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Warming accelerates decomposition of decades-old carbon in forest soils

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AUTHOR SUMMARY

Soils store more than two times as much carbon as the atmosphere, and the vulnerability of soil carbon to warming is a critical uncertainty in predictions of 21st century climate (1). In particular, the effect of warming on the decomposition of decades-old carbon, which makes up the majority of soil carbon stocks in temperate forest soils, is highly debated (2). We took advantage of a long-term carbon isotope label in forest soils in the eastern United States to show that soil carbon fixed more than 10 y ago is just as sensitive to warming as carbon fixed more recently. Some portion of soil carbon aged 7–13 y was even more sensitive to warming. If decades-old soil carbon stocks are released by increasing temperatures, they could accelerate global warming.

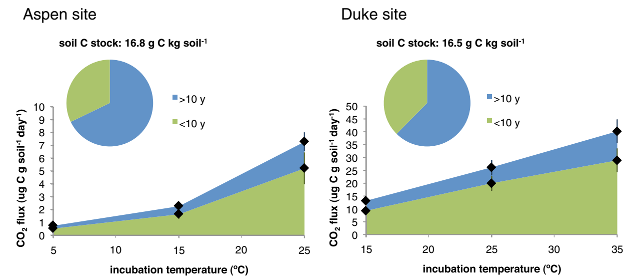

Fig. P1. The contribution of carbon fixed more than 10 y ago (blue, >10 y) and carbon fixed more recently (green, <10 y) to soil carbon stocks (pie charts) and decomposition-derived CO_2 fluxes under three temperature treatments at two sites (Aspen FACE and Duke FACE). Decades-old (>10 y) carbon made up 70% of carbon stored in the soil and 30% of CO_2 flux at all temperatures. The proportional increase in CO_2 flux of both age classes with warming suggests that they have similar vulnerability to increased decomposition as temperatures rise.

Decomposition of young soil carbon is well-known to be temperature-sensitive, but much less is known about the temperature response of older carbon, which constitutes a major component of soil carbon stocks. The temperature sensitivity of young soil carbon is commonly measured by the increase in decomposition-derived CO_2 fluxes with warming; however, older carbon is difficult to detect in CO_2 fluxes. We overcame this difficulty by using two carbon isotope approaches to distinguish the contribution of decades-old carbon to CO_2 fluxes in a laboratory incubation study.

The first approach uses elevated CO_2 plots in forest free air CO_2 enrichment (FACE) experiments: Aspen FACE in Wisconsin and Duke FACE in North Carolina. In FACE, the local atmosphere is enriched with fossil-derived CO_2 that has a markedly different radiocarbon (^{14}C) and stable carbon isotope (^{13}C) signature from the background atmosphere; therefore, carbon fixed since the start of CO_2 enrichment (more than 10 y ago) could be distinguished easily from carbon fixed after that time. The second approach uses the history ^{14}C in the atmosphere, which has declined since the early 1960s when large-scale atmospheric testing of nuclear weapons testing ended; this decline resulted in measurable differences in the ^{14}C content of carbon fixed from 1 y to the next. In nonenriched, ambient CO_2 plots, the ^{14}C signature of decomposing carbon indicates the mean time elapsed since it was originally fixed from the atmosphere. ^{14}C measurements of CO_2 efflux from soils of ambient CO_2 plots allow us to calculate the mean age of carbon being decomposed on timescales of years to decades. Applying these approaches at the two study sites, we determined that about two-thirds of carbon stored in the soil at each site was more than a decade old, consistent with other temperate and tropical estimates. In contrast, decomposing carbon, measured as CO_2 flux, is, on average, much younger than overall soil carbon. About one-third of actively decomposing carbon was more than a decade old; however, this finding is a much larger fraction of decades-old carbon than is typically assumed.

To study how temperature affected the age structure of decomposing carbon, we incubated topsoil from the two sites at three temperatures: mean annual site temperature (control) and warming by 10 °C and 20 °C over the control. As expected, warming consistently increased decomposition-derived CO_2 flux from the soils. The proportion of decades-old carbon decomposing did not change with warming, meaning that warming accelerated decomposition losses of older carbon and younger carbon to a similar extent (Fig. P1). This finding suggests that the temperature sensitivity of decades-old carbon is the same as the sensitivity of younger carbon.

Despite similar temperature sensitivity of the two age classes, the bomb ^{14}C tracer showed that warming increased the mean age of decomposing carbon by 3–5 y at both sites. On the basis of combined information from both these isotopic approaches, the increase in the age of decomposing carbon can be attributed to the greater decomposition of carbon of an intermediate age (7–13 y old) under the warming treatment. Thus, warming increased the amount of soil carbon actively decomposing in the form of slightly older carbon substrates.

Decades-old soil carbon constitutes a major component of soil carbon stocks, and thus, its temperature sensitivity ultimately controls the magnitude of feedback between soil carbon and climate warming (3). Fast-cycling carbon is relatively easier to study; it makes up the majority of decomposition-derived CO_2, but it is less important to soil carbon stocks. We could not measure carbon losses from older, passive pools (centuries to millennia old) using this approach, but very slow decomposition rates of passive carbon suggest that its temperature sensitivity is not important over the next century (4). Our

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finding that decades-old carbon is vulnerable to warming suggests the potential for release of soil carbon to the atmosphere as CO_2 as temperatures rise, which in turn, would lead to more warming.

Taken together, the temperature sensitivity of decades-old soil organic carbon and the increase in the amount of soil carbon decomposing highlight the vulnerability of soil carbon stocks to global warming. Although we do not have predictions of the amount of carbon globally in pools of decadal age, measurements of the ^{14}C content of surface soils indicate predominance of decadal-aged carbon in temperate forests (5). The results from our two temperate forest sites suggest that a large fraction (50–95%) of 0- to 15-cm soil carbon is in forms that will decompose faster when temperature increases.

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