November 13, 2018

Dear Dr. Rumpel,

Thank you for the opportunity to submit a revised version of "Global meta-analysis of the relationship between soil organic matter and crop yields." We appreciate your handling of this manuscript and the constructive comments from the reviewers. We have revised the paper in response to your comment and those from the reviewers and have included our responses below. Please let us know if you have further questions or seek additional clarification on any points.

Sincerely,

Emily Oldfield (on behalf of all co-authors)
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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).

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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) where 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 to 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 the 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.

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

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Abstract

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

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

1 Introduction

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

A primary hurdle to managing SOM for sustainable intensification is the lack of predictive, quantitative targets of SOM for specific agricultural and environmental objectives (Herrick, 2000; NRC, 2010). While several studies show correlations between SOM and yield (Culman et al., 2013; de Moraes Sa et al., 2014; Lucas and Weil, 2012; Stine and Weil, 2002), it remains unclear how much yield could be expected to increase per unit change in organic matter (Herrick, 2000; NRC, 2010). Establishing these quantitative metrics is challenging because research shows increases (Bauer and Black, 1992), decreases (Bhardwaj et al., 2011), and no change (Hijbeek et al., 2017) in yields with increased SOM. This lack of a general relationship is likely the result of a number of interacting factors related to management, climate, and soil type that can confound the SOM-yield relationship. This confusion has led some to claim that the amount of SOM is unnecessary for crop yields, so long as there is sufficient N fertilizer (Hijbeek et al., 2017; Loveland and Webb, 2003; Oelofse et al., 2015); whereas others highlight the need to build SOM to increase crop yields while minimizing environmental harm (Lal, 2004). The growing momentum to launch global scale initiatives to manage SOM (Banwart et al., 2014; Lal, 2004; Minasny et al., 2017; Zomer et al., 2017) suggests the need to test competing claims about the effects of SOM on these agricultural and environmental outcomes.

One could critique the effort to establish a global-level understanding of the SOM-yield relationship on the grounds that farm-level responses are necessarily heterogeneous and poorly predicted by global assessments. Yet, global initiatives for managing SOM could create policy environments that stimulate regional- and local-prescriptions for SOM levels that inform practice (Chabbi et al., 2017; Minasny et al., 2017; Zomer et al., 2017). Whereas it is difficult to disentangle the extent to which SOM-yield relationships are driven by SOM effects on yield, as opposed to yield (i.e. higher plant carbon inputs) effects on SOM, there is nevertheless experimental evidence showing that building SOM positively affects yield (Bauer and Black, 1994; Majumder et al., 2008; Oldfield et al., 2017). In addition, numerous soil properties that relate to soil fertility, such as water holding capacity, respond positively to increasing SOM and in turn are expected to increase yields (Williams et al., 2016). As such, correlative SOM-yield relationships suggest the potential – but likely not the true – effect of SOM on yield.

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

2 Results and Discussion

2.1 The relationship between SOC and yield

At the global level and focusing specifically on the potential effect size of SOC on yield, we found that the largest gains in yield occur between SOC concentrations of 0.1 to 2.0%. For instance, yields are 1.2 times higher at 1.0% SOC than 0.5% SOC (Fig. 1). Gains in yield leveled off at a concentration of approximately 2% SOC (Fig. 1). Two percent SOC has previously been suggested as a critical threshold, with values below this concentration threatening the structure, and ultimately, the ability of a soil to function (Kemper and Koch, 1966). Importantly, 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. That is, if yield was an explanatory variable for SOC, we would expect greater yields to keep driving greater levels of SOC (i.e. the relationship would appear more linear) since we know that soils can accumulate concentrations much greater than 2% (Castellano et al., 2015). However, our data do not display a linear pattern, suggesting that higher yields are not driving higher levels of SOC.

It has been suggested that there is no evidence for 2% SOC being a critical threshold for productivity, as long as there is sufficient mineral fertilizer to support crop production (Edmeades, 2003; Loveland and Webb, 2003; Oelofse et al., 2015). Such conclusions deem the amount of SOM as substitutable by mineral fertilizers (at least for crop growth), but are inconsistent with the motivation for sustainable intensification to minimize environmental harm caused by mineral fertilizers in relation to emissions of greenhouse gases and eutrophication of waters (Vitousek et al., 2009). The same logic about substitutability also does not account for the other co-benefits associated with building SOM in agricultural lands, such as reductions in nutrient run-off, drought resistance, and yield stability (Robertson et al., 2014). Field- and regional-scale studies have shown a similar pattern as that observed from our global analysis: there exists a positive relationship between SOC and yield that starts to level off at ~2% SOC (Kravchenko and Bullock, 2000; Pan et al., 2009; Zvomuya et al., 2008). Our analysis suggests that this relationship holds on average at the global scale and when N fertilization is controlled for.

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

2.2 The interaction between SOC and N fertilizer on yield

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

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

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

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

Gains in yield from fertilizer input leveled off at about 200 kg N ha^{-1} y^{-1} (Fig. 3), meaning that optimum yields appear achievable, at least on average, with this fertilizer input level and an SOC target concentration of 2%. Using this target N input rate, we explored potential fertilizer reductions on agricultural lands using more than 200 kg N ha^{-1} y^{-1}. We found that for lands receiving more than 200 kg N ha^{-1} y^{-1}, current yields could be maintained, while decreasing global N fertilizer inputs by 7% for maize and 5% for wheat. It is estimated that 25 to 30% of fertilizer N is exported to streams and rivers, resulting in eutrophication (Raymond et al., 2012). Targeted reductions in the application of fertilizer N on the order of magnitude our analysis suggests could then prevent the annual export of as much as 3.73 million tonnes of N into inland waters, which amounts to 10% of mineral fertilizer applied to maize and wheat lands (see Methods for an explanation of how this percentage was obtained).

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

With a majority of cultivated lands containing less than 2% SOC and a growing imperative to build, restore, and protect SOC in agricultural soils (NSTC, 2016; FAO, 2008; NRCS, 2012), we used global gridded datasets coupled with our regression model (Table 1) to examine the potential gains in yield and production if opportunities to increase SOC are realized (Table 2). We then calculated how these gains in production would impact global yield gaps of maize and wheat, the difference between observed and attainable yields (Mueller et al., 2012). Although our model identified 2% as a global target for SOC, we created regionally-specific SOC targets given the fact that achieving 2% SOC in some soils (e.g. those of drylands) may be unachievable due to inherent constraints of physical soil properties and climate (see Methods). We found that increasing SOC concentrations to the defined targets has the potential capacity to increase average yields on a per hectare basis by 10±11% (mean±SD) for maize and 23±37% for wheat. These gains in yield translate to a 5% and 10% increase in the global annual tonnes produced of maize and wheat, respectively (Table 2). These increases in production would close 32% of the global yield gap for maize and 60% of the gap for wheat (Fig 4a,b).

These yield gap results represent an exploration of potential “best case” impacts of increasing SOC concentrations. We recognize there are inherent and logistical challenges to building SOM in agricultural soils; and when managing for and building SOM, it is important to account for its dynamic nature. For instance, to derive some of the nutrient benefits of SOM, it must be mineralized and used (Janzen, 2006), and so frequent additions of organic inputs may be necessary to sustain SOM levels. Furthermore, soil characteristics such as texture can have a large effect on SOC content because sandier (rather than more clay rich) soils have less surface area to stabilize SOC (Rasmussen et al., 2018), and so hold much less water and nutrients than clay-rich soils (Johnston et al., 2009). Maintaining SOC contents in sandy soils may require more frequent additions of organic amendments because these soils do not have the surface area to retain nutrients, moisture, and to stabilize SOC (Lehmann and Kleber, 2015).

Different regions and climate types also face different imperatives for building SOM. In the mid-western United States, for instance, building SOM may be a good strategy to reduce fertilizer inputs and irrigation needs; whereas in sub-Saharan Africa, building SOM may be critical for drought protection and nutrient provision. Notably, high SOM values are not common in dryland environments (for our dataset, mean SOC = 0.9% for dryland climates versus 1.4% SOC for mesic soils), and building and maintaining SOM in arid zones is typically hindered by the lack of organic matter to return to soils (Rasmussen et al., 1980). On a positive note, however, our analysis suggests that increases in SOC in drylands, for example, from 0.5 to 0.8%, could potentially increase yields by 10%, likely due to impacts on water retention as well as improved nutrient supply.

The goal of our analysis was to establish a global, average relationship between SOC and yield. Whereas we did use lower SOC targets (ranging from 1.0 to 1.5%) for the arid AEZs in our analysis, the majority of data used for our analysis is from the more temperate and tropical humid zones (Fig. S2) and a large proportion of our data comes from China (Fig. 1). We recognize that the distribution of our data could potentially bias our results. As such, we explored the SOM-yield relationship in the absence of data from China and also for Chinese observations only. While the effect size of SOC changes depending on the subset of data analyzed (Table S2), the qualitative patterns of this relationship remain the same. That is, SOC leads to gains in yield that are most pronounced at lower SOC concentrations and decline in their magnitude as ~2% SOC is reached (Fig. S3). Notably, when exploring the subset of data from China, the effect size of SOC was higher than that from the entire dataset (Table S2). However, China only had 10 observations above 2% SOC, and so the modeled relationship for China captures the part of the SOM-yield relationship where an increase in SOC leads to the largest gains in yield (i.e. where the modeled slope is the steepest). Our analysis then 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 to more directly inform practice.

Moving from the global relationship presented in our paper to bolstering and/or refining SOC targets, our correlative analysis needs to be supplemented with well-replicated experimental studies incorporating different management strategies across multiple soil and climate types to develop SOC-yield relationships that can be applied to the specific set of local farm conditions. Further, these studies should ideally report data related to soil texture and mineralogy, nutrient management, and paired SOC-yield observations with SOC taken to meaningful depths, such as those that represent plant-rooting depth. These experimental studies will help generate information that practitioners can use to inform management by taking into account the potential benefits of SOC, compared against the inherent and logistical challenges to building SOC to target levels.

3 Conclusions

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

4 Methods

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

4.1 Data collection

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

The initial search resulted in 1,384 articles and the second 169 articles (Fig. S1). For each citation, we reviewed titles and abstracts to select articles that met the following criteria: experimental field studies whose abstract included information on yield and SOC for systems growing wheat and/or maize. This initial screening resulted in 523 records for which we assessed the full text. We assessed these records for eligibility based on inclusion of data on crop yield, SOC, and N fertilizer rates for each observation. For inclusion within our analysis, it was essential that studies reported paired SOC and yield data. Furthermore, we required SOC concentrations (as opposed to stocks). Studies did not meet our criteria for inclusion if they reported SOC stocks with no corresponding data on bulk density to convert into concentrations; and also if they reported baseline SOC concentrations as opposed to experimental SOC concentrations that we could pair with yield data. In addition to our literature search, we also contacted authors to see if they were willing to include raw data within our database. This resulted in three datasets (Adiku et al., 2009; Birkhofer et al., 2008; Kautz et al., 2010). Finally, we consulted the recently published database by the Swedish Board of Agriculture that is a key repository of peer reviewed literature focusing specifically on studies (735 in total) related to the effects of agricultural management on soil organic carbon (Haddaway et al., 2015). We explored this database to find studies from regions that were under-represented within our literature search (e.g. the southern hemisphere). This resulted in a search of 55 studies to see if they met our criteria for inclusion. We scanned each paper to see if they included SOC data paired with matching yield data. From these papers, we extracted data from 12 studies, which resulted in an additional 52 data points. We encountered limitations similar to our initial search: Namely, SOC and yield data were not paired, studies included only baseline SOC concentrations, or SOC stocks were reported without any corresponding bulk density data to convert into concentrations. Overall, our dataset included 840 individual observations from 90 articles covering sites across the globe (Adiku et al., 2009; Agegnehu et al., 2016; Albizua et al., 2015; Alijani et al., 2012; Araya et al., 2012; Atreya et al., 2006; Bai et al., 2009; Bedada et al., 2014; Bhardwaj et al., 2011; Bhattacharyya et al., 2015; Birkhofer et al., 2008; Boddey et al., 2010; Boulal et al., 2012; Bremer et al., 1994; Calegari et al., 2008; Campbell et al., 2007; Castellanos-Navarrete et al., 2012; Celik et al., 2010; Chen et al., 2015; Chirinda et al., 2010; Cid et al., 2014; Costa et al., 2010; D'Hose et al., 2014; Datta et al., 2010; DeMaria et al., 1999; Diacono et al., 2012; Grandy et al., 2006; Guo et al., 2012; 2009; He et al., 2011; Hossain et al., 2016; Hu et al., 2015; 2014; Kaihura et al., 1999; Karbozova Saljnikov et al., 2004; Kautz et al., 2010; Kazemeini et al., 2014; Kucharik et al., 2001; Larsen et al., 2014; Lebbink et al., 1994; Leogrande et al., 2016; Li et al., 2015; Liu et al., 2014a; 2016; 2014b; 2014c; López-Garrido et al., 2014; Lu et al., 2016; Ma et al., 2012; 2016; Madejón et al., 2001; Mandal et al., 2013; Masto et al., 2007; Mikanová et al., 2012; Mishra et al., 2015; Mupangwa et al., 2013; N'Dayegamiye, 2006; Niu et al., 2011; Njoku and Mbah, 2012; Paul et al., 2013; Qin et al., 2015; Quiroga et al., 2009; Sadeghi and Bahrani, 2009; Saikia et al., 2015; Scalise et al., 2015; Seremesic et al., 2011; Singh and Dwivedi, 2006; Singh et al., 2016; Sisti et al., 2004; Soldevilla-Martinez et al., 2013; Spargo et al., 2011; Šimon et al., 2015; Tejada et al., 2016; Tiecher et al., 2012; van Groenigen et al., 2011; Vieira et al., 2007; 2009; Wang et al., 2015; 2014a; 2014b; Wortman et al., 2012; Wu et al., 2015; Yang et al., 2013; 2015a; 2015b; Yeboah et al., 2016; Zhang et al., 2015; 2009; 2016; Zhao et al., 2016). Where necessary, we extracted data from manuscript figures using GraphClick Software (v. 3.0.3, http://www.arizona-software.ch/graphclick/).

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

4.2 Data compilation

For each extracted observation, we compiled the following information: latitude, longitude, year of data collection, crop type, yield, SOC or SOM, depth of SOC or SOM measurement, N fertilization rate, P fertilization rate, soil pH, texture, and whether or not crops were irrigated. We used SOC (as opposed to SOM) for our analysis given that SOC is a common proxy for SOM. Carbon, as an element that is easily identified and measured within soil, is thought to comprise ~50-60% of SOM and is commonly reported in the literature (Pribyl, 2010). When SOM was reported, we converted it to SOC by dividing the value by 1.724 (Cambardella et al., 2001). Different studies reported SOC concentrations to different depths, which ranged from 0-5 cm to 0-30 cm, with the majority of studies reporting SOC to 0-20 cm. When studies reported SOC to multiple depths, we averaged SOC values across depths to 30 cm. If no information on irrigation was provided, we scored the observation as rain-fed. Soil texture and pH were not reported for every study; 79% of included studies reported pH, and so we used the study's latitude and longitude to extract these data using ISRIC SoilGrids (Hengl et al., 2014) to fill in the missing pH values. Texture was reported for about half (49%) of included studies, and so we used coordinates to pull these data from SoilGrids as well (Hengl et al., 2014). We also used latitude and longitude to obtain an "aridity index" through the CGIAR-CSI database (Zomer et al., 2008). We chose to use aridity as our primary climatic variable since it is expressed as a function of precipitation, temperature, and potential evapo-transpiration (Trabucco 2009).

4.3 Data analysis

We used a linear mixed model (LMM) to analyze the observations we extracted from the literature. Our model included SOC, N fertilizer rate, crop type (maize or wheat, coded as a binary variable), irrigation (coded as a binary variable), aridity index, latitude, pH, and texture (% clay) as fixed effects. The differences in soil carbon observed in our dataset are from experimental plots capturing long-term differences in SOC within a given site. Specifically, our data capture differences within SOC largely driven by management interventions related to inputs (e.g. compost, fertilizer, manure, crop residues) and tillage (e.g. no-till versus till). Site-specific differences in management as well as spatial and temporal correlation among the studies were accounted for by nesting year within study as random effects (Bolker et al., 2009). The LMMs were fit with a Gaussian error distribution in the "lme4" package for the "R" statistical program (version 3.3.1), using the "lmer" function. The first stage of our data analysis was to test the data distributions. We removed data points with N fertilization rates >600 kg N ha^{-1} (4 data points) and yields >18 t ha^{-1} (2 data points) since these represented outliers for our dataset (being beyond 3 times the inter-quartile range of the meta-dataset) and are not representative of on-farm management practices or outcomes. Our final model was based on 834 observations across 90 studies. We added quadratic terms for both SOC and N input rate since these variables exhibited a nonlinear relationship with yield. The square-root of the variance inflation factors (vif) was <2 for all factors when included as main effects, indicating that collinearity was low among all variables. As would be expected, there was a correlation between SOC and its quadratic term and N input rate and its quadratic term. We re-ran our regression after removing four seemingly influential data points (those that had high SOC concentrations with low yields, see Fig. 2) and model coefficients remained essentially the same. We calculated the r^2 values for our model following Nakagawa and Schielzeth (Nakagawa and Schielzeth, 2013) to retain the random effects structure. The r^2 of our model was 83% for the full model, with the fixed effects explaining 42% of observed variance within our dataset.

We based the choice of factors for inclusion in our model on the approach of Hobbs et al. (Hobbs and Hilborn, 2006), by only investigating factors where biological mechanism as to their influence on yield is firmly established and where we were interested in their effect sizes relative to one another. Also following Hobbs et al. (Hobbs and Hilborn, 2006), we did not carry out model selection. Operationally, there is substantial subjectivity and lack of agreement in model selection approaches, with different decisions leading to markedly different conclusions as to the influence of different factors. Instead, coefficients are generally most robust when all terms are retained in a model, assuming that inclusion of each is biologically justified. We decided to include an SOC by N interaction to 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 acknowledge that there are a number of interactions we could have included within our statistical model, and we did run our regression model with additional interactions to include SOC by irrigation, SOC by clay, and SOC by aridity. Including these interactions, however, did not offer any additional explanatory power and our main results between SOC, N inputs, and yield were essentially unchanged with these additional interactions (Table S3). As such, we chose to present our analysis including only the SOC x N interaction.

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

4.4 Global extrapolations

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

To establish regionally appropriate SOC targets, we classified maize and wheat producing areas by their agro-ecological zones (AEZ). The Food and Agricultural Organization have 18 zones defined on the basis of combinations of soil, landform, and climatic characteristics (Ramankutty et al., 2007). For each AEZ, we examined the distribution of SOC in areas classified as naturally vegetated (e.g. not in urban or agricultural land uses). We did this by stacking two GIS raster layers of SOC (SoilGrids) and land use (Friedl et al., 2010), excluding agricultural and urban land use classifications. We then extracted SOC data for each AEZ using a shape file outlining the geographical extent of each AEZ (Ramankutty et al., 2007). Examining the distribution of SOC across each AEZ, we identified targets based on the mean SOC value within each zone. All but four zones had means greater than 2% SOC, so we set target values for those zones at 2%. Mean SOC concentrations were lower for the more arid zones and so we set those targets to 1% for AEZ 1 and 1.5% for AEZ zones 2, 3, and 7. These targets were in line with recent quantitative assessments based on similar climatic classifications. For instance, recent analysis of global SOC concentrations across globally defined Ecoregions shows mean values of SOC at or greater than 2% for all regions except land classified as desert and xeric shrubland (Stockmann et al., 2015).

Prior to our global extrapolations, we performed a suite of data checks. We wanted to ensure that global yields predicted using our regression model were comparable to those from EarthStat. These checks helped validate the strength of our extrapolations. Firstly, we explored the range of variation in variables from experimental data used to generate our model as well as the range of global variation in variables we project across. The range of our regressors encompasses the range of global variation, except for aridity, in which case 4.6% percent of our projections fall in grids that have axis conditions outside of our range of measurements. These values fall in extremely arid systems, with aridity values of less than 0.1. In these extremely arid zones, we do make a point to use lower target SOC values, recognizing that achieving 2% SOC in these very arid areas is not very likely. Secondly, using our regression model to predict global yields for both maize and wheat (separately), we first removed all values from the analysis that had predicted yields of less than 0 because negative yields are not possible. This amounted to 0.004% of the total predictions for maize and 0.15% for wheat. For clarification, we refer to predictions from our regression model as “predicted” or “model-predicted.” We then calculated the proportional difference between model-predicted and globally gridded yield data from EarthStat. We dropped all cells for which the proportional difference between predicted and gridded data was >3-times. This threshold represents the mean ± half of the standard deviation for the distribution of the proportional difference between predicted and EarthStat yield data. This amounted to 14% of cells for maize and 7% for wheat. The mean proportional difference between predicted and gridded data was 0.85±0.91 for maize (Fig. S4b) and 0.45±0.87 for wheat (Fig. S5b). The correlation between predicted and gridded data was r=0.73 for maize (Fig. S4c) and r=0.38 for wheat (Fig. S5c). We also visualized overlap in the distribution of model-predicted and gridded data. Model-predicted maize yield had a global mean of 4.66±1.84 t ha^{-1} and EarthStat had a global mean of 3.34±2.62 t ha^{-1} (Fig. S4a). Model-predicted wheat yield had a global mean of 3.18±1.66 t ha^{-1} and EarthStat had a global mean of 2.43±1.58 t ha^{-1} (Fig. S5a).

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

After the data checks, we then used our model to extrapolate global yield potentials of maize and wheat given increases in SOC. We masked EarthStat production and cultivated area data layers for maize and wheat for cells that had SoilGrids SOC concentrations of >2%. We compared the subsetted data (i.e. cultivated lands with < 2% SOC) with the original data layers to determine the fraction of global maize and wheat production and cropland that is on soils with less than 2% SOC. We used this subsetted data along with our regression model to predict yields at current SOC levels. As stated above, we used EarthStat, ISRIC SoilGrids, and CGIAR-CSI data layers to fill in the values for each of the factors in our regression model. This new data layer was used as a baseline with which to compare to potential gains in yield with an increase to SOC target values. This created a second data layer with model-predicted yields given an increase in SOC. We calculated the percentage increase in yield between these two layers (the baseline and the improved-SOC layer) and multiplied this by EarthStat yield and production data to determine potential gains in maize and wheat yields and production (Table 2). We then used EarthStat yield gap data to see how such an increase in SOC would reduce projected yields gaps. Using the new yield data layer (with yields at SOC target values), we calculated the proportion of EarthStat yield gaps that was reduced for both maize and wheat.

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

Data availability

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

Author contributions

EEO, MAB, and SAW conceived of the study. EEO and SAW performed data analysis. EEO wrote the first draft of the manuscript. All authors contributed to data interpretation and paper writing.

Competing Interests

The authors declare that they have no conflict of interest.

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Table 1. Modeled regression coefficients with standard errors, standardized coefficients, and *P* values for our regression model.

Variable	Unstandardized Coefficients	Standardized Coefficients	*P* 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
SOC*N input	0.0039 ± 0.00099	0.96 ± 0.25	0.00010

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

Table 2. Scenarios for increases in yield and reductions in N input with an increase 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

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

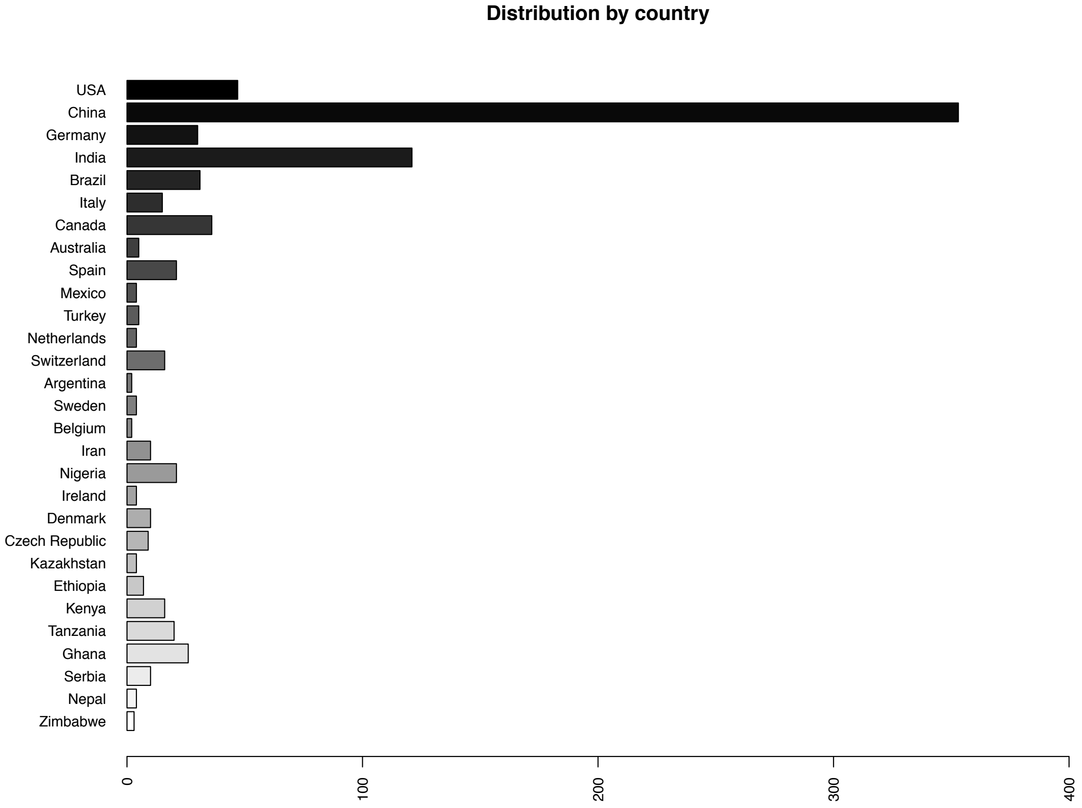

Figure 1: Distribution of data points by country. Countries are ordered by Gross Domestic Product (GDP) in order from largest (top) to smallest (bottom). The dataset used for this study contains a total of 840 individual observations from 29 different countries.

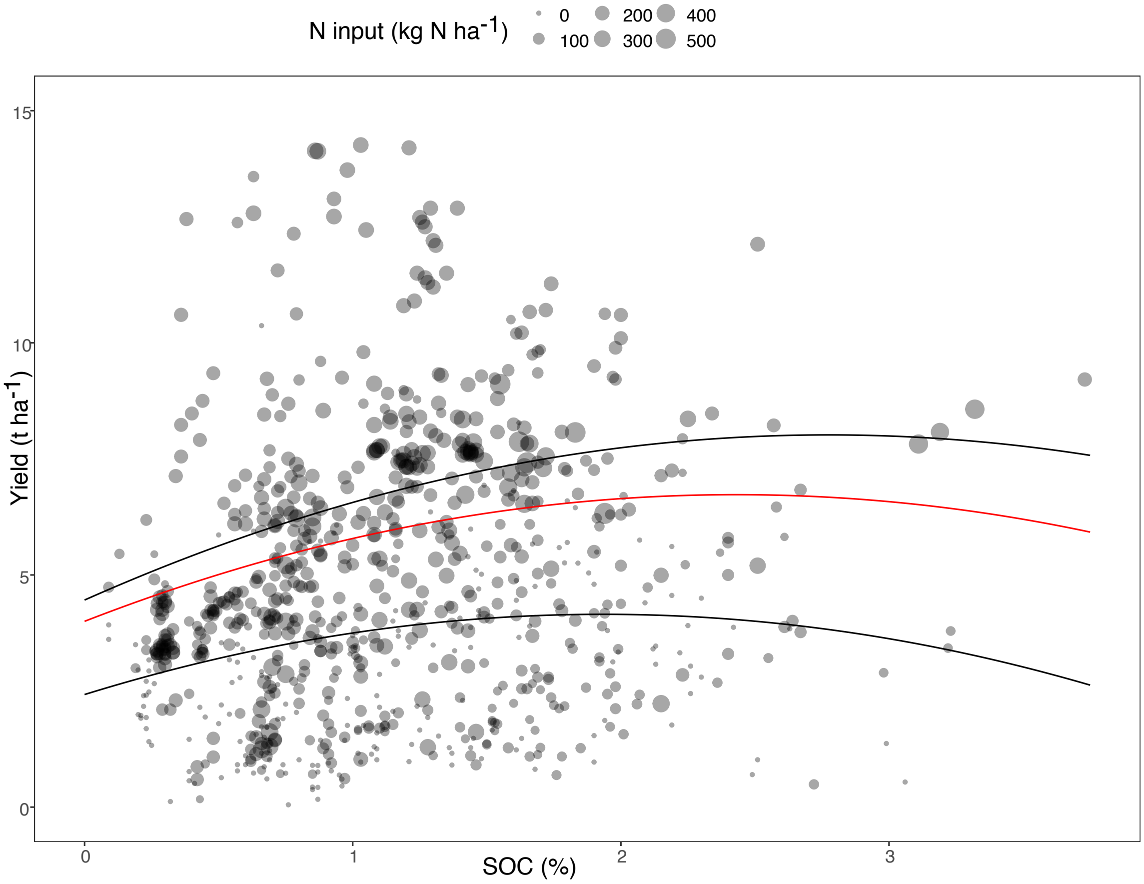

Figure 2: Relationship between SOC and yield of maize for published studies. The regression lines are modeled yields (i.e. effect sizes) for rain-fed (i.e. non-irrigated) maize using observed means of our meta-dataset for aridity, pH, texture, and latitude at different N input rates. We varied SOC (x-axis)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

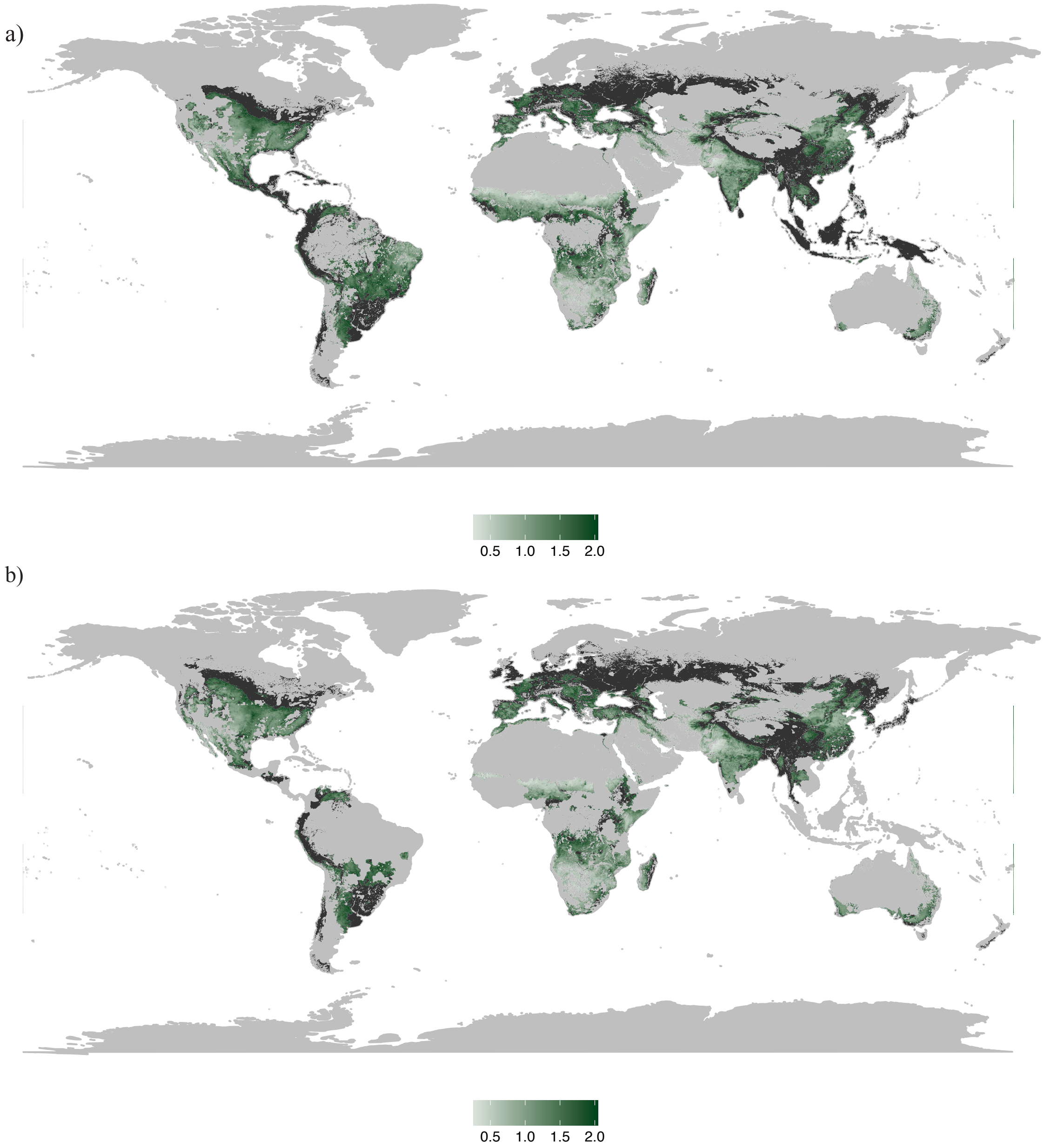

Figure 3: Global maize and wheat lands with less than 2% SOC. Cultivated (a) maize lands and (b) wheat lands on soils with SOC contents less than 2%. Approximately two thirds of all maize (61%) and of all wheat (64%) producing areas are on soils with less than 2% SOC. Black areas on the maps are cultivated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

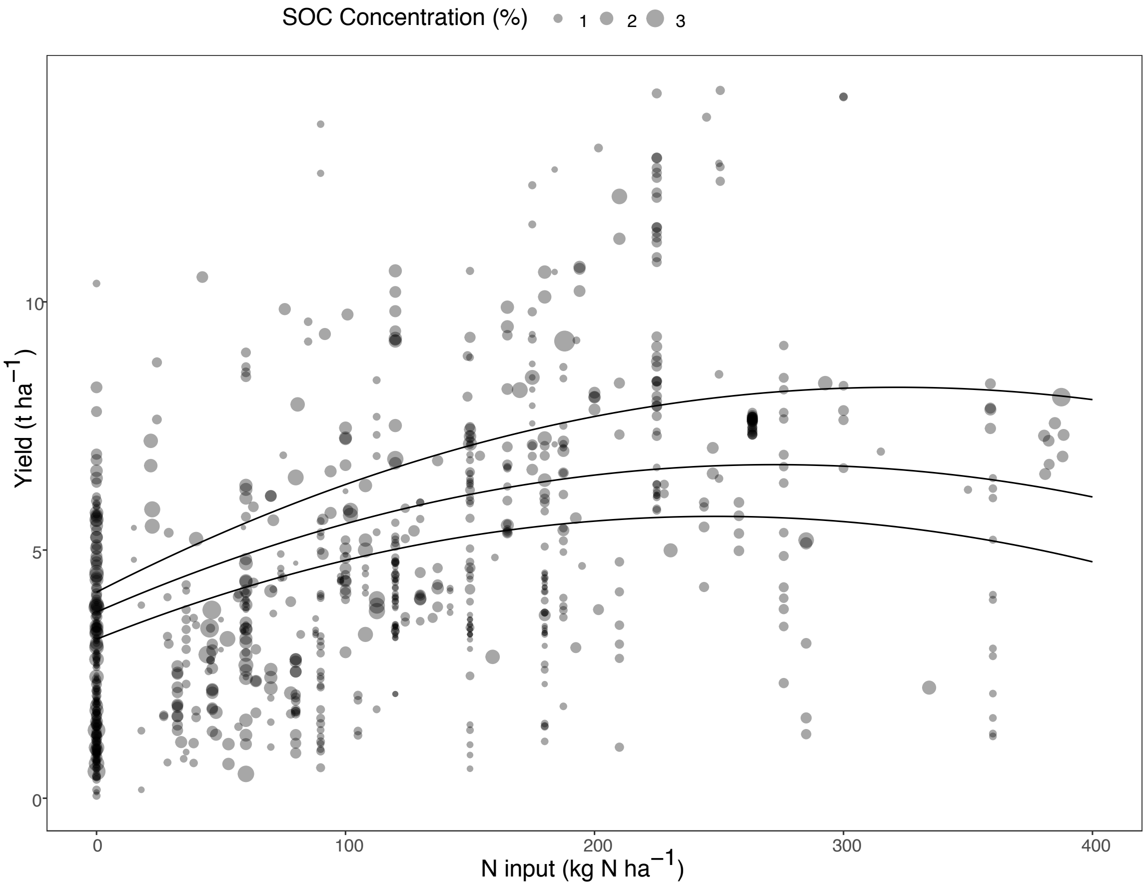

Figure 4: Potential reductions in nitrogen fertilizer with an increase in SOC concentration. The lines on the graph represent varying SOC concentrations, 2.0%, 1.0%, and 0.5% SOC from top to bottom for rain-fed maize. These lines are plotted on top of the observations from our dataset with SOC mapped as a continuous variable across its range from 0.1% (smallest circles) to 3.0% (largest circles). Our model shows that keeping yield constant by increasing SOC contents allows for potentially significant reductions in N input (e.g. the same yield is achievable with 0 N input and 2% SOC, as with 50 kg N ha^{-1} y^{-1} and 0.5% SOC). Recognizing that the 0 N input values may influence the modeled relationship, we analyzed data excluding these values. The qualitative patterns remain the same if the 0 N input values are excluded from the analysis; and while the absolute quantitative patterns shift slightly, the general trends

remain intact.

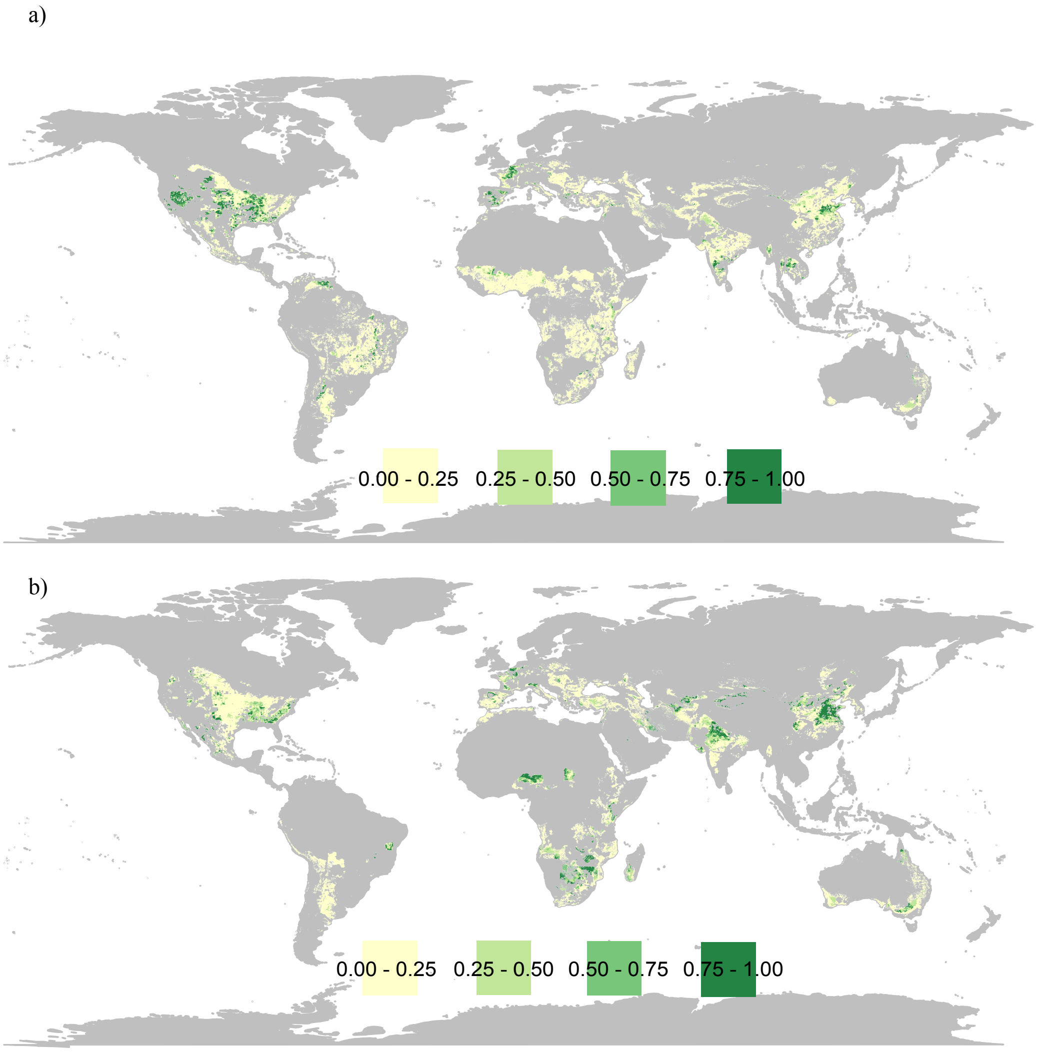

Figure 5: Proportion closure of yield gap for (a) maize and (b) wheat given an increase in SOC concentration to target values for each AEZ (ranging from 1-2%). Modeled gains come from our regression relationship between SOC and yield and applying it to EarthStat yield gap data. Doing so determines the potential increase in yield and therefore projected reductions in yield gaps for maize and wheat.