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Permalink
https://escholarship.org/uc/item/1b60g2n2

Journal
Science, 355(6332)

ISSN
0036-8075

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Publication Date
2017-03-31

DOI
10.1126/science.aal1319

Peer reviewed

Science REPORTS

Cite as: C. E. Hicks Pries *et al*., *Science*
10.1126/science.aal1319 (2017).

The whole-soil carbon flux in response to warming

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Soil organic carbon harbors three times as much carbon as Earth's atmosphere, and its decomposition is a potentially large climate change feedback and major source of uncertainty in climate projections. The response of whole-soil profiles to warming has not been tested in situ. In this deep warming experiment in mineral soil, CO_2 production from all soil depths increased significantly with 4°C warming—annual soil respiration increased by 34-37%. All depths responded to warming with similar temperature sensitivities, driven by decomposition of decadal-aged carbon. Whole-soil warming reveals a larger soil respiration response than many in situ experiments, most of which only warm the surface soil, and models.

Globally, almost 3000 Pg C is stored as soil organic carbon (SOC) (*1*). Warming is expected to increase microbial decomposition of SOC, releasing more CO_2 into the atmosphere. However, the amount and rate of this response are highly uncertain because the mechanisms controlling the microbial accessibility of SOC are not fully understood (*2*). Empirical determination of the temperature response from whole-soil profiles (0 to 100+ cm) has been difficult. The majority of in situ warming experiments focus on warming the top five to 20 cm of surface soil (table S1) and may thus miss the response of subsoils (below 20 cm), which contain >50% of global SOC stocks (*3*). Alternatives to field manipulations are not ideal—incubations have large experimental artifacts while seasonal temperature gradients confound warming with other factors like phenology and soil moisture (*4*). As a result, we currently lack data on the whole-soil warming response (*5*).

Uncertainty surrounding the SOC warming response increases with soil depth because the mechanisms controlling subsoil OC's long turnover times (often 1000's of years; (*6*, *7*) and their temperature sensitivity are unknown (*8*). These long turnover times do not preclude subsoil OC from playing an active role in global carbon cycling (*6*, *9*). If the slow turnover times of subsoil OC are due to inherent chemical recalcitrance, then subsoil OC may be more responsive to warming than surface SOC according to kinetic theory (*10*). However, if reduced microbial access to SOC (*11*) slows turnover times due to physical protection (in aggregates), mineral associations (formation of organo-mineral complexes), or spatial heterogeneity of microbially-active "hotspots" (i.e., roots or preferential flow paths), subsoil OC may be less responsive to warming than surface SOC (*11*, *12*), but we lack a theoretical or empirical basis with which to predict this. The subsoil response to temperature has been tested in laboratory incubations with inconsistent results (*11*, *13*, *14*), but has yet to be tested in situ.

Here we present results from a controlled, replicated in situ deep mineral soil warming experiment to determine the response of an undisturbed whole-soil profile to warming (+4°C). We tested the sensitivity of soil CO_2 production to warming from 0 to 100 cm and whether there was acclimation over 2 years. We used radiocarbon to determine if warming resulted in the decomposition of older SOC. This study was located in a coniferous temperate forest in soils classified as Alfisols containing 16.6 ± 1 kg C m^{-2} in the top meter. Alfisols cover 13.5% of Earth's ice-free land area and store 8% of global soil C (*15*).

Over the next century, subsoils are projected to warm at roughly the same rate as surface soils. Intergovernmental Panel on Climate Change simulations of global average soil temperature under Representative Concentration Pathway 8.5 predict that the whole-soil profile will warm 4°C by 2100 (*16*). We warmed soils 4 ± 0.75°C from 10 cm down to 100 cm in the soil profile in three pairs of control and heated plots from November 2013 through February 2016 (Fig. 1 and figs. S1 and S2). We used 22, 2.4 m deep heating rods arranged around 3 m diameter plots (*17*) with two additional circular heating cables buried 5 cm below the soil surface at 0.5 and 1 m radii from plot center. This method imposed 4°C warming while preserving the natural depth gradient and temporal variations in soil temperature. At 5 cm, due to the lack of aboveground heating, the heated plots were on average only 2.4 ± 1.2°C warmer than the control. Soil moisture was slightly decreased in the warmed plots by an average of 1.5-3.5% volumetric water content (fig. S3). The soil respiration response, which included microbial and root respiration (but see supplementary text), was determined monthly, from seven replicate surface flux measurements per plot and by measuring gas well CO_2 concentrations at five depths (15, 30, 50, 70, and 90 cm), from which depth-resolved CO_2 production estimates were modeled using Fick's Law.

Warming 4°C increased whole profile soil respiration by 34-37%, depending on the measurement method. The response measured from the surface was a 34% increase from 1100 ± 31 to 1450 ± 43 g C m^{-2} y^{-1} (Treatment effect, $p < 0.0001$; table S2). The response estimated from gas well data was a similar 37% increase from 1300 to 1750 g C m^{-2} y^{-1}. The mean Q_{10}, the factor by which respiration increases due to a 10°C rise in temperature, for the whole-soil profile (measured from the surface) was 2.4 ± 0.3; this Q_{10} is "apparent" because it describes the emergent response of many processes and is constrained by field conditions. For each sampling date, Q_{10} was calculated comparing the respiration and soil temperature (10 cm) in each control and heated plot pair. By directly comparing plot pairs to calculate Q_{10} instead of fitting a curve to all respiration and temperature data, we avoided confounding the temperature response with seasonal changes in soil moisture (fig. S4) or plant inputs (*4*). A Q_{10} of 2.4 is equivalent to the estimated global median for soil respiration (*18*) and similar to the mean Q_{10} of 2.6 for sites spanning the 10-20°C temperature range in the global soil respiration database (*19*).

There was no decline in temperature sensitivity (Q_{10}) of whole profile soil respiration over 27 months of warming (linear regression, $p = 0.5$; fig. S5), indicating soil respiration did not acclimate to warming or become substrate limited in line with a recent meta-analysis (*20*). Generally, the greatest production rates and Q_{10}'s occurred in the wet winter months (fig. S5). However, there were no clear seasonal trends due to the compensatory effects of low soil temperature and high soil moisture in this Mediterranean climate ($r = -0.8$, fig. S4).

The observed 34-37% increase in soil respiration due to warming is larger than the 9% (*21*) and 12% (*22*) average increases in soil respiration calculated in meta-analyses of warming experiments and is larger than most responses from individual warming experiments (table S1). While our large warming response may be a function of our soil type or forest ecosystem (*21*), it is also due, in part, to warming the wholesoil profile. Most warming studies likely miss a substantial proportion of the warming response by only warming the surface soil. The magnitude of the missing response is unclear since most studies do not report warming below 20 cm (table S1). Furthermore, in the few warming studies that measured warming at multiple depths, the magnitude of warming attenuated with depth (table S1). If anything, our measured increase in soil respiration underestimates the actual response to 4°C warming because the top 5 cm of the soil profile was only warmed 2.4°C.

About 50% of soil respiration and 40% of the warming response occurred below 15 cm in the soil profile, where 63% of the SOC stock (to 1 m) resides, and about 20% of soil respiration and 10% of the warming response occurred below 30 cm, where 32% of the SOC stock resides (Table 1). CO_2 production within all soil depth increments increased significantly due to warming (Treatment effect, $p = 0.0001$; Fig. 2A and table S2). All depth increments were sensitive to warming with a mean apparent Q_{10} of 2.7 ± 0.3 (Fig. 2B). There was an increase in Q_{10} for depth increments above 30 cm, but depth was not a significant effect in a regression model ($p > 0.17$; table S2). As a result of the slightly lower Q_{10} at depth, subsoils below 30 cm contributed more to total CO_2 production in the control plots than in the warmed plots (23.4% versus 19.8%). This relatively consistent response across depth increments contrasts with those of many lab incubations (*11*, *13*, *23*). Our results support the assumption of depth-resolved terrestrial biosphere models (*24*, *25*) that SOC has similar temperature sensitivities across depths, but do not support the magnitude of modeled temperature sensitivity. Our soil's Q_{10} was greater than the Q_{10} used by most Earth system models (*26*).

At all depths, respiration was dominated by carbon fixed within the past 50 years based on $^{14}CO_2$ values (40.9 ± 1.7‰; Fig. 3A), as previously seen in other soils (*27*, *28*). There was no significant difference in soil profile $^{14}CO_2$ between control and warmed plots (Treatment effect, $p = 0.21$), so warming did not preferentially increase decomposition of old relative to new SOC. Thus, the "carbon-quality-temperature" hypothesis that older, and potentially more recalcitrant, SOC has greater temperature sensitivities than younger SOC was not supported. The radiocarbon sampling occurred in February, when the respiration response was greatest and plants were less active (*29*), so the carbon source was mainly heterotrophic. Furthermore, the ^{14}C of heterotrophic respiration (42.5 ± 3.7‰; from short-term, root-free soil incubations) was similar to the soil $^{14}CO_2$ and also did not differ among 10-20, 45-55, and 85-95 cm depths (Depth effect, $p = 0.28$). The heterotrophic and soil $^{14}CO_2$ values are consistent with the modern $\Delta^{14}C$ of the free light fraction SOC (35.9 ± 16‰), which is not physically or mineral-protected, making the light fraction a likely source of respired CO_2. Light fraction SOC remained modern throughout the soil profile, unlike bulk and dense-fraction, mineral-associated SOC, which became significantly more depleted with depth (Depth x Fraction interaction, $p = 0.02$; Fig. 3B). A similar proportion of SOC was in the light fraction at 5-15, 40-50, and 90-100 cm depths (Depth effect, $p = 0.62$; Table 1). Thus, while the amount of SOC decreased significantly with depth, 25-36% of SOC below 30 cm was decadal-aged light fraction. Subsoil likely had similar temperature sensitivities to surface soil because this modern SOC pool, not protected in aggregates or by minerals, drove the warming response.

Despite having bulk residence times on the order of 1000 years, the decomposition of subsoil carbon responds to warming. Subsoils (>30 cm) contributed to 20-25% of whole profile soil respiration and to 10% of the warming response in a temperate Alfisol. These values had not been observed before and are substantial when projecting potential soil carbon feedbacks to climate change. Given the presence of decadal-cycling SOC (*9*) and the predominance of modern $^{14}CO_2$ throughout diverse soil profiles (*27*, *28*, *30*), other subsoils are likely also responsive to warming. In our study, warming caused subsoils to respire an additional 47 g C m^{-2} y^{-1}, corresponding to 2.8 g C per kg whole profile soil C. As a preliminary test of global significance, extrapolating the subsoil response to all mineral soil orders (leaving out Cryosols, Histosols, and moisture-limited Aridisols) on a C stock basis (1091 Pg; (*15*)), subsoils could lose 3.1 Pg C y^{-1} due to 4°C warming. This estimate assumes all mineral soils have similar microbial accessibility and depth distributions of SOC and is based on our soil's initial response, which may be transient (*31*). However, this potentially large subsoil response to warming should not be ignored. The response would be roughly 3% of current global ecosystem respiration (*32*) and roughly 30% of current anthropogenic emissions (*33*). Because previous warming experiments have missed the response of deeper soils to warming and because terrestrial models often have a low Q_{10}, the strength of the soil organic carbon-climate change feedback may be currently underestimated.

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ACKNOWLEDGMENTS

Data presented in this paper are available in the supplementary online material, tables S3 to S5. This work was supported as part of the Terrestrial Ecosystem Science Program by the Director, Office of Science, Office of Biological and Environmental Research, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. Thanks to Biao Zhu, Bryan Curtis, Paul Cook, Alex Morales, Justin Erspamer, Ariel Thomson, Jen York, Caitlin O'Neill, Corinna West, Erik Poppleton, Rose Abramoff, and Katerina Georgiou.

SUPPLEMENTARY MATERIALS

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30 September 2016; accepted 24 February 2017
Published online 9 March 2017
10.1126/science.aal1319

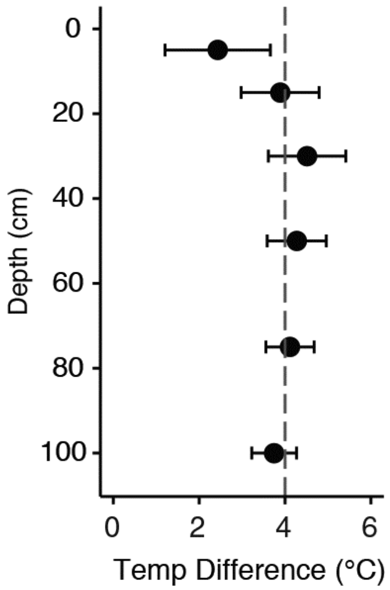

Fig. 1. The mean temperature difference between the control and heated plots by depth over the study period (March 2014 through February 2016). The error bars are the standard deviation of the temporal variability.

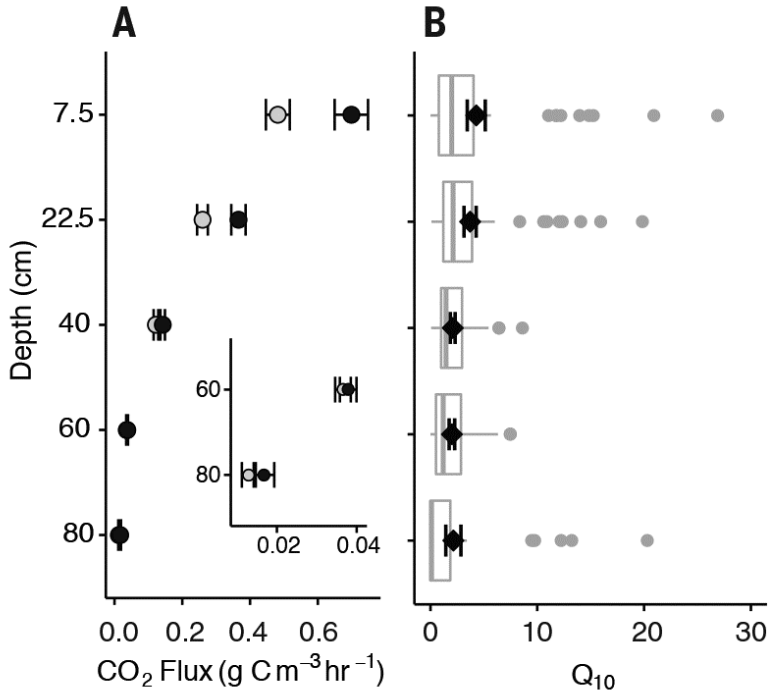

Fig. 2. (**A**) Mean CO_2 production (±SE) by depth increment in the control (grey circles) and heated (black circles) plots averaged over 20 months (n = 3). The depth increments are as follows: 0-15, 15-30, 30-50, 50-70, and 70-90 cm. The inset expands the 50-70 and 70-90 cm depths. (**B**) Mean apparent Q_{10} (±SE, black diamonds) averaged over 20 months is similar across depths with a slight, insignificant increase at depths above 30 cm. The boxplots in grey show the median (thick grey line), the 25th and 75th percentiles (thin vertical lines), and outliers (grey circles).

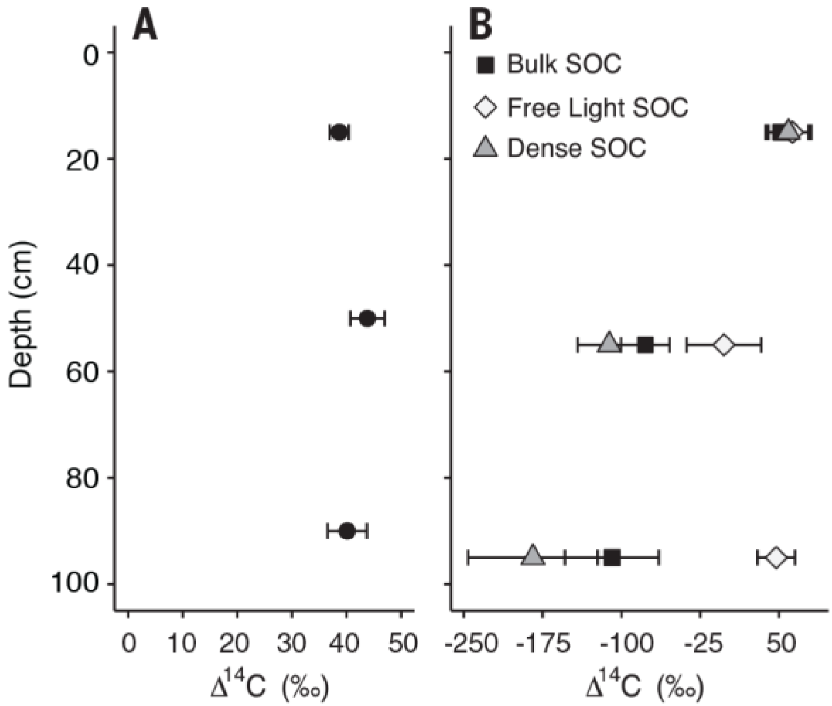

Fig. 3. (**A**) Mean radiocarbon values (±SE) of soil profile CO_2 are modern (>0‰) and do not differ among depths ($n = 6$, $p = 0.77$) or between treatments (not shown, $n = 9$, $p = 0.21$). (**B**) Mean radiocarbon values (±SE) of bulk, free light, and dense mineral-associated SOC. A potential source of the modern soil profile CO_2 is the free light fraction, which is also modern and does not differ significantly among depths ($n = 3$, $p = 0.02$).

Table 1. Mean soil carbon properties ± SE (n = 3) in 10 cm increments from 0 to 100 cm.

Mid depth (cm)	%C	C:N	$\delta^{13}C$ (‰)	g C m^{-2}	Proportion total C	Proportion C in free light fraction	Proportion C in occluded light fraction	Proportion C in dense fraction
5	8.3 ± 0.8	28.1 ± 2.7	−25.3 ± 0.3	6052 ± 478	0.365 ± 0.015			
15	3.0 ± 0.3	24.8 ± 1.5	−25.1 ± 0.0	3048 ± 399	0.183 ± 0.018	0.23 ± 0.03	0.15 ± 0.01	0.48 ± 0.05
25	1.9 ± 0.1	23.7 ± 1.3	−24.9 ± 0.1	2223 ± 139	0.134 ± 0.002			
35	1.1 ± 0.1	23.9 ± 0.5	−24.4 ± 0.2	1331 ± 94	0.080 ± 0.002			
45	0.7 ± 0.1	24.1 ± 0.1	−23.8 ± 0.1	903 ± 68	0.055 ± 0.004	0.25 ± 0.02	0.10 ± 0.03	0.47 ± 0.04
55	0.5 ± 0.1	25.9 ± 1.9	−23.7 ± 0.1	751 ± 108	0.045 ± 0.005			
65	0.3 ± 0.0	23.6 ± 1.2	−23.2 ± 0.1	429 ± 5	0.026 ± 0.001			
75	0.4 ± 0.1	26.0 ± 1.7	−23.1 ± 0.4	553 ± 98	0.034 ± 0.008			
85	0.4 ± 0.1	30.3 ± 2.6	−23.5 ± 0.2	563 ± 124	0.034 ± 0.006			
95	0.5 ± 0.2	34.4 ± 3.6	−23.8 ± 0.4	718 ± 192	0.044 ± 0.014	0.36 ± 0.03	0.10 ± 0.03	0.46 ± 0.09

The whole-soil carbon flux in response to warming
Caitlin E. Hicks Pries, C. Castanha, R. Porras and M. S. Torn (March 9, 2017)

Editor's Summary

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