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Controls on soil respiration: Implications for climate change

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The disruption of the global C cycle by human activity in both developed and developing countries is one of the key environmental issues facing human populations as we move into the 21st century. The earth contains approximately 10^8 Pg C in the following principal pools: (1) geological formations in the earth's crust (90,000,000 Pg), (2) dissolved oceanic carbonates (38,000 Pg); (3) gas hydrates, primarily methane hydrate, (10,000 Pg), (4) fossil fuels (4,000 Pg), (5) terrestrial biosphere (560 Pg), (6) soils (1,600 Pg), and (7) atmosphere (750 Pg) (Sundquist 1993; Kvenvolden 1993). Natural systems and biogeochemical cycles have historically maintained these pools in dynamic equilibrium. More recently, anthropogenic activities such as deforestation, agricultural practices, and the burning of fossil fuels have resulted in large shifts among carbon pools, particularly since the beginning of the industrial revolution (IPCC 1995). Estimates of the current global carbon budget indicate atmospheric sources of $\sim$1.6 Pg C yr^{-1} via tropical deforestation and other land-use changes and $\sim$5.4 Pg C yr^{-1} via burning of fossils fuels (Tans et al. 1990; Sundquist 1993). These atmospheric sources are balanced by a $\sim$2.0 Pg C yr^{-1} oceanic sink and a $\sim$3.3 Pg C yr^{-1} atmospheric sink. Recent evidence indicates that the imbalance, $\sim$1.7 Pg C yr^{-1}, is probably accounted for in carbon sinks in terrestrial ecosystems in the Northern temperate latitudes (Ciais et al. 1995).

Atmospheric CO_2 concentrations have been increasing in response to these disruptions to the carbon cycle (IPCC 1995; Keeling et al. 1989). This has raised concerns about potential global warming and, perhaps more seriously, about possible positive feedback effects that warming could have on further release of CO_2 from terrestrial carbon pools, particularly soils (Gates et al. 1992; Houghton et al. 1996; Mann et al. 1998). World soils contain an estimated 1550 Pg C in the surface meter alone (Eswaran et al.

1993). This is more than two times the amount of carbon in the atmosphere. Increased storage of carbon in world soils could help offset further anthropogenic emissions of CO_2, whereas a release could significantly exacerbate the atmospheric increases.

The flux of carbon from soils to the atmosphere occurs primarily in the form of CO_2, and is the result of 'soil respiration'. Soil respiration represents the combined respiration of roots and soil micro and macro-organisms. Estimates of the magnitude of this flux range from 68 Pg C yr^{-1} (Raich & Schlesinger 1992) to 100 Pg C yr^{-1} (Musselman & Fox 1991), which makes soil respiration one of the major pathways of flux in the global C cycle, second only to gross primary productivity, which is estimated to range from 100 to 120 Pg C yr^{-1} (Houghton & Woodwell 1989). Even a small change in soil respiration could thus equal or exceed the annual input of CO_2 to the atmosphere via land-use changes and/or fossil fuel combustion, and could significantly exacerbate – or mitigate – atmospheric increases of CO_2, with consequent feedbacks to climate change. However, despite its global significance as well as the dedication of considerable scientific resources to its study over the last several decades, we have only a limited understanding of the magnitude of soil respiration within and across ecosystems (for recent reviews, see Raich & Nadelhoffer 1989; Raich & Schlesinger 1992; Raich & Potter 1995) and the factors controlling soil respiration.

Critical factors reported to influence rates of soil respiration include (1) temperature (Witkamp 1969; Singh & Gupta 1977; Schleser 1982; Schlenter & Van Cleve 1985; Peterjohn et al. 1993, 1994; Kirschbaum 1996; Winkler et al. 1996; Rustad & Fernandez 1998), (2) soil moisture (Howard & Howard 1979; Schlenter & Van Cleve 1985; Singh & Gupta 1977; Davidson et al. 1998), (3) vegetation and substrate quality (Tewary et al. 1982; Raich & Schlesinger 1992), (4) net ecosystem productivity (Schlesinger 1977; Raich & Potter 1995), (5) the relative allocation of NPP above- and belowground (Boone et al. 1998), (6) population and community dynamics of the aboveground vegetation and belowground flora and fauna (Raich & Schlesinger 1992), and (7) land-use and/or disturbance regimes, including fire (Ewel et al. 1987; Gordon et al. 1987; Weber 1990). Despite this complex array of factors which affect soil respiration, soil respiration is typically modeled as either a simple Q_{10} function or as a step relationship based on temperature response curves.

A contributing factor to our limited understanding of soil respiration is a lack of consensus on methods for measuring soil respiration. Measurement techniques range from relatively simple static chamber methods with soda lime (Edwards 1975), to dynamic open or closed flow-through chamber methods utilizing gas chromatography (Ewel et al. 1987; Rochette et al.

1991) or infrared gas analysis (IRGA), to calculations based on soil air CO_2 concentrations and diffusivity constants (De Jong & Schappert 1972), to micrometeorological techniques based on eddy correlations and concentration gradients (Chahuneau et al. 1989). Although several recent papers have compared two or more of these techniques (De Jong et al. 1979; Raich et al. 1990; Rochette et al. 1992; Jensen et al. 1996), a comprehensive study contrasting all techniques has not yet been reported, making it difficult to compare data collected from different sites with different methods. The quantification of measurement error is also a formidable challenge. As an example of the problems involved, Healy et al. (1996) have discussed the theoretical basis for the measurement (diffusion through a porous medium) and concluded that chamber measurements should underestimate flux because of distortion to the concentration gradient that are imposed at the instant of chamber placement. They further noted that theory dictates that the observed chamber headspace CO_2 concentration time series should show a continuously declining rate of increase in CO_2 concentration. However, in practice, chamber methods have been shown to result in higher estimates of soil respiration than measured by eddy flux towers (night-time respiration measured above the canopy or daytime respiration measured in below-canopy towers) (Goulden et al. 1996). Furthermore, chamber-based field measurements have shown a consistent pattern of first increasing followed by decreasing rates of increase in headspace CO_2 concentration during 5-minute measurement periods (Huntington et al. 1998). More research on the measurement techniques is required to resolve these apparent inconsistencies.

Problems of spatial and temporal scale also need to be addressed, particularly the problem of scaling-up results from small chambers to the stand or ecosystem level, let alone the regional or global level. Finally, although total and/or heterotrophic respiration has received considerable attention in recent decades, much less is known about the contribution of autotrophic respiration, or root respiration, to total respiration. Again, limitations in available methods to separate autotrophic and heterotrophic respiration have impeded progress in understanding potential differential responses of autotrophic and heterotrophic respiration to changing environmental factors and resource limitations.

It is considered likely that global warming will increase soil respiration, releasing more CO_2 that will further exacerbate warming (Schleser 1982; Raich & Schlesinger 1992; Townsend et al. 1992; Schimel et al. 1994; McGuire et al. 1995). It is therefore critical to develop a better understanding of the controls on soil respiration and its components, particularly the decomposition of soil organic matter (SOM). This should promote a better assessment of the rate and direction of change of soil carbon, which is an essential component of developing and implementing policies and measures to mitigate climate change. To address this information need, a symposium on “Controls on Soil Respiration: Implications for Climate Change” was held at the annual meetings of the Soil Science Society of America in Anaheim, CA on 27–28 October 1997. The following seven papers highlight the results from this symposium, and include a general introduction to soil respiration (Schlesinger & Andrews), a review of the likely impact of global warming on soil respiration and soil C storage (Kirschbaum et al.), an evaluation of the role of soil water on rates of soil respiration in forests and cattle pastures of eastern Amazonia (Davidson et al.), an evaluation of relationships between vegetation and soil respiration (Raich), a review of methods for separating root versus microbial respiration (Hanson et al.), a description of a model simulating cold season heterotrophic respiration (McGuire et al.), and a review of management options for reducing CO_2 emissions from agricultural soils (Paustian et al.).

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