CLIMATE CHANGE

Comment on "Climate legacies drive global soil carbon stocks in terrestrial ecosystems"

Jonathan Sanderman

Delgado-Baquerizo *et al.* (*Science Advances*, 12 April 2017, e1602008) use statistical correlations to infer that paleoclimate (6000 to 22,000 years ago) is a more important driver of current soil organic carbon stocks than the current-day climate. On the other hand, a wealth of radiocarbon measurements indicates that the organic carbon in most topsoils is only a few decades to perhaps a few centuries old. These seemingly incongruous results can perhaps be reconciled by considering that the long-term pedogenic development of a soil strongly influences the physiochemical properties, which lead to stabilization of new carbon entering that soil regardless of current climate.

Delgado-Baquerizo *et al.* (*1*) present a compelling ecological story that paleoclimate rather than current climate is a better predictor of present-day soil organic carbon (SOC) stocks. The argument goes that if the past vegetative community was more productive than the current-day ecosystem due to a more favorable climate, then the soil under that past vegetation would have had higher organic carbon stocks and that those higher SOC stocks would still persist today even under a less favorable current climate for building large SOC stocks in the absence of agricultural activities.

Soil scientists have a powerful tool to directly assess the mean age and turnover time of SOC in the form of radiocarbon measurements (*2*). More than 1000 globally distributed radiocarbon measurements of SOC (*3*) suggest that the average radiocarbon age of SOC in the upper 10 cm of soil is only a few decades to at most a few centuries old (Fig. 1). Therefore, little if any of the current SOC contained in the upper 10 cm is derived from the vegetative community 22,000 or even 6000 years ago. Carbon cycling in the topsoil is simply way to fast in all but the most extreme environments to preserve any paleovegetation signal.

Although one-off soil radiocarbon measurements such as presented in Fig. 1 give an indication of the mean radiocarbon age of the entire SOC pool, more detailed information on turnover rates can be obtained from time series radiocarbon measurements of SOC during the atmospheric nuclear weapons testing period (1960 to present). Typical of the results obtained using this approach, Sanderman *et al.* (*4*) found that bulk SOC turnover rates varied from 30 to 40 years in low-productivity crop-fallow system to under 10 years under a highly productive pasture for the same soil in a Mediterranean climate.

Thus far, I have only discussed radiocarbon measurements on bulk soil samples. Decades of research indicate that SOC is made up of materials with a wide range of turnover rates (*5*). Most radiocarbon data indicate that a large fraction of topsoil carbon cycles at decadal or faster time scales. But, multipool modeling and chemical fraction methods reveal that there is also a highly resistant fraction of SOC that can be up to a few thousand years old (*6*). This highly resistant fraction can comprise 20 to 60% of the SOC (*4*, *6*), suggesting that this carbon was incorporated into the soil under a different climate than found today but the relevant paleoclimate period should be at most 2000 years before present.

Further examination of Fig. 1 reveals that it is only below 50 cm that a small fraction of soils start to contain organic carbon with mean radiocarbon ages approaching 6000 to 22,000 years. At greater depths is where the authors' argument should be strongest, but strangely, the correlations with paleoclimate fell apart with increasing depth [figure S5 of Delgado-Baquerizo *et al.* (*1*)]. In Fig. 1, most of the sites with exceedingly old $\Delta^{14}C$ values were permafrost-affected soils. In many current permafrost regions, the amount of SOC contained in the permafrost layer is thought to be a function of a warmer paleoclimate (*7*). However, only a handful of the ~5000 soil profiles used by Delgado-Baquerizo *et al.* (*1*) came from permafrost soils. The great majority of data below 50 cm in Fig. 1 suggest that soil carbon in these lower horizons has a legacy of centuries to a few millennia. Repeat sampling over the atmospheric

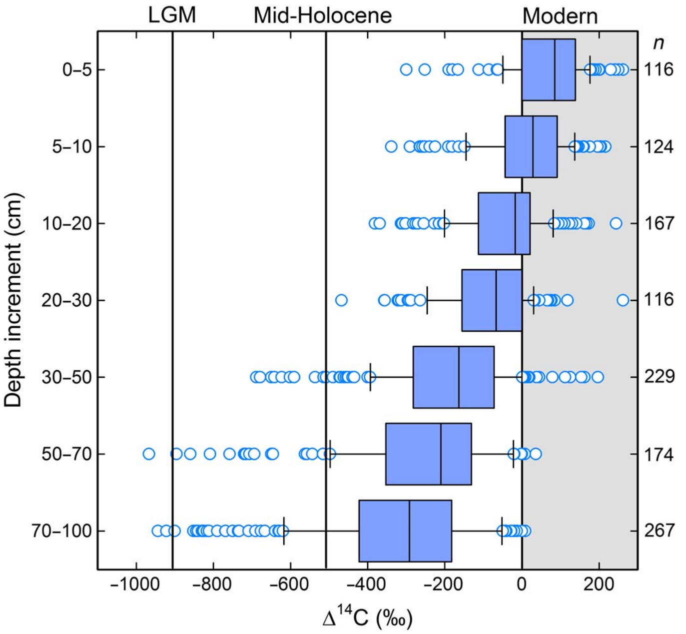

Fig. 1. Distribution of bulk soil radiocarbon values with depth from a global compilation (*3*). Radiocarbon measurements represent a proxy for the average age of organic carbon in the soil (*2*). Midpoint depth of each horizon was binned into seven discrete depth intervals. Boxes enclose the 25th to 75th percentile of data, median is given as a vertical line within the box, and whiskers enclose the 10th and 90th percentile, whereas data points are individual values that fall outside of the whiskered interval. The number of samples in each interval is given on the right. Reference lines indicate the location of the Last Glacial Maximum (LGM; 22,000 years ago) and mid-Holocene period (6000 years) on the $\Delta^{14}C$ scale, and any $\Delta^{14}C$ value > 0 is considered modern (after 1955).

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weapons testing period also reveals that a substantial fraction of SOC in these deeper depths has a turnover time of only a few decades (*8*).

If the organic carbon present in soils, especially topsoils, today was derived from current vegetation grown under current or at least recent climate conditions, then why did Delgado-Baquerizo *et al.* (*1*) find stronger relationships with paleoclimate? The soil itself may hold the answer. The capacity to stabilize new carbon entering the soil is heavily influenced by the physiochemical characteristics of the soil (*5*), and these characteristics have developed slowly under the influence of past climates (*9*). To expand on the theoretical example given in figure 2 of Delgado-Baquerizo *et al.* (*1*), two sites with the same geologic substrate but under mesic versus arid paleoclimates will develop soils with different carbon stabilization potentials. Under a mesic climate, mineral weathering will result in an accumulation of reactive secondary minerals (*10*) with great capacity for stabilizing SOC (*11*) but not the arid site. This argument of paleoclimate controlling soil properties was recently posited by Delgado-Baquerizo *et al.* (*1*) to explain a large fraction of the variance in global soil bacterial communities (*12*).

To summarize, radiocarbon data indicate that the organic carbon found in modern topsoils is not derived directly from the vegetation of a bygone epoch. Rather, it is likely that paleoclimate was found to be a slightly better correlate than current climate due to the indirect influence of past climate on soil properties. If this is the case, then the proper way to implement the recommendation of Delgado-Baquerizo *et al.* (*1*) to include "paleoclimatic conditions in contemporary climate models" would be to include better information on current-day soil properties that influence the fate of SOC.

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