

Editor Comments to the Author:

The authors provided convincing answer to the reviewer comments except one point. The study is strongly biased towards contributions from China, where input of inorganic fertilisers can be very high. It could be good to run the model without studies from China to see if the relationships found are still valid.

As suggested, we ran our model both excluding data points from China and also with only observations from China. We found that the effect size of N did not change significantly, however, the effect size of SOC did change depending on the subset of data analyzed. We found a stronger impact of SOC on yield when analyzing Chinese-only observations. The reason for this difference is that the majority (all but 10) of Chinese observations had SOC contents of less than 2%. Therefore, the strong effect size is capturing the range of SOC that appears to lead to the largest gains in yield. We now address these geographic differences in the discussion (lines 257-272) and also include regression output and figures within the supplementary material of our revision (specifically Table S2 and Figure S3). We believe this additional analysis highlights both the need for studies to come evenly from systems where maize and wheat are grown and also the importance of analyzing regional datasets that capture the observed range of SOC values in order to quantify a regionally-specific relationship between SOC and yield. We now emphasize these points within our discussion (lines 270-273).

Response to reviewer comments (reviewer comments in italic)

The authors use a global data set on maize and wheat yields together with soil and other environmental variables to derive statistical relationships between SOC and yield. The overall value of the study is appreciated. The interpretation of the data and observed relationships is, however, going too far because direct evidence for the postulated effects, as it could be derived from long-term experiments at different SOC levels, cannot be derived and many other influencing factors were ignored.

Title and abstract. In both, SOM is described as the key variable but the study relies on SOC data. This should be reflected in the title and the abstract. This already touches a more fundamental problem – the study does not provide mechanistic insight as to why higher SOC results in higher yields. More SOC is often obtained using more organic inputs, i.e., more macro- and micro-nutrients bound to SOM. A second issue here, related to the first one is that, correctly, a higher SOC concentration might reduce the amount of N needed as fertilizer to get the same yield, but it is not discussed how much more N must be fertilized to reach the higher SOC level.

We appreciate the reviewer's comments and have made revisions to address these concerns. The first major concern is that we do not provide mechanistic insight as to why SOM (or SOC) would increase yield. We believe that the mechanisms between SOM/SOC and crop yield have been well established, but poorly quantified. For instance, we would expect SOC to be associated with greater cation exchange capacity for the exchange of micronutrients and greater water holding capacity. SOC, because it is the

majority constituent of SOM, is also highly correlated with macro-elements contained in SOM. The contribution of our project is not to tease apart the relative importance of the separate mechanisms by which SOM/SOC operates, though we do believe this would be a very important, but challenging, project. Instead, our aim is to establish relationships at broad scales between SOC and yield to provide better quantification of this relationship for policy initiatives such as the recently launched Global Soil Health Challenge. This has been identified as a critical knowledge gap among producers, policy makers, and researchers alike (Adhikari and Hartemink, 2016; Chabbi et al., 2017; Hatfield et al., 2017). For instance, the U.S. National Research Council stated in their 2010 report on sustainable agriculture that “measures of [SOM] are a cornerstone of most sustainability and soil quality assessments...However, the numerical level that would be considered good, or what change in [SOM] levels constitutes a significant functional change, has not been established (NRC, 2010).” Our paper is an attempt to answer that call, and we have made this clear in our revision (lines 90-91).

Secondly, the reviewer raises concerns related to the challenge of using observational differences across broad spatial scales to test SOC-yield relationships. We note here and now make clear in our revision (lines 98-100, 404-408) that the differences in soil carbon observed in our data set are from experimental plots capturing long-term differences in SOC within a given site. Specifically, our data capture differences within SOC in experimental plots largely driven by management interventions related to inputs (e.g. compost, fertilizer, manure, crop residues) and tillage (e.g. no-till versus till). We capture these site-specific differences in management with site-level random intercept terms.

Regarding our analysis of potential fertilizer reductions: we recognize that a combination of both organic and inorganic nutrients will be necessary to help build SOM and improve crop yields. We highlight this further in our revision and stress that building SOM and cutting back on N fertilizer will require achieving an agricultural N balance where SOM-N mineralization accounts for the reductions in mineral fertilizer (lines 192-201). This will depend on the amount and C:N ratios of inputs used in specific agricultural systems. We also note and provide relevant citations that this may prove especially challenging in smallholder systems where there is often lack of access to and insufficient quality of organic inputs (Giller et al., 2009; Palm et al., 2001).

L. 96 and methods. It is not clear why authors only used aridity and latitude as variables related to climate. Yields are strongly related to rainfall and temperature, which are easily available variables.

We chose to use aridity since it is a variable that is expressed as a function of precipitation, temperature, and potential evapo-transpiration. We now include this information and relevant citation in a revised manuscript (Trabucco 2009) (lines 396-398). We did initially include rainfall and temperature variables in our statistical model, but since they were highly correlated, we chose to leave them out and include aridity since it is derived from temperature and precipitation data. The use of aridity has been used in other large-scale yield studies (Pittelkow et al., 2014).

L. 121. More recent literature suggests that higher yield is not coming along with higher plant residue inputs (e.g., Hirte et al. 2018 Agriculture Ecosystems Environment 265).

This is a good point, and one we highlight in the Introduction. Specifically, previous work has found positive, negative, and no relationship between soil carbon and yields. Our work is not designed to resolve which of these patterns is correct because we believe that those site-specific relationships capture local realities. Rather, we are trying to capture global, average relationships that can help quantify the relationship between SOC and yield for broad-scale policy targets.

L. 141. Authors argue that two thirds of maize and wheat cultivation takes place on soils with less than 2 % SOC. What is, for comparison, the average % SOC of croplands worldwide? Are these two staple crops planted on particularly C-poor soils?

As our study focuses on two of the most important staple crops that are planted globally, we chose to focus on the SOC contents for maize and wheat. This two-thirds percentage reflects the dataset we collected from published literature as well: Namely, the majority of soils from our dataset contained SOC concentrations equal to or less than 2%. For comparison, when we explored the average SOC contents for each agro-ecological zone (AEZ) for our analysis, we found that all AEZs aside from tropical humid, temperate humid, and boreal systems all had average SOC contents of 2% or less.

L. 160. Are the authors aware of any long-term field experiment where an increase from 0.5 to 2 % SOC has been observed? This seems unlikely to me. Even a doubling (previous sentence) is ambitious. The following argumentation, that higher SOM soils may supply enough plant available nutrients to sustain crop yields with drastically cutting back N fertilizer input overlooks that these are typical situations of SOM decline, as observed in many long-term experiments, where plant productivity can be maintained at low nutrient input rates only because of SOM decline and the associated release of organically bound nutrients.

This is a good point, and we recognize that building SOC from 0.5 to 2.0% represents a very large increase. Such an increase would require a significant amount of inputs that may not be feasible due to inherent and logistical difficulties related to soil properties, climate, and farmer access to inputs (lines 231-242). We now further stress the challenges associated with increasing SOC, while also highlighting experimental results recently published that show a range of annual increases in SOC for temperate agricultural soils (lines 163-174). The annual increases reported in this study range from 0.3 to 18% and are a result of a number of different inputs ranging from farmyard manure to mineral fertilization, some of which the authors of this study acknowledge may not be practical for farmers (Poulton et al., 2018).

L. 193 ff. The first para in section 2.3. belongs largely to the method section and is partially a repetition of that.

We have revised this text in our revision to avoid repetition with our Methods section.

L. 215. It is not clear where the yield gap comes from – how was it calculated, was it taken from the literature? Clarification needed.

We now provide more context and the relevant citation for our yield gap analysis. Specifically, we are using a global data set (Mueller et al., 2012) that provides a global assessment of the difference between observed yields and attainable yields (lines 220-222).

L. 302. Authors refer to Söderström et al. 2014. I looked up that reference where I could not find a database as key repository but rather a research approach. Should be clarified.

Thank you for pointing this out. Söderström et al. is another manuscript from this database effort, but we now cite the original paper in our revision (Haddaway et al., 2015).

L. 352. I suggest to use three classes: rainfed, irrigated, unknown.

When extracting data, in cases where authors did not specify how crops were watered, we scored them as rainfed. In light of this comment, we went back to each paper that we classified as rainfed within our database and found a number of data points (n=46) that did not explicitly provide any information regarding irrigation and/or rainfall patterns over the growing season. For these instances, we scored them as unknown and ran our regression models again. The coefficients did not significantly change and so we decided to leave irrigation data as is in order to provide the greatest number of observations for our analysis.

L. 353. Filling data gaps for soil pH and texture for experimental sites by a global database may introduce large errors and, potentially, biased estimates, given that these soil properties vary much over short distances. I suggest to either exclude those variables as explanatory ones or to ask authors of the studies to provide those data for their sites. Alternatively, these parameters can be categorized and used as categorical variables.

We note that many of the studies were published prior to recent initiatives to deposit data products for published papers, making the kind of analysis we did additionally challenging. As such, we acknowledge that using values from a global database is not ideal and do acknowledge this as a limitation with our manuscript (lines 273-279). We did contact all authors for meta-data and raw data from their published studies, however, we only received data from three of the authors. As part of our original data exploration, we calculated the correlation coefficient for pH ($r = 0.83$) and soil texture ($r = 0.61$) between SoilGrids data and measured data from experimental studies in our data set. We also ran our regression model without texture and pH, and the coefficients on our model terms were essentially unchanged. We chose to retain these terms, however, because we believe that they do have established biological mechanisms as to their influence on yield. Furthermore, the range of both pH and percent clay data observed in SoilGrids reflects the range of data observed in our data set. Therefore, we believe that the

relationships between variables are transferable between data sets even if the two data sets predict different values for the same place.

Table 2. I suggest to add a percentage increase in production from an increase in SOC to the table to make the global yield average and the increase in production comparable to each other.

This is a good suggestion and one we now include in our revision.

Figure 2. Not clear why the figure relates to maize and yield in line 1114 whereas the caption in line 1115 refers to maize only.

Thank you for catching this. We have revised the figure title to say, “Relationship between SOC and yield of maize for published studies.”

Figure 5. The figure is interesting but results would better be presented as percentage increase in yield, and not as percentage closure of yield gap. The yield gap itself is prone to large uncertainty, both in extent and possible reasons, and these uncertainties are not explicitly included.

When making our figures, we did create a map that featured percentage yield increase, however, it was difficult to visualize gains when presented at the broad global scale. We believe the yield gap map provides a clearer illustration of the areas that stand to gain the most in terms of identifying impacts of SOC on yield.

Figure 4. The provided interpretation of this results ignores the fact that building up additional SOC requires additional N.

This is a good point, and as we mention above, we now provide more discussion related to the challenges of building SOM/SOC, and that it may require the addition of inorganic N or organic N amendments (lines 192-201).

References

Adhikari, K. and Hartemink, A. E.: Linking soils to ecosystem services — A global review, *Geoderma*, 262, 101–111, doi:10.1016/j.geoderma.2015.08.009, 2016.

Chabbi, A., Lehmann, J., Ciais, P., Loescher, H. W., Cotrufo, M. F., Don, A., SanClements, M., Schipper, L., Six, J., Smith, P. and Rumpel, C.: Aligning agriculture and climate policy, *Nature Clim. Change*, 7(5), 307–309, 2017.

Giller, K. E., Witter, E., Corbeels, M. and Tittonell, P.: Conservation agriculture and smallholder farming in Africa: The heretics' view, *Field Crop Res.*, 114(1), 23–34, 2009.

Haddaway, N. R., Hedlund, K., Jackson, L. E., Kätterer, T., Lugato, E., Thomsen, I. K., Jørgensen, H. B. and Söderström, B.: What are the effects of agricultural management on soil organic carbon in boreo-temperate systems? *Environmental Evidence* 2014 3:1, 4(1), 23, doi:10.1186/s13750-015-0049-0, 2015.

Hatfield, J. L., Sauer, T. J. and Cruse, R. M.: Soil: The Forgotten Piece of the Water, Food, Energy Nexus, Adv. Agron., 143, 1–46, doi:10.1016/bs.agron.2017.02.001, 2017.

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N. and Foley, J. A.: Closing yield gaps through nutrient and water management, Nature, 490(7419), 254–257, doi:10.1038/nature11420, 2012.

NRC: Understanding agricultural sustainability, in Toward Sustainable Agricultural Systems in the 21st Century, pp. 1–29, National Academies Press, Washington, DC, 2010.

Palm, C. A., Giller, K. E., Mafongoya, P. L. and Swift, M. J.: Management of organic matter in the tropics: translating theory into practice, Nutr. Cycl. Agroecosys., 61(1997), 63–75, doi:10.1023/A:1013318210809, 2001.

Pittelkow, C. M., Liang, X., Linquist, B. A., van Groenigen, K. J., Lee, J., Lundy, M. E., van Gestel, N., Six, J., Venterea, R. T. and van Kessel, C.: Productivity limits and potentials of the principles of conservation agriculture, Nature, 517(7534), 365–368, doi:10.1038/nature13809, 2014.

Poulton, P., Johnston, J., Macdonald, A., White, R. and Powlson, D.: Major limitations to achieving “4 per 1000” increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom, Glob. Change Biol., 24(6), 2563–2584, doi:10.1111/gcb.14066, 2018.

Trabucco, A., and Zomer, R.J. 2009. *Global Aridity Index (Global-Aridity) and Global Potential Evapo-Transpiration (Global-PET) Geospatial Database*. CGIAR Consortium for Spatial Information. Published online, available from the CGIAR-CSI GeoPortal at: <http://www.csi.cgiar.org>.

Response to Reviewer 2

This study examines the relationship between SOM and yields of wheat and maize across a range of agroecological contexts around the globe. The authors then apply this relationship to better understand the potential of increased SOM stocks to improve yields, as well as reduce N fertilizer inputs.

The study is ambitious in scope and their approach involved a number of assumptions and simplifications, and therefore requires considerable caution in the interpretation of their findings. Despite these drawbacks, I appreciated the effort and feel that the study represents a valuable and novel contribution towards addressing a complex issue with relevance to global agricultural sustainability. While I enjoyed this paper, I have several comments/critiques for the authors.

Thank you for this overall positive assessment. We do indeed view our work as a step

forward in addressing a complex issue with relevance – academically, for policy, and for practice – to global agricultural sustainability. Equally, we appreciate the limitations of our work. We believe that our response to your comments below will ensure that we detail these limitations openly in our manuscript so that the advance we offer can be built upon constructively to evaluate the inferences we make.

General comments:

The premise that increased SOM will reduce N inputs seems a bit misleading. Both the building of SOM (to 2% SOC) and its continued maintenance at this higher level will require considerable quantities of organic matter inputs both now and into the foreseeable future. So it seems unlikely that total N inputs will actually decrease, but really we are talking about a shift from inorganic to organic N sources. The authors allude to this in several places, but it could be spelled out more clearly. In reading the authors' responses to Reviewer 1, it seems that they now better recognize the need to address this.

Thank you for this comment. As Reviewer 2 mentions, this also came up with Reviewer 1. In our revision, we address this more comprehensively. Specifically, as we mentioned in response to Reviewer 1, we recognize that a combination of both organic and inorganic nutrients will be necessary to both build SOM and improve crop yields. Building SOM and cutting back on N fertilizer will require that the SOM-N mineralization compensates for the reductions in mineral N fertilizer, and we now state this in our revised manuscript (lines 192-201).

Related to this, the study largely ignores the dynamic state of SOM. For example, soils in a state of rapid SOM decline may actually be supporting yields better than a soil at a similar level of SOM, simply because more nutrients are being mineralized as this SOM is lost.

This is a good point, and we now provide further explanation in our discussion related to the “soil carbon dilemma” (Janzen, 2006). Namely, that to derive the nutrient benefits of SOM, it must be mineralized and used. As Janzen mentions in this paper, to both build SOM and derive nutrients from it, continuous inputs of organic matter will be needed to account for that which is lost through mineralization. Our revised discussion highlights this expected effect of SOM (i.e. nutrient supply), but also highlights that SOM is expected to have positive effects on productivity for other reasons (e.g. improved aeration and moisture supply). See lines 233-253.

I appreciate Fig. 1 showing origin of the datasets considered in this study, but am a little concerned about the high number of observations from China and how this might bias the findings. This should be addressed in the discussion.

We do have a large proportion of studies from China in our dataset as is highlighted in Fig. 1. We state, however, in our methods that the variation observed in our dataset for our model parameters reflects that observed within the global datasets we used for our

extrapolations (lines 500-504). However, we agree this is an important point when making “global generalities,” and in our revised discussion we emphasize the need for studies to inform such understanding to come more evenly from systems where wheat and maize are grown (lines 268-272). We also removed data points from China and performed our regression analysis on this amended data set. We found that the impact of N input on yield did not vary dramatically from that of our original model, however, the effect size of SOC on yield was smaller. We also performed our regression analysis on observations from China only. With this analysis, we found a stronger impact of SOC on yield than that for the entire dataset. The reason for this difference is that the majority (all but 10) of Chinese observations had SOC contents of less than 2%. Therefore, the strong effect size is capturing the range of SOC that appears to lead to the largest gains in yield. We now address these geographic differences in the discussion (lines 257-268) and also include regression output and figures from these additional analyses within the supplementary material of our revision (specifically Table S2 and Figure S3).

Related to the above comment, it would be nice to see a table that provides a breakdown of how the sites were distributed in terms of number of sites with and without irrigation and with wheat vs. corn, as well as different ranges of pH, aridity, clay content, latitude, so that readers can better assess potential biases in the dataset on their own. This could be a new table in the main text or alternatively in the supplementary materials.

This is a good idea, and we now include such a table in our supplemental materials. Furthermore, we have uploaded our entire dataset to KNB repository and provided a link to it within our manuscript for anyone to view and use. This way, readers can explore the data to see the breakdown in variables as Reviewer 2 mentions.

I understand the value of keeping the model relatively simple, but was surprised that several potentially important interaction terms were left out, while others (i.e., SOM x N input) were included. For example, I would expect to see a strong interaction between SOM and irrigation, such that SOM would be more important in rain-fed systems (particularly in semi-arid regions) than in irrigated agriculture, where the water related benefits of SOM would be less important. Also, I would have expected the different soils with higher SOC, crop types (and potentially sandy vs. clay textured soils) to respond differently to varying SOM levels. Please consider including these terms or at least explain why the SOM x N interaction was included in the model and some of these other terms not.

When we initially created our model, we did not include any interactions because of the sheer number of potential interactions that could be included, which would take up too many degrees of freedom. Additionally, and perhaps more importantly, 3-and-more way interactions are very hard to disentangle and their statistical significance should be interpreted with caution (Gelman and Loken, 2013). Following the philosophical and operational statistical methods we adopted (Hobbs and Hilborn, 2006) – cited in our methods – we limited most of our exploration to only two-way interactions where we had a strong ecological rationale for expected effects. As such, we decided to include an SOM x N interaction to specifically explore potential reductions in N fertilizer with increased

SOC concentrations. This was an effort to see if there is a level of SOC that can compensate for N input. We now further justify our decision for including this interaction and not others in our revision (lines 436-445). However, we do acknowledge that the interactions Reviewer 2 suggests present interesting lines of inquiry. We re-ran our regression model with additional interactions to include SOC x irrigation, SOC x clay, and SOC x aridity. These interactions did not offer any additional explanatory power (the r^2 was essentially unchanged and the coefficients were small). Furthermore, the main findings between SOC, N inputs, and yield were essentially unchanged with additional interactions. As our main findings remain the same with and without these additional interactions, we are choosing to maintain our analysis as it is. We now provide as supplementary material a table (Table S3) that shows the lack of sensitivity of SOC and N input effects to inclusion of these additional two-way interactions, justifying the regression model results we focus on.

Specific comments:

L112: the reported value of 0.25 is not very informative here in the text without providing units or some sort of additional explanation.

This number was meant to point out the fact that the slope of the relationship between SOC and yield levels off at 2% SOC.

L116-121: the logic behind the sentence “the asymptotic relationship between SOC and yield lends support to the idea that building SOC will increase yields – at least to a certain extent – as opposed to simply being an outcome of higher yields.” Is not entirely clear. Could it not be that yields have a larger effect on building SOM at higher levels? These two sentences should be perhaps omitted or further clarified.

This discussion was meant to highlight the challenges of quantifying the relationship between SOM and yield since the relationship could potentially be causative in both directions, with greater SOC leading to higher yields but also higher yields increasing SOC concentrations. This sentence was intended to demonstrate SOC as a cause – at least to some extent – of higher yields in the case of our analysis. For instance, if yield was on the x-axis as an explanatory variable for SOC on the y-axis, we would expect higher yields to keep driving higher levels of SOC (i.e. the relationship would appear more linear) since we know that soils can accumulate concentrations much greater than 2% (i.e. we are at a point that is well below theoretical and/or empirical soil C saturation points); however, our data do not display this pattern and higher yields do not appear to be driving higher levels of SOC. We now clarify this point in our revision (lines 117-122).

L133: It seems the asymptotic relationship and leveling off above 2% (in Fig 2) may be strongly influenced by relatively few observations and I wonder if the authors conducted any sort of leverage tests (e.g., Cook’s distance) to examine the potential influence of extreme observations. This is especially notable for the 4-5 sites that were at or above 2.5% SOC and with very low fertilizer addition and yields (in the bottom right corner of Fig. 2).

We did not perform any leverage tests for our initial analysis. However, as suggested by Reviewer 2, we did evaluate Cook's distance and did not find any influential data points that would significantly change our regression relationship. Additionally, we re-ran our regression after removing the 4 data points in question, and model coefficients remained essentially the same. We now mention this in the revised methods (lines 422-424).

Also, It is not entirely clear how inter-annual variability was taken into account, especially for rain-fed sites, where a severe drought in the year of yield data collection could drastically skew results.

We nested year within site as a random effect in our regression model to account for spatial and temporal correlation (lines 408-410). There were some instances of low yields at rain-fed sites within our data set. We believe these observations are important to include as they capture the local realities of the relationship between climatic variables and yield. Our data set then uses these locally observed data points to capture a global average relationship between SOC and yield, which we state in the paper will need to be built on at sub-regional scales to provide data directly relevant to farmers and land managers.

L154: specify that your are referring more to 'inorganic' of 'synthetic N inputs'

We have made this change.

L155: suggest replacing 'achieving' with 'obtaining', as crops do not achieve nutrients they obtain them.

We have edited this sentence.

L159-163: As mentioned above, the authors should acknowledge that higher SOC is not necessarily allowing for lower total N inputs, but perhaps lower synthetic N inputs, since there is likely to be relatively higher inputs of organic matter (and organic N) in soils with higher SOC, or at least there should be if are managed in a way that that seeks to maintain these levels of SOC.

We have now made this point clear in our revision.

L164-165: Again, why where interactions only examined between SOC and N input and not for other factors that are very likely to interact with SOC, such as irrigation, crop type, texture, and aridity?

As mentioned above, we chose to include only an SOC x N interaction since we were asking a question specifically related to the interaction between SOC and N as it relates to agricultural inputs. In our revision's supplementary materials, we now include the additional regression analyses to show that including these interactions did not offer any more explanatory power to our model and our main findings (i.e. coefficient estimate

sizes) essentially remained the same.

L165-167: Could this also have to do with Liebig's law of the minimum, such that higher SOM levels are really just supplying more P, K and other essential nutrients that may be co-limiting to N at higher N levels, but not at low N application levels. Please clarify

This is a good point and one we now include as a way to explain why N had a greater impact on yield at higher SOC concentrations (lines 180-182). Other benefits of higher SOM include better moisture retention, improved structure and aeration, etc., so there is a substantive list of benefits expected for plants at higher SOM concentrations.

L188-191: What is this calculation and the 3.73 million tons based on? Please elaborate.

We include the basis for this calculation in our methods (lines 552-559). In the revision, we will refer specifically to the Methods in this section of the discussion.

L233: yes, water retention is important, but also improved nutrient (especially N) supply from decaying SOM

This is a good point and one we now include in our revision (lines 252).

L372-374: Again, based on this section and Table 1, what was rationale for including the SOM x N interaction? Also, as mentioned above why were other variables, that were likely to strongly interact with SOM (e.g., irrigation, clay, crop type), not included? This seems rather arbitrary and inclusion of these other interaction could have helped explain significant variability in yield across sites.

We agree that there are a number of potential interactions between SOC and other variables included in our model. As mentioned above, we now explain our decision and also include the additional regression output as a supplemental table (Table S3).

Fig 1: again need to discuss the potential bias of having so many sites from one country, China, especially since fertilizer inputs in China are typically much higher than other parts of the world.

As mentioned above, in the revised discussion we emphasize the need for studies to inform such understanding to come more evenly from systems where wheat and maize are grown. We have also provided additional discussion and supplemental analysis of our data when all observations from China were removed. We found that the impact of N is essentially the same for both regression analyses, however, the effect size for SOC is smaller for the amended data set (see Table S2). We now include more discussion addressing these points (lines 257-268).

Fig 2: this is confusing, as the title suggest that the relationship includes maize and wheat, but then the next sentence says that its just for rain-fed maize. Please clarify.

Thank you for bringing this to our attention. Reviewer 1 also noticed this error, and we have edited our caption to specify that the regression relationship only includes rain-fed maize.

Fig 4: which crops/conditions are being presented here. As for Fig 2, this needs to be better clarified.

We have clarified this to specify that the regression relationships are plotted for rain-fed maize.

Fig 5: the numbers on top of the colored boxes are small and difficult to read, especially when printed in B&W

We have edited these to increase their font size for readability.

References

Gelman, A. and Loken, E.: *The garden of forking paths: Why multiple comparisons can be a problem, even when there is no “fishing expedition” or “p-hacking” and the research hypothesis was posited ahead of time.* Retrieved from http://www.stat.columbia.edu/~gelman/research/unpublished/p_hacking.pdf

Hobbs, N. T. and Hilborn, R.: Alternatives to statistical hypothesis testing in ecology: A guide to self teaching, *Ecol. App.*, 16(1), 5–19.

Janzen, H.: The soil carbon dilemma: Shall we hoard it or use it? *Soil Biol. Biochem.*, 38(3), 419–424, doi:10.1016/j.soilbio.2005.10.008, 2006.

1 **Global meta-analysis of the relationship between soil organic matter and crop yields**

2 Emily E. Oldfield^{1*}, Mark A. Bradford¹, Stephen A. Wood^{1,2}

3

4 ¹School of Forestry and Environmental Studies, Yale University, 370 Prospect Street,

5 New Haven, CT 06511, USA

6 ²The Nature Conservancy, Arlington, VA 22201, USA

7

8 Correspondence: Emily E. Oldfield, School of Forestry and Environmental Studies, Yale

9 University, 370 Prospect St, New Haven, CT, 06511, USA

10 Email: emily.oldfield@yale.edu

11 Co-author emails: MAB (mark.bradford@yale.edu); SAW (stephen.wood@tnc.org)

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14 yield gap

15 **Abstract**

16 Resilient, productive soils are necessary to sustainably intensify agriculture to increase
17 yields while minimizing environmental harm. To conserve and regenerate productive
18 soils, the need to maintain and build soil organic matter (SOM) has received considerable
19 attention. Although SOM is considered key to soil health, its relationship with yield is
20 contested because of local-scale differences in soils, climate, and farming systems. There
21 is a need to quantify this relationship to set a general framework for how soil
22 management could potentially contribute to the goals of sustainable intensification. We
23 developed a quantitative model exploring how SOM relates to crop yield potential of
24 maize and wheat in light of co-varying factors of management, soil type, and climate. We
25 found that yields of these two crops are on average greater with higher concentrations of
26 SOC. However, yield increases level off at ~2% SOC. Nevertheless, approximately two
27 thirds of the world's cultivated maize and wheat lands currently have SOC contents of
28 less than 2%. Using this regression relationship developed from published empirical data,
29 we then estimated how an increase in SOC concentrations up to regionally-specific
30 targets could potentially help reduce reliance on nitrogen (N) fertilizer and help close
31 global yield gaps. Potential N fertilizer reductions associated with increasing SOC
32 amount to 7% and 5% of global N fertilizer inputs across maize and wheat fields,
33 respectively. Potential yield increases of $10 \pm 11\%$ (mean \pm SD) for maize and $23 \pm 37\%$ for
34 wheat amount to 32% of the projected yield gap for maize and 60% of that for wheat. Our
35 analysis provides a global-level prediction for relating SOC to crop yields. Further work
36 employing similar approaches to regional and local data, coupled with experimental work

- 37 to disentangle causative effects of SOC on yield and vice-versa, are needed to provide
- 38 practical prescriptions to incentivize soil management for sustainable intensification.

39 **1 Introduction**

40 The pressure to increase crop production has resulted in the expansion of land area
41 dedicated to agriculture and the intensification of cropland management through practices
42 such as irrigation and fertilization. These practices have led to degradation of land and
43 waters prompting “sustainable intensification” initiatives to increase yields on existing
44 farmland while decreasing the environmental impact of agriculture (Foley et al., 2011;
45 Godfray et al., 2010; Mueller et al., 2012). One sign of land degradation is the loss of soil
46 organic matter (SOM) (Reeves, 1997). Re-building SOM in agricultural lands holds the
47 promise of improving soil fertility, as SOM affects many properties of soils, including
48 their ability to retain water and nutrients, to provide structure promoting efficient
49 drainage and aeration, and to minimize loss of top-soil via erosion (Reeves et al., 1997;
50 Robertson et al., 2014). As such, managing SOM to ensure stable and long-lasting crop
51 productivity and to decrease reliance on external inputs such as mineral fertilizers and
52 irrigation has been identified as a critical component of sustainable intensification (Foley
53 et al., 2011). Yet the emphasis on soil management has remained qualitative, meaning
54 that the potential contribution of building SOM as a means to increase crop production
55 and minimize the environmental impact of agriculture has not yet been broadly quantified
56 (Adhikari and Hartemink, 2016; Chabbi et al., 2017; Hatfield et al., 2017).

57 A primary hurdle to managing SOM for sustainable intensification is the lack of
58 predictive, quantitative targets of SOM for specific agricultural and environmental
59 objectives (Herrick, 2000; NRC, 2010). While several studies show correlations between
60 SOM and yield (Culman et al., 2013; de Moraes Sa et al., 2014; Lucas and Weil, 2012;
61 Stine and Weil, 2002), it remains unclear how much yield could be expected to increase
62 per unit change in organic matter (Herrick, 2000; NRC, 2010). Establishing these

63 quantitative metrics is challenging because research shows increases (Bauer and Black,
64 1992), decreases (Bhardwaj et al., 2011), and no change (Hijbeek et al., 2017) in yields
65 with increased SOM. This lack of a general relationship is likely the result of a number of
66 interacting factors related to management, climate, and soil type that can confound the
67 SOM-yield relationship. This confusion has led some to claim that the amount of SOM is
68 unnecessary for crop yields, so long as there is sufficient N fertilizer (Hijbeek et al.,
69 2017; Loveland and Webb, 2003; Oelofse et al., 2015); whereas others highlight the need
70 to build SOM to increase crop yields while minimizing environmental harm (Lal, 2004).
71 The growing momentum to launch global scale initiatives to manage SOM (Banwart et
72 al., 2014; Lal, 2004; Minasny et al., 2017; Zomer et al., 2017) suggests the need to test
73 competing claims about the effects of SOM on these agricultural and environmental
74 outcomes.

75 One could critique the effort to establish a global-level understanding of the
76 SOM-yield relationship on the grounds that farm-level responses are necessarily
77 heterogeneous and poorly predicted by global assessments. Yet, global initiatives for
78 managing SOM could create policy environments that stimulate regional- and local-
79 prescriptions for SOM levels that inform practice (Chabbi et al., 2017; Minasny et al.,
80 2017; Zomer et al., 2017). Whereas it is difficult to disentangle the extent to which SOM-
81 yield relationships are driven by SOM effects on yield, as opposed to yield (i.e. higher
82 plant carbon inputs) effects on SOM, there is nevertheless experimental evidence
83 showing that building SOM positively affects yield (Bauer and Black, 1994; Majumder et
84 al., 2008; Oldfield et al., 2017). In addition, numerous soil properties that relate to soil
85 fertility, such as water holding capacity, respond positively to increasing SOM and in

86 turn are expected to increase yields (Williams et al., 2016). As such, correlative SOM-
87 yield relationships suggest the potential – but likely not the true – effect of SOM on yield.

88 We developed a quantitative model exploring how SOM relates to crop yield
89 potential in light of co-varying factors of management, soil type, and climate. The aim is
90 that this model can then be used to **establish relationships at broad scales between SOM**
91 **and yield to provide better quantification of this relationship for policy initiatives.** We
92 quantified the relationship between SOM (measured as SOC, a common proxy for SOM)
93 and yield at a global level using data from published studies. We focused our analyses on
94 wheat and maize, two common staple crops that (along with rice) constitute two-thirds of
95 the energy in human diets (Cassman, 1999). Along with SOC, we modeled the effects on
96 crop yields of several factors widely reported in yield studies: N input rate, irrigation, pH,
97 soil texture (% clay), aridity, crop type (i.e. wheat or maize), and latitude (as a proxy for
98 growing-season day length). The data informing our model came from empirical studies
99 that capture local scale variation in these variables, and hence we interpret our results in
100 light of the correlative nature of the database we assembled. Using the resulting multiple-
101 regression relationship, we then estimated how an increase in SOC concentrations up to
102 regionally-specific target thresholds might affect global yields. Our overarching aim was
103 to estimate the potential extent to which restoring SOC in global agricultural lands could
104 help close global yield gaps and potentially help reduce reliance on – and the negative
105 effects of – N fertilizer.

106

107 **2 Results and Discussion**

108 **2.1 The relationship between SOC and yield**

109 At the global level and focusing specifically on the potential effect size of SOC on yield,
110 we found that the largest gains in yield occur between SOC concentrations of 0.1 to
111 2.0%. For instance, yields are 1.2 times higher at 1.0% SOC than 0.5% SOC (Fig. 1).
112 Gains in yield leveled off at a concentration of approximately 2% SOC (Fig. 1). Two
113 percent SOC has previously been suggested as a critical threshold, with values below this
114 concentration threatening the structure, and ultimately, the ability of a soil to function
115 (Kemper and Koch, 1966). Importantly, the asymptotic relationship between SOC and
116 yield lends support to the idea that building SOC will increase yields – at least to a
117 certain extent – as opposed to simply being an outcome of higher yields. **That is, if yield**
118 **was an explanatory variable for SOC, we would expect greater yields to keep driving**
119 **greater levels of SOC (i.e. the relationship would appear more linear) since we know that**
120 **soils can accumulate concentrations much greater than 2% (Castellano et al., 2015).**
121 **However, our data do not display a linear pattern, suggesting that higher yields are not**
122 **driving higher levels of SOC.**

123 It has been suggested that there is no evidence for 2% SOC being a critical
124 threshold for productivity, as long as there is sufficient mineral fertilizer to support crop
125 production (Edmeades, 2003; Loveland and Webb, 2003; Oelofse et al., 2015). Such
126 conclusions deem the amount of SOM as substitutable by mineral fertilizers (at least for
127 crop growth), but are inconsistent with the motivation for sustainable intensification to
128 minimize environmental harm caused by mineral fertilizers in relation to emissions of
129 greenhouse gases and eutrophication of waters (Vitousek et al., 2009). The same logic
130 about substitutability also does not account for the other co-benefits associated with
131 building SOM in agricultural lands, such as reductions in nutrient run-off, drought
132 resistance, and yield stability (Robertson et al., 2014). Field- and regional-scale studies

133 have shown a similar pattern as that observed from our global analysis: there exists a
134 positive relationship between SOC and yield that starts to level off at ~2% SOC
135 (Kravchenko and Bullock, 2000; Pan et al., 2009; Zvomuya et al., 2008). Our analysis
136 suggests that this relationship holds on average at the global scale and when N
137 fertilization is controlled for.

138 Ninety-one percent of the published studies used for our analysis were carried out
139 in fields with less than 2% SOC, with a mean of 1.1%. To see whether these observations
140 in SOC distribution reflected global patterns, we used globally gridded data on crop yield
141 and SOC (to a depth of 15 cm) (Hengl et al., 2014; Monfreda et al., 2008). We found that,
142 by both area and production, two thirds of maize and wheat cultivation takes place on
143 soils with less than 2% SOC (Fig. 2). Indeed, a recent analysis estimates that agricultural
144 land uses (including cropland and grazing) have resulted in a loss of 133 Pg of carbon
145 over the past 12,000 years of human land use (Sanderman et al., 2017). There appears to
146 be, therefore, significant opportunity to increase SOC on maize and wheat lands to
147 improve crop yields.

148

149 **2.2 The interaction between SOC and N fertilizer on yield**

150 One of the key goals of sustainable intensification is to reduce the environmental impacts
151 of agriculture (Foley et al., 2011; Mueller et al., 2012). Nitrogen fertilization, while a
152 boon to yields, can cause environmental damages, such as eutrophication of waters and
153 increased soil emissions of nitrous oxide, a potent greenhouse gas (Vitousek et al., 2009).
154 Using our regression model, we asked whether there might be target N fertilizer addition
155 rates that suggest the possibility of maximizing yield per unit N applied by building SOC
156 and reducing **inorganic** N inputs. We wanted to see if yields converge at higher levels of

157 SOC, suggesting that crops are **obtaining** sufficient nutrients through SOM and excess
158 mineral N is not necessary. Our analysis suggests that SOC is not directly substitutable
159 for mineral fertilizer (Fig. 1); however, at lower rates of N input (≤ 50 kg N ha⁻¹), we
160 found that increasing SOC from 0.5 to 1.0% could potentially maintain current yields and
161 reduce fertilizer inputs by approximately half (50%). At higher rates of N input (≥ 200 kg
162 N ha⁻¹), an increase from 0.5 to 2.0% SOC could potentially reduce synthetic N inputs by
163 up to 70% per hectare (Fig. 3). **Building SOC from 0.5 to 2.0% represents a very large**
164 **increase, which would require a significant amount of inputs that may not be feasible due**
165 **to inherent and logistical difficulties related to soil properties, climate, and farmer access**
166 **to inputs. Furthermore, such an increase could take several years or decades to**
167 **accomplish. For example, results from long-term field trials show a range of annual**
168 **increases in SOC for temperate agricultural soils, which were as low as 0.3% and as high**
169 **as 18% (Poulton et al., 2018). At the low end of this range, and starting at 0.5% SOC, it**
170 **would take ~47 years to build to 2% SOC if the annual relative rate of increase was**
171 **constant, and ~9 years at the high end of the range. Admittedly, the range emerged as a**
172 **result of a number of different inputs ranging from farmyard manure to sewage sludge to**
173 **mineral fertilization, some of which may not be available to farmers given cost and/or**
174 **access (Poulton et al., 2018). Feasibility aside, however, our results suggest that building**
175 **SOM in agricultural lands may supply enough plant available nutrients to sustain crop**
176 **yields while drastically cutting back on N fertilizer inputs.**

177 There was an interaction between SOC and N input, where at higher SOC
178 concentrations N input had a greater impact on yield (Fig. 1, Table 1). This may be
179 because higher SOC improves soil structure and water holding properties, resulting in
180 improved crop growth at a given level of N input (Powlson et al., 2011). **Higher levels of**

181 SOM could also provide more essential macro- and micro-nutrients that are limiting in
182 soils with lower SOC concentrations. Additionally, soils receiving more N may have
183 greater SOC because N increases crop yields, which can increase the return of plant
184 residues into the soil and potentially build SOC (Powlson et al., 2011). However, if the
185 relationship was simply an effect of greater inputs building SOC, we should not have
186 seen an interaction between SOC and N on yields (because SOC should then just have
187 been additively related to yield). Whatever the specific explanation, the SOC by N
188 interaction we detect suggests that a combination of both building SOM and using
189 targeted N applications could lead to potential increases in yield (Fig. 3). Practices such
190 as cover-cropping represent a strategy that can both increase N supply and build SOM
191 through biological N fixation and the return of high quality residues (narrow C:N ratios)
192 to the soil (Drinkwater et al., 1998). Building SOM and reducing fertilizer N input would
193 require a balance where SOM-N mineralization accounts for any limitations in N supply
194 that arise from reducing mineral fertilizer applications. The balance required will depend
195 on the amount and C:N ratios of inputs used in specific agricultural systems, and could
196 prove challenging to achieve in some small-holder systems where low SOC
197 concentrations might be compounded by a lack of access to and insufficient quality of
198 organic inputs (Giller et al., 2009; Palm et al., 2001). As such, the combination of both
199 SOM improvement and targeted fertilizer input will likely be especially important for
200 degraded soils, which require a suite of organic and inorganic nutrients to help build
201 SOM and improve crop yields (Palm et al., 1997).

202 Gains in yield from fertilizer input leveled off at about 200 kg N ha⁻¹ y⁻¹ (Fig. 3),
203 meaning that optimum yields appear achievable, at least on average, with this fertilizer
204 input level and an SOC target concentration of 2%. Using this target N input rate, we

205 explored potential fertilizer reductions on agricultural lands using more than 200 kg N ha⁻¹
206 y⁻¹. We found that for lands receiving more than 200 kg N ha⁻¹ y⁻¹, current yields could
207 be maintained, while decreasing global N fertilizer inputs by 7% for maize and 5% for
208 wheat. It is estimated that 25 to 30% of fertilizer N is exported to streams and rivers,
209 resulting in eutrophication (Raymond et al., 2012). Targeted reductions in the application
210 of fertilizer N on the order of magnitude our analysis suggests could then prevent the
211 annual export of as much as 3.73 million tonnes of N into inland waters, which amounts
212 to 10% of mineral fertilizer applied to maize and wheat lands (see Methods for an
213 explanation of how this percentage was obtained).

214

215 **2.3 Exploring potential reductions in global yield gaps of maize and wheat**

216 With a majority of cultivated lands containing less than 2% SOC and a growing
217 imperative to build, restore, and protect SOC in agricultural soils (NSTC, 2016; FAO,
218 2008; NRCS, 2012), we used global gridded datasets coupled with our regression model
219 (Table 1) to examine the potential gains in yield and production if opportunities to
220 increase SOC are realized (Table 2). We then calculated how these gains in production
221 would impact global yield gaps of maize and wheat, the difference between observed and
222 attainable yields (Mueller et al., 2012). Although our model identified 2% as a global
223 target for SOC, we created regionally-specific SOC targets given the fact that achieving
224 2% SOC in some soils (e.g. those of drylands) may be unachievable due to inherent
225 constraints of physical soil properties and climate (see Methods). We found that
226 increasing SOC concentrations to the defined targets has the potential capacity to increase
227 average yields on a per hectare basis by 10±11% (mean±SD) for maize and 23±37% for
228 wheat. These gains in yield translate to a 5% and 10% increase in the global annual

229 tonnes produced of maize and wheat, respectively (Table 2). These increases in
230 production would close 32% of the global yield gap for maize and 60% of the gap for
231 wheat (Fig 4a,b).

232 These yield gap results represent an exploration of potential “best case” impacts
233 of increasing SOC concentrations. We recognize there are inherent and logistical
234 challenges to building SOM in agricultural soils; and **when managing for and building**
235 **SOM, it is important to account for its dynamic nature. For instance, to derive some of**
236 **the nutrient benefits of SOM, it must be mineralized and used (Janzen, 2006), and so**
237 **frequent additions of organic inputs may be necessary to sustain SOM levels.**

238 Furthermore, soil characteristics such as texture can have a large effect on SOC content
239 because sandier (rather than more clay rich) soils have less surface area to stabilize SOC
240 (Rasmussen et al., 2018), and so hold much less water and nutrients than clay-rich soils
241 (Johnston et al., 2009). Maintaining SOC contents in sandy soils may require more
242 frequent additions of organic amendments because these soils do not have the surface
243 area to retain nutrients, moisture, and to stabilize SOC (Lehmann and Kleber, 2015).

244 **D**ifferent regions and climate types also face different imperatives for building
245 SOM. In the mid-western United States, for instance, building SOM may be a good
246 strategy to reduce fertilizer inputs and irrigation needs; whereas in sub-Saharan Africa,
247 building SOM may be critical for drought protection and nutrient provision. Notably,
248 high SOM values are not common in dryland environments (for our dataset, mean SOC =
249 0.9% for dryland climates versus 1.4% SOC for mesic soils), and building and
250 maintaining SOM in arid zones is typically hindered by the lack of organic matter to
251 return to soils (Rasmussen et al., 1980). On a positive note, however, our analysis
252 suggests that increases in SOC in drylands, for example, from 0.5 to 0.8%, could

253 potentially increase yields by 10%, likely due to impacts on water retention as well as
254 improved nutrient supply.

255 The goal of our analysis was to establish a global, average relationship between
256 SOC and yield. Whereas we did use lower SOC targets (ranging from 1.0 to 1.5%) for the
257 arid AEZs in our analysis, the majority of data used for our analysis is from the more
258 temperate and tropical humid zones (Fig. S2) and a large proportion of our data comes
259 from China (Fig. 1). We recognize that the distribution of our data could potentially bias
260 our results. As such, we explored the SOM-yield relationship in the absence of data from
261 China and also for Chinese observations only. While the effect size of SOC changes
262 depending on the subset of data analyzed (Table S2), the qualitative patterns of this
263 relationship remain the same. That is, SOC leads to gains in yield that are most
264 pronounced at lower SOC concentrations and decline in their magnitude as ~2% SOC is
265 reached (Fig. S3). Notably, when exploring the subset of data from China, the effect size
266 of SOC was higher than that from the entire dataset (Table S2). However, China only had
267 10 observations above 2% SOC, and so the modeled relationship for China captures the
268 part of the SOM-yield relationship where an increase in SOC leads to the largest gains in
269 yield (i.e. where the modeled slope is the steepest). Our analysis then highlights both the
270 need for studies to come evenly from systems where maize and wheat are grown and also
271 the importance of analyzing regional datasets that capture the observed range of SOC
272 values in order to quantify a regionally-specific relationship between SOC and yield to
273 more directly inform practice.

274 Moving from the global relationship presented in our paper to bolstering and/or
275 refining SOC targets, our correlative analysis needs to be supplemented with well-
276 replicated experimental studies incorporating different management strategies across

277 multiple soil and climate types to develop SOC-yield relationships that can be applied to
278 the specific set of local farm conditions. Further, these studies should ideally report data
279 related to soil texture and mineralogy, nutrient management, and paired SOC-yield
280 observations with SOC taken to meaningful depths, such as those that represent plant-
281 rooting depth. These experimental studies will help generate information that
282 practitioners can use to inform management by taking into account the potential benefits
283 of SOC, compared against the inherent and logistical challenges to building SOC to target
284 levels.

285

286 **3 Conclusions**

287 Despite uncertainties and calls for further research into how SOM affects agricultural
288 performance (Cassman, 1999; Herrick, 2000; Oldfield et al., 2015), policy for sustainable
289 intensification already widely supports the merits of increasing SOM in agricultural lands
290 (FAO, 2008; NRCS, 2012). The purported benefits include improved yields, increased
291 resilience, and decreased inputs of fertilizer and irrigation water. However, although
292 consensus exists around the importance of SOM to soil health, translating SOM policy to
293 practice is hindered by the lack of a predictive capacity for SOM target setting to inform
294 management efforts focused on yield and reducing fertilizer and irrigation (Chabbi et al.,
295 2017; Herrick, 2000; NRC, 2010). Our analysis helps establish a quantitative framework
296 for SOC targets that achieve measurable agricultural outcomes as part of sustainable
297 intensification efforts. It quantifies the potential effect size of SOC on yield while also
298 accounting for climate, soil, and management variables that influence crop yield. We find
299 that greater concentrations of SOC are associated with greater yields up to an SOC
300 concentration of 2%. With two thirds of global maize and wheat lands having SOC

301 concentrations of less than 2%, there seems significant opportunity to increase SOC to
302 reduce N inputs and potentially help close global yield gaps.

303

304 **4 Methods**

305 Our approach consisted of a two-stage process. In the first stage, we assembled published
306 empirical data from studies that reported both SOC and yield data for maize and wheat.

307 From this meta-dataset, we then quantified how both SOC concentrations and N input
308 rates are related to yields, in the context of spatial variation in climatic, management, and
309 soil co-variables. In the second stage, we used globally-gridded datasets to extract values
310 for the factors we investigated in the first stage for global lands where maize and wheat is
311 produced. Using the regression relationship developed from the published empirical data
312 compiled under the first stage, we then estimated how an increase in SOC concentrations
313 up to target thresholds we identified (ranging from 1 to 2% depending on agro-ecological
314 zoning) affected global yield potentials. Finally, we used an N input threshold identified
315 through our regression analysis ($200 \text{ kg N ha}^{-1} \text{ yr}^{-1}$) to calculate potential N reductions on
316 global maize and wheat lands.

317

318 **4.1 Data collection**

319 In the first stage of our approach, we searched the database Web of Science (Thomson
320 Reuters) in January 2016 and again in October 2016 using the following topic search
321 terms: “soil organic matter” OR “soil organic carbon” OR “soil carbon” OR “soil c”
322 AND “yield” OR “crop yield” OR “productivity” AND “agricult*.” We restricted the
323 initial search to articles published in English between 1980 through December 2015, and
324 excluded conference proceedings; the second search captured articles published in 2016.

325 The initial search resulted in 1,384 articles and the second 169 articles (Fig. S1). For each
326 citation, we reviewed titles and abstracts to select articles that met the following criteria:
327 experimental field studies whose abstract included information on yield and SOC for
328 systems growing wheat and/or maize. This initial screening resulted in 523 records for
329 which we assessed the full text. We assessed these records for eligibility based on
330 inclusion of data on crop yield, SOC, and N fertilizer rates for each observation. For
331 inclusion within our analysis, it was essential that studies reported paired SOC and yield
332 data. Furthermore, we required SOC concentrations (as opposed to stocks). Studies did
333 not meet our criteria for inclusion if they reported SOC stocks with no corresponding data
334 on bulk density to convert into concentrations; and also if they reported baseline SOC
335 concentrations as opposed to experimental SOC concentrations that we could pair with
336 yield data. In addition to our literature search, we also contacted authors to see if they
337 were willing to include raw data within our database. This resulted in three datasets
338 (Adiku et al., 2009; Birkhofer et al., 2008; Kautz et al., 2010). Finally, we consulted the
339 recently published database by the Swedish Board of Agriculture that is a key repository
340 of peer reviewed literature focusing specifically on studies (735 in total) related to the
341 effects of agricultural management on soil organic carbon (Haddaway et al., 2015). We
342 explored this database to find studies from regions that were under-represented within our
343 literature search (e.g. the southern hemisphere). This resulted in a search of 55 studies to
344 see if they met our criteria for inclusion. We scanned each paper to see if they included
345 SOC data paired with matching yield data. From these papers, we extracted data from 12
346 studies, which resulted in an additional 52 data points. We encountered limitations
347 similar to our initial search: Namely, SOC and yield data were not paired, studies
348 included only baseline SOC concentrations, or SOC stocks were reported without any

349 corresponding bulk density data to convert into concentrations. Overall, our dataset
350 included 840 individual observations from 90 articles covering sites across the globe
351 (Adiku et al., 2009; Agegnehu et al., 2016; Albizua et al., 2015; Alijani et al., 2012;
352 Araya et al., 2012; Atreya et al., 2006; Bai et al., 2009; Bedada et al., 2014; Bhardwaj et
353 al., 2011; Bhattacharyya et al., 2015; Birkhofer et al., 2008; Boddey et al., 2010; Boulal
354 et al., 2012; Bremer et al., 1994; Calegari et al., 2008; Campbell et al., 2007; Castellanos-
355 Navarrete et al., 2012; Celik et al., 2010; Chen et al., 2015; Chirinda et al., 2010; Cid et
356 al., 2014; Costa et al., 2010; D'Hose et al., 2014; Datta et al., 2010; DeMaria et al., 1999;
357 Diacono et al., 2012; Grandy et al., 2006; Guo et al., 2012; 2009; He et al., 2011; Hossain
358 et al., 2016; Hu et al., 2015; 2014; Kaihura et al., 1999; Karbozova Saljnikov et al., 2004;
359 Kautz et al., 2010; Kazemeini et al., 2014; Kucharik et al., 2001; Larsen et al., 2014;
360 Lebbink et al., 1994; Leogrande et al., 2016; Li et al., 2015; Liu et al., 2014a; 2016;
361 2014b; 2014c; López-Garrido et al., 2014; Lu et al., 2016; Ma et al., 2012; 2016;
362 Madejón et al., 2001; Mandal et al., 2013; Mastro et al., 2007; Mikanová et al., 2012;
363 Mishra et al., 2015; Mupangwa et al., 2013; N'Dayegamiye, 2006; Niu et al., 2011; Njoku
364 and Mbah, 2012; Paul et al., 2013; Qin et al., 2015; Quiroga et al., 2009; Sadeghi and
365 Bahrani, 2009; Saikia et al., 2015; Scalise et al., 2015; Seremesic et al., 2011; Singh and
366 Dwivedi, 2006; Singh et al., 2016; Sisti et al., 2004; Soldevilla-Martinez et al., 2013;
367 Spargo et al., 2011; Šimon et al., 2015; Tejada et al., 2016; Tiecher et al., 2012; van
368 Groenigen et al., 2011; Vieira et al., 2007; 2009; Wang et al., 2015; 2014a; 2014b;
369 Wortman et al., 2012; Wu et al., 2015; Yang et al., 2013; 2015a; 2015b; Yeboah et al.,
370 2016; Zhang et al., 2015; 2009; 2016; Zhao et al., 2016). Where necessary, we extracted
371 data from manuscript figures using GraphClick Software (v. 3.0.3, [http://www.arizona-
software.ch/graphclick/](http://www.arizona-
372 software.ch/graphclick/)).

373 Studies that presented individual data points recorded over multiple years were
374 included as well as studies that averaged both yield and SOC data over multiple years. To
375 avoid over-representation of studies that included data points recorded for both yield and
376 SOC over multiple years (>10 y), we took observations from the beginning, middle, and
377 last year of the study.

378

379 **4.2 Data compilation**

380 For each extracted observation, we compiled the following information: latitude,
381 longitude, year of data collection, crop type, yield, SOC or SOM, depth of SOC or SOM
382 measurement, N fertilization rate, P fertilization rate, soil pH, texture, and whether or not
383 crops were irrigated. We used SOC (as opposed to SOM) for our analysis given that SOC
384 is a common proxy for SOM. Carbon, as an element that is easily identified and
385 measured within soil, is thought to comprise ~50-60% of SOM and is commonly reported
386 in the literature (Pribyl, 2010). When SOM was reported, we converted it to SOC by
387 dividing the value by 1.724 (Cambardella et al., 2001). Different studies reported SOC
388 concentrations to different depths, which ranged from 0-5 cm to 0-30 cm, with the
389 majority of studies reporting SOC to 0-20 cm. When studies reported SOC to multiple
390 depths, we averaged SOC values across depths to 30 cm. If no information on irrigation
391 was provided, we scored the observation as rain-fed. Soil texture and pH were not
392 reported for every study; 79% of included studies reported pH, and so we used the
393 study's latitude and longitude to extract these data using ISRIC SoilGrids (Hengl et al.,
394 2014) to fill in the missing pH values. Texture was reported for about half (49%) of
395 included studies, and so we used coordinates to pull these data from SoilGrids as well
396 (Hengl et al., 2014). We also used latitude and longitude to obtain an "aridity index"

397 through the CGIAR-CSI database (Zomer et al., 2008). We chose to use aridity as our
398 primary climatic variable since it is expressed as a function of precipitation, temperature,
399 and potential evapo-transpiration (Trabucco 2009).

400

401 **4.3 Data analysis**

402 We used a linear mixed model (LMM) to analyze the observations we extracted from the
403 literature. Our model included SOC, N fertilizer rate, crop type (maize or wheat, coded as
404 a binary variable), irrigation (coded as a binary variable), aridity index, latitude, pH, and
405 texture (% clay) as fixed effects. The differences in soil carbon observed in our dataset
406 are from experimental plots capturing long-term differences in SOC within a given site.
407 Specifically, our data capture differences within SOC largely driven by management
408 interventions related to inputs (e.g. compost, fertilizer, manure, crop residues) and tillage
409 (e.g. no-till versus till). Site-specific differences in management as well as spatial and
410 temporal correlation among the studies were accounted for by nesting year within study
411 as random effects (Bolker et al., 2009). The LMMs were fit with a Gaussian error
412 distribution in the “lme4” package for the “R” statistical program (version 3.3.1), using
413 the “lmer” function. The first stage of our data analysis was to test the data distributions.
414 We removed data points with N fertilization rates $>600 \text{ kg N ha}^{-1}$ (4 data points) and
415 yields $>18 \text{ t ha}^{-1}$ (2 data points) since these represented outliers for our dataset (being
416 beyond 3 times the inter-quartile range of the meta-dataset) and are not representative of
417 on-farm management practices or outcomes. Our final model was based on 834
418 observations across 90 studies. We added quadratic terms for both SOC and N input rate
419 since these variables exhibited a nonlinear relationship with yield. The square-root of the
420 variance inflation factors (vif) was <2 for all factors when included as main effects,

421 indicating that collinearity was low among all variables. As would be expected, there was
422 a correlation between SOC and its quadratic term and N input rate and its quadratic term.
423 We re-ran our regression after removing four seemingly influential data points (those that
424 had high SOC concentrations with low yields, see Fig. 2) and model coefficients
425 remained essentially the same. We calculated the r^2 values for our model following
426 Nakagawa and Schielzeth (Nakagawa and Schielzeth, 2013) to retain the random effects
427 structure. The r^2 of our model was 83% for the full model, with the fixed effects
428 explaining 42% of observed variance within our dataset.

429 We based the choice of factors for inclusion in our model on the approach of
430 Hobbs et al. (Hobbs and Hilborn, 2006), by only investigating factors where biological
431 mechanism as to their influence on yield is firmly established and where we were
432 interested in their effect sizes relative to one another. Also following Hobbs et al. (Hobbs
433 and Hilborn, 2006), we did not carry out model selection. Operationally, there is
434 substantial subjectivity and lack of agreement in model selection approaches, with
435 different decisions leading to markedly different conclusions as to the influence of
436 different factors. Instead, coefficients are generally most robust when all terms are
437 retained in a model, assuming that inclusion of each is biologically justified. We decided
438 to include an SOC by N interaction to explore potential reductions in N fertilizer with
439 increased SOC concentrations. This was an effort to see if there is a level of SOC that can
440 compensate for N input. We acknowledge that there are a number of interactions we
441 could have included within our statistical model, and we did run our regression model
442 with additional interactions to include SOC by irrigation, SOC by clay, and SOC by
443 aridity. Including these interactions, however, did not offer any additional explanatory
444 power and our main results between SOC, N inputs, and yield were essentially

445 unchanged with these additional interactions (Table S3). As such, we chose to present our
446 analysis including only the SOC x N interaction.

447 To examine the effects sizes of the factors on yield, we took two approaches.
448 First, we compared the size of the standardized coefficients, where standardizing
449 involved subtracting the mean of the factor from each observed value and dividing by
450 two standard deviations (Gelman, 2008). Dividing by two standard deviations is useful
451 when binary predictors are included within regression models (in our case, crop type and
452 irrigation are coded as a binary predictors). This way, continuous and binary variables all
453 have a mean of 0 and a standard deviation of 0.5 (Gelman, 2008). This accounts for the
454 fact that the factors were measured on different unit scales (Table 1). Second, we
455 examined the influence of changing SOC concentration or N fertilization rates on yield.
456 To do this, we used the regression relationship derived from our statistical model, held all
457 other factors at a constant value (e.g. the mean of all observations for that factor), and
458 systematically varied SOC or N fertilization across the range of values we extracted from
459 the literature. For SOC, this meant varying SOC values from 0.1 to 3.5% to estimate
460 changing yield of rain-fed maize or wheat as SOC concentrations were increased (Fig. 1).
461 For N fertilization, we varied N input rates from 0 to 300 kg N ha⁻¹ for rain-fed maize or
462 wheat at different SOC concentrations (Fig. 3). When these factor-yield relationships
463 were plotted, we identified threshold values where yield became minimally responsive to
464 SOC or N fertilization as the point where the slope of the relationship became <0.25 (for
465 SOC) and < 0.002 (for N fertilization).

466

467 **4.4 Global extrapolations**

468 We used the regression relationship developed in the first stage of our approach to predict
469 how building SOC concentrations would potentially affect global crop yield averages. To
470 obtain values for each of the factors in our regression model at a global scale, we used
471 globally gridded data products. Global SOC, pH, and texture data were taken from ISRIC
472 SoilGrids (Hengl et al., 2014) at a 10-km grid cell resolution to match the spatial grain for
473 maize and wheat yields and N fertilization data, which we obtained from the EarthStat
474 product (Monfreda et al., 2008; Mueller et al., 2012). SoilGrids has multiple layers for
475 SOC concentrations, and we used the 0-15 cm layer as the average depth to which SOC
476 was reported for our dataset was 0-20 cm. The aridity index was obtained from the
477 CGIAR-CSI database (Zomer et al., 2008). We used the resulting global dataset to
478 explore the potential impact of increasing SOC (up to regionally identified threshold
479 levels ranging from 1 to 2%) on yield for lands across the globe where maize and wheat
480 are produced.

481 To establish regionally appropriate SOC targets, we classified maize and wheat
482 producing areas by their agro-ecological zones (AEZ). The Food and Agricultural
483 Organization have 18 zones defined on the basis of combinations of soil, landform, and
484 climatic characteristics (Ramankutty et al., 2007). For each AEZ, we examined the
485 distribution of SOC in areas classified as naturally vegetated (e.g. not in urban or
486 agricultural land uses). We did this by stacking two GIS raster layers of SOC (SoilGrids)
487 and land use (Friedl et al., 2010), excluding agricultural and urban land use
488 classifications. We then extracted SOC data for each AEZ using a shape file outlining the
489 geographical extent of each AEZ (Ramankutty et al., 2007). Examining the distribution
490 of SOC across each AEZ, we identified targets based on the mean SOC value within each
491 zone. All but four zones had means greater than 2% SOC, so we set target values for

492 those zones at 2%. Mean SOC concentrations were lower for the more arid zones and so
493 we set those targets to 1% for AEZ 1 and 1.5% for AEZ zones 2, 3, and 7. These targets
494 were in line with recent quantitative assessments based on similar climatic classifications.
495 For instance, recent analysis of global SOC concentrations across globally defined
496 Ecoregions shows mean values of SOC at or greater than 2% for all regions except land
497 classified as desert and xeric shrubland (Stockmann et al., 2015).

498 Prior to our global extrapolations, we performed a suite of data checks. We
499 wanted to ensure that global yields predicted using our regression model were
500 comparable to those from EarthStat. These checks helped validate the strength of our
501 extrapolations. Firstly, we explored the range of variation in variables from experimental
502 data used to generate our model as well as the range of global variation in variables we
503 project across. The range of our regressors encompasses the range of global variation,
504 except for aridity, in which case 4.6% percent of our projections fall in grids that have
505 axis conditions outside of our range of measurements. These values fall in extremely arid
506 systems, with aridity values of less than 0.1. In these extremely arid zones, we do make a
507 point to use lower target SOC values, recognizing that achieving 2% SOC in these very
508 arid areas is not very likely. Secondly, using our regression model to predict global yields
509 for both maize and wheat (separately), we first removed all values from the analysis that
510 had predicted yields of less than 0 because negative yields are not possible. This
511 amounted to 0.004% of the total predictions for maize and 0.15% for wheat. For
512 clarification, we refer to predictions from our regression model as “predicted” or “model-
513 predicted.” We then calculated the proportional difference between model-predicted and
514 globally gridded yield data from EarthStat. We dropped all cells for which the
515 proportional difference between predicted and gridded data was >3-times. This threshold

516 represents the mean \pm half of the standard deviation for the distribution of the
517 proportional difference between predicted and EarthStat yield data. This amounted to
518 14% of cells for maize and 7% for wheat. The mean proportional difference between
519 predicted and gridded data was 0.85 ± 0.91 for maize (Fig. S4b) and 0.45 ± 0.87 for wheat
520 (Fig. S5b). The correlation between predicted and gridded data was $r=0.73$ for maize
521 (Fig. S4c) and $r=0.38$ for wheat (Fig. S5c). We also visualized overlap in the distribution
522 of model-predicted and gridded data. Model-predicted maize yield had a global mean of
523 4.66 ± 1.84 t ha⁻¹ and EarthStat had a global mean of 3.34 ± 2.62 t ha⁻¹ (Fig. S4a). Model-
524 predicted wheat yield had a global mean of 3.18 ± 1.66 t ha⁻¹ and EarthStat had a global
525 mean of 2.43 ± 1.58 t ha⁻¹ (Fig. S5a).

526 We also compared the distribution of EarthStat yield data with observed yield
527 data from the studies included in our analysis. We found that correlation (r values)
528 between the gridded and collected data was 0.56 for maize and 0.39 for wheat. Average
529 observed maize yield was 5.61 ± 3.32 t ha⁻¹ and wheat yield was 4.02 ± 2.11 t ha⁻¹
530 (mean \pm SD). EarthStat maize yield, again, was 3.34 ± 2.62 t ha⁻¹ and wheat yield was
531 2.43 ± 1.58 t ha⁻¹. These differences between predicted and EarthStat yield averages are
532 likely due to the fact that EarthStat data is based on regional census data, incorporating
533 much more variability in terms of management practices and skill than experimental field
534 studies.

535 After the data checks, we then used our model to extrapolate global yield
536 potentials of maize and wheat given increases in SOC. We masked EarthStat production
537 and cultivated area data layers for maize and wheat for cells that had SoilGrids SOC
538 concentrations of $>2\%$. We compared the subsetting data (i.e. cultivated lands with $< 2\%$
539 SOC) with the original data layers to determine the fraction of global maize and wheat

540 production and cropland that is on soils with less than 2% SOC. We used this subsetted
541 data along with our regression model to predict yields at current SOC levels. As stated
542 above, we used EarthStat, ISRIC SoilGrids, and CGIAR-CSI data layers to fill in the
543 values for each of the factors in our regression model. This new data layer was used as a
544 baseline with which to compare to potential gains in yield with an increase to SOC target
545 values. This created a second data layer with model-predicted yields given an increase in
546 SOC. We calculated the percentage increase in yield between these two layers (the
547 baseline and the improved-SOC layer) and multiplied this by EarthStat yield and
548 production data to determine potential gains in maize and wheat yields and production
549 (Table 2). We then used EarthStat yield gap data to see how such an increase in SOC
550 would reduce projected yields gaps. Using the new yield data layer (with yields at SOC
551 target values), we calculated the proportion of EarthStat yield gaps that was reduced for
552 both maize and wheat.

553 Finally, we used data on global N use (EarthStat) to explore potential reductions
554 in fertilizer use for both maize and wheat, separately. We used a value of 200 kg N ha^{-1}
555 yr^{-1} as our N input threshold, as this is the value from our regression model at which gains
556 in yields level off. We created a new data layer for those areas that have N input rates
557 greater than $200 \text{ kg N ha}^{-1} \text{ yr}^{-1}$. We then calculated the potential N reductions, in tonnes,
558 by multiplying this new data layer by EarthStat cultivated maize and wheat lands,
559 separately. Finally, we divided the potential reduction in N input (in tonnes) by total N
560 input (in tonnes) as provided through the EarthStat data product.

561

562 **Data availability**

563 The dataset generated and analyzed during the current study is available through the
564 KNB repository: <https://doi.org/10.5063/F19W0CQ5>

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566

567 **Author contributions**

568 EEO, MAB, and SAW conceived of the study. EEO and SAW performed data analysis.

569 EEO wrote the first draft of the manuscript. All authors contributed to data interpretation

570 and paper writing.

571

572 **Competing Interests**

573 The authors declare that they have no conflict of interest.

574

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587 **References**

- 588 Adhikari, K. and Hartemink, A. E.: Linking soils to ecosystem services — A global
589 review, *Geoderma*, 262, 101–111, doi:10.1016/j.geoderma.2015.08.009, 2016.
- 590 Adiku, S. G. K., Jones, J. W., Kumaga, F. K. and Tonyigah, A.: Effects of crop rotation
591 and fallow residue management on maize growth, yield and soil carbon in a savannah-
592 forest transition zone of Ghana, *Journal of Agricultural Science*, 147(3), 313–322,
593 doi:10.1017/s002185960900851x, 2009.
- 594 Agegnehu, G., Bass, A. M., Nelson, P. N. and Bird, M. I.: Benefits of biochar, compost
595 and biochar-compost for soil quality, maize yield and greenhouse gas emissions in a
596 tropical agricultural soil, *Sci. Total Environ.*, 543, 295–306,
597 doi:10.1016/j.scitotenv.2015.11.054, 2016.
- 598 Albizua, A., Williams, A., Hedlund, K. and Pascual, U.: Crop rotations including ley and
599 manure can promote ecosystem services in conventional farming systems, *Appl. Soil
600 Ecol.*, 95, 54–61, doi:10.1016/j.apsoil.2015.06.003, 2015.
- 601 Alijani, K., Bahrani, M. J. and Kazemeini, S. A.: Short-term responses of soil and wheat
602 yield to tillage, corn residue management and nitrogen fertilization, *Soil Till. Res.*, 124,
603 78–82, doi:10.1016/j.still.2012.05.005, 2012.
- 604 Araya, T., Cornelis, W. M., Nyssen, J., Govaerts, B., Getnet, F., Bauer, H., Amare, K.,
605 Raes, D., Haile, M. and Deckers, J.: Medium-term effects of conservation agriculture
606 based cropping systems for sustainable soil and water management and crop productivity
607 in the Ethiopian highlands, *Field Crop Res.*, 132, 53–62, doi:10.1016/j.fcr.2011.12.009,
608 2012.
- 609 Atreya, K., Sharma, S., Bajracharya, R. M. and Rajbhandari, N. P.: Applications of
610 reduced tillage in hills of central Nepal, *Soil Till. Res.*, 88(1-2), 16–29,
611 doi:10.1016/j.still.2005.04.003, 2006.
- 612 Bai, Y. H., He, J., Li, H. W., Wang, Q. J., Chen, H., Kuhn, N. J., Hikel, H., Chen, F. and
613 Gong, Y. S.: Soil Structure and Crop Performance After 10 Years of Controlled Traffic
614 and Traditional Tillage Cropping in the Dryland Loess Plateau in China, *Soil Science*,
615 174(2), 113–119, doi:10.1097/SS.0b013e3181981ddc, 2009.
- 616 Banwart, S. S., Black, H. B., Cai, Z. Z., Gicheru, P. G., Joosten, H. J., Victoria, R. V.,
617 Milne, E. E., Noellemeyer, E. N., Pascual, U. P., Nziguheba, G. G., Vargas, R. R.,
618 Bationo, A. B., Buschiazzo, D. B., de-Brogniez, D. D., Melillo, J. M., Richter, D. R.,
619 Termansen, M. T., van Noordwijk, M. N., Goverse, T. G., Ballabio, C. C., Bhattacharyya,
620 T. B., Goldhaber, M. M., Nikolaidis, N. N., Zhao, Y. Z., Funk, R. F., Duffy, C. C., Pan,
621 G. P., la Scala, N. L., Gottschalk, P. G., Batjes, N. B., Six, J., van Wesemael, B. W.,
622 Stocking, M. S., Bampa, F. B., Bernoux, M. B., Feller, C. C., Lemanceau, P. P. and
623 Montanarella, L. L.: Benefits of soil carbon: report on the outcomes of an international
624 scientific committee on problems of the environment rapid assessment workshop, *Carbon
625 Management*, 5(2), 185–192, 2014.

- 626 Bauer, A. and Black, A. L.: Organic carbon effects on available water capacity of three
627 soil textural groups, *Soil Sci. Soc. Am. J.*, 56(1), 248–254, 1992.
- 628 Bauer, A. and Black, A. L.: Quantification of the Effect of Soil Organic Matter Content
629 on Soil Productivity, *Soil Sci. Soc. Am. J.*, 58(1), 185,
630 doi:10.2136/sssaj1994.03615995005800010027x, 1994.
- 631 Bedada, W., Karlton, E., Lemenih, M. and Tolera, M.: Long-term addition of compost
632 and NP fertilizer increases crop yield and improves soil quality in experiments on
633 smallholder farms, *Agr. Ecosyst. Environ.*, 195, 193–201,
634 doi:10.1016/j.agee.2014.06.017, 2014.
- 635 Bhardwaj, A. K., Jasrotia, P., Hamilton, S. K. and Robertson, G. P.: Ecological
636 management of intensively cropped agro-ecosystems improves soil quality with sustained
637 productivity, *Agr. Ecosyst. Environ.*, 140(3-4), 419–429, doi:10.1016/j.agee.2011.01.005,
638 2011.
- 639 Bhattacharyya, R., Das, T. K., Sudhishri, S., Dudwal, B., Sharma, A. R., Bhatia, A. and
640 Singh, G.: Conservation agriculture effects on soil organic carbon accumulation and crop
641 productivity under a rice-wheat cropping system in the western Indo-Gangetic Plains,
642 *European Journal of Agronomy*, 70, 11–21, doi:10.1016/j.eja.2015.06.006, 2015.
- 643 Birkhofer, K., Bezemer, T. M., Bloem, J., Bonkowski, M., Christensen, S., Dubois, D.,
644 Ekelund, F., Fließbach, A., Gunst, L., Hedlund, K., Mäder, P., Mikola, J., Robin, C.,
645 Setälä, H., Tatin-Froux, F., van der Putten, W. H. and Scheu, S.: Long-term organic
646 farming fosters below and aboveground biota: Implications for soil quality, biological
647 control and productivity, *Soil Biol. Biochem.*, 40(9), 2297–2308,
648 doi:10.1016/j.soilbio.2008.05.007, 2008.
- 649 Boddey, R. M., Jantalia, C. P., Conceia ã O, P. C., Zanatta, J. A., Bayer, C. L.,
650 Mielniczuk, J. O., Dieckow, J., Santos, dos, H. P., Denardin, J. E., Aita, C., Giacomini, S.
651 J., Alves, B. J. R. and Urquiaga, S.: Carbon accumulation at depth in Ferralsols under
652 zero-till subtropical agriculture, *Glob. Change Biol.*, 16(2), 784–795, doi:10.1111/j.1365-
653 2486.2009.02020.x, 2010.
- 654 Bolker, B. M., Brooks, M. E., Clark, C. J., Geange, S. W., Poulsen, J. R., Stevens, M. H.
655 H. and White, J.-S. S.: Generalized linear mixed models: a practical guide for ecology
656 and evolution, *Trends Ecol. Evol.*, 24(3), 127–135, doi:10.1016/j.tree.2008.10.008, 2009.
- 657 Boulal, H., Gomez-Macpherson, H. and Villalobos, F. J.: Permanent bed planting in
658 irrigated Mediterranean conditions: Short-term effects on soil quality, crop yield and
659 water use efficiency, *Field Crop Res.*, 130, 120–127, doi:10.1016/j.fcr.2012.02.026,
660 2012.
- 661 Bremer, E., Janzen, H. H. and Johnston, A. M.: Sensitivity of total, light fraction and
662 mineralizable organic matter to management practices in a Lethbridge soil, *Can. J. Soil
663 Sci.*, 74(2), 131–138, 1994.

- 664 Calegari, A., Hargrove, W. L., Rheinheimer, D. D. S., Ralisch, R., Tessier, D., de
665 Tourdonnet, S. and de Fatima Guimarães, M.: Impact of Long-Term No-Tillage and
666 Cropping System Management on Soil Organic Carbon in an Oxisol: A Model for
667 Sustainability, *Agronomy Journal*, 100(4), 1013–7, doi:10.2134/agronj2007.0121, 2008.
- 668 Cambardella, C. A., Gajda, A. M., Doran, J. W., Wienhold, B. J. and Kettler, T. A.:
669 Assessment Methods for Soil Carbon, edited by R. Lal, J. M. Kimble, R. F. Follett, and
670 B. A. Stewart, Boca Raton. 2001.
- 671 Campbell, C. A., VandenBygaart, A. J., Zentner, R. P., McConkey, B. G., Smith, W.,
672 Lemke, R., Grant, B. and Jefferson, P. G.: Quantifying carbon sequestration in a
673 minimum tillage crop rotation study in semiarid southwestern Saskatchewan, *Can. J. Soil*
674 *Sci.*, 87(3), 235–250, 2007.
- 675 Cassman, K. G.: Ecological intensification of cereal production systems: Yield potential,
676 soil quality, and precision agriculture, *Proc. Natl. Acad. Sci. U.S.A.*, 96(11), 5952–5959,
677 doi:10.1073/pnas.96.11.5952, 1999.
- 678 Castellano, M. J., Mueller, K. E., Olk, D. C., Sawyer, J. E. and Six, J.: Integrating plant
679 litter quality, soil organic matter stabilization, and the carbon saturation concept, *Glob.*
680 *Change Biol.*, 21(9), 1–10, doi:10.1111/gcb.12982, 2015.
- 681 Castellanos-Navarrete, A., Rodríguez-Aragónés, C., De Goede, R. G. M., Kooistra, M. J.,
682 Sayre, K. D., Brussaard, L. and Pulleman, M. M.: Earthworm activity and soil structural
683 changes under conservation agriculture in central Mexico, *Soil Till. Res.*, 123, 61–70,
684 doi:10.1016/j.still.2012.03.011, 2012.
- 685 Celik, I., Gunal, H., Budak, M. and Akpinar, C.: Effects of long-term organic and mineral
686 fertilizers on bulk density and penetration resistance in semi-arid Mediterranean soil
687 conditions, *Geoderma*, 160(2), 236–243, doi:10.1016/j.geoderma.2010.09.028, 2010.
- 688 Chabbi, A., Lehmann, J., Ciais, P., Loescher, H. W., Cotrufo, M. F., Don, A.,
689 SanClements, M., Schipper, L., Six, J., Smith, P. and Rumpel, C.: Aligning agriculture
690 and climate policy, *Nature Clim. Change*, 7(5), 307–309, 2017.
- 691 Chen, H. X., Zhao, Y., Feng, H., Li, H. J. and Sun, B. H.: Assessment of climate change
692 impacts on soil organic carbon and crop yield based on long-term fertilization
693 applications in Loess Plateau, China, *Plant Soil*, 390(1-2), 401–417, doi:10.1007/s11104-
694 014-2332-1, 2015.
- 695 Chirinda, N., Olesen, J. E., Porter, J. R. and Schjøning, P.: Soil properties, crop
696 production and greenhouse gas emissions from organic and inorganic fertilizer-based
697 arable cropping systems, *Agr. Ecosyst. Environ.*, 139(4), 584–594,
698 doi:10.1016/j.agee.2010.10.001, 2010.
- 699 Cid, P., Carmona, I., Murillo, J. M. and Gomez-Macpherson, H.: No-tillage permanent
700 bed planting and controlled traffic in a maize-cotton irrigated system under
701 Mediterranean conditions: Effects on soil compaction, crop performance and carbon

- 702 sequestration, *European Journal of Agronomy*, 61, 24–34, doi:10.1016/j.eja.2014.08.002,
703 2014.
- 704 Costa, S. E. V. G. A., Souza, E. D., Anghinoni, I., Flores, J. P. C., Vieira, F. C. B.,
705 Martins, A. P. and Ferreira, E. V. O.: Patterns in phosphorus and corn root distribution
706 and yield in long-term tillage systems with fertilizer application, *Soil Till. Res.*, 109(1),
707 41–49, doi:10.1016/j.still.2010.04.003, 2010.
- 708 Culman, S. W., Snapp, S. S., Green, J. M. and Gentry, L. E.: Short- and long-term labile
709 soil carbon and nitrogen dynamics reflect management and predict corn agronomic
710 performance, *Agronomy Journal*, 105(2), 493–502, doi:10.2134/agronj2012.0382, 2013.
- 711 D'Hose, T., Cougnon, M., De Vlieghe, A., Vandecasteele, B., Viaene, N., Cornelis, W.,
712 Van Bockstaele, E. and Reheul, D.: The positive relationship between soil quality and
713 crop production: A case study on the effect of farm compost application, *Appl. Soil Ecol.*,
714 75, 189–198, doi:10.1016/j.apsoil.2013.11.013, 2014.
- 715 Datta, S. P., Rattan, R. K. and Chandra, S.: Labile soil organic carbon, soil fertility, and
716 crop productivity as influenced by manure and mineral fertilizers in the tropics, *J. Plant
717 Nutr. Soil Sc.*, 173(5), 715–726, doi:10.1002/jpln.200900010, 2010.
- 718 de Moraes Sa, J. C., Tivet, F., Lal, R., Briedis, C., Hartman, D. C., Santos, dos, J. Z. and
719 Santos, dos, J. B.: Long-term tillage systems impacts on soil C dynamics, soil resilience
720 and agronomic productivity of a Brazilian Oxisol, *Soil Till. Res.*, 136, 38–50,
721 doi:10.1016/j.still.2013.09.010, 2014.
- 722 DeMaria, I. C., Nnabude, P.C. and de Castro, O. M.: Long-term tillage and crop rotation
723 effects on soil chemical properties of a Rhodic Ferralsol in southern Brazil, *Soil Till.
724 Res.*, 51(1-2), 71–79, doi:10.1016/S0167-1987(99)00025-2, 1999.
- 725 Diacono, M., Ferri, D., Ciaccia, C., Tittarelli, F., Ceglie, F., Verrastro, V., Ventrella, D.,
726 Vitti, C. and Montemurro, F.: Bioassays and application of olive pomace compost on
727 emmer: effects on yield and soil properties in organic farming, *Acta Agriculturae
728 Scandinavica Section B: Soil and Plant Science*, 62(6), 510–518,
729 doi:10.1080/09064710.2012.663785, 2012.
- 730 Drinkwater, L. E., Wagoner, P. and Sarrantonio, M.: Legume-based cropping systems
731 have reduced carbon and nitrogen losses, *Nature*, 396(6708), 262–265, 1998.
- 732 Edmeades, D. C.: The long-term effects of manures and fertilisers on soil productivity
733 and quality: a review, *Nutr. Cycl. Agroecosys.*, 66(2), 165–180, 2003.
- 734 FAO: Underpinning conservation agriculture's benefits: the roots of soil health and
735 function, Food and Agriculture Organization of the United Nations, Rome. 2008.
- 736 Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M.,
737 Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M.,
738 Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert,
739 S., Tilman, D. and Zaks, D. P. M.: Solutions for a cultivated planet, *Nature*, 478(7369),

- 740 337–342, doi:10.1038/nature10452, 2011.
- 741 Friedl, M. A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A. and
742 Huang, X.: MODIS Collection 5 global land cover: Algorithm refinements and
743 characterization of new datasets, *Remote Sensing of Environment*, 114(1), 168–182,
744 doi:10.1016/j.rse.2009.08.016, 2010.
- 745 Gelman, A.: Scaling regression inputs by dividing by two standard deviations, *Statistics*
746 *in Medicine*, 27(15), 2865–2873, doi:10.1002/sim.3107, 2008.
- 747 Giller, K. E., Witter, E., Corbeels, M. and Tittonell, P.: Conservation agriculture and
748 smallholder farming in Africa: The heretics' view, *Field Crop Res.*, 114(1), 23–34, 2009.
- 749 Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F.,
750 Pretty, J., Robinson, S., Thomas, S. M. and Toulmin, C.: Food Security: The Challenge
751 of Feeding 9 Billion People, *Science*, 327(5967), 812–818, doi:10.1126/science.1185383,
752 2010.
- 753 Grandy, A. S., Loecke, T. D., Parr, S. and Robertson, G. P.: Long-term trends in nitrous
754 oxide emissions, soil nitrogen, and crop yields of till and no-till cropping systems,
755 *Journal of Environment Quality*, 35(4), 1487–1495, doi:10.2134/jeq2005.0166, 2006.
- 756 Guo, S. L., Wu, J. S., Coleman, K., Zhu, H. H., Li, Y. and Liu, W. Z.: Soil organic
757 carbon dynamics in a dryland cereal cropping system of the Loess Plateau under long-
758 term nitrogen fertilizer applications, *Plant Soil*, 353(1-2), 321–332, doi:10.1007/s11104-
759 011-1034-1, 2012.
- 760 Guo, Z. L., Cai, C. F., Li, Z. X., Wang, T. W. and Zheng, M. J.: Crop residue effect on
761 crop performance, soil N₂O and CO₂ emissions in alley cropping systems in subtropical
762 China, *Agroforestry Systems*, 76(1), 67–80, doi:10.1007/s10457-008-9170-1, 2009.
- 763 Haddaway, N. R., HEDLUND, K., Jackson, L. E., Kätterer, T., Lugato, E., Thomsen, I.
764 K., Jørgensen, H. B. and Söderström, B.: What are the effects of agricultural management
765 on soil organic carbon in boreo-temperate systems? *Environmental Evidence* 2014 3:1,
766 4(1), 23, doi:10.1186/s13750-015-0049-0, 2015.
- 767 Hatfield, J. L., Sauer, T. J. and Cruse, R. M.: Soil: The Forgotten Piece of the Water,
768 *Food, Energy Nexus, Adv. Agron.*, 143, 1–46, doi:10.1016/bs.agron.2017.02.001, 2017.
- 769 He, J., Li, H. W., Rasaily, R. G., Wang, Q. J., Cai, G. H., Su, Y. B., Qiao, X. D. and Liu,
770 L. J.: Soil properties and crop yields after 11 years of no tillage farming in wheat-maize
771 cropping system in North China Plain, *Soil Till. Res.*, 113(1), 48–54,
772 doi:10.1016/j.still.2011.01.005, 2011.
- 773 Hengl, T., de Jesus, J. M., MacMillan, R. A., Batjes, N. H., Heuvelink, G. B. M., Ribeiro,
774 E., Samuel-Rosa, A., Kempen, B., Leenaars, J. G. B., Walsh, M. G. and Gonzalez, M. R.:
775 SoilGrids1km — Global Soil Information Based on Automated Mapping, edited by B.
776 Bond-Lamberty, *Plos One*, 9(8), e105992, doi:10.1371/journal.pone.0105992, 2014.

- 777 Herrick, J. E.: Soil quality: an indicator of sustainable land management? *Appl. Soil*
778 *Ecol.*, 15(1), 75–83, 2000.
- 779 Hijbeek, R., van Ittersum, M. K., Berge, ten, H. F. M., Gort, G., Spiegel, H. and
780 Whitmore, A. P.: Do organic inputs matter - a meta-analysis of additional yield effects
781 for arable crops in Europe, *Plant Soil*, 411(1-2), 293–303, doi:10.1007/s11104-016-3031-
782 x, 2017.
- 783 Hobbs, N. T. and Hilborn, R.: Alternatives to statistical hypothesis testing in ecology: A
784 guide to self teaching, *Ecol. App.*, 16(1), 5–19, 2006.
- 785 Hossain, M. S., Hossain, A., Sarkar, M. A. R., Jahiruddin, M., da Silva, J. A. T. and
786 Hossain, M. I.: Productivity and soil fertility of the rice-wheat system in the High Ganges
787 River Floodplain of Bangladesh is influenced by the inclusion of legumes and manure,
788 *Agr. Ecosyst. Environ.*, 218, 40–52, doi:10.1016/j.agee.2015.11.017, 2016.
- 789 Hu, C., Li, S. L., Qiao, Y., Liu, D. H. and Chen, Y. F.: Effects of 30 years repeated
790 fertilizer applications on soil properties, microbes and crop yields in rice-wheat cropping
791 systems, *Experimental Agriculture*, 51(3), 355–369, doi:10.1017/s0014479714000350,
792 2015.
- 793 Hu, W. G., Jiao, Z. F., Wu, F. S., Liu, Y. J., Dong, M. X., Ma, X. J., Fan, T. L., An, L. Z.
794 and Feng, H. Y.: Long-term effects of fertilizer on soil enzymatic activity of wheat field
795 soil in Loess Plateau, China, *Ecotoxicology*, 23(10), 2069–2080, doi:10.1007/s10646-
796 014-1329-0, 2014.
- 797 Janzen, H. H.: The soil carbon dilemma: Shall we hoard it or use it? *Soil Biol. Biochem.*,
798 38(3), 419–424, doi:10.1016/j.soilbio.2005.10.008, 2006.
- 799 Johnston, A. E., Poulton, P. R. and Coleman, K.: Soil Organic Matter: Its Importance in
800 Sustainable Agriculture and Carbon Dioxide Fluxes, *Adv. Agron.*, 101, 1–57,
801 doi:10.1016/S0065-2113(08)00801-8, 2009.
- 802 Kaihura, F. B. S., Kullaya, I. K., Kilasara, M., Aune, J. B., Singh, B. R. and Lal, R.: Soil
803 quality effects of accelerated erosion and management systems in three eco-regions of
804 Tanzania, *Soil Till. Res.*, 53(1), 59–70, doi:10.1016/s0167-1987(99)00077-x, 1999.
- 805 Karbozova Saljnikov, E., Funakawa, S., Akhmetov, K. and Kosaki, T.: Soil organic
806 matter status of Chernozem soil in North Kazakhstan: effects of summer fallow, *Soil*
807 *Biol. Biochem.*, 36(9), 1373–1381, doi:10.1016/j.soilbio.2004.02.027, 2004.
- 808 Kautz, T., Stumm, C., Kösters, R. and Köpke, U.: Effects of perennial fodder crops on
809 soil structure in agricultural headlands, *J. Plant Nutr. Soil Sc.*, 173(4), 490–501,
810 doi:10.1002/jpln.200900216, 2010.
- 811 Kazemeini, S. A., Bahrani, M. J., Pirasteh-Anosheh, H. and Momeni, S. M. M.: Maize
812 growth and yield as affected by wheat residues and irrigation management in a no-tillage
813 system, *Archives of Agronomy and Soil Science*, 60(11), 1543–1552,
814 doi:10.1080/03650340.2014.896457, 2014.

- 815 Kemper, W. D. and Koch, E. J.: Aggregate stability of soils from Western United States
816 and Canada, United States Department of Agriculture, Washington, DC. 1966.
- 817 Kravchenko, A. N. and Bullock, D. G.: Correlation of corn and soybean grain yield with
818 topography and soil properties, *Agronomy Journal*, 92(1), 75–83,
819 doi:10.1007/s100870050010, 2000.
- 820 Kucharik, C. J., Brye, K. R., Norman, J. M., Foley, J. A., Gower, S. T. and Bundy, L. G.:
821 Measurements and modeling of carbon and nitrogen cycling in agroecosystems of
822 southern Wisconsin: Potential for SOC sequestration during the next 50 years,
823 *Ecosystems*, 4(3), 237–258, doi:10.1007/s10021\N001\N0007-2, 2001.
- 824 Lal, R.: Soil Carbon Sequestration Impacts on Global Climate Change and Food Security,
825 *Science*, 304(5677), 1623–1627, doi:10.1126/science.1097396, 2004.
- 826 Larsen, E., Grossman, J., Edgell, J., Hoyt, G., Osmond, D. and Hu, S. J.: Soil biological
827 properties, soil losses and corn yield in long-term organic and conventional farming
828 systems, *Soil Till. Res.*, 139, 37–45, doi:10.1016/j.still.2014.02.002, 2014.
- 829 Lebbink, G., Vanfaassen, H. G., Vanouwerkerk, C. and Brussaard, L.: The Dutch
830 Programme on Soil Ecology of Arable Farming Systems: Farm management monitoring
831 program and general results, *Agr. Ecosyst. Environ.*, 51(1-2), 7–20, doi:10.1016/0167-
832 8809(94)90032-9, 1994.
- 833 Lehmann, J. and Kleber, M.: The contentious nature of soil organic matter, *Nature*,
834 528(7580), 60–68, doi:10.1038/nature16069, 2015.
- 835 Leogrande, R., Vitti, C., Stellacci, A. M., Coccozza, C. and Ventrella, D.: Response of
836 wheat crop during transition to organic system under Mediterranean conditions,
837 *International Journal of Plant Production*, 10(4), 565–577, 2016.
- 838 Li, Z. T., Yang, J. Y., Drury, C. F. and Hoogenboom, G.: Evaluation of the DSSAT-CSM
839 for simulating yield and soil organic C and N of a long-term maize and wheat rotation
840 experiment in the Loess Plateau of Northwestern China, *Agricultural Systems*, 135, 90–
841 104, doi:10.1016/j.agsy.2014.12.006, 2015.
- 842 Liu, E. K., Tecler, S. G., Yan, C. R., Yu, J. M., Gu, R. S., Liu, S., He, W. Q. and
843 Liu, Q.: Long-term effects of no-tillage management practice on soil organic carbon and
844 its fractions in the northern China, *Geoderma*, 213, 379–384,
845 doi:10.1016/j.geoderma.2013.08.021, 2014a.
- 846 Liu, H. T., Meng, J., Bo, W. J., Cheng, D., Li, Y., Guo, L. Y., Li, C. H., Zheng, Y. H.,
847 Liu, M. Z., Ning, T. Y., Wu, G. L., Yu, X. F., Feng, S. F., Tana, W. Y., Li, J., Li, L. J.,
848 Zeng, Y., Liu, S. V. and Jiang, G. M.: Biodiversity management of organic farming
849 enhances agricultural sustainability, *Scientific Reports* 2016 6, 6, doi:10.1038/srep23816,
850 2016.
- 851 Liu, X. E., Li, X. G., Hai, L., Wang, Y. P., Fu, T. T., Turner, N. C. and Li, F. M.: Film-
852 Mulched Ridge-Furrow Management Increases Maize Productivity and Sustains Soil

- 853 Organic Carbon in a Dryland Cropping System, *Soil Sci. Soc. Am. J.*, 78(4), 1434–1441,
854 doi:10.2136/sssaj2014.04.0121, 2014b.
- 855 Liu, X. Y., Ye, Y. X., Liu, Y. M., Zhang, A., Zhang, X. H., Li, L. Q., Pan, G. X., Kibue,
856 G. W., Zheng, J. F. and Zheng, J. W.: Sustainable biochar effects for low carbon crop
857 production: A 5-crop season field experiment on a low fertility soil from Central China,
858 *Agricultural Systems*, 129, 22–29, doi:10.1016/j.agsy.2014.05.008, 2014c.
- 859 Loveland, P. and Webb, J.: Is there a critical level of organic matter in the agricultural
860 soils of temperate regions: A review, *Soil Till. Res.*, 70(1), 1–18, 2003.
- 861 López-Garrido, R., Madejón, E., León-Camacho, M., Girón, I., Moreno, F. and Murillo,
862 J. M.: Reduced tillage as an alternative to no-tillage under Mediterranean conditions: A
863 case study, *Soil Till. Res.*, 140, 40–47, doi:10.1016/j.still.2014.02.008, 2014.
- 864 Lu, X. L., Lu, X. N., Tanveer, S. K., Wen, X. X. and Liao, Y. C.: Effects of tillage
865 management on soil CO₂ emission and wheat yield under rain-fed conditions, *Soil Res.*,
866 54(1), 38–48, doi:10.1071/sr14300, 2016.
- 867 Lucas, S. T. and Weil, R. R.: Can a Labile Carbon Test be Used to Predict Crop
868 Responses to Improve Soil Organic Matter Management? *Agronomy Journal*, 104(4),
869 1160–11, doi:10.2134/agronj2011.0415, 2012.
- 870 Ma, Q., Yu, W. T., Jiang, C. M., Zhou, H. and Xu, Y. G.: The influences of mineral
871 fertilization and crop sequence on sustainability of corn production in northeastern China,
872 *Agr. Ecosyst. Environ.*, 158, 110–117, doi:10.1016/j.agee.2012.05.023, 2012.
- 873 Ma, Z. M., Chen, J., Lyu, X. D., Liu, L. L. and Siddique, K. H. M.: Distribution of soil
874 carbon and grain yield of spring wheat under a permanent raised bed planting system in
875 an arid area of northwest China, *Soil Till. Res.*, 163, 274–281,
876 doi:10.1016/j.still.2016.05.010, 2016.
- 877 Madejón, E., Lopes, R., Murillo, J. M. and Cabrera, F.: Agricultural use of three (sugar-
878 beet) vinasse composts: effect on crops and chemical properties of a Cambisol soil in the
879 Guadalquivir river valley (SW Spain), *Agr. Ecosyst. Environ.*, 84(1), 55–65,
880 doi:10.1016/s0167-8809(00)00191-2, 2001.
- 881 Majumder, B., Mandal, B. and Bandyopadhyay, P. K.: Soil organic carbon pools and
882 productivity in relation to nutrient management in a 20-year-old rice-berseem
883 agroecosystem, *Biol. Fertil. Soils*, 44(3), 451–461, 2008.
- 884 Mandal, N., Dwivedi, B. S., Meena, M. C., Singh, D., Datta, S. P., Tomar, R. K. and
885 Sharma, B. M.: Effect of induced defoliation in pigeonpea, farmyard manure and
886 sulphitation pressmud on soil organic carbon fractions, mineral nitrogen and crop yields
887 in a pigeonpea-wheat cropping system, *Field Crop Res.*, 154, 178–187,
888 doi:10.1016/j.fcr.2013.08.007, 2013.
- 889 Masto, R. E., Chhonkar, P. K., Singh, D. and Patra, A. K.: Soil quality response to long-
890 term nutrient and crop management on a semi-arid Inceptisol, *Agr. Ecosyst. Environ.*,

- 891 118(1-4), 130–142, doi:10.1016/j.agee.2006.05.008, 2007.
- 892 Mikanová, O., Šimon, T. and Javůrek, M.: Relationships between winter wheat yields
893 and soil carbon under various tillage systems, *Plant* [online] Available from:
894 <http://www.agriculturejournals.cz/publicFiles/78760.pdf>, 2012.
- 895 Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers,
896 A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B. S., Field, D. J., Gimona, A., Hedley, C.
897 B., Hong, S. Y., Mandal, B., Ben P Marchant, Martin, M., McConkey, B. G., Mulder, V.
898 L., O'Rourke, S., Richer-de-Forges, A. C., Odeh, I., Padarian, J., Paustian, K., Pan, G.,
899 Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.-C., Vågen,
900 T.-G., van Wesemael, B. and Winowiecki, L.: Soil carbon 4 per mille, *Geoderma*, 292,
901 59–86, doi:10.1016/j.geoderma.2017.01.002, 2017.
- 902 Mishra, V. K., Srivastava, S., Bhardwaj, A. K., Sharma, D. K., Singh, Y. P. and Nayak,
903 A. K.: Resource conservation strategies for rice-wheat cropping systems on partially
904 reclaimed sodic soils of the Indo-Gangetic region, and their effects on soil carbon,
905 *Natural Resources Forum*, 39(2), 110–122, doi:10.1111/1477-8947.12071, 2015.
- 906 Monfreda, C., Ramankutty, N. and Foley, J. A.: Farming the planet: 2. Geographic
907 distribution of crop areas, yields, physiological types, and net primary production in the
908 year 2000, *Global Biogeochem. Cycles*, 22(1), n/a–n/a, doi:10.1029/2007GB002947,
909 2008.
- 910 Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N. and Foley, J. A.:
911 Closing yield gaps through nutrient and water management, *Nature*, 490(7419), 254–257,
912 doi:10.1038/nature11420, 2012.
- 913 Mupangwa, W., Twomlow, S. and Walker, S.: Cumulative effects of reduced tillage and
914 mulching on soil properties under semi-arid conditions, *Journal of Arid Environments*,
915 91, 45–52, doi:10.1016/j.jaridenv.2012.11.007, 2013.
- 916 National Science and Technology Council (NSTC): The State and Future of U.S. Soils,
917 Washington DC. [online] Available from:
918 [https://www.whitehouse.gov/sites/default/files/microsites/ostp/ssiwg_framework_decemb](https://www.whitehouse.gov/sites/default/files/microsites/ostp/ssiwg_framework_december_2016.pdf)
919 [er_2016.pdf](https://www.whitehouse.gov/sites/default/files/microsites/ostp/ssiwg_framework_december_2016.pdf), 2016
- 920 N'Dayegamiye, A.: Mixed paper mill sludge effects on corn yield, nitrogen efficiency,
921 and soil properties, *Agronomy Journal*, 98(6), 1471–1478, doi:10.2134/agronj2005.0339,
922 2006.
- 923 Nakagawa, S. and Schielzeth, H.: A general and simple method for obtaining R² from
924 generalized linear mixed-effects models, edited by R. B. O'Hara, *Methods in Ecology and*
925 *Evolution*, 4(2), 133–142, doi:10.1111/j.2041-210x.2012.00261.x, 2013.
- 926 Niu, L. A., Hao, J. M., Zhang, B. Z. and Niu, X. S.: Influences of long-term fertilizer and
927 tillage management on soil fertility of the North China plain, *Pedosphere*, 21(6), 813–
928 820, 2011.

- 929 Njoku, C. and Mbah, C. N.: Effect of burnt and unburnt rice husk dust on maize yield and
 930 soil physico-chemical properties of an ultisol in Nigeria, *Biological Agriculture and*
 931 *Horticulture*, 28(1), 49–60, doi:10.1080/01448765.2012.664374, 2012.
- 932 NRC: Understanding agricultural sustainability, in *Toward Sustainable Agricultural*
 933 *Systems in the 21st Century*, pp. 1–29, National Academies Press, Washington, DC.
 934 2010.
- 935 NRCS: *Farming in the 21st century: a practical approach to improve soil health*, USDA,
 936 Natural Resources Conservation Service, Washington, DC. 2012.
- 937 Oelofse, M., Markussen, B., Knudsen, L., Schelde, K., Olesen, J. E., Jensen, L. S. and
 938 Bruun, S.: Do soil organic carbon levels affect potential yields and nitrogen use
 939 efficiency? An analysis of winter wheat and spring barley field trials, *European Journal*
 940 *of Agronomy*, 66, 62–73, doi:10.1016/j.eja.2015.02.009, 2015.
- 941 Oldfield, E. E., Wood, S. A. and Bradford, M. A.: Direct effects of soil organic matter on
 942 productivity mirror those observed with organic amendments, *Plant Soil*, 348, 1–11,
 943 doi:10.1007/s11104-017-3513-5, 2017.
- 944 Oldfield, E. E., Wood, S. A., Palm, C. A. and Bradford, M. A.: How much SOM is
 945 needed for sustainable agriculture? *Front. Ecol. Environ.*, 13(10), 527–527 [online]
 946 Available from: [http://onlinelibrary.wiley.com/store/10.1890/1540-9295-](http://onlinelibrary.wiley.com/store/10.1890/1540-9295-13.10.527/asset/fee20151310527.pdf?v=1&t=ixtclsl1y&s=3007996d5c38b9951072fe2f295552168440e6e0)
 947 [13.10.527/asset/fee20151310527.pdf?v=1&t=ixtclsl1y&s=3007996d5c38b9951072fe2f2](http://onlinelibrary.wiley.com/store/10.1890/1540-9295-13.10.527/asset/fee20151310527.pdf?v=1&t=ixtclsl1y&s=3007996d5c38b9951072fe2f295552168440e6e0)
 948 [95552168440e6e0](http://onlinelibrary.wiley.com/store/10.1890/1540-9295-13.10.527/asset/fee20151310527.pdf?v=1&t=ixtclsl1y&s=3007996d5c38b9951072fe2f295552168440e6e0), 2015.
- 949 Palm, C. A., Giller, K. E., Mafongoya, P. L. and Swift, M. J.: Management of organic
 950 matter in the tropics: translating theory into practice, *Nutr. Cycl. Agroecosys.*, 61(1997),
 951 63–75, doi:10.1023/A:1013318210809, 2001.
- 952 Palm, C. A., Myers, R. J. K. and Nandwa, S. M.: Combined Use of Organic and
 953 Inorganic Nutrient Sources for Soil Fertility Maintenance and Replenishment,
 954 *Replenishing Soil Fertility in Africa*, sssaspecialpubl(replenishingsoi), 193–217,
 955 doi:10.2136/sssaspepub51.c8, 1997.
- 956 Pan, G., Smith, P. and Pan, W.: The role of soil organic matter in maintaining the
 957 productivity and yield stability of cereals in China, *Agr. Ecosyst. Environ.*, 129(1-3),
 958 344–348, doi:10.1016/j.agee.2008.10.008, 2009.
- 959 Paul, B. K., Vanlauwe, B., Ayuke, F., Gassner, A., Hoogmoed, M., Hurisso, T. T., Koala,
 960 S., Lelei, D., Ndabamenye, T., Six, J. and Pulleman, M. M.: Medium-term impact of
 961 tillage and residue management on soil aggregate stability, soil carbon and crop
 962 productivity, *Agr. Ecosyst. Environ.*, 164, 14–22, doi:10.1016/j.agee.2012.10.003, 2013.
- 963 Poulton, P., Johnston, J., Macdonald, A., White, R. and Powlson, D.: Major limitations to
 964 achieving “4 per 1000” increases in soil organic carbon stock in temperate regions:
 965 Evidence from long-term experiments at Rothamsted Research, United Kingdom, *Glob.*
 966 *Change Biol.*, 24(6), 2563–2584, doi:10.1111/gcb.14066, 2018.

- 967 Powlson, D. S., Whitmore, A. P. and Goulding, K. W. T.: Soil carbon sequestration to
968 mitigate climate change: a critical re-examination to identify the true and the false, *Eur. J.*
969 *Soil Sci.*, 62(1), 42–55, doi:10.1111/j.1365-2389.2010.01342.x, 2011.
- 970 Pribyl, D. W.: A critical review of the conventional SOC to SOM conversion factor,
971 *Geoderma*, 156(3-4), 75–83, doi:10.1016/j.geoderma.2010.02.003, 2010.
- 972 Qin, W., Wang, D. Z., Guo, X. S., Yang, T. M. and Oenema, O.: Productivity and
973 sustainability of rainfed wheat-soybean system in the North China Plain: results from a
974 long-term experiment and crop modelling, *Scientific Reports* 2016 6, 5,
975 doi:10.1038/srep17514, 2015.
- 976 Quiroga, A., Fernández, R. and Noellemeyer, E.: Grazing effect on soil properties in
977 conventional and no-till systems, *Soil Till. Res.*, 105(1), 164–170,
978 doi:10.1016/j.still.2009.07.003, 2009.
- 979 Ramankutty, N., Hertel, T., Lee, H. L. and Rose, S. K.: Global Agricultural Land Use
980 Data Global Agricultural Land Use Data for Integrated Assessment Modeling, in *Human-*
981 *induced climate change: An interdisciplinary assessment*. 2007.
- 982 Rasmussen, C., Heckman, K., Wieder, W. R., Keiluweit, M., Lawrence, C. R., Berhe, A.
983 A., Blankinship, J. C., Crow, S. E., Druhan, J. L., Pries, C. E. H., Marin-Spiotta, E.,
984 Plante, A. F., Schädel, C., Schimel, J. P., Sierra, C. A., Thompson, A. and Wagai, R.:
985 Beyond clay: towards an improved set of variables for predicting soil organic matter
986 content, *Biogeochemistry*, 1–10, doi:10.1007/s10533-018-0424-3, 2018.
- 987 Rasmussen, P. E., Allmaras, R. R., Rohde, C. R. and Roager, N. C.: Crop Residue
988 Influences on Soil Carbon and Nitrogen in a Wheat-Fallow System1, *Soil Sci. Soc. Am.*
989 *J.*, 44(3), 596, doi:10.2136/sssaj1980.03615995004400030033x, 1980.
- 990 Raymond, P. A., David, M. B. and Saiers, J. E.: The impact of fertilization and hydrology
991 on nitrate fluxes from Mississippi watersheds, *Current Opinion in Environmental*
992 *Sustainability*, 4(2), 212–218, doi:10.1016/j.cosust.2012.04.001, 2012.
- 993 Reeves, D. W.: The role of soil organic matter in maintaining soil quality in continuous
994 cropping systems, *Soil Till. Res.*, 43(1), 131–167, 1997.
- 995 Reeves, M., Lal, R., Logan, T. and Sagarán, J.: Soil nitrogen and carbon response to
996 maize cropping system, nitrogen source, and tillage, *Soil Sci. Soc. Am. J.*, 61(5), 1387–
997 1392, 1997.
- 998 Robertson, G. P., Gross, K. L., Hamilton, S. K., Landis, D. A., Schmidt, T. M., Snapp, S.
999 S. and Swinton, S. M.: Farming for Ecosystem Services: An Ecological Approach to
1000 Production Agriculture, *Bioscience*, 64(5), 404–415, doi:10.1093/biosci/biu037, 2014.
- 1001 Sadeghi, H. and Bahrani, M. J.: Effects of crop residue and nitrogen rates on yield and
1002 yield components of two dryland wheat (*Triticum aestivum* L.) cultivars, *Plant*
1003 *Production Science*, 12(4), 497–502, 2009.

- 1004 Saikia, P., Bhattacharya, S. S. and Baruah, K. K.: Organic substitution in fertilizer
1005 schedule: Impacts on soil health, photosynthetic efficiency, yield and assimilation in
1006 wheat grown in alluvial soil, *Agr. Ecosyst. Environ.*, 203, 102–109,
1007 doi:10.1016/j.agee.2015.02.003, 2015.
- 1008 Sanderman, J., Hengl, T. and Fiske, G. J.: Soil carbon debt of 12,000 years of human land
1009 use, *Proc. Natl. Acad. Sci. U.S.A.*, 114(36), 9575–9580, doi:10.1073/pnas.1706103114,
1010 2017.
- 1011 Scalise, A., Tortorella, D., Pristeri, A., Petrovičová, B., Gelsomino, A., Lindström, K.
1012 and Monti, M.: Legume-barley intercropping stimulates soil N supply and crop yield in
1013 the succeeding durum wheat in a rotation under rainfed conditions, *Soil Biol. Biochem.*,
1014 89, 150–161, doi:10.1016/j.soilbio.2015.07.003, 2015.
- 1015 Seremesic, S., Milosev, D., Djalovic, I., Zeremski, T. and Ninkov, J.: Management of soil
1016 organic carbon in maintaining soil productivity and yield stability of winter wheat, *Plant
1017 Soil and Environment*, 57(5), 216–221, 2011.
- 1018 Singh, V. K. and Dwivedi, B. S.: Yield and nitrogen use efficiency in wheat, and soil
1019 fertility status as influenced by substitution of rice with pigeon pea in a rice-wheat
1020 cropping system, *Australian Journal of Experimental Agriculture*, 46(9), 1185–1194,
1021 doi:10.1071/ea04046, 2006.
- 1022 Singh, V. K., Yadvinder-Singh, Dwivedi, B. S., Singh, S. K., Majumdar, K., Jat, M. L.,
1023 Mishra, R. P. and Rani, M.: Soil physical properties, yield trends and economics after
1024 five years of conservation agriculture based rice-maize system in north-western India,
1025 *Soil Till. Res.*, 155, 133–148, doi:10.1016/j.still.2015.08.001, 2016.
- 1026 Sisti, C. P. J., Santos, dos, H. P., Kohhann, R., Alves, B. J. R., Urquiaga, S. and Boddey,
1027 R. M.: Change in carbon and nitrogen stocks in soil under 13 years of conventional or
1028 zero tillage in southern Brazil, *Soil Till. Res.*, 76(1), 39–58,
1029 doi:10.1016/j.still.2003.08.007, 2004.
- 1030 Soldevilla-Martinez, M., Martin-Lammerding, D., Tenorio, J. L., Walter, I., Quemada,
1031 M. and Lizaso, J. I.: Simulating improved combinations tillage-rotation under dryland
1032 conditions, *Spanish Journal of Agricultural Research*, 11(3), 820–832,
1033 doi:10.5424/sjar/2013113-3747, 2013.
- 1034 Spargo, J. T., Cavigelli, M. A., Mirsky, S. B., Maul, J. E. and Meisinger, J. J.:
1035 Mineralizable soil nitrogen and labile soil organic matter in diverse long-term cropping
1036 systems, *Nutr. Cycl. Agroecosys.*, 90(2), 253–266, doi:10.1007/s10705-011-9426-4,
1037 2011.
- 1038 Stine, M. A. and Weil, R. R.: The relationship between soil quality and crop productivity
1039 across three tillage systems in South Central Honduras, *American Journal of Alternative
1040 Agriculture*, 17(1), 2–8, 2002.
- 1041 Stockmann, U., Padarian, J., McBratney, A., Minasny, B., de Brogniez, D., Montanarella,

- 1042 L., Hong, S. Y., Rawlins, B. G. and Field, D. J.: Global soil organic carbon assessment,
1043 Global Food Security-Agriculture Policy Economics and Environment, 6, 9–16,
1044 doi:10.1016/j.gfs.2015.07.001, 2015.
- 1045 Šimon, T., Kunzová, E. and Friedlová, M.: The effect of digestate, cattle slurry and
1046 mineral fertilization on the winter wheat yield and soil quality parameters, *Plant Soil and*
1047 *Environment*, 62(11), 522–527, 2015.
- 1048 Tejada, M., Rodriguez-Morgado, B., Gómez, I., Franco-Andreu, L., Benitez, C. and
1049 Parrado, J.: Use of biofertilizers obtained from sewage sludges on maize yield, *European*
1050 *Journal of Agronomy*, 78, 13–19, doi:10.1016/j.eja.2016.04.014, 2016.
- 1051 Tiecher, T., Santos, dos, D. R. and Calegari, A.: Soil organic phosphorus forms under
1052 different soil management systems and winter crops, in a long term experiment, *Soil Till.*
1053 *Res.*, 124, 57–67, doi:10.1016/j.still.2012.05.001, 2012.
- 1054 van Groenigen, K. J., Hastings, A., Forristal, D., Roth, B., Jones, M. and Smith, P.: Soil
1055 C storage as affected by tillage and straw management: An assessment using field
1056 measurements and model predictions, *Agr. Ecosyst. Environ.*, 140(1-2), 218–225,
1057 doi:10.1016/j.agee.2010.12.008, 2011.
- 1058 Vieira, F. C. B., Bayer, C., Zanatta, J. A., Dieckow, J., Mielniczuk, J. and He, Z. L.:
1059 Carbon management index based on physical fractionation of soil organic matter in an
1060 Acrisol under long-term no-till cropping systems, *Soil Till. Res.*, 96(1-2), 195–204,
1061 doi:10.1016/j.still.2007.06.007, 2007.
- 1062 Vieira, F. C. B., Bayer, C., Zanatta, J. and Ernani, P. R.: Organic matter kept Al toxicity
1063 low in a subtropical no-tillage soil under long-term (21-year) legume-based crop systems
1064 and N fertilisation, *Soil Res.*, 47(7), 707–714, doi:10.1071/SR08273, 2009.
- 1065 Vitousek, P. M., Naylor, R., Crews, T., David, M. B., Drinkwater, L. E., Holland, E.,
1066 Johnes, P. J., Katzenberger, J., Martinelli, L. A., Matson, P. A., Nziguheba, G., Ojima,
1067 D., Palm, C. A., Robertson, G. P., Sanchez, P. A., Townsend, A. R. and Zhang, F. S.:
1068 Nutrient Imbalances in Agricultural Development, *Science*, 324(5934), 1519–1520,
1069 doi:10.1126/science.1170261, 2009.
- 1070 Wang, J. Y., Yan, X. Y. and Gong, W.: Effect of long-term fertilization on soil
1071 productivity on the North China Plain, *Pedosphere*, 25(3), 450–458, 2015.
- 1072 Wang, Q. J., Lu, C. Y., Li, H. W., He, J., Sarker, K. K., Rasaily, R. G., Liang, Z. H.,
1073 Qiao, X. D., Hui, L. and Mchugh, A. D. J.: The effects of no-tillage with subsoiling on
1074 soil properties and maize yield: 12-Year experiment on alkaline soils of Northeast China,
1075 *Soil Till. Res.*, 137, 43–49, doi:10.1016/j.still.2013.11.006, 2014a.
- 1076 Wang, Z. G., Jin, X., Bao, X. G., Li, X. F., Zhao, J. H., Sun, J. H., Christie, P. and Li, L.:
1077 Intercropping Enhances Productivity and Maintains the Most Soil Fertility Properties
1078 Relative to Sole Cropping, *Plos One*, 9(12), doi:10.1371/journal.pone.0113984, 2014b.
- 1079 Williams, A., Hunter, M. C., Kammerer, M., Kane, D. A., Jordan, N. R., Mortensen, D.

- 1080 A., Smith, R. G., Snapp, S. and Davis, A. S.: Soil Water Holding Capacity Mitigates
1081 Downside Risk and Volatility in US Rainfed Maize: Time to Invest in Soil Organic
1082 Matter?, edited by J. L. Gonzalez-Andujar, *Plos One*, 11(8), e0160974,
1083 doi:10.1371/journal.pone.0160974, 2016.
- 1084 Wortman, S. E., Galusha, T. D., Mason, S. C. and Francis, C. A.: Soil fertility and crop
1085 yields in long-term organic and conventional cropping systems in Eastern Nebraska,
1086 *Renewable Agriculture and Food Systems*, 27(3), 200–216,
1087 doi:10.1017/s1742170511000317, 2012.
- 1088 Wu, J., Wang, W., Wang, X., Zhu, L., Yang, H., Han, X., Gao, J., Guo, W. and Bian, X.:
1089 Residue management affects greenhouse gas emissions and soil organic carbon in wheat-
1090 rice rotation system, *Fresenius Environmental Bulletin*, 24(9), 2751–2762, 2015.
- 1091 Yang, J. M., Yang, J. Y., Dou, S., Yang, X. M. and Hoogenboom, G.: Simulating the
1092 effect of long-term fertilization on maize yield and soil C/N dynamics in northeastern
1093 China using DSSAT and CENTURY-based soil model, *Nutr. Cycl. Agroecosys.*, 95(3),
1094 287–303, doi:10.1007/s10705-013-9563-z, 2013.
- 1095 Yang, J., Gao, W. and Ren, S. R.: Long-term effects of combined application of chemical
1096 nitrogen with organic materials on crop yields, soil organic carbon and total nitrogen in
1097 fluvo-aquic soil, *Soil Till. Res.*, 151, 67–74, doi:10.1016/j.still.2015.03.008, 2015a.
- 1098 Yang, Z. C., Zhao, N., Huang, F. and Lv, Y.: Long-term effects of different organic and
1099 inorganic fertilizer treatments on soil organic carbon sequestration and crop yields on the
1100 North China Plain, *Soil Till. Res.*, 146, 47–52, doi:10.1016/j.still.2014.06.011, 2015b.
- 1101 Yeboah, S., Zhang, R., Cai, L., Li, L., Xie, J., Luo, Z., Liu, J. and Wu, J.: Tillage effect
1102 on soil organic carbon, microbial biomass carbon and crop yield in spring wheat-field pea
1103 rotation, *Plant Soil and Environment*, 62(6), 279–285, doi:10.17221/66/2016-pse, 2016.
- 1104 Zhang, S. X., Chen, X. W., Jia, S. X., Liang, A. Z., Zhang, X. P., Yang, X. M., Wei, S.
1105 C., Sun, B. J., Huang, D. D. and Zhou, G. Y.: The potential mechanism of long-term
1106 conservation tillage effects on maize yield in the black soil of Northeast China, *Soil Till.*
1107 *Res.*, 154, 84–90, doi:10.1016/j.still.2015.06.002, 2015.
- 1108 Zhang, W. J., Xu, M. G., Wang, B. R. and Wang, X. J.: Soil organic carbon, total
1109 nitrogen and grain yields under long-term fertilizations in the upland red soil of southern
1110 China, *Nutr. Cycl. Agroecosys.*, 84(1), 59–69, doi:10.1007/s10705-008-9226-7, 2009.
- 1111 Zhang, Y. L., Li, C. H., Wang, Y. W., Hu, Y. M., Christie, P., Zhang, J. L. and Li, X. L.:
1112 Maize yield and soil fertility with combined use of compost and inorganic fertilizers on a
1113 calcareous soil on the North China Plain, *Soil Till. Res.*, 155, 85–94,
1114 doi:10.1016/j.still.2015.08.006, 2016.
- 1115 Zhao, Y. C., Yan, Z. B., Qin, J. H., Ma, Z. J., Zhang, Y. F. and Zhang, L.: The potential
1116 of residues of furfural and biogas as calcareous soil amendments for corn seed
1117 production, *Environmental Science and Pollution Research*, 23(7), 6217–6226,

- 1118 doi:10.1007/s11356-015-5828-1, 2016.
- 1119 Zomer, R. J., Bossio, D. A., Sommer, R. and Verchot, L. V.: Global Sequestration
1120 Potential of Increased Organic Carbon in Cropland Soils, Scientific Reports 2016 6, 1–8,
1121 doi:10.1038/s41598-017-15794-8, 2017.
- 1122 Zomer, R. J., Trabucco, A., Bossio, D. A. and Verchot, L. V.: Climate change mitigation:
1123 A spatial analysis of global land suitability for clean development mechanism
1124 afforestation and reforestation, *Agr. Ecosyst. Environ.*, 126(1-2), 67–80,
1125 doi:10.1016/j.agee.2008.01.014, 2008.
- 1126 Zvomuya, F., Janzen, H. H., Larney, F. J. and Olson, B. M.: A Long-Term Field Bioassay
1127 of Soil Quality Indicators in a Semiarid Environment, *Soil Sci. Soc. Am. J.*, 72(3), 683,
1128 doi:10.2136/sssaj2007.0180, 2008.
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1147 **Table 1. Modeled regression coefficients with standard errors, standardized**
 1148 **coefficients, and *P* values for our regression model.**

Variable	Unstandardized Coefficients	Standardized Coefficients	<i>P</i> value
Intercept	-1.61 ± 1.71	5.59 ± 0.18	0.35
SOC	1.79 ± 0.59	1.44 ± 0.30	0.003
SOC ²	-0.46 ± 0.18	-0.66 ± 0.27	0.012
N input	0.018 ± 0.0014	2.71 ± 0.15	< 0.00001
N input ²	-0.000039 ± 0.0000036	-1.64 ± 0.15	< 0.00001
Irrigation	0.75 ± 0.35	0.77 ± 0.34	0.032
pH	0.053 ± 0.18	0.12 ± 0.42	0.76
Aridity	0.16 ± 0.51	0.12 ± 0.41	0.76
Crop Type	1.54 ± 0.15	1.54 ± 0.15	< 0.00001
Clay (%)	0.013 ± 0.014	0.29 ± 0.31	0.37
Latitude	0.054 ± 0.016	1.40 ± 0.41	0.001
<u>SOC*N input</u>	<u>0.0039 ± 0.00099</u>	<u>0.96 ± 0.25</u>	<u>0.00010</u>

1149 The output of our linear mixed effect model (n=834). The full model explained 83% of
 1150 observed variability within the dataset with fixed effects (included in the table)
 1151 accounting for 42% of the variability. Standardized coefficients allow for direct
 1152 comparison of the relative effect size of each modeled variable despite different scales on
 1153 which the variables are measured. For example, crop type's effect on yield is two-times
 1154 greater than that of irrigation. Crop type was coded as a binary variable with 0 for wheat
 1155 and 1 for maize. Irrigation was also coded as a binary variable with 0 for no irrigation and
 1156 1 for irrigation.

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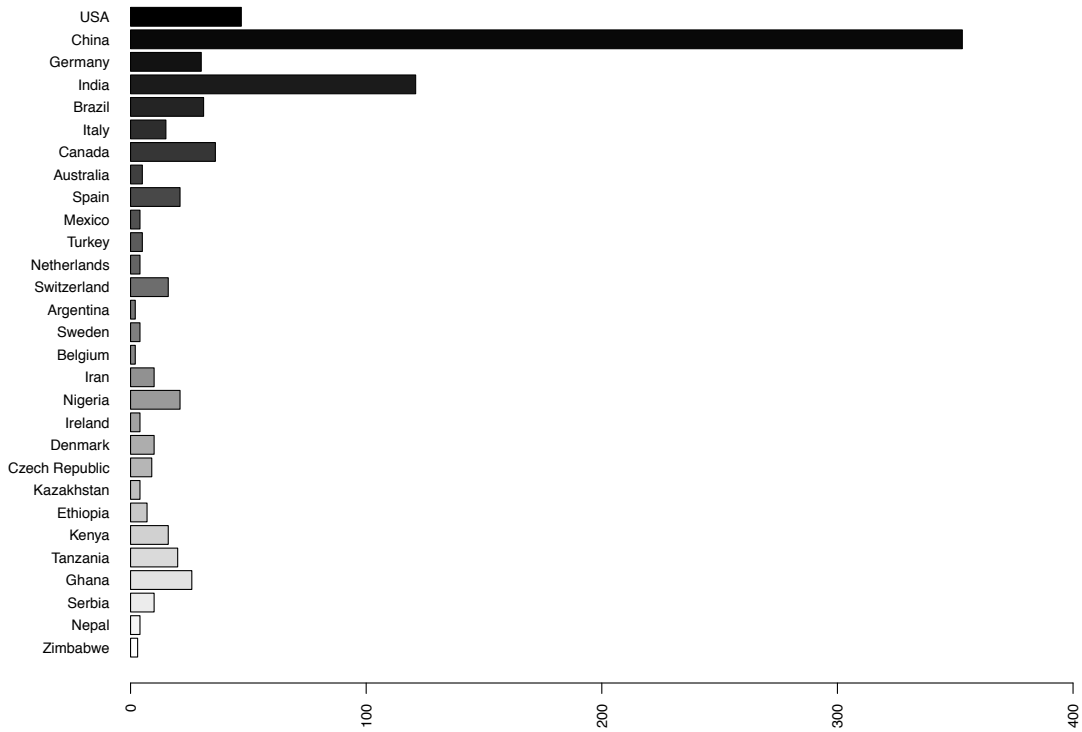
1163 **Table 2. Scenarios for increases in yield and reductions in N input with an increase**
 1164 **in SOC concentration to target values.**

Scenario	Crop	Global Yield Average (t ha ⁻¹)	Increase in production (Mt)	Nitrogen input (Mt N ha ⁻¹)
Current condition	Maize	3.34 ± 2.62	NA	17.24
	Wheat	2.43 ± 1.58	NA	33.07
Increase SOC to target concentrations	Maize	3.93 ± 3.08	29.96 (5%)	15.96
	Wheat	3.17 ± 2.06	55.41 (10%)	32.04

1165 Values (mean±SD) represent current EarthStat yields and projected gains in yield and
 1166 production (with % increase in parentheses) resulting from an increase in SOC
 1167 concentration to target values for each agro-ecological zone (targets ranged from 1.0 to
 1168 2.0%). We used our regression model to determine potential gains in EarthStat yield and
 1169 reductions in EarthStat N input. Global yield averages represent tonnes produced per unit
 1170 land area, whereas production represents tonnes of maize and wheat produced globally.

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Distribution by country



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1184 **Figure 1: Distribution of data points by country.** Countries are ordered by Gross
1185 Domestic Product (GDP) in order from largest (top) to smallest (bottom). The dataset
1186 used for this study contains a total of 840 individual observations from 29 different
1187 countries.

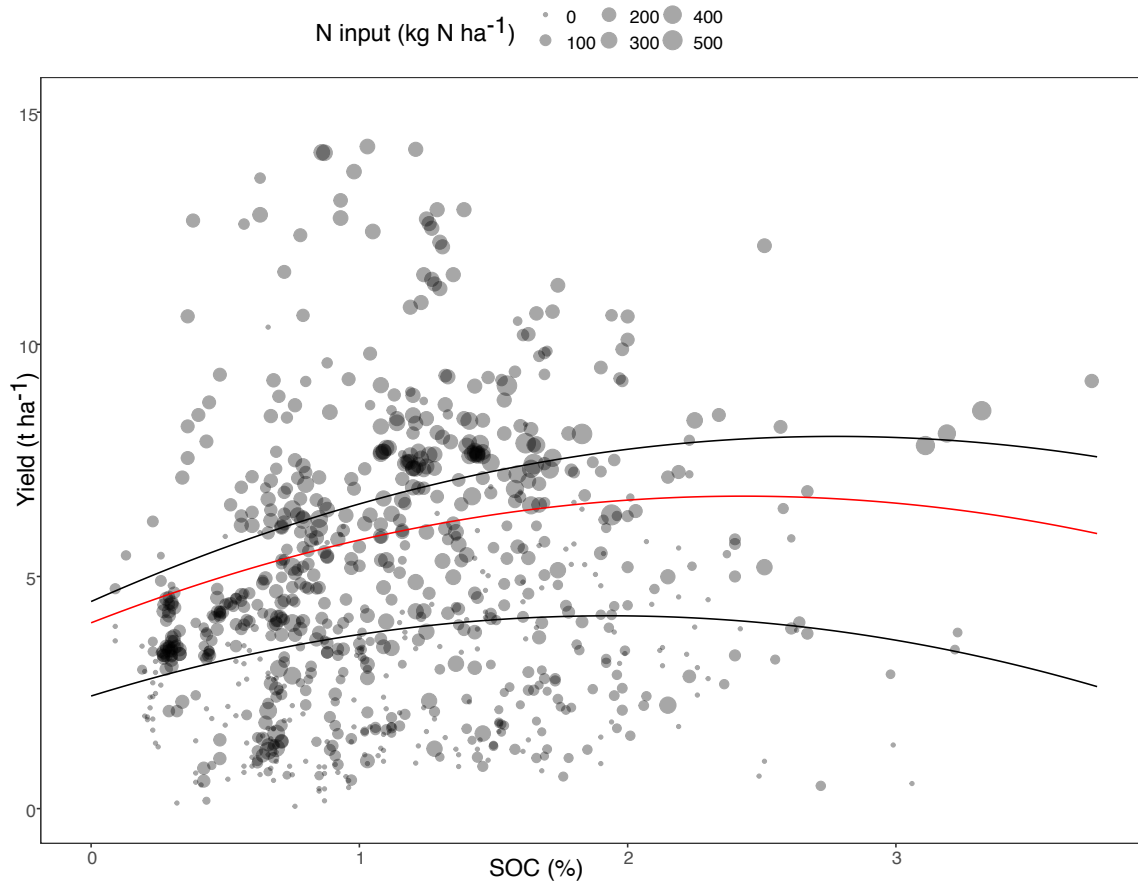
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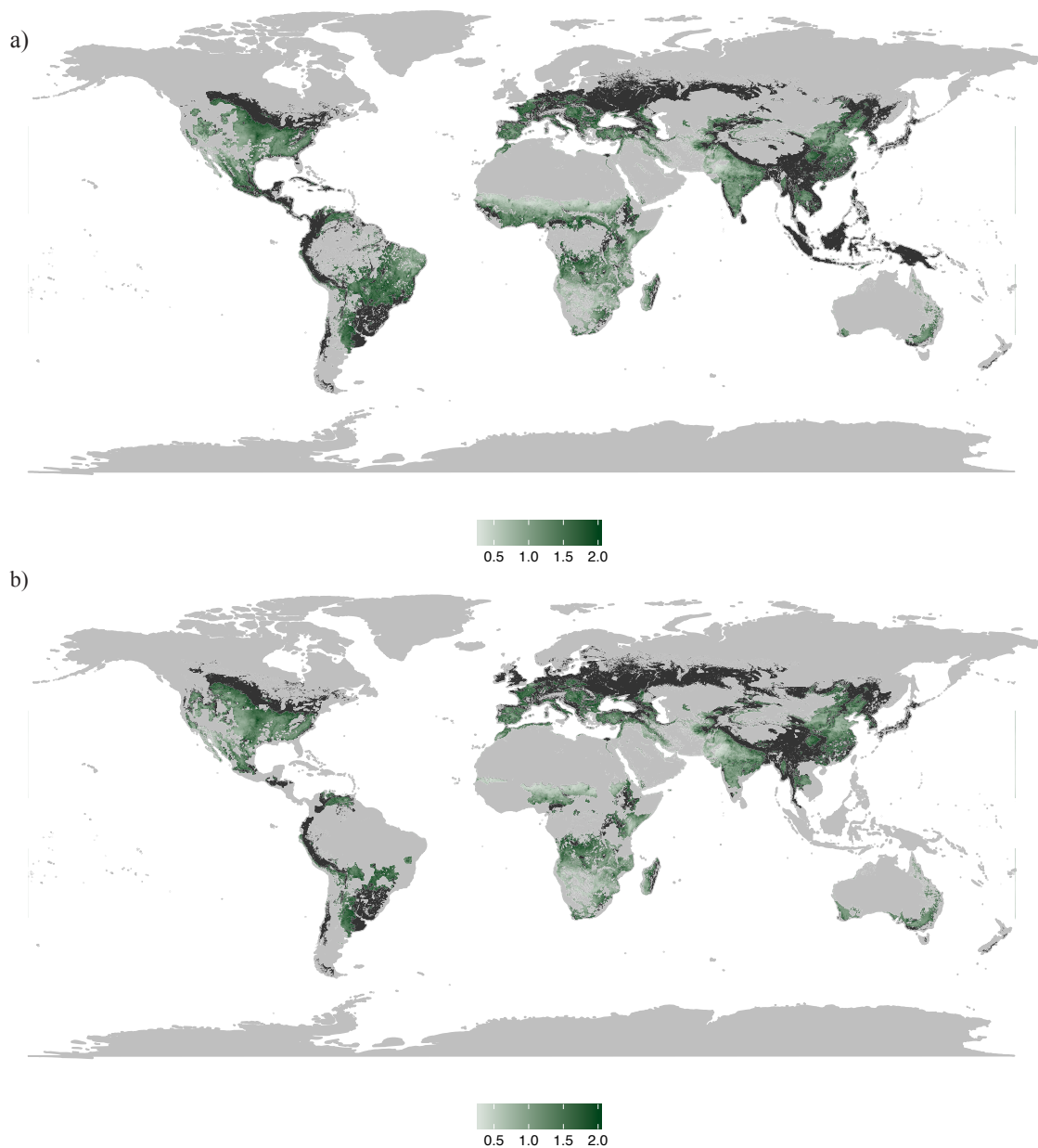
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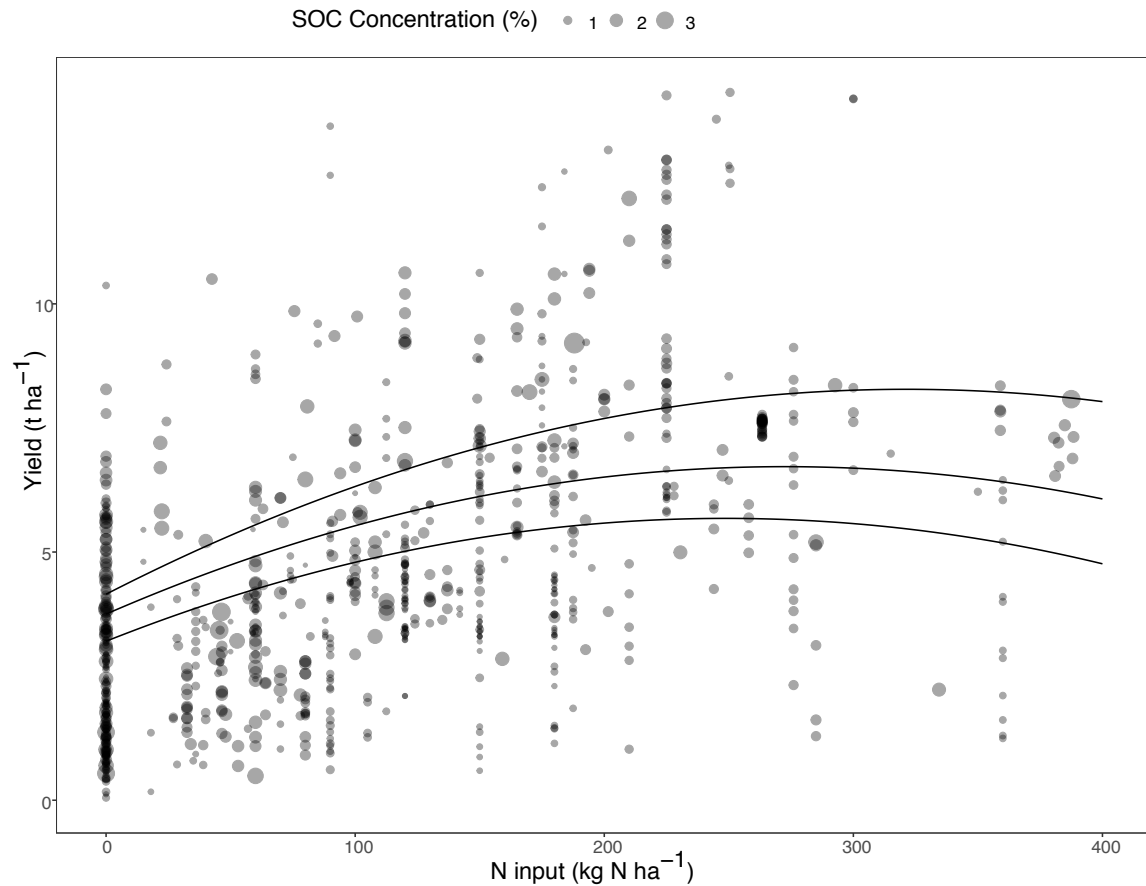
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1194 **Figure 2: Relationship between SOC and yield of maize for published studies.** The
 1195 regression lines are modeled yields (i.e. effect sizes) for rain-fed (i.e. non-irrigated) maize
 1196 using observed means of our meta-dataset for aridity, pH, texture, and latitude at different
 1197 N input rates. We varied SOC (x-axis) across the range of values extracted from the
 1198 literature. The red line represents the mean N input rate (118 kg N ha⁻¹ y⁻¹) across all
 1199 studies, with the bottom line representing 0 inputs of N and the top line representing 200
 1200 kg N ha⁻¹ y⁻¹. For the raw data points, N input is mapped as a continuous variable across
 1201 its range from 0 (smallest circles) to 500 kg N ha⁻¹ y⁻¹ (largest circles). Note that the
 1202 observed scatter of the individual observations is an outcome of the fact yield is
 1203 controlled by multiple factors (Table 1), and therefore the regression lines isolate just the
 1204 potential effect of SOC with all other factors held constant.



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1206 **Figure 3: Global maize and wheat lands with less than 2% SOC.** Cultivated (a) maize
 1207 lands and (b) wheat lands on soils with SOC contents less than 2%. Approximately two
 1208 thirds of all maize (61%) and of all wheat (64%) producing areas are on soils with less
 1209 than 2% SOC. Black areas on the maps are cultivated maize and wheat lands that have
 1210 concentrations over 2% SOC. Yield data is taken from EarthStat and SOC data is taken
 1211 from ISRIC-SoilGrids.



1212

1213 **Figure 4: Potential reductions in nitrogen fertilizer with an increase in SOC**

1214 **concentration.** The lines on the graph represent varying SOC concentrations, 2.0%,

1215 1.0%, and 0.5% SOC from top to bottom for rain-fed maize. These lines are plotted on

1216 top of the observations from our dataset with SOC mapped as a continuous variable

1217 across its range from 0.1% (smallest circles) to 3.0% (largest circles). Our model shows

1218 that keeping yield constant by increasing SOC contents allows for potentially significant

1219 reductions in N input (e.g. the same yield is achievable with 0 N input and 2% SOC, as

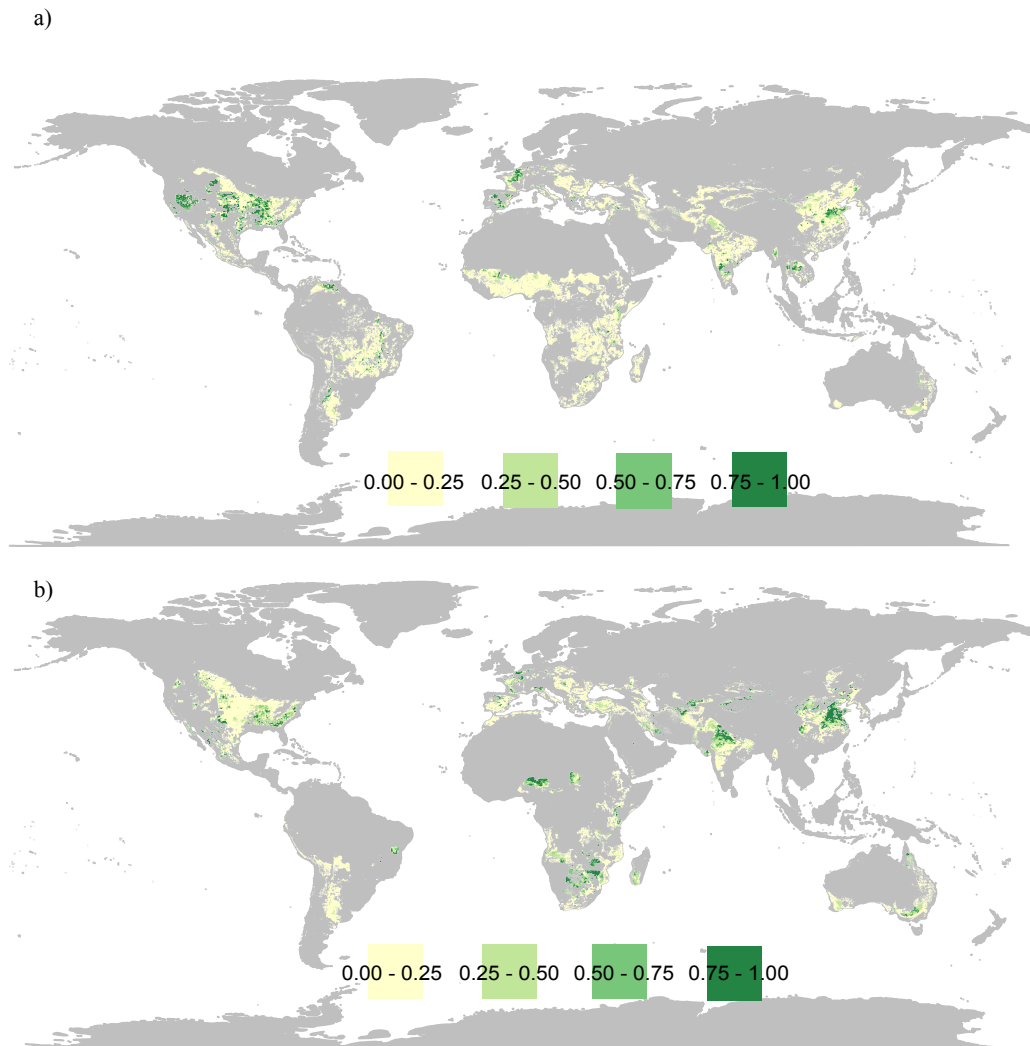
1220 with 50 kg N ha⁻¹ y⁻¹ and 0.5% SOC). Recognizing that the 0 N input values may

1221 influence the modeled relationship, we analyzed data excluding these values. The

1222 qualitative patterns remain the same if the 0 N input values are excluded from the

1223 analysis; and while the absolute quantitative patterns shift slightly, the general trends

1224 remain intact.



1225

1226 **Figure 5: Proportion closure of yield gap for (a) maize and (b) wheat given an**
1227 **increase in SOC concentration to target values for each AEZ (ranging from 1-2%).**

1228 Modeled gains come from our regression relationship between SOC and yield and
1229 applying it to EarthStat yield gap data. Doing so determines the potential increase in yield
1230 and therefore projected reductions in yield gaps for maize and wheat.

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