Journal of Environmental Quality SPECIAL SECTION

PREDICTING SOIL ORGANIC CARBON IN AGROECOSYSTEMS UNDER CLIMATE CHANGE

Measurements and Models to Identify Agroecosystem Practices That Enhance Soil Organic Carbon under Changing Climate

Hero T. Gollany* and Rodney T. Venterea

Abstract

Adapting to the anticipated impacts of climate change is a pressing issue facing agriculture, as precipitation and temperature changes are expected to have major effects on agricultural production in many regions of the world. These changes will also affect soil organic matter decomposition and associated stocks of soil organic C (SOC), which have the potential to feed back to climate change and affect agroecosystem resiliency. This special section brings together multiple efforts to assess effects of climate change on SOC stocks around the globe in grassland, pasture, and crop agroecosystems under varying management practices. The overall goal of these efforts is to identify optimum practices to enhance SOC accumulation. In this article, we summarize the highlights of these papers and assess their broader implications for future research to enhance agroecosystem SOC accumulation and resiliency to climate change. Fourteen of the twenty contributions apply dynamic process-based models to assess climate and/or long-term management impacts on SOC stocks, and four papers use statistical SOC models across landscapes or regions. Also included are one meta-analysis and one long-term study. The models applied in this collection performed well when reliable input data were available, underlining the usefulness of modeling efforts to inform management decisions that enhance SOC stocks. Overall, the findings confirm that most agroecosystems have the potential to store SOC through improved management. However, this will be challenging, particularly for dryland agriculture, unless crop yield and crop biomass increase under projected climate change.

Core Ideas

- Maintaining crop yields and increasing cropping intensity will be required to sustain SOC.
- Improving yields and reducing tillage is required to sustain SOC under dryland cropping.
- CQESTR is an effective tool for simulating SOC dynamics to a depth of 1 m.
- Grasslands are likely to sequester more SOC than annual cropping systems.
- Rotational grazing increases SOC vs. continuous grazing in semihumid and humid climates.

J. Environ. Qual. 47:579–587 (2018)
doi:10.2134/jeq2018.05.0213

Received 29 May 2018.
Accepted 18 June 2018.
*Corresponding author (hero.gollany@ars.usda.gov).

Adapting to the anticipated impacts of climate change is a pressing issue facing agriculture. Precipitation and temperature changes are expected to have major effects on agriculture in many regions of the world and therefore an impact on food production for the world's growing population. The impacts of climate change on soil organic C (SOC) stocks are largely unknown, yet understanding the drivers of SOC losses or gains is of critical importance for assessing the potential for C sequestration (Smith, 2008). Better understanding of the management role in regulating SOC dynamics will assist in the development of practices that enhance SOC stocks, as well as increase agroecosystem resiliency under a changing climate. Additionally, critical to this effort are assessments of current SOC stocks and their expected responses to changes in precipitation and temperature, which is the focus of this special section.

Many factors regulate SOC, including inputs of crop residue and organic amendment, soil nutrient status, tillage, landscape position, climate, microfauna, and macrofauna (Jackson et al., 2017). The impacts of climate change on SOC stocks in agroecosystems is highly uncertain due to (i) limited understanding of the magnitude of the feedback from changes in temperature and precipitation, especially for subsoils (Hicks Pries et al., 2017); (ii) the largely unknown nature of the priming effect (i.e., the potential for increased SOC decomposition as a result of adding easily degradable compounds; Van der Wal and de Boer, 2017); (iii) the uncertainty of microbial responses to climate change (Gougoulias et al., 2014) and the time required for microbial communities to adapt to warmer environments (Crowther et al., 2016); (iv) limited empirical data of SOC to a depth of greater than 10 to 30 cm; and (v) the limitation of most process-based models to simulate soil C dynamics within the topsoil depth or one soil layer. Furthermore, measurements of SOC stocks are

---

H.T. Gollany, USDA-ARS Soil & Water Conservation Research Unit, Pendleton, OR 97801; R.T. Venterea, USDA-ARS, Soil & Water Management Research Unit, St. Paul, MN 55108, Dep. of Soil, Water, and Climate, Univ. of Minnesota, St. Paul, MN 55108.
Assigned to Technical Editor Tsutomu Ohno.

Abbreviations: CC, continuous corn; CCSS, corn–corn–soybean–soybean; COAA, corn–oats–alfalfa–alfalfa; CS, corn–soybean; CT, conventional tillage; CTB-F, conventional-till barley–fallow; DNDC, DeNitrification-DeComposition; EPIC, Environmental Productivity Integrated Climate; FAF, fulvic acid fraction; GWR, geographically weighted regression; MIR, mid-infrared; MLR, multiple linear regression; MONICA, Model for Nitrogen and Carbon in Agro-Ecosystems; NPP, net primary production; NSI, National Soil Inventory; NT, no-till; NTB-F, no-till barley–fallow; NTB-P, no-till barley–pea; NTCB, no-till continuous barley; PET, potential evapotranspiration; POM-C, particulate organic matter carbon; SOC, soil organic carbon; RCP, representative concentration pathway; SOM, soil organic matter; W–F, wheat–fallow; W–F/MP, wheat–fallow under moldboard plow tillage; W–W/NT, continuous wheat under no-till.

complicated by the spatial and temporal variability of SOC and soil bulk density measurements, and by soil sample processing, all of which affect the accuracy of reported SOC stocks (Gollany et al., 2012).

Studies on the effects of temperature and soil water content on organic matter decomposition have been performed mostly in laboratory incubation experiments and in fields for a given ecosystem type, but few extended beyond 1 to 2 yr (Harmon et al., 2009) until recently (Harmon et al., 2009; Gregorich et al., 2017). Using 5 yr of field data and a kinetic model, Gregorich et al. (2017) projected that the time required to decompose 90% of the plant residue (including the recalcitrant fraction) would be reduced by 1 to 2 yr depending on temperature of the site. Although increased temperature increases microbial mineralization or decomposition of soil organic matter (SOM), it might also increase plant production, consequently increasing C inputs (Keestrea et al., 2016). Increases in CO_2 are mainly attributed to the combustion of fossil fuels and land use change, especially deforestation (Pachauri et al., 2014), but soil respiration from decomposed SOM and the flux of respired CO_2 by soil fauna and belowground roots represents the second-largest terrestrial C flux (Raich and Potter, 1995). Rising atmospheric CO_2 concentration could have a large impact on plant growth and net primary production (NPP) of plant biomass. However, it is unclear whether increases in NPP will translate into increased SOC storage. Free-air CO_2 enrichment studies often observe no change in SOC despite increased NPP, possibly due to increased loss rates of C inputs or increased decomposition of SOC through the priming effect (Van der Wal and de Boer, 2017). Crop models suggest that positive fertilization effects of CO_2 would offset the negative effect of rising temperature and lowering soil water content (Hatfield et al., 2011; Webber et al., 2017). However, a challenge is to understand the interactions among plant growth and development, CO_2, temperature, and precipitation (Hatfield et al., 2011).

Overview of the Special Section

This collection of 20 papers was inspired by the USDA-ARS GRACEnet cross-location database and the desire to improve current and future SOC estimates. Most of these papers fall into two general categories (Table 1): (i) dynamic, process-based models that evaluate SOC stocks under changing climate and/or varying management (14 papers), and (ii) statistical models that assess SOC stocks across landscapes and regions (four papers). In addition, one paper reports a meta-analysis of SOC stocks in response to differing grazing regimes, and another reports the results of a long-term field experiment evaluating SOC pools under various management. We provide a brief introduction to each topic under each subheading, followed by a concise summary of the objectives and contributions of these papers.

Before highlighting the contributions of this collection, we first present a generalized overview to illustrate key concepts and components under study. By the term "climate," we refer mainly to temperature and precipitation but recognize that other factors, including radiation, humidity, and wind, can also be important in regulating SOC stocks. Climate is the key driver of agroecosystem function and is therefore a key driver of SOC dynamics in at least three different respects, as shown in Fig. 1. First, climate factors largely regulate the potential for NPP of plant biomass, which, from the perspective of the soil system,

Table 1. List of papers in this special section.

Reference	Title
	Dynamic process-based models to evaluate SOC† stocks
Cavigelli et al. (2018)	Simulated Soil Organic Carbon Changes in Maryland are Affected by Tillage, Climate Change, and Crop Yield
Chu et al. (2018)	A Modeling Framework to Evaluate the Impacts of Future Climate on Soil Organic Carbon Dynamics
Crow and Sierra (2018)	Dynamic, Intermediate Soil Carbon Pools May Drive Future Responsiveness to Environmental Change
Dell et al. (2018)	Implications of Observed and Simulated Soil Carbon Sequestration for Management Options in Corn-based Rotations
Gollany and Polumsky (2018)	Simulating Soil Organic Carbon Responses to Cropping Intensity, Tillage, and Climate Change in Pacific Northwest Dryland
Jarecki et al. (2018)	Long-term Trends in Corn Yields and Soil Carbon under Diversified Crop Rotations
Jebari et al. (2018)	Modeling Regional Effects of Climate Change on Soil Organic Carbon in Spain
Nash et al. (2018a)	Simulated Soil Organic Carbon Responses to Crop Rotation, Tillage, and Climate Change in North Dakota
Nash et al. (2018b)	Simulated Soil Organic Carbon Response to Tillage, Yield, and Climate Change in the Southeastern Coastal Plains
Nash et al. (2018c)	CQESTR-Simulated Response of Soil Organic Carbon to Management, Yield, and Climate Changes in the Northern Great Plains Region
Robertson et al. (2018)	Climate Change Impacts on Yields and Soil Carbon in Row Crop Dryland Agriculture
Sakrabani and Hollis (2018)	Evaluating Changes in Soil Organic Matter with Climate Using CENTURY in England and Wales
Wienhold et al. (2018)	Soil Carbon Response to Projected Climate Change in the US Western Corn Belt
Jones et al. (2018)	Perennialization and Cover Cropping Mitigate Soil Carbon Loss from Residue Harvesting
	Statistical models to assess SOC stocks
Costa et al. (2018)	Mapping Soil Organic Carbon and Organic Matter Fractions by Geographically Weighted Regression
Flathers and Gessler (2018)	Building an Open Science Framework to Model Soil Organic Carbon
Reyes Rojas et al. (2018)	Projecting Soil Organic Carbon Distribution in Central Chile Under Future Climate Scenarios
Vågen et al. (2018)	Spatial Gradients of Ecosystem Health Indicators across a Human Impacted Semiarid Savannah
	Meta-analysis
Byrnes et al. (2018)	A Global Meta-Analysis of Grazing Impact on Soil Health Indicators
	Long-term field experiment
Sherrod et al. (2018)	Soil Carbon Pools in Dryland Agroecosystems as Affected by Several Years of Drought

† SOC, soil organic C.

is the main source of SOM in the form of above- and belowground plant residues. Second, climate is a main driver of several biological, chemical, and physical processes occurring in soil that regulate the net accumulation or depletion of SOM. These processes include (i) decomposition or mineralization, which transforms the plant macromolecules into microbial byproducts having varying degrees of stability and potentially includes CO_2; (ii) chemical or biochemical processes that result in the formation of secondary organic compounds and/or organo-mineral complexes that contribute to soil aggregate formation that can lead to greater stabilization of SOC; and (iii) physical processes, including erosion or deposition, and dissolved organic C leaching (Mertens et al., 2007), which can result in net loss of SOM from or input into a given land area or from outside its boundaries. Third, climate can also influence and constrain the range of feasible management options within a given agroecosystem, including the specific types of crops that are adapted to the climate regime and their yield potential, the feasibility of overwinter or year-round crops and/or cover crops, and the need for and availability of irrigation. In addition to setting constraints on management options, climate can also determine the effectiveness of practices such as tillage, fertility, or residue management for enhancing crop biomass production and/or SOC accumulation. Management decisions under a changing climate have the potential to affect both the magnitude of C inputs to the system and the degree to which SOC-regulating processes act to retain or transform those inputs within the soil profile. Finally, the net accumulation or depletion of SOC stocks has the potential to feed back, either positively or negatively, to biomass production and thereby to affect agroecosystem resiliency in the face of a climate that is becoming increasingly variable (Hatfield et al., 2011).

The underlying assumption of the efforts reported in this collection is that a better understanding of climate and management impacts on SOC dynamics will lead to development of practices that increase, or at least maintain, SOC stocks, buffer against the impact of climate change on crop production, and build greater resiliency to drought and other stresses that may become more frequent and extreme under future climate conditions.

Applying predictive models to the above climate–plant–management-soil system allows us to address key questions, including: How will changes in precipitation and temperature impact SOC stocks in different regions and systems if current management is maintained under a business as usual approach? Which management modifications will maintain or increase SOC accumulation under climate change for a given system, and how do effects of these management modifications depend on any positive or negative changes in yield potential resulting from climate change? There is a critical need for answers to these questions as agriculture adapts to and, in turn, potentially influences a changing climate over the coming decades.

Process-based Models to Evaluate Soil Organic Carbon Dynamics

Fourteen contributions to this special section applied dynamic process-based models to assess the effects of climate and/or management on SOC dynamics. As described below, seven papers used the CQESTR model, whereas other models included were DeNitrification-DeComposition (DNDC), DayCent, CENTURY, RothC, the Model for Nitrogen and Carbon in Agro-Ecosystems (MONICA), the Environmental Productivity Integrated Climate (EPIC) model, and a detailed mathematical model of soil C dynamics devised by Crow and Sierra (2018).

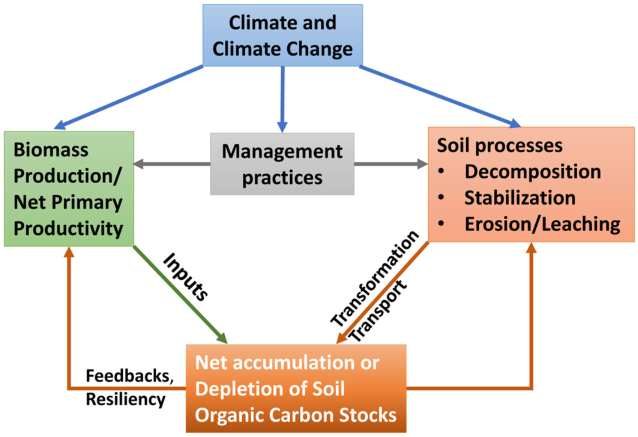

Fig. 1. The climate–plant–management–soil system that regulates soil organic C stocks.

Cavigelli et al. (2018) used SOC data from the long-term Farming Systems Project and the CQESTR model to examine the impact of projected climate change on SOC to 50-cm soil depth for grain cropping systems in the Mid-Atlantic United States. Since future crop yields are uncertain, they simulated five scenarios with differing yield levels for a 3-yr crop rotation: corn (*Zea mays* L.)–rye (*Secale cereal L.*)/soybean [*Glycine max* (L.) Merr.]–winter wheat (*Triticum aestivum* L.)/soybean. For a baseline scenario CQESTR predicted an increase in SOC of 0.014 and 0.021 Mg C ha^{-1} yr^{-1} in conventional tillage (CT) and no-till (NT), respectively, without change in climate or crop yields. Predicted climate change alone resulted in an SOC increase of only 0.002 Mg ha^{-1} yr^{-1} in NT and a decrease of 0.017 Mg ha^{-1} yr^{-1} in CT. Crop yield declines of 10 and 30% by 2052 led to SOC decreases between 2 and 8% compared with SOC stocks in 2012. Increasing crop yield by 10 and 30% was sufficient to raise SOC by 2 and 7%, respectively, above the climate-only scenario under both CT and NT from 2012 to 2052, indicating that the negative impact of climate change on SOC levels could be mitigated by increasing crop yield if improved varieties or technology were to be developed for the southern Mid-Atlantic region of the United States.

Chu et al. (2018) used projected precipitation and air temperature, collected from 32 global circulation models, to estimate local-scale climate variables and cropping operation schedules. The local-scale parameters and cropping operations were input into the process-based MONICA to quantify the impacts of future climate on SOC dynamics for three rotation experiments at the University of Illinois Crop Science Research Centers. Results indicated that SOC in the upper 30-cm depth was expected to decrease by 43 to 70% from 2015 to 2075, with an uncertainty range of ~15% due to variations in climate prediction. The SOC in corn–soybean (CS) rotation schemes did not vary significantly from continuous corn (CC) rotation under the same tillage. High precipitation and warm air temperature, which affected soil processes and crop operation schedules, can decrease SOC stocks. This study provided a platform to facilitate the prediction of SOC and uncertainties in the climate data that drive SOC dynamics.

Crow and Sierra (2018) sought to understand the size and responsiveness of dynamic, intermediate C pools using a combination of field and laboratory experiments and detailed process modeling. They measured soil C dynamics under elevated temperature over time in a soil incubation study and measured physical fractionation of different soil C pools via density and sonication. Three-pool transfer modeling revealed (i) small pools of readily available microbial substrate that were responsive to temperature, time since cultivation, and inputs; and (ii) larger, kinetically slow-cycling pools that were more indicative of long-term changes in C stock and were strongly associated with changes in physical fractions. Combining the sensitivity of readily available microbial substrate with three-pool transfer model of physical fractions revealed that dynamic transfers of inputs occurred between the free organic and aggregate-protected fractions, and from these fractions to the mineral-associated fraction. Increased C transfer rates outweighed elevated decomposition losses under 5°C-elevated temperature. They concluded that the complexity of soil response to change must be incorporated into soil C simulation models to more effectively monitor agroecosystems response for climate change mitigation and management plans.

Dell et al. (2018) monitored SOC changes to the 1-m depth in a study in the northeastern United States (Pennsylvania) that included a bioenergy rotation, consisting of three seasons of corn followed by one season of soybean followed by four seasons of alfalfa (*Medicago sativa* L.), which was compared with continuous cropping (8 yr) of switchgrass (*Panicum virgatum* L.), and reed canarygrass (*Phalaris arundinacea* L.). They used the CQESTR model to predict the influence of cropping system (with and without climate change), tillage, manure, cover cropping, and corn stover removal in typical dairy forage (silage corn–alfalfa) or grain CS rotations, and reed canarygrass. Significant correlation ($p < 0.001$) between simulated and measured data indicated that CQESTR is a powerful tool for evaluating management impacts on SOC stocks to the 1-m depth. Measured SOC increased by 0.4, 0.8, and 1.1 Mg C ha^{-1} yr^{-1} in the bioenergy rotation, switchgrass, and reed canarygrass, respectively. Simulation of a dairy forage rotation with CQESTR indicated that an increase of ~0.2 Mg ha^{-1} yr^{-1} is expected over 40 yr even with intermittent tillage, because of the multiple years of perennial alfalfa. Climate change and yield increase had little impact on predicted SOC over a 20-yr period, suggesting that this regime is stable with respect to SOC over this timeframe.

Gollany and Polumsky (2018) collected samples to the 1-m depth and used CQESTR to predict the management that best increased SOC under changing climate in continuous wheat under NT (W–W/NT), wheat and sorghum [*Sorghum bicolor* (L.) Moench] × sudangrass (*Sorghum sudanese* L.) under NT, wheat–fallow (W–F) under sweep tillage, and W–F under moldboard plow (W–F/MP) tillage cropping systems. Twenty scenarios were simulated for each cropping system with four climate projections and five crop-yield scenarios. Measured and simulated SOC were significantly ($p < 0.0001$) correlated ($r = 0.98$). Predicted SOC changes ranged from −12.03 to 2.56 Mg C ha^{-1} in the 1-m soil depth for W–F/MP and W–W/NT, respectively. Only W–W/NT sequestered SOC, at a rate of 0.06 Mg C ha^{-1} yr^{-1}, under current crop yields and climate. Under climate change and yield scenarios, W–W/NT lost SOC except when there was a 30% wheat yield increase for 40 yr. Predicted SOC increases in W–W/NT were 0.018, 0.029, and 0.022 Mg C ha^{-1} yr^{-1}under the Oregon Climate Assessment Report for low (Representative Concentration Pathway [RCP] 4.5; Stocker et al., 2013) emissions and high (RCP 8.5) emissions and the Regional Climate Model version 3 with boundary conditions from the Third Generation Coupled Global Climate Model (RCM3-CGCM3), respectively, with 30% yield increases. Assuming yields increases are possible, continuous NT cropping would increase SOC and resiliency to lessen the impact of extreme weather.

Jarecki et al. (2018) modified a process-based biogeochemical model, DNDC, to predict corn yield and SOC dynamics under future climate scenarios, for long-term trials of CC and corn–oats (*Avena sativa* L.)–alfalfa–alfalfa (COAA) at Woodslee, ON; and CC, corn–corn–soybean–soybean (CCSS), corn–corn–soybean–winter wheat, corn–corn–soybean–winter wheat + red clover (*Trifolium pratense* L.), and corn–corn–alfalfa–alfalfa at Elora, ON. The revised DNDC model improved yield estimates for diversified rotations at Elora and resulted in higher SOC for COAA at Woodslee. Predicted and observed SOC agreed for simple rotations (CC or CCSS) at both sites. Increases in corn yield for RCP8.5 in relation to RCP4.5 were predicted for Woodslee due to the positive influence of increased atmospheric CO_2. They concluded that diversified rotations mitigated crop water stress and increased yields and SOC content under climate scenarios compared with simpler rotations. The results suggest that diversified rotations will be more resilient and SOC could increase under the impacts of future climate change compared with CC or CCSS rotations.

Jebari et al. (2018) estimated the changes in SOC at the regional level under climate change conditions in agricultural land in Spain using the RothC model. Four different Intergovernmental Panel on Climate Change (IPCC) scenarios (CGCM2-A2, CGCM2-B2, ECHAM4-A2, and ECHAM4-B2) were used to simulate SOC changes during 2010 to 2100. Although RothC predicted a general increase in SOC stocks in Spain by 2100 under all climate change scenarios, some losses of SOC occurred and responses differed among climate change scenarios. The SOC sequestration rates were smaller than those under baseline conditions. The greatest losses of C stocks were predicted under ECHAM4 (highest temperature rise and precipitation drop) scenarios and for rainfed and certain woody crops (lower C inputs). Under climate change conditions, management practices including NT for rainfed crops and vegetation cover for woody crops were predicted to increase SOC stock by 0.47 and 0.35 Mg C ha^{-1} yr^{-1}, respectively. Cover crops and NT doubled SOC stocks, and irrigated crops had the largest SOC stocks.

Nash et al. (2018b) elucidated the impact of intensive tillage, low-residue crops, crop yields, and projected climate change on SOC in the top 15 cm of a loamy sand soil under CT or conservation tillage using CQESTR, a process-based C model, in the southeastern Coastal Plains region in South Carolina. Conservation tillage was predicted to increase SOC by 0.005 to 0.032 Mg C ha^{-1} yr^{-1} for six of eight crop rotations compared with CT by 2033. The addition of a winter crop (rye or winter wheat) to a corn–cotton (*Gossypium hirsutum* L.) or CS rotation increased SOC by 0.073 to 0.128 Mg C ha^{-1} yr^{-1}. CQESTR predicted an increase in SOC of 0.014 Mg C ha^{-1} yr^{-1} with continued increase in crop yields following historical trends, whereas climate change was unlikely to have a significant impact on SOC except in the corn–cotton or CS rotations, where SOC decreased up to 0. 008 Mg C ha^{-1} yr^{-1} by 2033. CQESTR predictions indicated that soil C saturation may be reached in high-residue rotations, and that increasing SOC deeper in the soil profile will be required for long-term SOC accretion beyond 2030 as long as conservation tillage and cover crops together with high-residue-producing corn are used in these loamy sand soils.

Nash et al. (2018a) simulated SOC dynamics in the top 30 cm in a 20-yr field study using a process-based C model, CQESTR, to predict the impact of changes in management, crop production, and climate change, and to identify the best dryland cropping systems to maintain or increase SOC stocks under projected climate change in central North Dakota. Intensifying crop rotations was predicted to have a greater impact on SOC stocks than minimum tillage or NT. Converting from a minimum tillage spring W–F rotation to an NT continuous spring wheat rotation increased annualized biomass additions by 2.77 Mg ha^{-1} (82%) and SOC by 0.220 Mg C ha^{-1} yr^{-1}. Climate change is predicted to have a minor impact on SOC relative to crop rotation management, and the addition of another spring wheat or rye crop would have a greater effect on SOC stocks than conversion from minimum tillage to NT or climate change, under the assumption that crop production will stay at the 1993 to 2012 average yield.

Nash et al. (2018c) used the CQESTR model to simulate SOC dynamics and identified the best dryland cropping systems to increase SOC under projected climate change in eastern Montana. Cropping sequences were CT barley (*Hordeum vulgare* L.)–fallow (CTB-F), NT barley–fallow (NTB-F), NT continuous barley (NTCB), and NT barley–pea (*Pisum sativum* L.) (NTB-P), with 0 and 80 kg N ha^{-1} applied to barley phase of the rotation. Under current crop production, climatic conditions, and averaged N rates, SOC in the top soil (0–10-cm) was predicted to increase by 0.058, 0.060, 0.099, and 0.152 Mg C ha^{-1} yr^{-1} by 2045 for CTB-F, NTB-F, NTB-P, and NTCB, respectively. When projected climate change and the current positive US barley yield trend were accounted for in the simulations, SOC accretion was projected to increase by ~0.023 Mg C ha^{-1} yr^{-1}. Elimination of fallow and N fertilizer management had the greatest impact on SOC stocks in the top soil as of 2045 in the Northern Great Plains.

Robertson et al. (2018) used long-term experimental data and the DayCent process-based model for three sites with various climates and soil conditions to examine the impacts of two climate change scenarios (moderate warming, RCP4.5; and high warming, RCP8.5) on yields and soil C dynamics in row crops in the High Plains of Colorado. They predicted a dryland yield decline for all crops and up to 50% for wheat, with small changes after 2050 under RCP4.5 and continued losses to 2100 under RCP8.5. Continuous cropping had the highest average productivity and C sequestration rates of 0.078 Mg C ha^{-1} yr^{-1} from 2015 to 2045 under RCP4.5, and any increase in soil C for cropped rotations was realized by 2050. However, grassland treatments increased soil C up to 69% through 2100, even under RCP8.5. Reduced frequency of summer fallow can increase annualized yields and SOC. Reducing fallow periods without live vegetation from dryland agricultural may enhance the resilience of these systems to climate change while also increasing soil C storage and reducing CO_2 emissions.

Sakrabani and Hollis (2018) used weather data for 1978 to 2000 from the UK Meteorological Office, soil property data derived from the National Soil Inventory (NSI), and the UK Climate Impacts Program of 2002 (including four emissions scenarios for the 2020s, 2050s, and 2080s) with the CENTURY model to predict changes in SOC between 1978 and 2000. The resampled NSI data for 1994 to 2000 were used in validating the predicted changes in SOC stocks. Simulation results from the CENTURY model were statistically unacceptable for C-rich and water-logged soils. Model predictions improved and were statistically acceptable for all ecosystem types when these soil types were omitted from the database. Model efficiency decreased in the following order: seminatural grassland (0.63) > woodland (0.27) > arable land (0.08) > managed grassland (0.02). CENTURY correctly predicted the direction of SOC changes but underpredicted the magnitude of change. Predicted reductions in SOC were 0.27 to 0.39% for managed grassland and 0.03 to 0.05% for arable land under climate change. The predicted changes between scenarios were small except for loss of 1.54% SOC in seminatural grassland under the high-emissions scenario.

Wienhold et al. (2018) used CQESTR and a long-term tillage study (1986–2015) conducted in the western US Corn Belt (Nebraska) to simulate changes in SOC stocks (0–30 cm) of CC and CS rotation under disk, chisel, ridge, and no tillage using projected growing season conditions for the next 50 yr. Model output was validated using measured changes in SOC from 1999 to 2011. The validated model was used to estimate changes in SOC over 17 yr under climatic conditions projected for 2065 under two scenarios: (i) crop yields increasing at the observed rate from 1971 to 2016, or (ii) crop yields reduced due to negative effects of increasing temperature. As yield increased, SOC in the 0- to 30-cm depth increased under NT CC but was unchanged under NT CS and ridge tillage regardless of cropping system. Under chisel and disk tillage, SOC declined regardless of cropping system. With declining yields, SOC decreased regardless of tillage or cropping system. Results highlighted the interaction between genetics and management in maintaining yield trends and SOC.

Jones et al. (2018) assessed the efficacy of increasing the duration of crop soil cover through cover crop or double cropping to offset residue-harvest-induced SOC losses by using the EPIC model with published long-term data across sites in the US Midwest. Model data integration was used to calibrate and evaluate model suitability, which was reasonable (R^2 = 0.97 and 0.63 for SOC stock and yield, respectively). Although climate change effects were not evaluated directly in this study, long-term simulations indicated the capacity of rye crop incorporation into CC and CS rotations to offset the SOC losses induced from residue harvesting by 21.2 and 38.3% of available stover, respectively. In addition, converting 20.4% of CS land to miscanthus (*Miscanthus* ×*giganteus* J.M. Greef & Deuter ex Hodkinson & Renvoize) or 27.5% of land to switchgrass could offset the SOC impacts of harvesting 60% of stover from the remaining CS lands. They concluded that adoption of such measures would affect the life-cycle consequences of residue-derived biofuels and expand Midwestern estimates of sustainable cellulosic feedstock production capacity.

Statistical Models to Assess Soil Organic Carbon Stocks

Four papers in the section (summarized below) applied statistical models to develop maps of current SOC stocks across different geographical regions and spatial scales, including a 15-km^2 area in southeastern Brazil (Costa et al., 2018), two different 100-km^2 regions in South Africa (Vågen et al., 2018), a 100,000-km^2 region of the northwestern United States (Flathers and Gessler, 2018), and a 150,000-km^2 region in central Chile (Reyes Rojas et al., 2018). Two of these efforts (Flathers and Gessler, 2018; Reyes Rojas et al., 2018) used random forest statistics with the *scorpan* modeling approach of McBratney et al. (2003), which uses seven categories of input data to make SOC predictions: known soil attributes, climatic values, organisms present, relief, parent material, age, and spatial location. In addition to assessing current SOC stocks, Reyes Rojas et al. (2018) extended their effort to assessing future climate effects.

Costa et al. (2018) compared and evaluated performance of classical multiple linear regression (MLR) and geographically weighted regression (GWR) models to predict SOC and chemical fractions of SOM in the Brazilian southeastern mountainous region. The regression models were fitted based on SOC and chemical fractions of SOM. Sampling points (n = 89) were selected along transects and toposequences using remote sensing indices derived from RapidEye sensor bands, a geology map, a legacy soils map, and terrain attributes derived from digital elevation models as covariates. The legacy soil map was selected as a covariate by the stepwise approach in all MLR models (except for fulvic acid fraction [FAF]), whereas the geology map was not selected as an important covariate to predict FAF or humin. The GWR models had the best performance in predicting the SOC, humin, and FAF, and the MLR models extrapolated the results, especially for SOC. The relationships among SOC, SOM fractions, and environmental covariates were affected by local landscape variability.

Flathers and Gessler (2018) applied the *scorpan* technique for modeling soil properties and as an example framework to model and map SOC stocks in the cereal grains production region of the northwestern United States. The map was produced using a random forest statistical model with *scorpan* inputs to predict SOC content on a 30-m spatial grid. Under an explicit open-source license, all modeling components including input data, metadata, computer code, and output were made freely available. The methods, output data, and code released are available to be reused by other researchers, and the research products are open to critical review and improvement to support reproducibility in the science of SOC mapping.

Reyes Rojas et al. (2018) evaluated the potential impact of predicted changes in temperature and precipitation across central Chile using current SOC content, pedon descriptions, and environmental variables (temperature, rainfall, land use, topography, soil types, and geology) as predictors. The random forest statistical model was used to predict SOC content by pedon. Maps were created for six standard depths of the Global Soil Map project. Model validation had R^2 values of 0.70, 0.73, 0.75, 0.65, 0.56, and 0.29 for depths of 0 to 5, 5 to 15, 15 to 30, 30 to 60, 60 to 100, and 100 to 200 cm, respectively. Two future temperature and precipitation scenarios for climate change, RCP4.5 and RCP8.5, were considered in predicting SOC in 2050 and 2080. They found that central Chile would experience a loss of SOC in the 0- to 30-cm depth averaging 9.7% for RCP4.5 and 12.9% for the RCP8.5 scenarios by the year 2050, and an additional decrease of 8% in the RCP4.5 scenario and 16.5% under RCP8.5 by 2080. The potential negative effect of climate change in areas with Andisols will be higher than the rest.

Vågen et al. (2018) developed high-resolution maps of SOC and key indicators of ecosystem health across savanna ecosystems in South Africa using a field-based approach coupled with statistical modeling (random forest), mid-infrared spectroscopy (MIR), and remote sensing (RapidEye imagery). Two 100-km^2 landscapes were surveyed, and 320 composite topsoil samples were collected. Validation results for the mapping of soil erosion prevalence and herbaceous cover using RapidEye imagery showed good model performance. The random forest model performance for mapping of SOC had an R^2 of 0.80 with root mean squared values of 2.6 g kg^{-1} for SOC content. They found that important driving factors of SOC dynamics included soil texture, soil erosion prevalence, and climate. The strong influence of climate on SOC in the study area shows that the impacts of climate change, such as higher temperatures and more erratic rainfall, can potentially have large implications for ecosystem health and the resilience of these rangelands. In addition, the spatial assessments produced as part of the study could be used to reduce land degradation and restore degraded areas, which would be critical for climate change adaptation of these rangelands.

Meta-Analysis of Soil Organic Carbon

Byrnes et al. (2018) conducted a global meta-analysis of SOC, total N, C/N ratio, and bulk density responses to grazing intensities (heavy, moderate, and light grazing) and strategies (continuous, rotational, and no grazing) from 64 studies around the world to determine the impacts of livestock grazing on soil health. Across all studies and grazing intensities, continuous grazing significantly reduced SOC, C/N, and total N compared with no grazing. The effect of grazing strategies on soil compaction (i.e., increased bulk density) was continuous grazing > rotational > no grazing. Although comparisons of grazing strategy were minimally conditioned by aridity class (i.e., arid, subhumid, and humid), complete observations were limited or missing for many rotational grazing comparisons. Rotational grazing had greater SOC than continuous grazing and was not different from no grazing. The positive responses of SOC to rotational grazing could improve resiliency to climate change.

Long-term Field Experiment and Soil Organic Carbon Pools

Sherrod et al. (2018) examined the effect of several years of drought on the persistence of SOC pools (0–20 cm) after 24 yr in NT as affected by potential evapotranspiration (PET), landscape position (slope), and cropping intensity at three sites with similar precipitation but increasing PET in Colorado. The C pool most affected by the drought years was the active pool.

After 24 yr, for the first 12 yr (wet) versus the subsequent 12 yr of frequent drought, water-soluble organic C increased by 0.25, 0.34, and 0.44 Mg C ha^{-1} and soil microbial biomass C by 1.50, 1.66, and 2.14 Mg C ha^{-1} with cropping intensity from wheat–corn–fallow continuous cropping to grass (Conservation Reserve Program mixture planted across slopes), respectively. The particulate organic matter C (POM-C) pool had a three-way interaction with PET, slope, and cropping intensity. Overall, SOC increased in grass by 16.9% at a rate of 0.42 Mg C ha^{-1} yr^{-1} compared with 10.5 and 1.4% for the wheat–corn–fallow and continuous cropping systems, respectively, between Years 12 and 24. They concluded that the POM-C fraction offers valuable insight about the potential impact of management and/or climate change on long-term SOM dynamics.

Conclusions and Implications

The process-based models used in this collection generally demonstrated good agreement between measured and modeled SOC stocks, when the soil C cycling components of the models were informed by reliable input data with respect to biomass production, climatic parameters, and management practices. This result promotes confidence in model projections under future climate conditions and therefore is encouraging for the usefulness of SOC-modeling efforts to inform management decisions to enhance SOC stocks. Also encouraging was the consistent observation of enhanced SOC stocks in response to increased cropping intensity, whether through avoiding fallow conditions or incorporating winter or cover crops. Another positive implication from several studies was the prediction for enhanced crop production and SOC accumulation in semiarid regions due to projected increases in precipitation, even, in some cases, in the absence of substantial changes in current management practices. However, there was also agreement among several studies that the more extreme RCPs available from climate models and used as climate projection inputs to process-based models are more likely to result in decreased SOC stocks.

The critical importance of crop-biomass inputs for maintaining or enhancing SOC stocks highlights that a large portion of the burden for accurate prediction of changes in SOC stocks under climate change will rely heavily on crop growth models, and the linkage of those crop models to climate models on the one hand, and soil C cycling and processing models on the other. The importance as well as the limitations of our current abilities to predict crop growth under future climate management scenarios cannot be overstated. In some cases, we cannot say with much confidence whether yields will increase or decrease in each region under a given climate regime, as acknowledged by several authors here. Some of these limitations of course derive directly from uncertainties in RCPs and future climate predictions. As pointed out here by Chu et al. (2018), there is a need for the temperature and precipitation predictions of large-scale climate models to be translated to more temporally and spatially meaningful climate variables that will drive local-scale crop responses as well as management constraints (e.g., planting and harvesting dates). Additional limitations of crop response models derive from a large uncertainty in the ability of crop genetic improvements to keep pace with climate-induced stresses, including both direct climate effects (e.g., drought, heat stress) and indirect effects (e.g., shifts in weeds, insects, and diseases). These latter effects, as pointed out by Wienhold et al. (2018), could have significant management implications, such as the need for periodic tillage, which has been shown to increase SOC stocks relative to continuous NT in some systems (Venterea et al., 2006). The need for improved model representation of linkages and feedbacks between crop and soil process models is also highlighted here. For example, Jarecki et al. (2018) incorporated pedotransfer functions into DNDC to account for soil property changes under diversified rotations, which can affect soil water availability and therefore feedback to crop production. Incorporation of this soil–plant linkage in crop growth models is a means of quantifying the enhanced "resiliency" of agroecosystems under increased climate stress.

The consensus around the need for enhanced cropping intensity to maintain or enhance SOC stocks implies that increased inputs of N (and possibly other nutrients) may be required to support increased crop biomass production. The extent of any changes in crop nutrient requirements will likely depend on improvements in crop genetics. However, in the context of climate change effects and feedbacks, the potential for increased N inputs also raises the likelihood of associated increases in emissions of N_2O (Cavigelli et al., 2012) that need to be considered in any comprehensive assessment of greenhouse gas budgets.

The emphasis on improving crop and climate inputs to soil C cycling model components should not imply that our fundamental understanding of the soil processes regulating the transformation of plant residues and models depicting those processes are not also in need of improvement. As shown by both Crow and Sierra (2018) and Sherrod et al. (2018), there is a need for better understanding and model representation of the responses of different pools of soil C to climate and management, as well as transfers of C among those pools.

Knowledge of current SOC stocks across broader landscapes and regions, and of the relationships between SOC stocks and a range of soil, vegetation, climate, and other physiographic features, is essential for establishing baseline conditions and for assessing responses to future changes in climate and other disturbances. This section highlights several advances in the application of statistical models, as well as measurement techniques (e.g., MIR spectroscopy used by Vågen et al., 2018) and "big data" approaches (Flathers and Gessler, 2018), which will facilitate the mapping of SOC stocks at landscape to national scales.

Increased SOC by itself will not provide resiliency to all potential stresses that may increase under climate change. However, because greater SOC can at the same time increase water-holding capacity and improve drainage, the general consensus is that it will provide some resiliency to extremes of drought and heat stress, as well as increased precipitation intensity by reducing the potential for runoff and erosion. Thus, it is appealing to consider a positive feedback in the soil C–plant input cycle under climate change, such that increased SOC promotes increased crop biomass, which in turn promotes increased SOC. However, there is a downside to this relationship in that if SOC stocks are not sufficient to promote some minimum level of resiliency in this regard, and then a downward spiral of decreased SOC and decreased plant biomass production, which may be very difficult to reverse, is also possible. This possibility underlines the great urgency to establish improved practices to enhance SOC stocks.

Knowledge of SOC stocks in subsoils and their response to warming and climate change are also important. Considerable efforts have been made to assess the response of SOC stocks in topsoil to warming (Davidson and Janssens, 2006; Conant et al., 2011; Crowther et al., 2016). Most SOC measurements were limited to the top 10- to 30-cm depths, and few papers accounted for subsoil SOC stocks (Cavigelli et al., 2018; Dell et al., 2018; Gollany and Polumsky, 2018; Reyes Rojas et al., 2018). Findings from these studies identified critical gaps in knowledge. Additional research is needed to: (i) incorporate microbial response to warming and feedback to SOM decomposition into process-based models, (ii) extend SOC measurements and predictions to subsoils, (iii) include saturation algorithms in process-based models to account for topsoil-saturation with C that can occur in some soils (e.g., sandy loam soils under high crop residue inputs in NT; Nash et al., 2018b), (iv) improve climatic projections at smaller scales for different regions, and (v) develop a framework for upscaling SOC stocks to predict influence of biotic and abiotic conditions on SOC stocks at landscape scales. These efforts will assist in further identifying best management practices to enhance SOC stocks and improve the resiliency of agroecosystem and crop production to climate change.

Acknowledgments

We thank all the authors who contributed to this special section, and the reviewers for their efforts and contributions. A special thanks to Drs. Richard Farrell, Maria Villamil, and Brian Wienhold for serving as guest editors, and Dr. Edward Gregorich and the editorial staff at the *Journal of Environmental Quality* for their efforts to put together this special section in a timely manner.

References

Byrnes, C.B., D.J. Eastburn, K.W. Tate, and L.M. Roche. 2018. A global meta-analysis of grazing impacts on soil health indicators. J. Environ. Qual. 47:758–765. doi:10.2134/jeq2017.08.0313

Cavigelli, M.A., S.J. Del Grosso, M.A. Liebig, C.S. Snyder, P.E. Fixen, R.T. Venterea, et al. 2012. US agricultural nitrous oxide emissions: Context, status, and trends. Front. Ecol. Environ. 10:537–546. doi:10.1890/120054

Cavigelli, M.A., P.R. Nash, H.T. Gollany, C. Rasmann, R.W. Polumsky, A.N. Le, and A.E. Conklin. 2018. Simulated soil organic carbon changes in Maryland are affected by tillage, climate change, and crop yield. J. Environ. Qual. 47:588–591. doi:10.2134/jeq2017.07.0291

Chu, M., J. Guzman, and M. Villamil. 2018. A modeling framework to evaluate the impacts of future climate on soil organic carbon dynamics. J. Environ. Qual. 47:596–606. doi:10.2134/jeq2017.07.0295

Conant, R.T., M.G. Ryan, G.I. Ågren, H.E. Birge, E.A. Davidson, P.E. Eliasson, et al. 2011. Temperature and soil organic matter decomposition: Synthesis of current knowledge and a way forward. Glob. Change Biol. 17:3392–3404. doi:10.1111/j.1365-2486.2011.02496.x

Costa, E.M., W.d.S. Tassinari, H.S.K. Pinheiro, S.J. Beutler, and L.H.C. Anjos. 2018. Mapping soil organic carbon and organic matter fractions by geographically weighted regression. J. Environ. Qual. 47:718–725. doi:10.2134/jeq2017.04.0178

Crow, S.E., and C.A. Sierra. 2018. Dynamic, intermediate soil carbon pools may drive future responsiveness to environmental change. J. Environ. Qual. 47:607–616. doi:10.2134/jeq2017.07.0280

Crowther, T.W., K.E.O. Todd-Brown, C.W. Rowe, W.R. Wieder, J.C. Carey, M.B. Machmuller, et al. 2016. Quantifying global soil carbon losses in response to warming. Nature 540:104–108. doi:10.1038/nature20150

Davidson, E.A., and I.A. Janssens. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440:165–173. doi:10.1038/nature04514

Dell, C.J., H.T. Gollany, P.R. Adler, R.H. Skinner, and R.W. Polumsky. 2018. Implications of observed and simulated soil carbon sequestration for management options in corn-based rotations. J. Environ. Qual. 47:617–624. doi:10.2134/jeq2017.07.0298

Flathers, E., and P.E. Gessler. 2018. Building an open science framework to model soil organic carbon. J. Environ. Qual. 47:726–734. doi:10.2134/jeq2017.08.0318

Gollany, H.T., A. Fortuna, M. Samuel, F.L. Young, W. Pan, and M. Pecharko. 2012. Estimating soil organic carbon accretion vs. sequestration using chemical and physical fractionation and the CQESTR model. Soil Sci. Soc. Am. J. 76:618–629 doi:10.2136/sssaj2012.0303

Gollany, H.T., and R.W. Polumsky. 2018. Simulating soil organic carbon responses to cropping intensity, tillage, and climate change in Pacific Northwest dryland. J. Environ. Qual. 47:625–634. doi:10.2134/jeq2017.09.0374

Gougoulias, C., M. Joanna, L. Clark, and J. Shaw. 2014. The role of soil microbes in the global carbon cycle: Tracking the below-ground microbial processing of plant-derived carbon for manipulating carbon dynamics in agricultural systems. J. Sci. Food Agric. 94:2362–2371. doi:10.1002/jsfa.6577

Gregorich, E.G., H. Janzen, B.H. Ellert, B.L. Helgason, B. Qian, B.J. Zebarth, et al. 2017. Litter decay controlled by temperature, not soil properties, affecting future soil carbon. Glob. Change Biol. 23:1725–1734. doi:10.1111/gcb.13502

Harmon, M.E., W.L. Silver, B. Fasth, H. Chen, I.C. Burke, W.J. Parton, et al. 2009. Long-term patterns of mass loss during the decomposition of leaf and fine root litter: An intersite comparison. Glob. Change Biol. 15:1320–1338. doi:10.1111/j.1365-2486.2008.01837.x

Hatfield, J.L., K.J. Boote, B.A. Kimball, L.H. Ziska, R.C. Izaurralde, D. Ort, et al. 2011. Climate impacts on agriculture: Implications for crop production. Agron. J. 103:351–370. doi:10.2134/agronj2010.0303

Hicks Pries, C.E., C. Castanha, R.C. Porras, and M.S. Torn. 2017. The whole-soil carbon flux in response to warming. Science 355:1420–1423. doi:10.1126/science.aal1319

Jackson, R.B., K. Lajtha, S.E. Crow, G. Hugelius, M.G. Kramer, and G. Piñeiro. 2017. The ecology of soil carbon: Pools, vulnerabilities, and biotic and abiotic controls. Annu. Rev. Ecol. Evol. Syst. 48:419–445. doi:10.1146/annurev-ecolsys-112414-054234

Jarecki, M., B. Grant, W. Smith, B. Deen, C. Drury, A. VanderZaag, B. Qian, J. Yang, and C. Wagner-Riddle. 2018. Long-term trends in corn yields and soil carbon under diversified crop rotations. J. Environ. Qual. 47:635–643. doi:10.2134/jeq2017.08.0317

Jebari, A., A. del Prado, G. Pardo, J.A.R. Martín, and J. Álvaro-Fuentes. 2018. Modeling regional effects of climate change on soil organic carbon in Spain. J. Environ. Qual. 47:644–653. doi:10.2134/jeq2017.07.0294

Jones, C.D., L.G. Oates, G.P. Robertson, and R.C. Izaurralde. 2018. Perennialization and cover cropping mitigate soil carbon loss from residue harvesting. J. Environ. Qual. 47:710–717. doi:10.2134/jeq2017.04.0177

Keestrea, S.D., J. Bourna, J. Wallinga, P. Tittonell, P. Smith, A. Cerdà, et al. 2016. The significance of soils and soil science towards realization of the United Nations sustainable development goals. SOIL 2:111–128. doi:10.5194/soil-2-111-2016

McBratney, A.B., M.L. Mendonça Santos, and B. Minasny. 2003. On digital soil mapping. Geoderma 117:3–52. doi:10.1016/S0016-7061(03)00223-4

Mertens, J., J. Vanderborght, R. Kasteel, T. Pütz, R. Merckx, J. Feyen, and E. Smolders. 2007. Dissolved organic carbon fluxes under bare soil. J. Environ. Qual. 36:597–606. doi:10.2134/jeq2006.0368

Nash, P.R., H.T. Gollany, M.A. Liebig, J.J. Halvorson, D.W. Archer, and D.L. Tanaka. 2018a. Simulated soil organic carbon responses to crop rotation, tillage, and climate change in North Dakota. J. Environ. Qual. 47:654–662. doi:10.2134/jeq2017.04.0161

Nash, P.R., H.T. Gollany, J.M. Novak, P.J. Bauer, P.G. Hunt, and D.L. Karlen. 2018b. Simulated soil organic carbon response to tillage, yield, and climate change in the southeastern Coastal Plains. J. Environ. Qual. 47:663–673. doi:10.2134/jeq2017.05.0190

Nash, P.R., H.T. Gollany, and U.M. Sainju. 2018c. CQESTR-simulated response of soil organic carbon to management, yield, and climate change in the Northern Great Plains region. J. Environ. Qual. 47:674–683. doi:10.2134/jeq2017.07.0273

Pachauri, R.K., M.R. Allen, V.R. Barros, J. Broome, W. Cramer, R. Christ, et al. 2014. Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. IPCC. Geneva.

Raich, J.W., and C.S. Potter. 1995. Global patterns of carbon dioxide emissions from soils. Global Biogeochem. Cycles 9:23–36. doi:10.1029/94GB02723

Reyes Rojas, L.A., K. Adhikari, and S.J. Ventura. 2018. Projecting soil organic carbon distribution in central Chile under future climate scenarios. J. Environ. Qual. 47:735–745. doi:10.2134/jeq2017.08.0329

Robertson, A.D., Y. Zhang, L.A. Sherrod, S.T. Rosenzweig, L. Ma, L. Ahuja, and M.E. Schipansk. 2018. Climate change impacts on yields and soil carbon in row crop dryland agriculture. J. Environ. Qual. 47:684–694. doi:10.2134/jeq2017.08.0309

Sakrabani, R., and J. Hollis. 2018. Evaluating changes in soil organic matter with climate using CENTURY in England and Wales. J. Environ. Qual. 47:695–703. doi:10.2134/jeq2017.08.0310

Sherrod, L.A., G.S. McMaster, J.A. Delgado, M.E. Schipanski, S.J. Fonte, R.L. Montenieri, and K. Larson. 2018. Soil carbon pools in dryland agroecosystems as affected by several years of drought. J. Environ. Qual. 47:766–773. doi:10.2134/jeq2017.09.0371

Smith, P. 2008. Land use change and soil organic carbon dynamics. Nutr. Cycling Agroecosyst. 81:169–178. doi:10.1007/s10705-007-9138-y

Stocker, T., D. Qin, G.-K. Plattner, M.M.B. Tignor, S.K. Allen, J. Boschung, et al., editors. 2013. Climate change 2013: The physical science basis. Working Group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, New York.

Vågen, T.-G., L.A. Winowiecki, W. Twine, and K. Vaughan. 2018. Spatial gradients of ecosystem health indicators across a human-impacted semiarid savanna. J. Environ. Qual. 47:746–757. doi:10.2134/jeq2017.07.0300

Van der Wal, A., and W. de Boer. 2017. Dinner in the dark: Illuminating drivers of soil organic matter decomposition. Soil Biol. Biochem. 105:45–48. doi:10.1016/j.soilbio.2016.11.006

Venterea, R.T., J.M. Baker, M.S. Dolan, and K.A. Spokas. 2006. Carbon and nitrogen storage are greater under biennial tillage in a Minnesota corn–soybean rotation. Soil Sci. Soc. Am. J. 70:1752–1762. doi:10.2136/sssaj2006.0010

Webber, H., P. Martre, S. Asseng, B. Kimball, J. White, M. Ottman, et al. 2017. Canopy temperature for simulation of heat stress in irrigated wheat in a semi-arid environment: A multi-model comparison. Field Crops Res. 202:21–35. doi:10.1016/j.fcr.2015.10.009

Wienhold, B.J., V.L. Jin, M.R. Schmer, and G.E. Varvel. 2018. Soil carbon response to projected climate change in the US Western Corn Belt. J. Environ. Qual. 47:704–709. doi:10.2134/jeq2017.09.0379