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

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Abstract

In a compelling study, Hicks Pries *et al*. (Reports, 31 March 2017, p. 1420) showed that 4°C warming enhanced soil CO_2production in the 1-meter soil profile, with all soil depths displaying similar temperature sensitivity (Q_{10}). We argue that some caveats can be identified in their experimental approach and analysis, and that these critically undermine their conclusions and hence their claim that the strength of feedback between the whole-soil carbon and climate has been underestimated in terrestrial models.

Hicks Pries *et al*. ([1]) used a deep soil warming experiment to examine CO_2 production in response to warming across the soil profile in a coniferous temperate forest. They found that a 2-year in situ warming of 4°C significantly enhanced the whole-soil CO_2production by 34 to 37%, and that all soil layers exhibited similar temperature sensitivity with a mean apparent Q_{10} of 2.7 ± 0.3. We argue that although the idea of subsoil carbon dynamics in response to warming is worth testing ([2], [3]), their conclusions are critically undermined by the experimental approach and analysis.

Hicks Pries *et al*. buried heating rods at a depth of 2.4 m (with additional circular heating cables near the surface at radii of 0.5 and 1 m) to warm the 1-m soil profile evenly by 4°C. This method differed from the majority of previous studies, in which soil temperature was elevated through heating surface air and/or topsoil layers to simulate the magnitude of rise in surface air temperature (2, 3). Although it is expected that ongoing and future air warming would increase the temperature of the soil profile, the magnitude of temperature elevation likely attenuates with depth. This happens because net energy inputs from air and subsequent heat conduction driven by a thermal gradient would inevitably invoke temperature variation in deep soils lagging behind that of surface soils under a dynamic climate system. Such a thermal lag effect is also ascribed to low thermal diffusivity and thickness of the soil profile (4). In an alpine meadow with clipping to simulate animal grazing under 4°C surface air warming, for instance, the magnitude of temperature elevation decreased by 88% and 77%, respectively, at 60- and 100-cm soil depths (5). In a boreal forest under 3.4°C soil warming at a depth of 10 cm, the magnitude of temperature elevation declined by 40% and 53%, respectively, at 75- and 100-cm soil depths (6). These previous findings imply that Hicks Pries *et al*.'s experimental warming approach may cause higher temperature elevations in deeper soil layers (e.g., <50 cm) than expected under air warming, thus overestimating the whole-soil CO_2 production.

To examine temperature sensitivity of CO_2 production across the soil profile, Hicks Pries *et al*. used the following equation to calculate the apparent Q_{10}, a factor by which the CO_2 production rate increases with a 10°C rise, of each soil layer:

$$Q_{10} = \left(\frac{R_{\mathrm{H}}}{R_{\mathrm{C}}}\right)^{\frac{10}{T_{\mathrm{H}} - T_{C}}} \quad (1)$$

where R_C and R_H are the CO_2 production rates of each control and heated plot pair, respectively, and T_C and T_H are the soil temperatures of the corresponding control and heated plots, respectively. By directly comparing CO_2 production between each treatment plot pair on every sampling date, however, a large number of anomalous Q_{10}values appeared (for example, 33% of them <1.0 and 20% of them >5). Hicks Pries *et al*. included Q_{10} values less than 1.0 but excluded those greater than 6.4 (45 of 281) as "unrealistic values" ($Q_{10} > 30$) or "outliers" ($6.4 < Q_{10} < 30$) in their analysis. At 7.5-cm soil depth, for instance, nearly one-third of the data points were not included in computing the mean apparent Q_{10}. Although many Q_{10} values were ignored in Hicks Pries *et al*., they did not propose a different mechanism (other than the warming treatment) underlying the emergence of these anomalous data points. We believe that the analysis of Hicks Pries *et al*. is inappropriate, leading to the biased conclusion that all soil depths responded to warming with very similar temperature sensitivity.

In a seminal work, Hawkins defined an outlier as "an observation which deviates so much from other observations as to arouse suspicions that it was generated by a different mechanism" (7). Evidently, the apparent Q_{10} was not a direct observation but was calculated from the paired soil CO_2 in their study. As such, the exclusion of any Q_{10} must be based on the statistical analysis of soil CO_2 measurements rather than the Q_{10} itself. If any Q_{10} value could be considered an outlier or even unrealistic, the corresponding paired soil CO_2 data should also be excluded in analyzing the mean soil CO_2production (figure 2A of Hicks Pries *et al*.). To reach a fair conclusion about the whole-soil response to warming, we reanalyzed the mean soil CO_2 production using the original data sets by omitting those not included in the estimation of the mean apparent Q_{10} in figure 2B of Hicks Pries *et al*. In contrast to Hicks Pries *et al*., results from the current analysis show that CO_2 flux from the whole-soil profile remained unchanged under warming (**Fig. 1A**, $P = 0.15$). This result indicates that the omission of many data points in the Hicks Pries *et al*. analysis could lead to inconsistent conclusions about the response of the whole soil to warming.

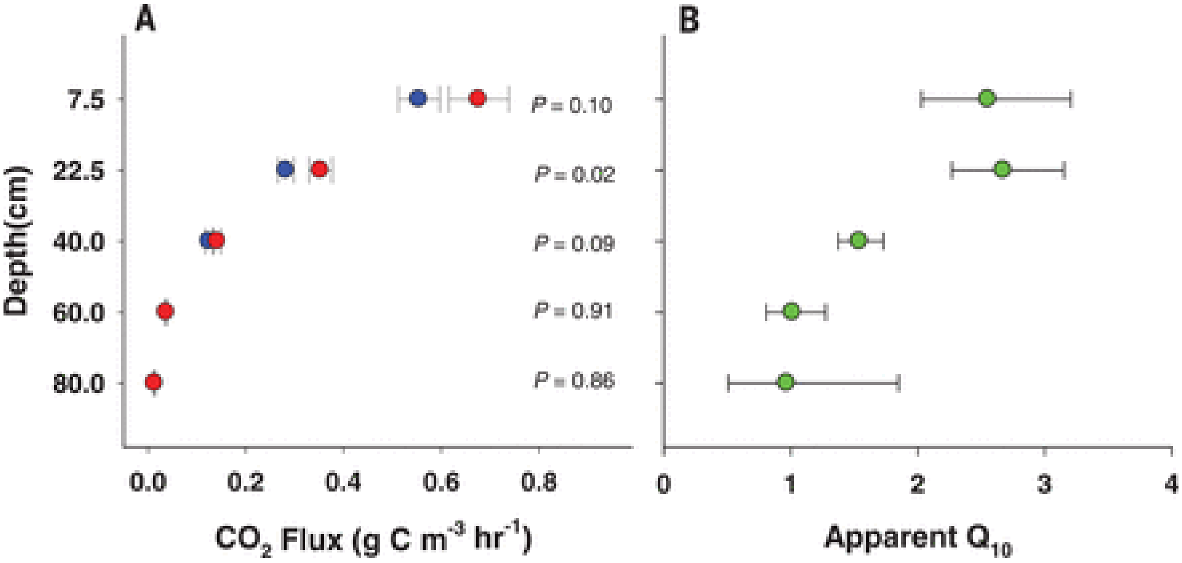

Fig. 1Soil CO_2 production of different soil depths in response to warming.

(**A**) Soil CO_2 production (mean ± SE, $n = 3$) at different soil layers in control plots (blue circles) and heated plots (red circles). $P < 0.05$ denotes a significant effect of warming. Data are from soil CO_2 measurements of Hicks Pries *et al*. but excluding the “outliers” and “unrealistic high values” in their Q_{10} analysis. (**B**) The mean apparent Q_{10} of each soil layer according to a linear regression model. Hicks Pries *et al*. estimated the mean apparent Q_{10} by averaging the Q_{10} values of each sampling point but excluded many data points because of high variation. Our method allows for a more accurate calculation of temperature sensitivity through an unbiased estimation of $\ln(Q_{10})$ with low deviation. Error bars were computed from SE of the fitted parameters. The apparent Q_{10} of the two upper depths $\left(2.62^{+0.38}_{-0.33}\right)$ is significantly higher than that of the three deeper depths $\left(1.20^{+0.21}_{-0.18}\right)$, $P < 0.001$. Data are from the Hicks Pries *et al*. analysis of soil CO_2production. All paired soil CO_2 data except for those equal to zero are included in the current analysis.

We argue that the exclusion of many data points in the Hicks Pries *et al*. analysis could be problematic because their data were collected from a time-series experiment. In their study, soil CO_2 measurements had been conducted repeatedly on the same object (i.e., each soil layer) over 2 years; thus, measurements at different time points were not independent of each other (***8***). Actually, soil CO_2 production decreased significantly over time in the whole-soil profile ($P < 0.001$). Moreover, two CO_2 measurements taken at adjacent time points were more highly correlated than two taken several time points apart [the fittest covariance structure: first-order autoregressive with heterogeneous variance ARH(1), $\phi = 0.994$]. If such repeated and self-correlated CO_2 measurements were treated erroneously as if they were random samples, as in the analysis of Hicks Pries *et al*., the exclusion of a large number of data points could lead to serious power loss in statistical analysis (***7***).

To avoid the occurrence of many “abnormal” Q_{10} values, we propose a different method to estimate the mean apparent Q_{10} of each soil depth. In the Hicks Pries *et al*. analysis, many anomalous Q_{10} values appeared because any variation in soil CO_2 data collection would be amplified exponentially by a power of $10/(T_H – T_C)$. To ameliorate error propagation, we use a least-squares regression model to estimate the apparent Q_{10} (***9***) by reformatting **Eq. 1** as follows: $\ln\frac{R_H}{R_C} = \frac{\ln(Q_{10})}{10}\cdot(T_H - T_C)$(2)Using **Eq. 2**, the apparent Q_{10} for each soil layer can be estimated through performing a linear regression between $\ln(R_H/R_C)$ and $(T_H – T_C)$. Meanwhile, the potentially confounding effects of seasonal changes, emphasized in Hicks Pries *et al*., could be minimized because the same paired data are used. In our analysis, only those data points with CO_2 production equal to zero were not included. Tests of difference in Q_{10} between soil depths were conducted based on a generalized linear model by introducing a dumb variable of depth. Interestingly, we found that the mean apparent Q_{10} of the two surface soil layers (mean $Q_{10} = 2.62$) was significantly higher than that of the three deeper soil layers (mean $Q_{10} = 1.20$) (**Fig. 1B**, $P < 0.001$). These results are in conflict with those of Hicks Pries *et al*. and suggest that the surface soil layers were more responsive to warming, with a much higher temperature sensitivity relative to the deep layers.

Hicks Pries *et al*. concluded their analysis with a claim that the strength of the carbon-climate feedback in terrestrial models has been underestimated because these models have ignored the warming effects on subsoil (e.g., >50 cm) and usually include relatively low apparent Q_{10} values of soil

CO_2 production. Given the above caveats with respect to how this experiment was carried out and how the data were interpreted, we believe that their recommendation lacks a solid foundation.

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