

CLIMATE CHANGE

Response to comment on “Climate legacies drive global soil carbon stocks in terrestrial ecosystem”

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The technical comment from Sanderman provides a unique opportunity to deepen our understanding of the mechanisms explaining the role of paleoclimate in the contemporary distribution of global soil C content, as reported in our article. Sanderman argues that the role of paleoclimate in predicting soil C content might be accounted for by using slowly changing soil properties as predictors. This is a key point that we highlighted in the supplementary materials of our article, which demonstrated, to the degree possible given available data, that soil properties alone cannot account for the unique portion of the variation in soil C explained by paleoclimate. Sanderman also raised an interesting question about how paleoclimate might explain the contemporary amount of C in our soils if such a C is relatively new, particularly in the topsoil layer. There is one relatively simple, yet plausible, reason. A soil with a higher amount of C, a consequence of accumulation over millennia, might promote higher contemporary C fixation rates, leading to a higher amount of new C in our soils. Thus, paleoclimate can be a good predictor of the amount of soil C in soil, but not necessarily of its age. In summary, Sanderman did not question the validity of our results but rather provides an alternative potential mechanistic explanation for the conclusion of our original article, that is, that paleoclimate explains a unique portion of the global variation of soil C content that cannot be accounted for by current climate, vegetation attributes, or soil properties.

The technical comment by Sanderman (1) provides an interesting perspective on the possible mechanisms explaining the patterns reported in our original article (2). Sanderman (1) argues that the role of paleoclimate in predicting current soil C content could be wholly accounted for by key soil properties that evolved slowly under the influence of past climates (accumulation of reactive secondary minerals). Although this is a valid point, it is inconsistent with the results of our original study (2), which we derived using available data. A similar reasoning prompted us to develop additional statistical models to include key soil properties (soil pH, electrical conductivity, and texture) and biotic features (total plant cover and species richness), in addition to paleoclimates and current climates, as predictors of soil C content in global soils. Figure S4 of our study (2) provides evidence that paleoclimate still predicted a unique portion of the variation in soil C content globally, even after accounting for other key abiotic and biotic environmental drivers. Of course, we were limited in the soil properties we considered (2). Similar results were found in another recent study focusing on soil microbes (3), where soil properties alone could not account for all the variation explained by paleoclimate in driving the variation in these organisms over large geographical scales.

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We agree with Sanderman (1) that slowly changing soil properties can play a key role in regulating the contemporary content of C found in our soils. This is clear from the portion of variation shared between paleoclimate and soil properties in predicting the distribution of soil C, as shown in figure S4 of our article (2). However, we disagree with Sanderman (1) that soil properties per se are good enough to account for the unique portion of the variation explained by paleoclimate, as demonstrated in the same figure S4 (2). Together, paleoclimatic data provide an important and easily available source of information available at the global scale and can help us to improve global predictions of soil C content. This procedure is likely to be more accurate than blindly quantifying multiple soil properties globally, which might result in expensive analyses in terms of time and cost.

Sanderman (1) also proposed an interesting argument from a mechanistic perspective, that very little soil in the top 10 cm is likely to be 6000 to 22,000 years old, and further suggested that such an argument makes it difficult to reconcile a direct role for paleoclimate in predicting contemporary C content in our soils. First, we would like to clarify that we did not evaluate the role of paleoclimate in predicting soil C age. Rather, we quantified the role of paleoclimate in predicting the global distribution of soil C content. Furthermore, the results from figure 1 of Sanderman (1) are largely expected; deeper soils are more likely to be older because they are less exposed to erosion, litter inputs, and microbial activity than shallower layers. Finally, we would like to highlight that the major findings we reported in our original paper (2) were consistent across different soil depths, a result questioned by Sanderman (1). Paleoclimate still predicted a unique portion of the variation of soil C that could not be accounted for by current climate [figures S5 and S6 of our article (2)] or other soil properties [figure S4 of the same article (2)].

Sanderman (1) raises a very interesting and intriguing question: How then can paleoclimate (6000 to 20,000 years old) influence the contemporary amount of C in our soils if soil C in the topsoil layer is not that old? There is one simple, but plausible, reason. The long-term

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climatic history of a region influences not only the age of soil C but also the contemporary rates of C fixation, that is, the rate of new C being fixed today. Thus, paleoclimate might not be a good predictor of soil C age, an interesting question not covered in our original article (2), but can still be a good predictor of contemporary C content. How is this possible? As supported by the large body of soil chronosequence studies, soil C tends to accumulate from centuries to millennia (Fig. 1) (4–6). Therefore, the unique and direct role of paleoclimate in predicting soil C is expected to be linked to the capacity of climate and vegetation types to regulate the fate of C accumulation during ecosystem development (Fig. 1). In other words, an ecosystem that developed over millennia as a forest and developed into a grassland, or a system under a cold climate that moved toward a hotter climate, might accumulate different rates of C today than systems that stayed as a forest system or where the climate remained cold (Fig. 1). Sanderman (1) alludes to this where he mentions that slowly changing physiochemical properties can largely influence the stabiliza-

tion of new C entering that soil regardless of current climate. However, he avoids any mention of other key factors regulating the amount of C currently fixed including plant-soil interactions and decomposition processes.

The rate of contemporary C fixation and storage (via photosynthesis and litter decomposition) is largely linked to preexistent C conditions (7, 8). These influences likely act in both directions. For example, at the global scale, contemporary net primary productivity rates (new C being fixed today) largely resemble the amount of C content in our soils (Fig. 2, A to C). Thus, previously productive sites likely remain productive today, and soils with more C might have higher rates of C fixation (Fig. 2, A to C) and decomposition (7), ultimately promoting the entrance of new C, all of which could still be statistically related to paleoclimatic information. The mechanisms behind these plant-soil and decomposition interactions lie in the intermediary role that organic matter (~58% organic C) plays in mineralizing soil nutrients such as nitrogen, which are used by plant and microbes to fix and release new C. For example, for the Global-Drylands and Australia data sets that we used (2), soil C was significantly and positively related to the amount of total N in soil (Pearson's $r > 0.76$, $P < 0.001$). This mechanism is likely to be valid for multiple ecosystems from tropical, temperate, continental, and arid regions but might be less accurate for bogs or permafrost soils, two types of soils that are rarely included in the databases analyzed (2). Further supporting this notion, a reanalysis of the soils included in the study of He *et al.* (9) provided evidence that the current primary plant productivity [2000–2016 period calculated by Delgado-Baquerizo *et al.* (10)] is significantly and positively (Pearson's $r = 0.24$, $P = 0.003$) related to the C-averaged $\Delta^{14}\text{C}$ for the top 1 m (9), providing strong evidence that locations with a greater plant productivity accumulate younger soil C than those with lower plant productivity. However, the C-averaged $\Delta^{14}\text{C}$ for the top 1 m was not related to the aridity index (Pearson's $r = 0.06$, $P = 0.469$) (11) of each location in the study of He *et al.* (9), as suggested by Sanderman (1).

In summary, Sanderman (1) initiates discussion of the likely mechanisms underlying the results we reported in our article. The major conclusion from our original article (2) is that paleoclimate explains a unique portion of the global variation of soil C content that cannot be accounted for by current climate or major vegetation attributes and soil properties. The mechanisms underlying the role of paleoclimate as a predictor of current soil C contents can be related to the way in which historical climatic legacies drive the stabilization of new soil C (via links with the preexisting C), which affects key ecosystem processes such as photosynthesis and litter decomposition.

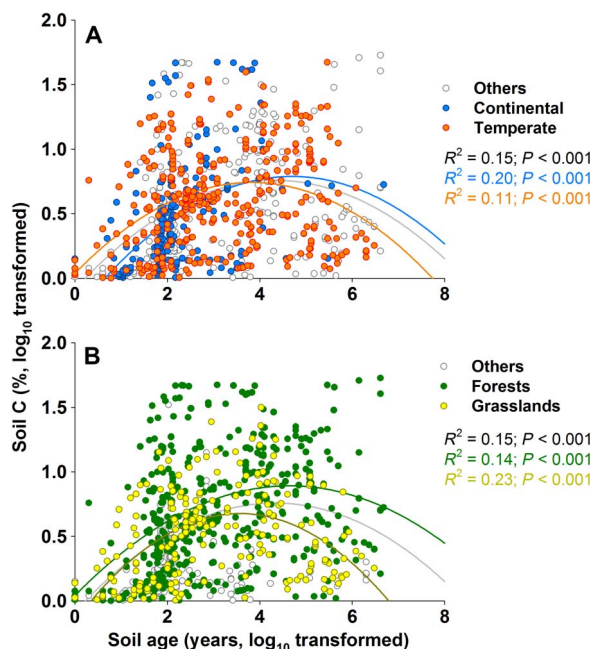


Fig. 1. Quadratic relationships between soil age and carbon content (%) across two climatic regions and vegetation types in soils from 68 long-term soil chronosequences available from the literature (see appendix S1).

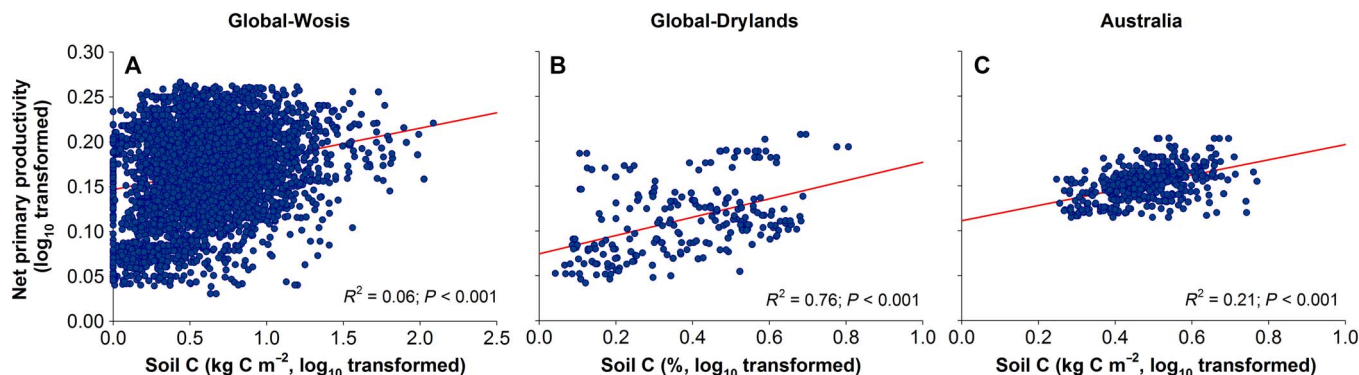


Fig. 2. Relationship between soil C content and net primary productivity [2000–2016 period as calculated by Delgado-Baquerizo *et al.* (9)] across the three regional and global data sets included in the study of Delgado-Baquerizo *et al.* (2).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/4/3/eaat1296/DC1> appendix S1. List of papers from which data used in figure 1 were extracted.

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