Title
Response to Comment on “The whole-soil carbon flux in response to warming”

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The whole-soil carbon flux in response to warming: Technical comment response

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In their technical comment, Xiao et al. raise several questions about our whole soil warming experiment and results (*1*), which we address in this response. We agree that this is an important topic, and appreciate the opportunity to clarify points that perhaps were not sufficiently clear in the article.

Xiao et al. question the relevance of heating the whole profile because they assert that deep soil will not warm as much as surface soil due to low thermal diffusivity. While the exact rates of warming in any location will depend on a host of factors, both direct observations and soil thermal modeling find that nearly synchronous warming of the subsurface is a realistic climate change scenario. Analyses of temperature records for 38 stations across North America showed no difference in average warming trends at 10 cm and 100 cm depth between 1967-2002 (0.31 and 0.31°C decade^{-1}, respectively; *2*). Analyses of soil temperature predictions from IPCC models (Coupled Model Intercomparison Project; CMIP5) show that both surface (0-2 cm) and deep soils (80-140 cm) will warm at roughly the same rate throughout this century, closely following air warming trends under RCP 8.5 (Fig 1), except in permafrost regions. The thermal diffusivity of soils does not impose meaningful lags to warming at 1 m depth over climatic timescales.

In addition, the lack of deep soil warming in most warming experiments is not evidence that deep soils will have reduced warming relative to the surface under future climates. The attenuation of warming with depth measured in the top-down warming (i.e., warming applied at or near the surface only) experiments cited by Xiao et al. (*3, 4*) occurred not due to the low thermal diffusivity of soil but due to lateral heat transfer. In top-down warming experiments the area being warmed is adjacent to areas of ambient temperature to which heat is lost. Thus many top-down warming experiments have soil heating profiles that attenuate much more steeply with depth than is predicted in climate change scenarios in which the entire surface is warmed. Our warming design corrects for this experimental artifact that occurs when surface warming is implemented over a limited soil volume. Our study, wherein the entire profile to 1 m was warmed by +4°C while allowing for natural differences in diurnal and seasonal temperature fluctuations among depths, is a more realistic scenario of future soil warming. Warming by a similar amount at all depths not only approximates future climate change scenarios, it also facilitated quantification of the temperature response of the whole profile.

Second, Xiao et al. critiqued our soil profile Q_{10} analysis, due to an apparent misunderstanding of data treatment and to a lack of clarity on our part regarding mechanisms. In setting up our analysis, we tried many ways of calculating Q_{10}, including curve fitting, before deciding on a comparison between the heated and control plots of each plot pair. This method avoided confounding seasonal effects that can arise when warmer and cooler temperatures from the same site are used to fit a curve. We dropped unrealistically high Q_{10} values (>30) from our analysis because these values were likely caused by differences in substrate availability and microbial communities among paired samples and were not a response to the warming manipulation. Unlike laboratory incubations experiments that calculate Q_{10}, we could not measure the temperature response of the same soil sample. In most laboratory incubations the soil is either homogenized, split, and subjected to different temperatures in parallel (*5*) or the same soil sample is subjected to different temperatures in series (*6*). In such experiments, the effects of natural spatial heterogeneity in substrate availability and microbial communities are reduced. Furthermore, in contrast to the description provided by Xiao et al., we did not exclude Q_{10} values >6.4 and <30 and took into account the non-independence of repeated measures.

Rather than removing data points as Xiao et al. did, we present the Q_{10} analysis with all data (Fig.2). Q_{10} values calculated using all data are still greater than 2 throughout the soil profile with more extreme variability at the shallowest and deepest depths. Furthermore, while the Q_{10} results of Xiao et al. differ in magnitude from ours, their analysis shows a similar pattern to ours (*1*) with a tendency towards stronger Q_{10} responses in the shallower soil at 0-15 and 15-30 cm depths.

Putting aside the different ways to calculate Q_{10}, our conclusions are also supported by the CO_2 production data. All depths responded to warming with an increase in CO_2 production. As stated in the original article, the warming response was greater (on an absolute basis) towards the surface, but it was a novel finding that the deeper soils responded at all. Although deeper soils only contributed 10% of the total warming response, neglecting their contributions, as has been standard in most experiments, has major implications when scaling up soil carbon feedbacks to climate change at from the site level to the global scale.

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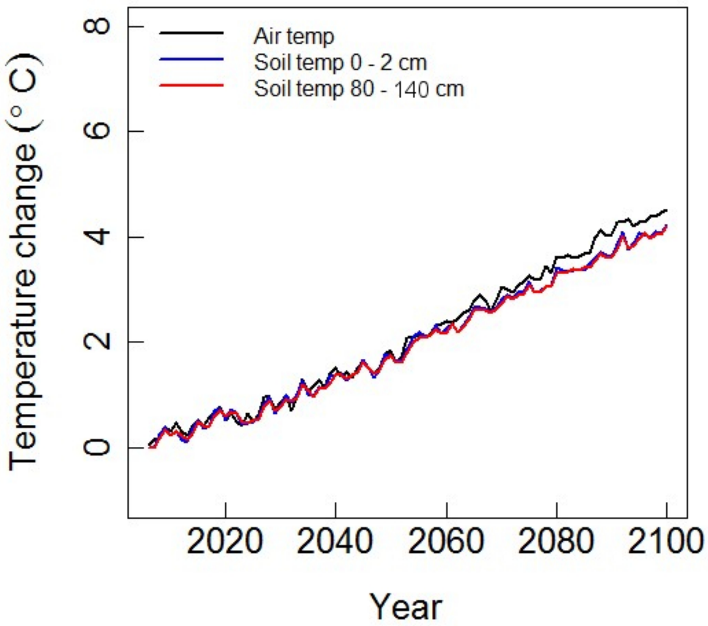

Figure 1. Within the next century, global air temperatures over land are projected to increase 4°C based on CESM1-BGC, scenario RCP 8.5. Globally, soil temperature at the surface and at depth will lag slightly behind air temperature in the later part of the century due to permafrost/snow feedbacks at high latitudes, but will also warm by approximately 4°C by 2100. Temperature change was reported as the difference between average global temperatures 2081-2100 for scenario RCP8.5 minus global averages for 1986-2005 simulated under a historic scenario.

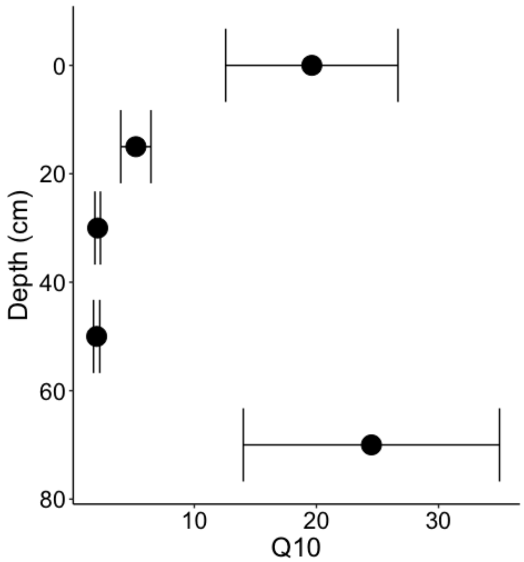

Figure 2. The soil profile of mean Q_{10} (± SE) with values >30 cm retained. All depths have a Q_{10} greater than >2 showing all soil depths are responding to warming.