Biogeochemistry

Soil warming and organic carbon content

Soils store two or three times more carbon than exists in the atmosphere as CO_2, and it is thought that the temperature sensitivity of decomposing organic matter in soil partly determines how much carbon will be transferred to the atmosphere as a result of global warming[1]. Giardina and Ryan[2] have questioned whether turnover times of soil carbon depend on temperature, however, on the basis of experiments involving isotope analysis and laboratory incubation of soils. We believe that their conclusions are undermined by methodological factors and also by their turnover times being estimated on the assumption that soil carbon exists as a single homogeneous pool, which can mask the dynamics of a smaller, temperature-dependent soil-carbon fraction. The real issue about release of carbon from soils to the atmosphere, however, is how temperature, soil water content and other factors interact to influence decomposition of soil organic matter. And, contrary to one interpretation[3] of Giardina and Ryan's results, we believe that positive feedback to global warming is still a concern.

Climate has long been believed to affect the accumulation of detrital carbon and nitrogen[4] — cool conditions and poor aeration in wet soils can impede decomposition[4], and soil carbon stocks are highest in cool and moist biomes and lowest in hot and dry biomes[5]; climate also affects plant productivity and the input of carbon to the soil. To determine decomposition (carbon output), a simplistic one-pool model (soil carbon stock/(field-measured soil respiration minus estimated root respiration)) can be used to calculate average turnover times (soil carbon stock/decomposition rate) of total soil carbon[6]. Although this one-pool model is not without problems (see later), a trend of increasing average turnover times with declining mean annual temperature and increasing latitude is apparent in these field data.

Temperature should not be viewed in isolation. For example, temperature affects evapotranspiration, which affects soil water content, which influences decomposition of soil organic matter (SOM)[1,6]. Climate is only one of a hierarchy of factors controlling decomposition, including clay mineralogy, chemical properties of leaf and root litter, activity of macrofauna and microorganisms, and disturbance[7]. Giardina and Ryan's proposal[2] that temperature has no effect on the turnover of soil carbon is based on their search for only a single factor in this complex matrix and also on, in our view, inappropriate tools and sampling design (involving a type II statistical error).

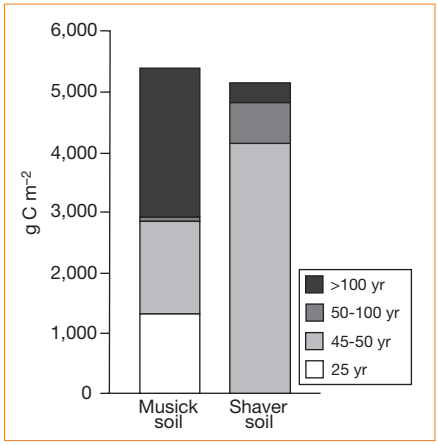

Figure 1 Radiocarbon estimates of turnover times of carbon fractions of two soils on an elevational gradient with similar parent material, vegetation and disturbance history[12]. Fractions were separated by density and hydrolysis for each soil depth[12]. The CO_2 that would be evolved during one-year incubations (98 and 92 g C m^{-2} yr^{-1} for Musick and Shaver soils, respectively) was calculated from carbon stocks and turnover times. Dividing respired CO_2 by total soil carbon, as Giardina and Ryan[2] do in their one-pool model, yields nearly identical turnover times estimates for the two soils (53 and 54 yr for Musick and Shaver soils, respectively). However, the cooler Shaver soil contains twice as much carbon with turnover times of about 50 yr and the warmer Musick soil has a small but important pool that cycles more rapidly.

Giardina and Ryan used changes in ^{13}C content of SOM following conversion of C_3 vegetation to C_4 vegetation, which necessitates different degrees of site disturbance. Ploughing causes rapid, large changes in decomposition, exposing SOM previously protected inside soil aggregates[8,9]. Conversion of forest to cattle pasture, however, causes only moderate soil disturbance and small changes in SOM decomposition[10]. The degree of disturbance may thus have a larger effect on calculated turnover times than either temperature or the time elapsed since disturbance.

Giardina and Ryan base their estimates of soil-carbon turnover times on the assumption that SOM can be represented as a single homogeneous pool, an approach that has yielded mixed results[2,6] because it ignores the widely varying age (from months to millennia)[11] of carbon in SOM. The proportion of SOM cycling over millennia ranges from zero to over 50%, depending on mineral type, clay content and soil depth. This variation has a large effect on the calculated turnover times when soil-carbon fractions that cycle at different rates are averaged together[11].

Figure 1 illustrates this point, showing results from radiocarbon analysis of two soils sampled along an elevation transect in the Sierra Nevada mountains of California[12], where turnover times of fractionated carbon pools in each soil range from 25 to over 1,000 years. Although the total soil carbon is comparable in both soils, the soil at lower elevation (Musick soil), which experiences higher annual temperatures and slightly less precipitation (not higher[2]), contains less labile carbon with a faster turnover time than the higher-elevation (Shaver) soil. Decomposition of the SOM fractions during a one-year incubation would sum to similar amounts of CO_2 for the two soils, hence the single-pool model of Giardina and Ryan would ascribe similar turnover times to both soils, obscuring the faster cycling of the smaller labile fraction of carbon in the warmer, lower-elevation soil.

Laboratory incubations, as used by Giardina and Ryan[2], involve procedures such as sieving and mixing, so are not comparable to decomposition *in situ*. In some soils, the small amount of easily decomposable humus can be spent before the end of a one-year incubation, so differences in calculated turnover times among samples may reflect different substrate limitations rather than temperature sensitivity[13]; they may also reflect differences in sampling depths, which affect the proportions of labile and non-labile carbon.

Rather than averaging turnover times of total extant SOM, it is the carbon that has already left the soil that may reveal the latitudinal importance of temperature on SOM dynamics — for example, slash-and-burn agriculture in the tropics must be abandoned after a few years as the small amount of labile soil humus releases nutrients for only a short time. By contrast, agricultural productivity in a northern temperate climate was maintained for decades without extra nutrients after ploughing soils with a similar sand content, but with more humus that decomposed gradually in the cooler climate[9]. Variations in mineralogy and aggregate stability also contribute to these differences.

The temperature sensitivity of soil carbon subject to climate change has been tested by fractionating SOM into pools that can be compared along climate gradients[9,11,12]. *In situ* experimental soil warming also increases soil CO_2 emissions unless it provokes drought[1]. Increased emission was limited to a few years after warming treatments began, indicating that only a fraction of the soil carbon is temperature-sensitive and supporting our assertion that carbon dynamics should be studied using multi-pool models.

In a field study along climate gradients[14], plant biomass increased in all the EUROFLUX sites, even those with a carbon budget close to neutral and one losing carbon annually — the site losing carbon was drained, exposing anaerobic soil layers to decomposition. Soil carbon loss also happens where warming helps to dry wetlands

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or thaw frozen soil[15]. The EUROFLUX sites with almost neutral carbon balance are at high latitudes where significant warming has occurred, which may provoke loss of soil carbon at a rate comparable to plant biomass gains[15].

Unlike Grace and Rayment[3], we consider that the key to climatic sensitivity of soil carbon is not total ecosystem respiration but decomposition rates (carbon loss per unit of fractionated carbon pool). The high respiration rates at the northern EUROFLUX sites[14] are probably due to detritus accumulation under cool moist conditions, and not to temperature insensitivity of decomposition; even slow turnover of large stocks produces a lot of CO_2.

We agree with Giardina and Ryan that temperature effects on soil carbon dynamics may be overestimated in current biogeochemical models. However, feedback to global warming does not concern just temperature, but also includes its effect on soil water content and drainage, for example, and applies to all detrital carbon, whether on top of mineral soil or buried in peatlands and permafrost.

On the basis of the new results[2,14], Grace and Rayment[3] suggest that the doomsday view of runaway global warming now seems unlikely. We believe that, on the contrary, the evidence remains in favour of a strong climatic control over storage of detrital carbon in terrestrial ecosystems.

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Giardina and Ryan reply — Davidson *et al.* question the validity of our conclusions on the grounds that differences in disturbance, high variability among sites, and the use of a single-pool model to estimate turnover time (TT) obscured the effect of temperature on the decomposition of soil carbon.

In our comparison of incubated soils, disturbance associated with sieving and mixing probably increased decomposition rates. However, soil processing was similar across sites, and the resulting increase in carbon availability should have accentuated an effect of temperature on TT. In our *in situ* comparison, most tropical sites were pastures and all of the temperate sites were cropped. But these differences did not obscure an effect of temperature on TT. First, a subset of tropical sites had been continuously cultivated with sugar cane, which involves biannual mechanized ploughing, burning and fertilization. For sites that had been similarly disturbed after conversion from forest — that is, under intensive cultivation — TT tended to increase with mean annual temperature (MAT; $R^2 = 0.14$, $P = 0.07$, $n = 25$). Second, tropical pastures are more severely disturbed than Davidson *et al.* suggest — bulldozers may be used to level a site and remove stumps, and mechanized disking is often used to control weeds[1,2]. Further, the effects of pasture conversion on carbon decomposition rates remain poorly understood[2].

There are two ways to test whether we missed significance because of high variability. First, how important is site-to-site variability? And second, given our sample size, how much variation must temperature explain in order to be significant? For the incubation comparison, variation in TT was low (coefficient of variation, 37%), and TT actually increased with temperature ($TT = 0.09 \times MAT + 6.2$). For the *in situ* comparison, time since conversion explained 34% of the variance in per cent carbon mass loss, a measure that assumes no model or age distribution of carbon in soil. With a sample size of 44 sites for the *in situ* comparison, MAT need only explain 8% of the variance to be significant at the 0.05 level. Given that MAT explained less than 1% of this variance, more than 1,000 sites would be needed to establish that there is a global relationship between temperature and soil carbon turnover.

We examined whether a single-pool model could obscure a temperature effect, and concluded that this is unlikely because our methods were robust[1,3], the tests were independent and well replicated, and neither comparison showed the negative trends between TT and temperature that would be expected from modelled patterns of carbon mass loss across latitude[4]. We agree with Davidson *et al.* that only a small fraction of total soil carbon may be sensitive to temperature — this was our point.

Although the ^{14}C approach preferred by Davidson *et al.* is useful for examining carbon turnover in soil, it has some methodological problems. For example, the ^{14}C decay of interest begins at photosynthesis, not after incorporation into soil, as is now assumed[1,5]. In forests, this lag could affect estimates of soil-carbon TT that are based on ^{14}C because carbon can reside in living biomass and the litter layer for decades before being released to mineral soil. The ^{14}C approach is also sensitive to contamination[3] and has yielded much faster estimates of soil-carbon turnover than more direct methods[1].

Modelling terrestrial carbon storage depends on an accurate understanding of how temperature affects carbon TT in soil, but this effect cannot be inferred from large-scale relationships between soil-carbon content and MAT. Along gradients similar to those used by Jenny[6] and cited by Davidson *et al.*, plant primary production declines with increasing MAT, and it is this decline, not an increase in soil-carbon decomposition rate, that explains decreasing soil-carbon content with increasing temperature[7]. Similar findings have been reported[8] for MAT gradients in northern Europe, and the gradient study cited by Davidson *et al.* actually reports[9] longer carbon TT for tropical forest than for temperate forest. Despite the evidence against an exponential effect of temperature on soil carbon turnover, future *in situ* warming studies are needed to settle this issue.

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