Predicting soil carbon loss with warming

ARISING FROM T. W. Crowther *et al. Nature* **540,** 104–108 (2016); doi:10.1038/nature20150

Crowther *et al.*[1] reported that the best predictor of surface soil carbon (top 10 cm) losses in response to warming is the size of the surface carbon stock in the soil (that is, carbon stocks in plots that have not been warmed), finding that soils that are high in soil carbon also lose more carbon under warming conditions. This relationship was based on a linear regression of soil carbon losses and soil carbon stocks in field warming studies, which was then used to project carbon losses over time and to generate a map of soil carbon vulnerability. However, a few extreme data points (high-leverage points) can strongly influence the slope of a regression line[2]. Only 5 of the 49 sites analysed by Crowther *et al.*[1] are in the upper half of the carbon stock range, which raises the possibility that the relationship they observed could be substantially altered by introducing data from sites with relatively high surface soil carbon stocks. There is a Reply to this Comment by Crowther, T. W. *et al. Nature* **554**, http://dx.doi.org/10.1038/nature25746 (2018).

We obtained information on soil carbon losses from 94 additional field warming studies worldwide and added these published and unpublished data to the dataset used by Crowther *et al.*[1], thereby tripling this previous dataset to a total of 143 studies (Supplementary Table 1). We performed the same mixed-model regression analyses as were used by Crowther *et al.*[1] to investigate spatial patterns of soil carbon responses to warming, by linking these to standing soil carbon stocks, climate data and soil properties (see Supplementary Methods for details, Supplementary Table 2 for study-specific data regarding soil properties and climate, and Supplementary Table 3 for Akaike information criterion results). In our models, we chose the same predictors as were used by Crowther *et al.*[1], which enables us to directly compare the results of both analyses. Our analysis of the expanded dataset shows that warming-induced losses in soil carbon are not a function of standing carbon stocks (Fig. 1), which challenges the conclusion that future soil carbon loss can be mapped on the basis of current surface soil carbon stocks. Consistent with a previous meta-analysis[3], average soil carbon responses to warming were not statistically different from zero, regardless of whether our dataset or the dataset from Crowther *et al.*[1] (Extended Data Fig. 1) was used. Even if soil carbon stocks remain unchanged in surface soil, this does not imply that decomposition rates are insensitive to warming. Instead, decomposition rates are likely to be higher; however, plant productivity is also likely to increase, which may offset carbon losses from soil. We found that adding other predictors, such as environmental variables or soil properties, provide little additional explanatory power (Supplementary Table 3) when predicting warming-induced changes in soil carbon stocks, a finding that is consistent with the results of Crowther and colleagues[1]. Thus, we still lack a clear understanding of the factors that drive spatial variation in the response of soil carbon to warming.

Our analysis of this larger dataset calls into question the proposition of Crowther and colleagues[1] that future soil carbon loss can be projected on the basis of current surface soil carbon stocks. We are further limited in our ability to produce global predictions of warming effects on soil carbon because warming experiments have mainly been clustered in North America, Europe and China (Fig. 2), with only a handful of experiments having been undertaken in the Southern Hemisphere or in large areas of the Northern Hemisphere at high latitudes (for example, Canada and Russia). Data from the tropics are also as yet unavailable. We suggest that future experimental work focus on regions that are currently underrepresented in our global database. The collection of global experimental data that better capture Earth's diverse terrestrial habitats, combined with an improved integration of data with process-based models[4], might represent the best way forward in the coming decades. A collaborative, multi-disciplinary and international approach is required to increase our understanding and quantification of the fate of soil carbon in a warming world.

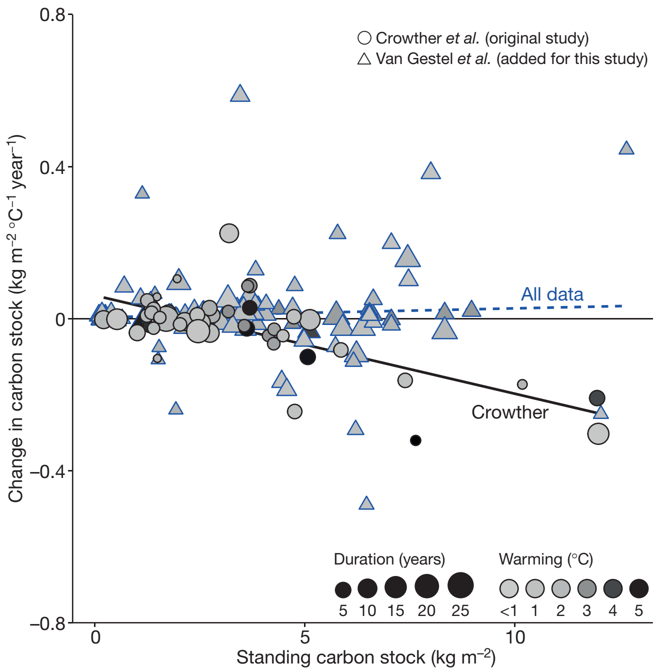

Figure 1 | The change in soil carbon per degree of warming per year is not a function of carbon stock size. Our dataset includes data used by Crowther and colleagues[1] ($n = 49$ studies) and data that we added ($n = 94$ additional studies). Our dataset shows no relationship between the warming effect on soil carbon and the initial size of the carbon stock. The r^2 dropped from 0.49 in Crowther *et al.*[1] to 0.01 ($P > 0.05$) in our dataset ($n = 143$), based on the same regression model as was applied in the previous study[1].

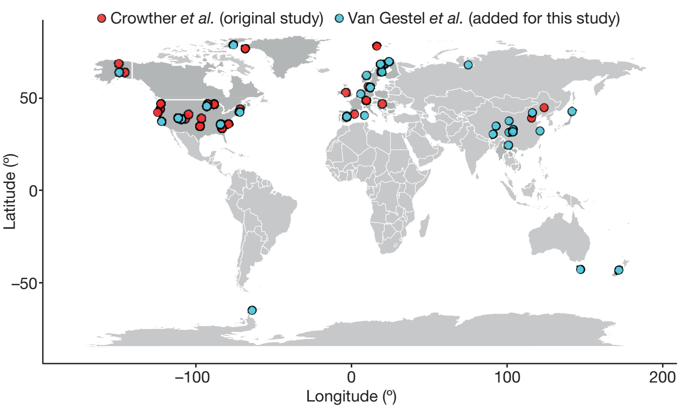

Figure 2 | Location of field warming studies used in our analyses. The dataset includes the data used by Crowther and colleagues[1] ($n = 49$ studies) and the data that we added ($n = 94$ studies). A single location may represent several separate warming experiments.

BRIEF COMMUNICATIONS ARISING

Natasja van Gestel[1], Zheng Shi[2], Kees Jan van Groenigen[3], Craig W. Osenberg[4], Louise C. Andresen[5], Jeffrey S. Dukes[6,7], Mark J. Hovenden[8], Yiqi Luo[9,10], Anders Michelsen[11], Elise Pendall[12], Peter B. Reich[12,13], Edward A. G. Schuur[9,10] & Bruce A. Hungate[9,10]
[1]Climate Science Center, Texas Tech University, Lubbock, Texas 79409, USA.
email: natasja.van-gestel@ttu.edu
[2]Department of Botany and Microbiology, University of Oklahoma, Norman, Oklahoma 73019, USA.
[3]Geography, College of Life and Environmental Sciences, University of Exeter, Exeter EX4 4RJ, UK.
[4]Odum School of Ecology, University of Georgia, Athens, Georgia 30602, USA.
[5]Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden.
[6]Department of Forestry and Natural Resources, Purdue University, West Lafayette, Indiana 47907, USA.
[7]Department of Biological Sciences, Purdue University, West Lafayette, Indiana 47907, USA.
[8]School of Biological Sciences, University of Tasmania, Hobart, Tasmania 7001, Australia.
[9]Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, Arizona 86011, USA.
[10]Department of Biology, Northern Arizona University, Flagstaff, Arizona 86011, USA.
[11]Department of Biology and Center for Permafrost, University of Copenhagen, Copenhagen, Denmark.
[12]Hawkesbury Institute for the Environment, Western Sydney University, Penrith, New South Wales 2751, Australia.
[13]Department of Forest Resources, University of Minnesota, St. Paul, Minnesota 55108, USA.

Received 16 August; accepted 15 November 2017.

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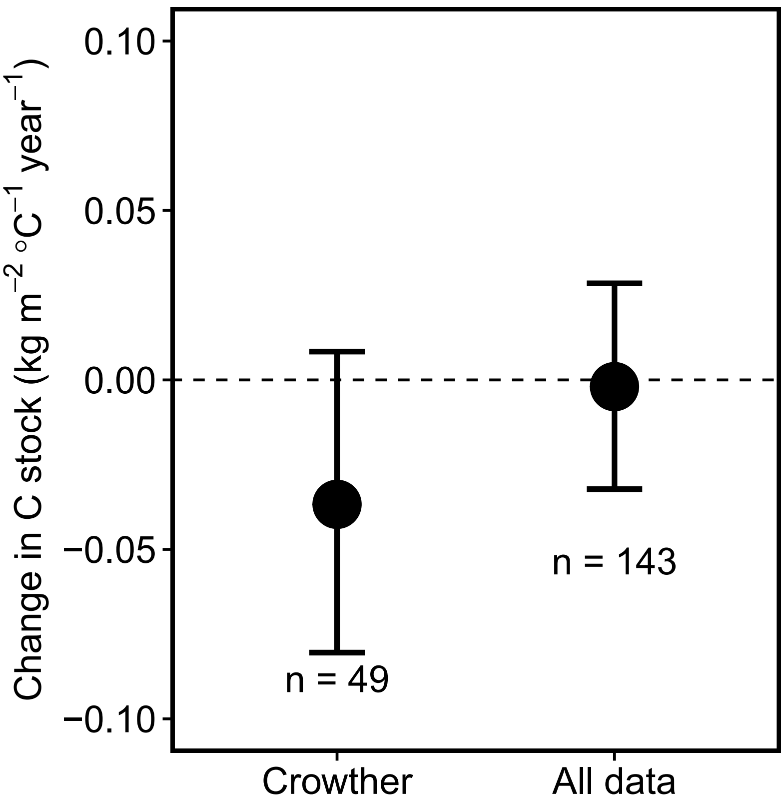
Supplementary Information is available in the online version of the paper.

Author Contributions N.v.G. extracted data from the literature and constructed the database. L.C.A., J.S.D., M.J.H., A.M., E.P., P.B.R, E.A.G.S., and B.A.H supplied non-published data from specific field warming experiments, Z.S., K.J.v.G., C.W.O. and Y.L. provided feedback on data analysis, N.v.G. performed the data analysis and wrote the manuscript draft. All authors contributed to interpretation of the findings and final writing of the manuscript.

Competing Financial Interests Declared none.

doi:10.1038/nature25745



Extended Data Figure 1 | Results of a meta-analysis on the change in soil carbon per degree of warming per year. The average response of soil carbon per degree of warming per year is not significantly different from zero (zero is within the 95% confidence interval of the mean) for the dataset used in Crowther *et al.*[1] or for our dataset. See Supplementary Information for details.

Crowther *et al.* reply

REPLYING TO N. van Gestel *et al. Nature* **554,** http://dx.doi.org/10.1038/nature25745 (2018)

In a Letter to *Nature*[1], we compiled a global dataset of field warming experiments that suggested that climate warming could cause the loss of carbon from high-latitude soils, with the potential to drive a positive feedback that stimulates further warming. This conclusion was based on the observation that areas with larger soil carbon stocks are likely to lose more soil carbon under warming conditions. In the accompanying Comment, having compiled data from even more warming experiments, van Gestel *et al.*[2] no longer find support for this relationship.

In their response, van Gestel *et al.*[2] suggest that our findings may be the result of having too few data points from regions with large soil carbon stocks. In the original Letter[1], we used extensive statistical cross-checking to investigate this possibility; this cross-checking showed that the relationship was consistent throughout our dataset, even after the random removal of approximately 77% of the studies. Nevertheless, with data from a greater number of sites, the analysis produced by van Gestel *et al.*[2] certainly can provide a more robust test of the relationship between carbon stocks and warming-induced soil carbon losses than was possible with our original dataset. Although it is possible that yet more data might provide the statistical power needed to detect such effects, we agree with van Gestel *et al*[2] that this relationship is unlikely to be as strong as expected on the basis of our initial synthesis. However, the analysis undertaken by van Gestel *et al.*[2] does not dispute our conclusions about global changes of soil carbon under warming conditions, because their analysis does not focus on spatial patterns in soil carbon changes under warming conditions.

In our initial analysis[1], we noted that there was considerable variation in the response of soil carbon to warming, with both increases and decreases in soil carbon levels observed across sites. We examined five possible drivers of this variation (standing soil carbon stock, annual temperature, annual precipitation, pH and clay content) and found that standing carbon stock was a strong predictor. The size of the standing carbon stock is known to correlate with various other climatic and geological characteristics, which may ultimately be the underlying drivers of the relationship that we detected[3]. This relationship nonetheless suggests that areas with large soil carbon stocks are more likely to lose carbon under warming conditions. As was the case in our earlier study[1], in the dataset analysed by van Gestel *et al.*[2] site-level responses to warming were also highly variable, which supports the proposition that large changes occur in some geographic regions. However, unlike in our analysis[1], the same five predictive variables were not sufficient to explain the variation in the soil carbon response in the analysis produced by van Gestel *et al.*[2]; consequently, it was not possible to predict which ecosystems are most responsive to warming. A wider range of predictive variables are therefore necessary to explain these large-scale patterns[4]. Until this variation is investigated using this wider range of variables, it is impossible to understand the spatial patterns in soil carbon changes under warming that are necessary to comprehend the net global balance.

We stress that this exchange does not mean that researchers are divided on this topic: we certainly do not disagree with the findings of van Gestel *et al.*[2] Their data provide an alternative perspective on the relationship we observed, but their analysis does not yet address the extent of global soil carbon losses under warming. We are supportive of the work by van Gestel *et al.*[2] and encourage the inclusion of more data, particularly from under-sampled regions of the globe, to comprehend the extent of warming-induced changes in global soil carbon stocks[5].

Most authors from the original paper contributed data that were collected from large field warming experiments. Some of them also contributed data to, and were included as authors on, the accompanying Comment. Overlapping authors were not included on both sides of this discussion, but they all agree to interpretations in both analyses.

T. W. Crowther[1], M. B. Machmuller[2], J. C. Carey[3], S. D. Allison[4,5], J. M. Blair[6], S. D. Bridgham[7], A. J. Burton[8], F. A. Dijkstra[9], B. Elberling[10], M. Estiarte[11,12], K. S. Larsen[13], H. Laudon[14], M. Lupascu[15], S. Marhan[16], J. Mohan[17], S. Niu[18], J. Peñuelas[11,12], I. K. Schmidt[19], P. H. Templer[20], G. Kröel-Dulay[21], S. Frey[22] & M. A. Bradford[23]

[1]Institute of Integrative Biology, ETH Zurich, Universitätstrasse 16, 8006 Zürich, Switzerland.
email: thomas.crowther11@gmail.com
[2]Natural Resource Ecology Laboratory, 1 499 Campus Delivery, Colorado State University, Fort Collins, Colorado 80523-1499, USA.
[3]Division of Math and Science, Babson College, Massachusetts 02457, USA.
[4]Department of Earth System Science, University of California Irvine, Irvine, California 92697, USA.
[5]Department of Ecology & Evolutionary Biology, University of California Irvine, Irvine, California 92697, USA.
[6]Division of Biology, Kansas State University, Manhattan, Kansas 66506, USA.
[7]Institute of Ecology & Evolution, University of Oregon, Eugene, Oregon 97403, USA.
[8]School of Forest Resources & Environmental Science, Michigan Technological University, Houghton, Michigan 49931, USA.
[9]Centre for Carbon, Water & Food, The University of Sydney, Camden, 2570 New South Wales, Australia.
[10]Center for Permafrost (CENPERM), Department of Geosciences and Natural Resource Management, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen K., Denmark.
[11]CSIC, Global Ecology Unit CREAF-CSIC-UAB, Cerdanyola del Vallès, 08193 Catalonia, Spain.
[12]CREAF, Cerdanyola del Vallès, 08193 Catalonia, Spain.
[13]Department of Geosciences & Natural Resource Management, University of Copenhagen, Rolighedsvej 23, 1958 Frederiksberg C, Denmark.
[14]Department of Forest Ecology & Management, Swedish University of Agricultural Sciences, 90183 Umeå, Sweden.
[15]Department of Geography, National University of Singapore, 1 Arts Link, 117570, Singapore.
[16]Institute of Soil Science & Land Evaluation, University of Hohenheim, 70593 Stuttgart, Germany.
[17]Odum School of Ecology, University of Georgia, Athens, Georgia 30601, USA.
[18]Key Laboratory of Ecosystem Network Observation & Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China.
[19]Department of Geosciences & Natural Resource Management, University of Copenhagen, Rolighedsvej 23, 1958 Frederiksberg C, Denmark.
[20]Department of Biology, Boston University, Boston, Massachusetts 02215, USA.
[21]Institute of Ecology & Botany, MTA Centre for Ecological Research, 2-4. Alkotmany U., Vacratot, 2163-Hungary.
[22]Department of Natural Resources & the Environment, University of New Hampshire, Durham, New Hampshire 03824, USA.

[23]School of Forestry & Environmental Studies, Yale University, 195 Prospect Street, New Haven, Connecticut 06511, USA.

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doi:10.1038/nature25746

CORRECTION
https://doi.org/10.1038/s41586-018-0192-1

Author Correction: Crowther *et al.* reply

T. W. Crowther, M. B. Machmuller, J. C. Carey, S. D. Allison, J. M. Blair, S. D. Bridgham, A. J. Burton, F. A. Dijkstra, B. Elberling, M. Estiarte, K. S. Larsen, H. Laudon, M. Lupascu, S. Marhan, J. Mohan, S. Niu, J. J. Peñuelas, I. K. Schmidt, P. H. Templer, G. Kröel-Dulay, S. Frey & M. A. Bradford

Correction to: Nature https://doi.org/10.1038/nature25746, published online 21 February 2018.

In this Brief Communications Arising Reply, the affiliation for author P. H. Templer was incorrectly listed as 'Department of Ecology & Evolutionary Biology, University of California Irvine, Irvine, California 92697, USA' instead of 'Department of Biology, Boston University, Boston, Massachusetts 02215, USA'. This has been corrected online.