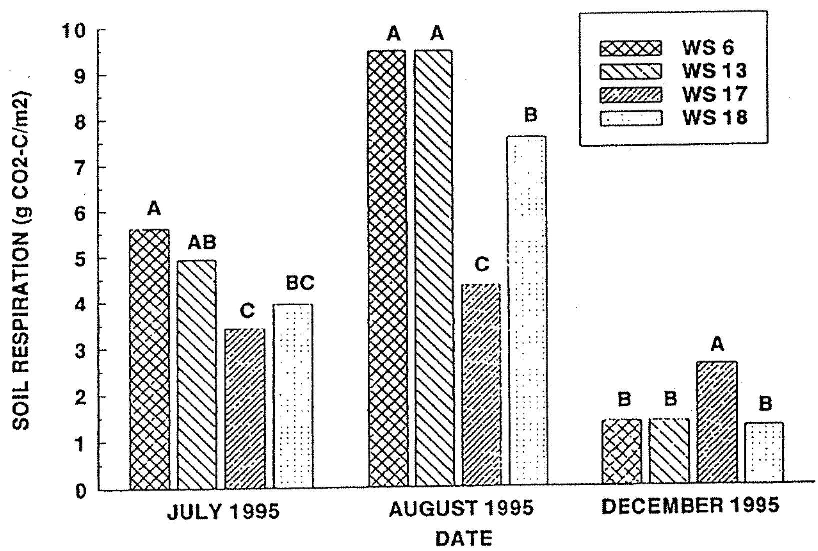

Fig. 3. Soil respiration (g CO_2–C/m^2 per day) during 1995 in four watersheds (WS) at the Coweeta Hydrologic Laboratory, NC. Each bar represents the mean of 10 replicates per site and bars with the same letters within groups are not significantly different from one another. WS 6 = former grassland, WS 13 = coppiced, WS 17 = pine plantation, WS 18 = mixed hardwood.

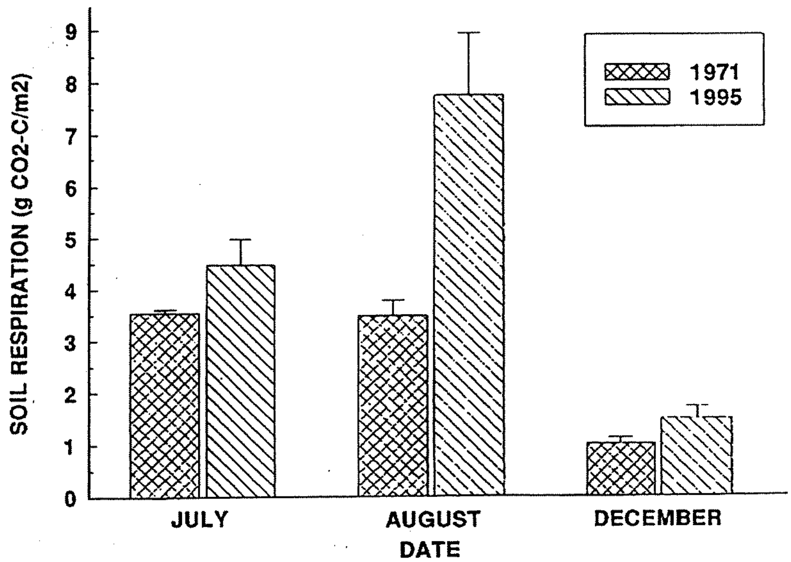

Fig. 4. Soil respiration (g CO_2–C/m^2 per day) during July, August and December of 1971 and 1995 at the Coweeta Hydrologic Laboratory, NC. Bars (± standard errors) are the means of four watersheds (WS) per date.

time (Fig. 3), ranging from a high of 9.54 g CO_2–C/m^2 per year in August in WS 6 (former grassland) and 13 (coppiced) to a low of 1.44 g CO_2–C/m^2 per year in December in WS 18 (hardwood). WS 6 and 13 showed the highest respiration rates in July and August, whereas WS 17 had a CO_2–C output twice that of all of the other watersheds in December (Fig. 3).

3.4. Respiration across years

Rates of soil respiration were higher in 1995 than in 1971 or 1972 ($F = 22.27$, d.f. $= 2, 57$, $P < 0.0001$). Direct comparisons of July, August and December in 1971 and 1995 indicate that the greatest difference was in August (Fig. 4) when 1995 rates were more than double those of 1971.

3.5. Principal abiotic drivers of soil respiration

In multiple regression analyses, temperature was a significant predictor of soil respiration rates on all four watersheds. P-values varied from 0.005 to less than 0.0001, and R^2 values from 0.54 to 0.65. Slopes did not differ among watersheds. In no case was soil moisture a significant predictor of soil respiration in multiple regression.

3.6. A global model of soil respiration

Overall, a combined model including year, watershed, month, temperature and soil moisture explained 87% of the variance in soil respiration observed over the quarter century of measurements (Table 1). Month and year had the greatest impact on soil respiration (35 and 37% of variance, respectively), whereas temperature and soil moisture had the weakest (5 and 4%, respectively).

Table 1
Results of a global ANCOVA model to explain variance in soil respiration measured in 1971, 1972, and 1995 across four watersheds at the Coweeta Hydrologic Laboratory, Otto, NC

Factor	Type III sums of squares	P-value	Variance explained (%)
Year	26.40	0.0001	35
Watershed	4.76	0.0523	6
Month	28.64	0.0001	37
Temperature	3.49	0.0174	5
Soil moisture	2.59	0.0395	4
Total	–	–	87

4. Discussion

CO_2 evolution from the soil–litter system is governed directly or indirectly by two major environmental factors, temperature and moisture (Singh and Gupta, 1977). All watersheds reached their peak respiration rates in August and then decreased steadily towards December. WS 17, the only evergreen site, had the lowest respiration rates in the summer months but then, as the other sites dropped to between 0.3 and 0.2 of their August rates by December, WS 17 was only 2–3% lower. Several studies show a similar temporal pattern with a seasonal maximum in middle to late summer, followed by a rapid decrease during Autumn (Anderson, 1973; Edwards and Harris, 1977; Toland and Zak, 1994). The patterns of respiration, but not absolute values, compare well with those obtained in 1971–1972. The earlier study also showed that all watersheds' respiration rates peaked in July, or August of 1971. The rates then decreased to approximately 20% for WS 6 and 50% of the peak for WS 13 by December with a further decrease in January and February.

4.1. Comparisons between years

For the 1995 data, watershed 17 (pine plantation) was statistically lower than the others in July and August. The Tukey Grouping linked watersheds 13 and 6 together in every month. This was expected, as the two are similar elevation, regenerating mixed hardwood stands of similar ages. The maximal WS 18 hardwood forest soil respiration output in 1971, 4.3 g CO_2–C, compares with the maximal seasonal value for a mixed deciduous woodland at Oak Ridge, TN, measured by dynamic techniques, of 6.8 g CO_2–C (Edwards and Harris, 1977). However, this is well under our mid-August maximum of 9.5 g CO_2–C/24 h in 1995. Mid-July CO_2 outputs in 1995 were similarly elevated over patterns measured a quarter-century earlier. This consistently higher output rate is comparable to the maximal efflux rates of Knoepp and Vose (unpublished data) measured in mid-July, 1997, in a site <1 km distant, with instantaneous measures of carbon dioxide efflux using IRGA techniques. Their values were: 1.10 for NaOH; 2.75 for open chamber and 1.97 for gas chromatograph systems. Knoepp and Swank (1994), in a study of changes in soils of WS 17 and 18, found decreases in C, N and cation concentrations over the time period from 1970–1990. Increased root mass was also found on another similar watershed, WS 1 (Knoepp and Swank, unpublished data). Perhaps due to decreasing nutrient availability, C allocation to the roots has increased to explore a greater volume of soil.

Estimates of temperature and soil moisture were very similar in 1995 and 1971, suggesting that these primary abiotic drivers are not responsible for the elevated rates of soil respiration in 1995. In fact, "year" explained 35% of the total variance in rates of respiration, whereas temperature and moisture explained only 5 and 4%, respectively. In sum, despite very similar levels of temperature and soil moisture, there was a significantly increased amount of carbon dioxide evolved in the same four Coweeta watersheds in 1995 compared with 1971 and 1972.

5. Conclusions

Summer CO_2 output from aggrading stands of hardwood forest at Coweeta more than doubled across a span of 23–24 years. Perhaps this increase in daily CO_2 outputs over a quarter century reflects greater standing crops of microbial biomass, and increased root growth.

Acknowledgements

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