Soil Organic Carbon and Nitrogen Feedbacks on Crop Yields under Climate Change

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Published August 16, 2018

Agricultural & Environmental Letters

Research Letter

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Core Ideas

- SOC decline, due to increased temperatures, reduces wheat and maize yields globally.
- CO_2 increase to 540 ppm partially compensates yield losses due to increased temperatures.
- Accounting for soil feedbacks is critical when evaluating climate change impacts on crop yield.

Abstract: A critical omission from climate change impact studies on crop yield is the interaction between soil organic carbon (SOC), nitrogen (N) availability, and carbon dioxide (CO_2). We used a multimodel ensemble to predict the effects of SOC and N under different scenarios of temperatures and CO_2 concentrations on maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) yield in eight sites across the world. We found that including feedbacks from SOC and N losses due to increased temperatures would reduce yields by 13% in wheat and 19% in maize for a 3°C rise temperature with no adaptation practices. These losses correspond to an additional 4.5% (+3°C) when compared to crop yield reductions attributed to temperature increase alone. Future CO_2 increase to 540 ppm would partially compensate losses by 80% for both maize and wheat at +3°C, and by 35% for wheat and 20% for maize at +6°C, relative to the baseline CO_2 scenario.

Demand for food production is expected to increase as the world's population rises to 9 billion by 2050 (Wheeler and von Braun, 2013). At the same time, increased climate variability, higher temperatures, and projected frequent droughts and floods will make meeting this demand more difficult (Sundström et al., 2014; FAO, 2016). Understanding the potential impacts and consequences of these climate risks has become a priority for agronomists and policymakers across the globe (Denton et al., 2014; Basso et al., 2015; Basso and Ritchie, 2018).

Agronomic inputs can increase yield and, at the same time, mitigate the climatic and environmental footprint of agriculture (Basso et al., 2015; Basso and Ritchie, 2018). Higher yields typically return a larger amount of crop residues to the soil. It is important to maintain and increase soil organic carbon (SOC) to improving soil-based ecosystem services and the overall sustainability of agricultural systems (Jarecki et al., 2018). While there is a general agreement on soil management practices that can help farmers achieve greater yields, the interactions between management, soil, and climate remain poorly understood (Godfray et al., 2010).

Process-based crop simulation models are important tools to assess and predict the effect of nonlinear interactions between climate, soil, and management on crop productivity and environmental outcomes such as SOC stock, greenhouse gas emissions, and nitrate leaching (Jones et al., 2016). Models have been used extensively to evaluate the effects of rising temperatures and the increased frequency of extreme events on yields, and to design strategies to mitigate and adapt to climate change (Byjesh et al., 2010; Rötter et al., 2011; Donatelli et al., 2012; Asseng et al., 2013, 2014; Moradi et al., 2013; Rosenzweig et al., 2014; Basso et al., 2015; Chenu et al., 2017). There remains, however, a

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Supplemental material is available online for this article.
Agric. Environ. Lett. 3:180026 (2018)
doi:10.2134/ael2018.05.0026

Received 27 May 2018.
Accepted 9 July 2018.
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Abbreviations: AgMIP, Agricultural Model Intercomparison and Improvement Project; SOC, soil organic carbon.

critical omission from all these projections—that changes in SOC occur concurrently with changes in air temperature and CO_2 concentration.

Basso et al. (2015) pointed out that most crop models previously used to predict climate change impact on yields did not account for the concomitant changes in SOC and soil nitrogen (N) content over time (Asseng et al., 2013, 2014; Bassu et al., 2014; Basso et al., 2015), as the models were reinitialized every year to same soil water, N, and C levels to evaluate the effects of climate alone.

Given the importance of SOC and N to crop productivity and the potential for climate change to affect SOC stocks, it is important to rectify this omission, especially since post-COP21 there have been numerous initiatives aimed at increasing SOC as a climate change mitigation measures (e.g., 4 per 1000 initiative in France; https://www.4p1000.org).

We hypothesize that yields will decrease under higher temperature because of the shorter vegetative period (Asseng et al., 2014; Bassu et al., 2014), whereas an increase in CO_2 may partially offset yield decline by increasing CO_2 uptake and water use efficiency (Leakey et al., 2009). We also hypothesize that SOC levels will decline under future climate scenarios because the higher temperatures will decrease biomass and the amount of crop residues returned to the soil. Due to the lower biomass produced, N removal by crops will be lower, and with no reduction in N inputs will leave more fertilizer N available for subsequent loss to the environment. The objective of the study was to evaluate the feedbacks from SOC and N to future maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) yield under climate change.

Materials and Methods

To project soil C sequestration, inorganic N loss, and yield, we used quantitative ensemble modeling to simulate maize and wheat fallow rotations at eight sites around the globe (Australia, Argentina, India, and the Netherlands for wheat; Brazil, France, Tanzania, and the United States for maize) under different scenarios of temperature and CO_2 concentrations. The sites were selected to represent a wide range of soil and growing conditions for these two crops. We simulated each site under different scenarios by testing all combinations of increased local temperature (–3, 0, +3, +6°C) and increased CO_2 concentration (360 and 540 ppm).

We first investigated whether the impact of increased temperature on SOC and N dynamics varied across individual model responses based on the ratio of simulated change in crop yield per degree of temperature increase. We calculated the median of the model ensemble separately for every site. We used the coefficient of variation as an estimator of uncertainty due to model differences. Each ensemble comprised either seven wheat or five maize models with and without the inclusion of SOC dynamics (Supplemental Table S1) to evaluate crop model uncertainties for SOC, yield, soil N, and water under increased temperatures and CO_2. Model simulations were generated for a 30-yr period to quantify the long-term dynamics of SOC, water, and N with the same model protocols as the maize and wheat pilots of the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al., 2013), where the models had previously been validated. The models were run using two distinct modes. In the first (reinitialized mode), we reinitialized SOC, soil N, and soil water annually to the same initial conditions every year, as in the previous AgMIP studies (Asseng et al., 2013; Bassu et al., 2014). In the second (continuous mode), the same models were run continuously for 30 yr, allowing the models to accumulate the effect of years of cultivation on SOC, soil N, soil water, and crop yield. The differences between reinitialized and continuous mode allowed us to understand how yield losses were affected by SOC decline under increased temperature and CO_2 increase compared with yield decline due to temperature increase alone without accounting for the SOC and N loss feedbacks.

Results

On average, our continuous simulations projected a decrease in plant transpiration from −1 to −10 mm per degree of temperature increase due to a shorter growing season, smaller plants, and higher fraction of soil evaporation in total evapotranspiration (Fig. 1). Simulated yields decreased by 0.1 to 0.3 tonnes ha^{-1} for wheat and by 0.2 to 0.6 tonnes ha^{-1} for maize for every degree of local temperature increase. We found a correlation between the simulated soil nitrate content at the end of the season and temperature increase in the different scenarios; more specifically, we found that an increase in temperature determines an increase in soil nitrate content at the end of the season. Values ranged from 2.5 (US maize) to 29.3 (Australian wheat) kg N ha^{-1} (Fig. 1).

We found that uncertainty was at a minimum when we ran the model under the baseline scenario and that uncertainty

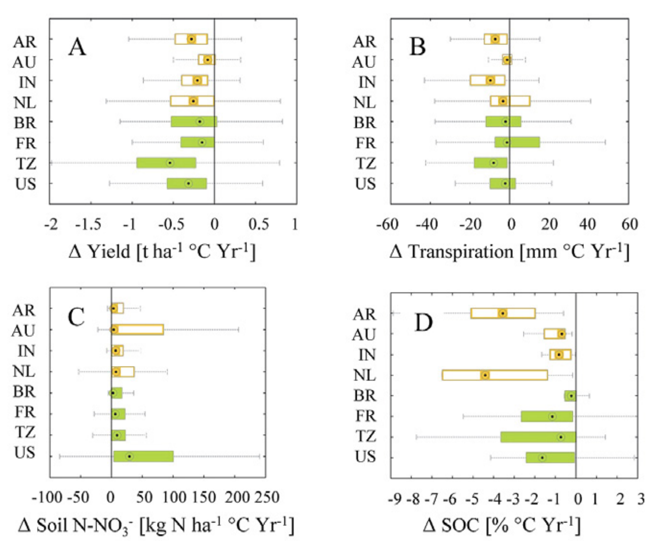

Fig. 1. Modeled average 30-yr changes in (A) yield, (B) transpiration, (C) soil nitrate, and (D) soil organic carbon (SOC) as a function of mean temperature increase over the range 0, +3°C, +6°C, under [CO_2] baseline conditions (360 ppm) for wheat (empty bars: AR, Argentina; AU, Australia; IN, India; NL, the Netherlands) and maize sites (filled bars: BR, Brazil; FR, France; TZ, Tanzania; US, United States). For each boxplot, the black dot represents the median (50th percentile), while the bars span 25th to 75th percentiles and lines span 10th to 90th percentiles of model ensemble results.

increased with increasing temperature. The increase in uncertainties under increased temperature is a result of the different approaches implemented by models to account for the effects of increased temperatures on crop yield and on C and N dynamics. Our results show uncertainties that are of the same order of magnitude and corroborate the findings of earlier models (Asseng et al., 2013; Bassu et al., 2014). All the models agreed on the direction of change (Fig. 1).

The results of our simulations with the inclusion of SOC indicate that increased temperature will reduce future average yield by 13% (+3°C) and 35% (+6°C) for wheat and by 19% (+3°C) and 32% (+6°C) for maize compared with baseline simulations (Table 1). We attribute these yield reductions under increased temperature mainly to the shorter effective growing period due to higher temperature's accelerating plant development. When these yield losses were compared with yields obtained by only increasing temperature without the inclusion of SOC changes, the differences corresponded to additional yield losses of 4% (+3°C) and 5% (+6°C) in wheat and 5% (+3°C) in maize (Supplemental Tables S4, S5).

Table 1. Relative percentage changes of simulated yields (model ensemble) for the different sites and temperature levels compared to the baseline scenario. Negative values depict the inability of [CO_2] to compensate for the loss of yield associated to the concomitant impact of soil organic C decline and temperature increase, while positive values indicate a mitigation of yield losses.

Site†	Temperature change, [CO_2] kept at 360 ppm			
	−3°C	Baseline	+3°C	+6°C
		Wheat		
AR	−4.13	0.00	−12.89	−34.93
AU	−28.20	0.00	−17.74	−41.08
IN	3.07	0.00	−16.58	−47.82
NL	−0.67	0.00	−3.90	−16.86
Avg. wheat	−7.48	0.00	−12.78	−35.17
		Maize		
BR	−12.50	0.00	−5.51	−22.98
FR	−39.27	0.00	−13.44	−20.06
TZ	−4.65	0.00	−38.98	−60.70
US	−6.15	0.00	−18.93	−25.23
Avg. maize	−15.64	0.00	−19.21	−32.24

† AR, Argentina; AU, Australia; IN, India; NL, the Netherlands; BR, Brazil ; FR, France; TZ, Tanzania; US, United States.

Simulated SOC changes on average decreased (relative to initial values) by 0.7 to 4.4% per year and per degree of temperature increase. We found that SOC decreased over time with increased temperatures, and sites with the highest initial SOC content exhibited the largest decrease (Fig. 2; Senthilkumar et al., 2009). Under lower temperature scenarios (baseline and −3°C), as shown in Fig. 2, the French site gained SOC over time due to increased residue inputs (baseline) and/or slower decomposition (−3°C). However, all sites lost SOC with increased temperatures. With a 6°C temperature increase, the reduction in SOC content after 30 yr ranged from 10 to 65% of initial values for wheat and 20 to 45% of initial values for maize. Under these high temperature change scenarios, maize sites that were initially below 1.5% SOC (i.e., Australia, India, Brazil, France, and Tanzania) showed a nonlinear change over time, with smaller relative changes occurring after the first years.

The cumulative difference between N input (mineral N fertilizer applied, N from crop residues) and the N removed from the system (leached N at end of the growing season, annual unused N, N used by the crop) indicate that N losses exceed N input for all combinations of sites and temperature and that N losses increased with temperature (Galloway et al. 2004).

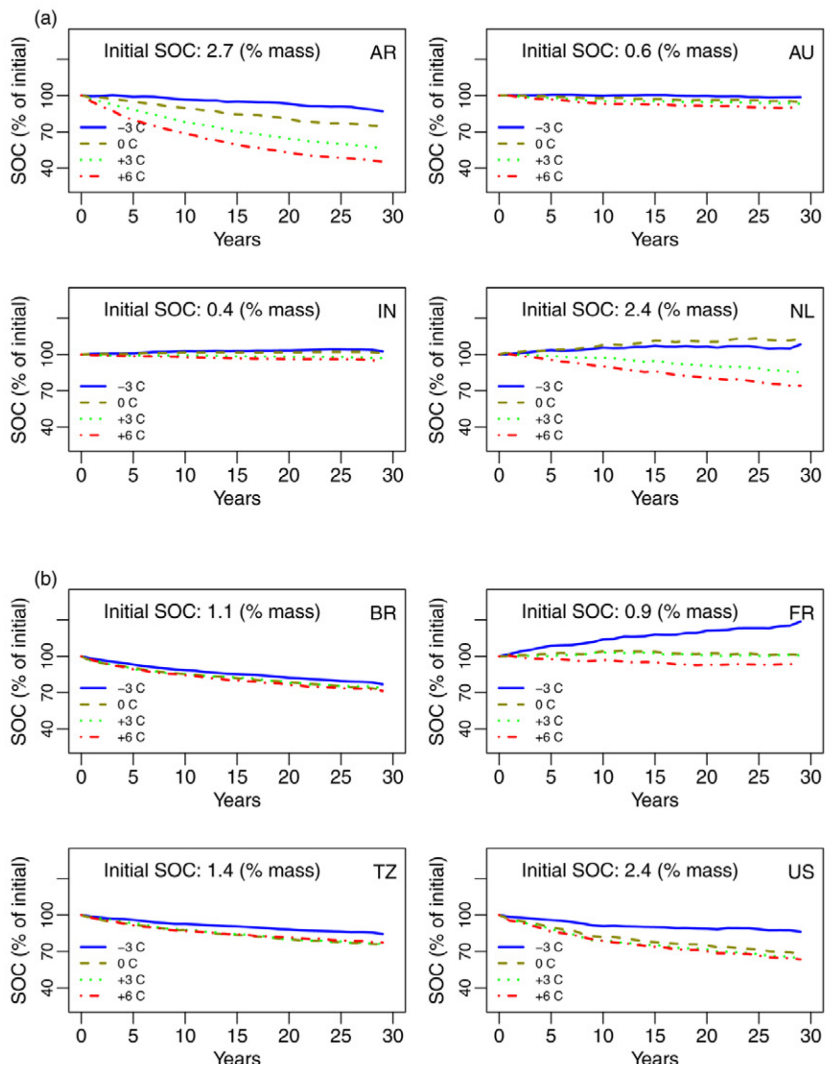

Fig. 2. Simulations of the soil organic carbon (SOC) stocks (0–25 cm) for the different sites under scenarios with different temperature and constant CO_2 concentration (360 ppm). The lines represent the median of the model ensemble predictions for the site and scenario. The site abbreviations (a) for wheat are Argentina (AR), Australia (AU), India (IN), and the Netherlands (NL) and (b) for maize are Brazil (BR), France (FR), Tanzania (TZ), and the United States (US).

Discussion

Our results suggest that reductions in residues returned to the soil, lower SOC levels, and lower soil N availability pose an additional threat to crop yields for key agricultural sites worldwide unless new adaptation strategies (changes in planting dates, new cultivars, N fertilization, disease prevention, and pest control) are implemented.

Future temperature increases are expected to reduce maize and wheat yields; however, results confirmed our hypothesis that the concurrent increments of CO_2 will partially compensate for these losses (Table 2), echoing a large body of literature (Long, 1991; Kimball et al., 2002; Long et al., 2006; Leakey et al., 2009). Increasing CO_2 concentration to 540 ppm reduced losses due to temperature increase by 80% in wheat and by 81% in maize in the +3°C scenario and by 35% (wheat) and 20% (maize) in the +6°C scenario. Lower temperatures have the most detrimental effect for maize cultivated in France (Supplemental Fig. S1); because this site is the coldest among the ones in this study, a −3°C in temperature would prevent the plants from receiving enough degree days to reach maturity (Bassu et al., 2014). On the opposite side, an increase of 6°C would be most detrimental for maize grown in Tanzania (Supplemental Fig. S1), the warmest of our sites (Bassu et al., 2014).

We showed that the predictions from our model ensemble agree with the current paradigm that increased temperatures accelerate crop development and thereby effectively shorten the growing season, consequently lowering yields, biomass production, and crop residues returned to the soil. Under higher temperature scenarios at nonirrigated sites, the removal of N in the form of harvested grain will decline, resulting in higher reactive N losses due to unused soil N (Supplemental Fig. S9, S10, S11).

Results of this study also demonstrate that it is critical to take into account changes occurring in the soil as the result of management, as these changes will shape the design of future strategies to adapt to and mitigate increased climate variability and change globally.

Supplemental Material

Supplemental information is available online. The supplemental material reports the simulations protocols, the multimodel ensemble, and additional details on the uncertainty analysis and on soil organic C and N dynamics under climate change.

Table 2. Relative percentage changes of simulated yields when moving from the baseline scenario ([CO_2] = 360 ppm and ΔT = 0°C) to higher temperature under and [CO_2] of 540 ppm. Negative values depict the inability of [CO_2] to compensate for the loss of yield associated to the concomitant impact of soil organic C decline and temperature increase, while positive values indicate a mitigation of yield losses.

Site†	Temperature change, [CO_2] increased to 540 ppm			
	−3°C	Baseline	+3°C	+6°C
		Wheat		
AR	–	6.29	−2.77	−20.70
AU	–	−2.64	−14.86	−35.80
IN	–	26.91	3.17	−29.94
NL	–	23.10	4.83	−5.03
Avg. wheat	–	13.41	−2.41	−22.87
		Maize		
BR	–	28.97	2.11	−15.26
FR	–	13.11	−5.22	−16.15
TZ	–	−1.77	−15.20	−55.98
US	–	13.82	3.03	−15.35
Avg. maize	–	13.53	−3.82	−25.69

† AR, Argentina; AU, Australia; IN, India; NL, the Netherlands; BR, Brazil ; FR, France; TZ, Tanzania; US, United States.

Conflict of Interest Disclosure

The authors declare no competing financial interests. The views expressed in this paper are the views of the authors and do not necessarily represent the views of the organization or institution to which they are currently affiliated.

Author Contributions

B.B. conceived and motivated the study. B.B., B.D., G.P.R, P.S., J.R.P., and K.P. led the writing of the paper; B.B., B.D., B.M, and I.S. analyzed the data; S.A., F.E., P.M., J.-L. D., and S.B. analyzed and provided the AgMIP wheat- and maize-pilots data; B.B., B.D., B.M, I.S. G.P.R., J.R.P., P.S., K.P., P.R.G. S.A., S.B., C.B., K.J.B., D.C., G.D.S., J.-L.D., F.E., S.G., D.W.H, J.K., P.M., C.N., E.P., D.R., A.C.R., J.S. P.J.T., J.L.H., J.W.J., and C.R. carried out crop model simulations, discussed the results, and contributed to writing the paper.

Acknowledgments

Support was provided by the UKAID for its primary financial support to the Agricultural Model Intercomparison and Improvement Project (AgMIP). Additional funding was provided by USDA–NIFA under awards 2015-68007-23133, 2011-67003-3025, and 2011-68002-30190, the FACCE JPI MACSUR project (031A103B) through the metaprogram Adaptation of Agriculture and Forests to Climate Change (AAFCC) of the French National Institute for Agricultural Research (INRA), and the Swiss National Science Foundation (project number 167689). We thank Anne Stanton and two anonymous reviewers for very helpful comments on an earlier draft.

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