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Soil respiration and the global carbon cycle

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Abstract. Soil respiration is the primary path by which CO_2 fixed by land plants returns to the atmosphere. Estimated at approximately 75×10^{15} gC/yr, this large natural flux is likely to increase due to changes in the Earth's condition. The objective of this paper is to provide a brief scientific review for policymakers who are concerned that changes in soil respiration may contribute to the rise in CO_2 in Earth's atmosphere. Rising concentrations of CO_2 in the atmosphere will increase the flux of CO_2 from soils, while simultaneously leaving a greater store of carbon in the soil. Traditional tillage cultivation and rising temperature increase the flux of CO_2 from soils without increasing the stock of soil organic matter. Increasing deposition of nitrogen from the atmosphere may lead to the sequestration of carbon in vegetation and soils. The response of the land biosphere to simultaneous changes in all of these factors is unknown, but a large increase in the soil carbon pool seems unlikely to moderate the rise in atmospheric CO_2 during the next century.

Introduction

Some of the earliest measurements of soil respiration – the emission of CO_2 from the soil surface – were made nearly 80 years ago (Gainey 1919). Now, the total global emission of CO_2 from soils is recognized as one of the largest fluxes in the global carbon cycle (Figure 1), and small changes in the magnitude of soil respiration could have a large effect on the concentration of CO_2 in the atmosphere. As an aid to policy makers, this paper provides a short scientific review of some of the expected changes in the flux of CO_2 from soils that may accompany changes in the global environment.

A number of papers have compiled data from field studies and estimated the global flux of CO_2 from soils; there is no attempt to provide a new review of this literature here. For example, Schlesinger (1977) estimated the global flux at approximately 75×10^{15} gC/yr, roughly 2.5× larger than the input of fresh debris to the soil surface. Raich and Schlesinger (1992) compiled all available studies from the literature and calculated a global flux of 68×10^{15} gC/yr from soils. And, more recently, Raich and Potter (1995) updated that estimate, showing a global flux of 77×10^{15} gC/yr from soil respiration. All

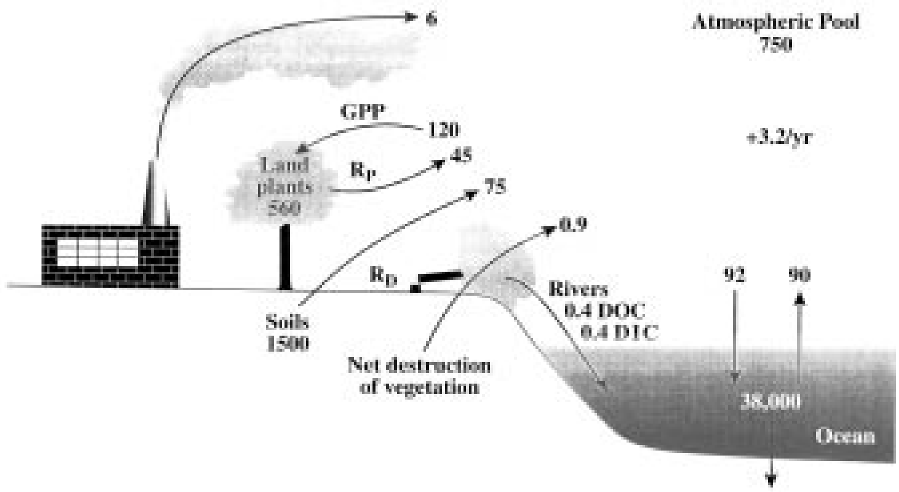

Figure 1. The global carbon cycle. All pools are expressed in units of 10^{15} gC and all fluxes in units of 10^{15} gC/yr, averaged for the 1980s. Modified from Schlesinger (1997).

these estimates are roughly compatible with estimates of net primary production (NPP; Field et al. 1998) and litterfall (Matthews 1997) in the range of 50 to 60 $\times$ 10^{15} gC/yr. Soil respiration is higher than NPP because of the respiration of plant roots and mycorrhizae. Representatives from government and industry should realize that while these fluxes are large, the uptake and loss of carbon by land plants and soils were closely balanced before human intervention. It is *changes* in the flux of CO_2 from human activities, including the disruption of soils, that play a role in the rise of atmospheric CO_2 and the potential for global warming.

It is not surprising that the flux of CO_2 from soils is closely tied to plant growth, which supplies organic residues to decomposers. Across major world biomes, Raich and Schlesinger (1992) show a direct relationship between soil respiration and NPP, with an $r^2 = 0.87$. When organic carbon is added to soils, the rate of soil respiration increases (Gallardo & Schlesinger 1994; Hogberg & Ekblad 1996). The greatest rates of soil respiration are found in the tropics, where plant growth is luxuriant and the conditions are ideal for decomposers.

Adjusting for the contributions from live root respiration, the flux of CO_2 from soils indicates an overall mean residence time (mass/flux) of 32 years for carbon in soil organic matter (Raich & Schlesinger 1992). However, this differs strongly between regions, and most models of soil carbon dynamics find it convenient to view the mass of soil organic matter as consisting of several pools with different turnover times. Typically a small amount of detritus, consisting of fresh residues, is found near the soil surface, where the input from litterfall and fine root turnover is greatest. Larger pools of humic substances are found dispersed throughout the soil profile, where they are often complexed with soil minerals.

Trumbore (1993) developed a 4-compartment model of soil organic matter, with turnover times ranging from 10 to 10000 years, based on the radiocarbon content of individual fractions. In postulating changes in the flux of carbon from soils, one must focus on changes in the labile pools near the surface. A sink for carbon in soil organic matter will appear most rapidly in the small pools with rapid turnover, while the immediate sink for carbon in humus is very small (Schlesinger 1990). Similarly, an increased flux of CO_2 from soils as a result of disturbance or global warming will largely derive from labile pools with the fastest turnover times.

Elevated atmospheric CO_2

All other variables held constant, one would expect that the rise in atmospheric CO_2, to the extent that it increases plant growth, should result in a greater delivery of plant debris to the soil, where a small fraction will remain undecomposed and contribute to a sink for atmospheric CO_2 (Van Veen et al. 1991). This process is perhaps aided by the fact that the largest increases in plant growth are often seen underground, as a result of plant allocations to roots and root activities (Rogers et al. 1994). Using a model with donor-compartment control, Harrison et al. (1993) suggested that the CO_2 stimulation of plant growth might explain about half of the "missing sink" for atmospheric CO_2 as a result of a greater storage of carbon in soils. A few field experiments suggest that soil organic matter increases when plants are grown at high CO_2 (Wood et al. 1994; Hungate et al. 1997). We believe, however, that many recent estimates of the global sink for carbon in soils are overly optimistic, because the microbial community in most soils is limited by the availability of organic substrates (Zak et al. 1994). Give them more carbon, and the microbes will happily decompose it! The exception, of course, is in the boreal forest, where cold temperatures inhibit decomposition and large quantities of organic debris accumulate in soils (Schlesinger 1977).

Increased activity of the belowground microbial community was seen when a grassland community in California was exposed to elevated CO_2 for 3 years (Hungate et al. 1997). The flux of CO_2 from the soil surface increased from 323 $gC/m^2/yr$ to 440 $gC/m^2/yr$. Similar responses were seen in a 15-year-old stand of loblolly pine, maintained under Free Air CO_2 Enrichment (FACE) in North Carolina; the concentration of CO_2 in the soil pore space and the flux of CO_2 from the soil surface both increased approximately 30% over values seen in ambient conditions (Figure 2). About 30 to 50%

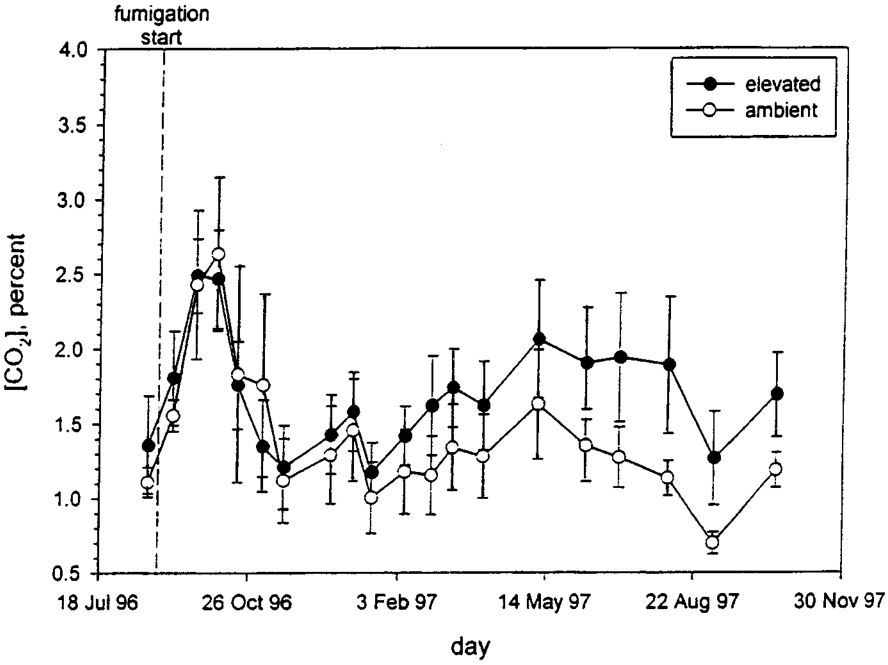

Figure 2. Concentration of CO_2 at 30-cm depth in the soil of 15-year old loblolly pine (*Pinus taeda*) plantations exposed to 550 ppm atmospheric CO_2, compared to that measured in reference stands at ambient CO_2. Unpublished data of the authors.

of the soil respiration of CO_2 is derived from root activity and the remainder from soil microbes (Bowden et al. 1993; Andrews et al., in press). Thus, plant growth at high CO_2 may add additional carbon to soils, but most of it is likely to return to the atmosphere as CO_2.

Elevated global temperature

If the Earth's temperature rises due to the greenhouse effect, we can expect soils, globally, to be warmer, especially at high latitudes. Except in some deserts, soil respiration increases with increasing temperature – seen both in compilations of literature values (Raich & Schlesinger 1992) and in studies with imposed soil warming (Peterjohn et al. 1994; Christensen et al. 1997; Rustad & Fernandez 1998). The increase in soil respiration per 10 ° C rise in temperature – the Q_{10} of the relationship – is about 2.0 (Kirschbaum 1995; Palmer-Winkler et al. 1996; Kätterer et al. 1998). The greatest response is found in samples of surface detritus and in soils from cold climates (Lloyd & Taylor 1994; Niklińska et al. 1999). Root respiration is particularly responsive to increases in temperature, showing a Q_{10} as high as 4.6 (Boone et al. 1998). Nearly all models of global climate change predict a loss of carbon from soils as a result of global warming (Schimel et al. 1994; McGuire et al. 1995).

Trumbore et al. (1996) suggested that the greatest losses of soil carbon would be seen in tropical regions, where their measurements of radiocarbon content show a large pool of soil organic matter with a relatively rapid turnover time (cf. McGuire et al. 1995). By themselves, however, radiocarbon measurements of turnover belie the situation in boreal forest and tundra habitats. As a result of cold, water-logged conditions, organic matter accumulates in these soils (Harden et al. 1997; Trumbore & Harden 1997). Radiocarbon measurements indicate limited turnover, but nearly all the organic matter is found in labile fractions that will be easily decomposed should the climate warm (Chapman & Thurlow 1998; Lindroth et al. 1998). Indeed, Oechel et al. (1993, 1995) found evidence of a large loss of soil organic matter in tundra habitats as a result of recent climatic warming in Alaska, and Goulden et al. (1998) found a significant loss of carbon from soils during several warm years, which caused an early spring thaw in a boreal forest of Manitoba. In the tundra, melting of permafrost and concomitant lowering of the water table may lead to a large increase in decomposition (Billings et al. 1983; Moore & Knowles 1989). We believe that in response to global warming, the losses of carbon from soils will be greatest in regions of boreal forest and tundra, which have the largest store of labile organic matter and the greatest predicted rise in temperature. Large losses of CO_2 from these soils could reinforce the greenhouse-warming of Earth's atmosphere (Woodwell 1995).

Elevated CO_2 and temperature

Of course, the most important scenario to understand – and unfortunately the scenario we know least about – is one with simultaneous increases in CO_2 and global temperature. Will soils be a net source or sink for carbon in these future conditions on our planet? Publicly, one of us has argued[1] that nature has performed this experiment for us: tropical rainforests have high NPP (as with higher CO_2) and warm, wet conditions (as with most models of global warming), yet the carbon content of tropical soils is much smaller than that of the boreal region (Schlesinger 1977; Batjes 1996). Cebrian and Duarte (1995) find only weak correlations between the pool of soil organic matter and NPP across world biomes (Figure 3). Apparently, large accumulations of soil organic matter do not derive from large inputs, but rather, soil organic matter accumulates where other factors (e.g., temperature) limit decomposers. As the planet warms, the area of temperature-limited decomposition should decline, and soils increasingly should become a source of CO_2 to the atmosphere.

Using the process-based model TEM, McGuire et al. (1995) argue that soils will be a sink for 28×10^{15} gC in soil organic matter under conditions of +1 °C in global temperature and 650 ppm in atmospheric CO_2. Occurring during the next 50 years, this sink is trivial (0.5×10^{15} gC/yr) compared to fossil fuel emissions, which rise to $\sim 15 \times 10^{15}$ gC/yr over the same interval. Consistent with this model, Oechel et al. (1994) found only a small sink in tundra soils that were exposed simultaneously to high CO_2 and warmer temperatures. McGuire et al. (1995) postulate that the largest absolute changes will occur in arid shrublands and xeromorphic woodlands, where it is logical to assume that higher NPP might leave a greater content of organic matter in soils, in which decomposition is co-limited by moisture and temperature (Wildung et al. 1975; Parker et al. 1983). The UN Convention to Combat Desertification recognizes that arid-land soils could serve as a sink for CO_2 with proper management.

Cultivation

When soils are disturbed through cultivation, their content of organic matter declines. The decline is seen because the conditions for decomposition – soil aeration and moisture content – are often improved when soils are disturbed, leading to greater rates of soil respiration, while the inputs of fresh plant debris to soils are lower when native vegetation is converted to agriculture. Cultivation also disrupts soil aggregates, exposing stable, adsorbed organic matter to decomposition (Elliott 1986; Six et al. 1998). Losses of carbon from cultivated soils may be as large as 0.8×10^{15} gC/yr globally (Schlesinger 1984). Increases in crop production needed to support the current exponential growth of the human population will require that new areas of land be brought into cultivation during the next century (Fischer & Heilig 1997) and existing agricultural lands be used intensively and efficiently.

The loss of soil organic matter is lower when "no-till" agriculture is practiced; indeed, the institution of no-till techniques on previously cultivated land may actually restore some soil organic matter (Dick 1983; Wood et al. 1991; Blevins et al. 1977; but see Campbell et al. 1999). Nevertheless, widespread use of no-till agriculture in the United States would act as a sink for only 277 to 452×10^{12} gC, about 1% of our fossil fuel emissions, during the next 30 years (Kern & Johnson 1993). Similarly, improved management and alternative land use for agricultural soils in Europe could potentially serve as a net sink for only 0.8% of the world's CO_2 release from fossil fuel combustion (Smith et al. 1997, 1998).

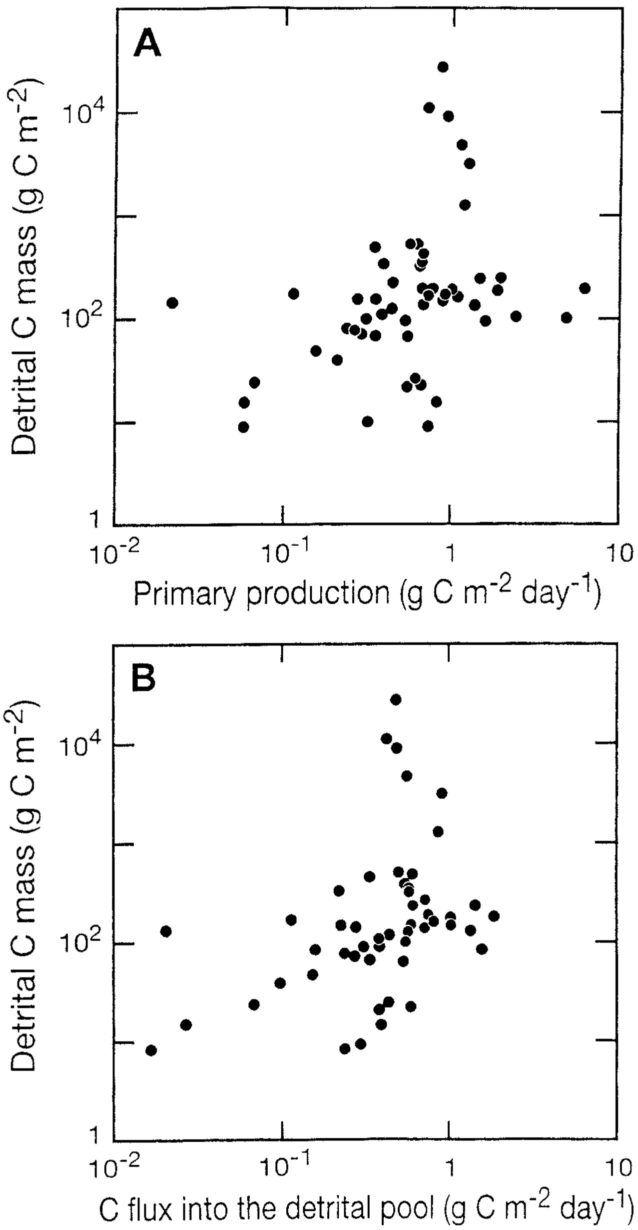

Figure 3. Relationships between the mass of soil organic matter (gC/m^2) and the net primary production (A) or litterfall deposition (B) in ecosystems of the world. From Cebrian and Duarte (1995).

In the U.S., the Conservation Reserve Program (CRP) allowed some farmland to be abandoned during the 1980s, and soil organic matter accumulated on these lands (Gebhart et al. 1994; Burke et al. 1995; Robles & Burke 1997). CRP lands may have accumulated as much as 17×10^{12} g of soil organic C during the last decade (Gebhart et al. 1994). Despite their value as wildlife habitat and a carbon sink, lands protected by the CRP program were nearly eliminated during the major congressional deregulation of agriculture in 1995. Policy makers should realize that some of the highest rates of carbon sequestration are found when cultivated soils are allowed to revert to native vegetation.

Nitrogen deposition

Recently, attention has focused on human contributions to the global nitrogen cycle, through the mobilization of fixed nitrogen in the atmosphere and its deposition in natural ecosystems (Galloway et al. 1995; Vitousek et al. 1997). Indeed, a substantial sink for carbon may be derived from the nitrogen fertilization of forests, especially if the nitrogen is stored in the form of wood, which carries a relatively high C/N ratio. Holland et al. (1997) suggest that nearly all of the carbon that is currently missing from the atmospheric budget of CO_2 could be accommodated by the stimulation of plant growth in response to nitrogen deposition. However, the large global sink for carbon in forests must be discounted because much of the nitrogen is deposited on lands that are cultivated or impacted by other pollutants (Townsend et al. 1996; Asner et al. 1997).

We know of no results from field experiments in which nitrogen has been added to an intact ecosystem maintained at elevated CO_2, but field fertilization experiments in natural ecosystems offer some insight to the potential changes in soil carbon storage and respiration that might be seen in regions of anthropogenic nitrogen deposition. Typically, only 10–20% of the nitrogen applied to forests accumulates in wood; a larger portion often accumulates in the soil organic matter, in which the C/N ratio is 12 to 15 (Table 1; Fenn et al. 1998; Nadelhoffer et al. 1999). Thus, we might expect that a carbon sink in soil organic matter could result from the nitrogen fertilization of forests. This expectation proves equivocal. Gallardo and Schlesinger (1994) found an increase in soil respiration when nitrogen was added experimentally to forest soils in central North Carolina. Similar results were reported in a temperate forest in Germany (Brume & Besse 1992), but not in abandoned agricultural fields in Canada (Kowalenko et al. 1978). Additions of nitrogen to forest soils often lower the C/N ratio without causing major changes in total amount of soil carbon (Neilsen et al. 1992; Harding & Jokela 1994). There

Table 1.

Ecosystem type	Age (years)	Method	Total application (kg N/ha)	Duration of study (years)	Percent recovery in: Plants	Litter	Soil: Inorganic	Soil: Organic	Leachate	Gaseous flux	Total measured recovery (%)	Reference
Pinus resinosa	50	(Treatement)–	276	6	21		1		1	Tr.	23	MaGille et al. (1997)
		(Control)	826	6	8		2		15	Tr.	25	
Mixed deciduous	50		276	6	20		1		2	Tr.	23	
			826	6	13		1		Tr.	Tr.	14	
Pinus contorta	11	$^{15}NH_4$	100	8	17	4	0	41			62	Preston and Mead (1994)
		$^{15}NO_3$	100	8	16	3	0	38			57	
Pinus elliottii	11	(Treatment)–	56	2	25	9		21			55	Mead and Pritchett (1975)
		(Control)	224		27	6		12			45	
Pinus radiata	16	(Treatment)– (Control)	922	9	15	5		21			50	Neilsen et al. (1992)
Pseudotsuga menziesii	35	$^{15}NH_4$	5	2	33	22		24	2		81	Koopmans et al. (1996)
			50	2	29	15		22	33		99	
Pinus sylvestris	45		5	2	10	46		20	10		86	
			50	2	17	21		16	17		71	

are several abiotic processes by which nitrogen can be fixed in soil organic matter (Johnson 1992). Thus, while plants respond to added fertilizers, it is unclear if large increases in soil carbon can be expected in areas that receive excess deposition of nitrogen from the atmosphere.

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Note

1. Schlesinger, W.H., Hearings before the U.S. Senate Subcommittee on Science, Technology and Space, 9 April 1992

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