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PREDICTING SOIL ORGANIC CARBON IN AGROECOSYSTEMS UNDER CLIMATE CHANGE

Simulated Soil Organic Carbon Response to Tillage, Yield, and Climate Change in the Southeastern Coastal Plains

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Abstract

Intensive tillage, low-residue crops, and a warm, humid climate have contributed to soil organic carbon (SOC) loss in the southeastern Coastal Plains region. Conservation (CnT) tillage and winter cover cropping are current management practices to rebuild SOC; however, there is sparse long-term field data showing how these management practices perform under variable climate conditions. The objectives of this study were to use CQESTR, a process-based C model, to simulate SOC in the top 15 cm of a loamy sand soil (fine-loamy, kaolinitic, thermic Typic Kandiudult) under conventional (CvT) or CnT tillage to elucidate the impact of projected climate change and crop yields on SOC relative to management and recommend the best agriculture management to increase SOC. Conservation tillage was predicted to increase SOC by 0.10 to 0.64 Mg C ha^{-1} for six of eight crop rotations compared with CvT by 2033. The addition of a winter crop [rye (*Secale cereale* L.) or winter wheat (*Triticum aestivum* L.)] to a corn (*Zea mays* L.)–cotton (*Gossypium hirsutum* L.) or corn–soybean [*Glycine max* (L.) Merr.] rotation increased SOC by 1.47 to 2.55 Mg C ha^{-1}. A continued increase in crop yields following historical trends could increase SOC by 0.28 Mg C ha^{-1}, whereas climate change is unlikely to have a significant impact on SOC except in the corn–cotton or corn–soybean rotations where SOC decreased up to 0.15 Mg C ha^{-1} by 2033. The adoption of CnT and cover crop management with high-residue-producing corn will likely increase SOC accretion in loamy sand soils. Simulation results indicate that soil C saturation may be reached in high-residue rotations, and increasing SOC deeper in the soil profile will be required for long-term SOC accretion beyond 2030.

Core Ideas

- High-residue crop rotation in conservation tillage maximized SOC accumulation.
- Cover crop and conservation tillage management would likely optimize SOC accretion.
- Anticipated climate change was predicted to have a minimal impact on SOC by 2033.
- Sorghum was not a viable option to replace corn in rotation for SOC accretion.
- Alternative management was required for deep SOC accretion beyond 2033.

Long-term cultivation and intensive tillage have greatly decreased soil organic carbon (SOC) stocks and contributed to soil health degradation in the southeastern United States (Causarano et al., 2006; Franzluebbers, 2010). This is an extremely important problem, because this region produces about a quarter of the US agricultural products (Ruth et al., 2007). Reversing the trend of SOC loss is being recognized as increasingly important for long-term soil sustainability, meeting rising global food, feed, fiber, and fuel demands, and mitigating CO_2–induced climate change through C sequestration (Lal, 2004).

Soil organic C content is inherently low in the southeastern United States due to warm and wet conditions that enhance soil organic matter (SOM) decomposition, and the same factors limit SOC accumulation (Franzluebbers, 2010). Degraded soil health, farm labor demands, and requirements to maintain surface residue cover to qualify for government crop insurance programs have promoted the adoption of conservation management practices. These practices can increase both soil C and crop production (Schwab et al., 2002). The management practices that (i) increase C sequestration and SOC stocks, and (ii) fit the existing framework of agricultural production systems will likely be the most economical, practical, and adopted throughout the region.

Total elimination of tillage in the sandy Coastal Plains soils of the southeastern United States is unlikely, because of a dense subsoil layer (i.e., E horizon) that can severely limit crop production (Karlen et al., 1991; Hunt et al., 2004). To address this inherent soil property, noninversion deep tillage that has minimal soil disturbance and residue incorporation has been practiced in conservation tillage (CnT; Bruce et al., 1990; Schwab et al., 2002; Hunt et al., 2004). For instance, paratillage or in-row subsoil tillage is often necessary to create conditions for deep root penetration. With these practices, there is increased access to critical plant-available subsoil water and nutrients, which increase crop yield (Vepraskas and Guthrie, 1992; Vepraskas et al., 1995; Hunt et al., 2004). Roberson (2006) reported that deep subsoil tillage

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Abbreviations: C-CT, corn–cotton; C-CT w/Rye, corn–cotton with rye; CnT, conservation tillage; C-SB, corn–soybean; C-SB w/Rye, corn–soybean with rye; CvT, conventional tillage; C/WW-SB, corn/winter wheat–soybean; MSD, mean square deviation; SG-CT, sorghum–cotton; SG-SB, sorghum–soybean; SG/WW-SB, sorghum/winter wheat–soybean; SOC, soil organic carbon; SOM, soil organic matter.

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increased SOC by 2.2 Mg ha^{-1} compared with conventional disk tillage across multiple soil types in North Carolina.

Conversion from conventional tillage (CvT) to CnT has been found to increase SOC in many southeastern soils (Franzluebbers, 2005, 2010; Causarano et al., 2006). Increased C sequestration with CnT is generally the result of reduced soil disturbance and reduced incorporation of organic residues, both factors that reduce SOM decomposition rates (Haas et al., 1957; Sylvia et al., 2005). Conservation tillage also increases surface residue cover, which reduces soil erosion (Unger et al., 2006) and decreases evaporation, increasing crop production (Lal, 2004). Novak et al. (2007) reported that removing disk tillage from the existing deep subsoil tillage practice increased the average C sequestration rate from 0.125 to 0.445 g kg^{-1} yr^{-1} in the 0- to 5-cm soil depth in a sandy Coastal Plains soil over the 1980 to 2003 period.

Moreover, crop rotations can greatly influence SOC stocks by changing the amount and quality of organic residue returned to the soil (Magdoff and Weil, 2004). As a result, many long-term studies have shown a direct relationship between organic matter inputs, N content, and SOC (Campbell and Zentner, 1993; Paustian et al., 1997). Among the major crops grown in the southeastern United States, corn (*Zea mays* L.) generally produces the most biomass (Johnson et al., 2006), whereas cotton (*Gossypium hirsutum* L.) produces the least (Causarano et al., 2006). Therefore, growing continuous cotton with CvT resulted in relatively low residue additions to the soil. This was a major contributor to regional SOC loss (Causarano et al., 2006). Conversely, adding a winter cover crop such as rye (*Secale cereale* L.) or double cropping with winter wheat (*Triticum aestivum* L.) has been reported to increase SOC by increasing organic residue additions, providing greater soil cover and reducing soil erosion (Bauer and Busscher, 1996; Causarano et al., 2006; Unger et al., 2006).

Soil C models are especially useful tools to examine the impact of management practices on SOC over time when considering long-term climate change (Gollany et al., 2012b; Gollany, 2016). In soil C models, the major driver of C stocks is C inputs from crop yield and the subsequent additions of crop biomass (Rickman et al., 2002; Liang et al., 2009). Therefore, the impact of projected climate change on crop production must be factored into the simulation over the predictive period. Current climate predictions for the southeastern Coastal Plains generally agree that air temperature will continue to rise by ~0.5°C, while rainfall will change from −6 to +20% by midcentury (Mearns et al., 2014). It is generally assumed that rising temperature has and will continue to negatively affect yields of most major crops on a global scale (Lobell and Field, 2007; Hatfield et al., 2011; Neenu et al., 2013). Crop production will likely be sustained in the southeastern Coastal Plains region through the midcentury, as long as growing season temperatures remain near the optimum temperature range for vegetative and reproductive development of the crop (Hatfield et al., 2008).

The CQESTR model is a process-based C model, developed by USDA-ARS scientists at the Columbia Plateau Conservation Research Center in Oregon. Initially, CQESTR was calibrated for the Pacific Northwest (Rickman et al., 2001, 2002). The model was modified, recalibrated, and validated for field-scale use in North America (Liang et al., 2008, 2009; Gollany et al., 2012a). CQESTR has been used successfully to simulate soil C dynamics in a variety of regions, climates, and soil types (Liang et al., 2008, 2009; Leite et al., 2009; Gollany et al., 2010, 2011, 2012a, 2012b; Plaza et al., 2012). Recently, it was validated for landscape-scale evaluation of agronomic practices (Gollany and Elnaggar, 2017).

The objectives of this study were: (i) to simulate SOC dynamics in the top 15 cm of soil during a 12-yr (2002–2013) field study in a Norfolk (fine-loamy, kaolinitic, thermic Typic Kandiudults) loamy sand soil in the southeastern Coastal Plains region using the CQESTR soil C model; (ii) to evaluate relative trends in SOC due to crop rotation and tillage during the 20-yr (2014–2033) predictive period; (iii) to elucidate the impact that projected climate change and crops yields will have on SOC stocks by 2033, relative to management; and (iv) to recommend the best management practices to increase SOC stocks through 2033 when projected effects of climate change are factored into the simulation.

Materials and Methods

Site Description and Management Practices

A long-term field study was initiated in 1979 at the Pee Dee Research and Education Center located near Florence, SC (34°18′ N, 79°44′ W) to examine the impact of tillage and crop residue removal on soil properties and crop yield. A detailed description of the study site and field experiments since 1979 can be found in Karlen et al. (1984), Hunt et al. (1997), and Bauer et al. (2006). The primary soil type was a Norfolk loamy sand. Soil samples were collected annually (2002–2013) from the CvT and CnT plots at depth increments of 0 to 5, 5 to 10, and 10 to 15 cm and soil bulk density (Grossman and Reinsch, 2002), and SOC content was determined using the dry combustion method (Nelson and Sommers, 1996). Basic soil properties for this field experiment can be found in Table 1. Average annual precipitation (2002–2013) was 877 mm, and daily air temperature averaged 18.8°C for April through October and 5.2°C for November through March.

Conventional tillage consisted of disking two or three times to a depth of 10 to 15 cm, smoothing with an S-tined harrow, and using subsoiling either in-row with a KMC shank (John Deere MaxEmerge XP) or with a six-legged paratill with shanks spaced 66 cm apart (Tye ParaTill, AGCO Corporation). Subsoil depths were ~30 cm for the in-row subsoiling and 42 cm for the paratill. Conservation tillage consisted of subsoiling only. All subsoiling was done just prior to planting the spring crops. No subsoiling occurred before the wheat or rye in the rotations with those crops. All seeding was done with planters or drills appropriate for conservation tillage management. Crop rotations changed at the study site over the 2002 to 2013 study period. The crop rotation was corn/winter wheat–soybean [*Glycine max* (L.) Merr.] (C/WW-SB) in 2002, corn–soybean rotation with annual rye cover crop (C-SB w/Rye) in 2003 to 2007, corn–soybean (C-SB) in 2008 to 2010, and corn–cotton (C-CT) in 2011 to 2013. Information on crop rotations, tillage, planting, harvests, and nitrogen (N) applications were reported previously (Hunt et al., 2004; Novak et al., 2007).

Model Description

CQESTR is a process-based C model operating on a daily time step that tracks each organic addition (amount and placement in soil) independently and is capable of simulating SOC content

Table 1. Mean soil fertility characteristics from the 0- to 15-cm soil depth for conventional (CvT) and conservation tillage (CnT) field plots (n = 3), averaged over 2002 to 2013.

Tillage	pH	CEC†	Macronutrients‡				Micronutrients	
			P	K	Ca	Mg	Cu	Zn
		cmol kg^{-1}	kg ha^{-1}					
CvT	6.8 (0.4)§	6.1 (0.8)	105 (20)	145 (12)	1674 (280)	310 (94)	0.3 (0.1)	13 (2)
CnT	6.5 (0.4)	5.0 (0.8)	75 (22)	100 (26)	1225 (287)	208 (78)	0.6 (0.1)	9 (2)

† CEC, cation exchange capacity.

‡ Methods available at Clemson Soil test laboratory.

§ Numeric values enclosed in parentheses represent the SD about the mean.

in multiple soil layers (Liang et al., 2008, 2009). The CQESTR model was developed to use readily available input data at the field scale to determine the short and long-term effects of management practices on SOC (Rickman et al., 2001). Model inputs include: (i) soil properties (i.e., soil texture, drainage class, bulk density, and initial percent SOC content); (ii) weather (monthly average air temperature, and precipitation); (iii) biomass additions (i.e., manure and crop biomass including roots); (iv) management (i.e., dates of residue additions or removal); and (v) soil disturbance events (i.e., tillage, planting, or nutrient applications). Each event that disturbs the soil requires information about the depth and percentage of the soil area disturbed, and the percentage of the residue remaining on the surface after the event. The amount of residue incorporated and the percentage of the soil area disturbed were estimated based on first-hand knowledge from the collaborators and literature (Conservation Tillage, MWPS-45). Model input data were organized into crop management files associated with the *c*-factor files of the Revised Universal Soil Loss Equation (RUSLE, Version 1) (Renard et al., 1996).

Model Simulation Scenarios

Soil organic C dynamics of measured data at the 0- to 15-cm soil depth over the experiment period (2002–2013) and predictive period (2014–2033) were simulated using the CQESTR model. The model inputs values over the experiment period were unique for CvT and CnT treatments (three replications) but shared an identical crop rotation. The input values available were weather data, biomass additions (excluding root biomass), biomass N content, soil bulk density, and SOC data (summed over the 0- to 5-, 5- to 10-, and 10- to 15-cm soil depths). Root biomass was estimated from the total biomass data, and root/shoot values were obtained from literature. The root/shoot values used were 0.42, 0.37, 0.31, 0.31, and 0.15 for corn, soybean, wheat, rye, and cotton, respectively (McMichael and Quisenberry, 1991; Gray et al., 2014).

The CQESTR simulations were divided into eight predictive periods according to specific crop rotations for CvT and CnT treatments, since crop rotations varied over the experiment period. The crop rotations evaluated were: corn–cotton or cotton–soybean with annual rye cover crop (C-CT w/Rye, C-SB w/Rye), sorghum [*Sorghum bicolor* (L.) Moench]–soybean (SG-SB), sorghum–cotton (SG-CT), and corn or sorghum followed by double-cropped winter wheat and soybean (C/WW-SB, SG/WW-SB). Biomass addition input values used throughout the predictive period were crop averages calculated from actual experiment period values for CvT and CnT treatments. Due to minimal winter wheat and no actual sorghum data during the experiment period, aboveground and root biomass inputs for sorghum and winter wheat were estimated from South Carolina (1940–1997) and US (1940–2013) yield data (USDA-NASS, 2014, 2015). Harvest indices, root/shoot ratios, and biomass N content values were obtained from the literature (Meisinger and Randall, 1991; Johnson et al., 2006; Sher et al., 2013; Gray et al., 2014).

Multiple climate change scenarios and/or crop yield trends for 2014 through 2033 were simulated for each tillage and crop rotation. The baseline simulations assumed that climate and biomass inputs remained constant at the 2002 to 2013 average. Climate change-only simulations assumed biomass inputs remained at the 2002 to 2013 average but had varied precipitation and temperature projections. Yield trend simulations factored in historical crop yield trends. The climate + yield simulations factored in both climate change and crop yield trends.

Climate predictions were obtained from the North American Regional Climate Change Assessment Program. The monthly values used for the CQESTR simulations were obtained from the University of California San Diego–Scripps Regional Spectral Model with boundary conditions from the Geophysical Fluid Dynamics Laboratory, NOAA CM2.0-AOGCM model (ECP2/GFDL). The selections were taken from 11 models and drivers to provide the best representation of average climate change predictions (Mearns et al., 2014). The climate change projections were made quarterly (December–February, March–May, June–August, and September–November). In annual terms, relative to 2013, the ECP2/GFDL model predicted an average increase of 0.5°C and a 2.1% increase in precipitation by 2033. Scenarios that included climate change had climate input values adjusted according to quarterly projections, and the temporal response in climate change over 2014 to 2033 was accounted for by incremental increase of input values based on the rate of change on a 10-yr basis.

Estimated crop biomass inputs over the period of 2014 to 2033 in simulation scenarios, which factored in crop yield trends, were based on the 12-yr site data and US and South Carolina crop yield trends, obtained from the USDA Economic Research Service and National Agricultural Statistics Service (USDA-NASS, 2014, 2015; USDA-ERS, 2015a, 2015b, 2015c, 2017). Recent yield increases for many crops have been shown to come at the expense of leaf and stem biomass (Evans, 1993; Morrison et al., 1999; Lorenz et al., 2010; Bender et al., 2015). Therefore, aboveground biomass inputs for 2014 through 2033 were calculated by regressing that factor against the 2002 to 2013 site-specific dataset (Table 2). For cotton and winter wheat, the regression was calculated using 13 yr of data from the study site prior to the current experiment because of limited cotton and winter wheat data available over the fitting period. Given those regressions, the projected biomass increases per unit grain increase used in the CQESTR simulations were 0.75, 0.06, 1.15, and 1.33 for corn, soybean, cotton, and winter wheat, respectively.

Table 2. The baseline model input values of aboveground biomass for each crop and tillage system (conventional [CvT] and conservation [CnT]), and the values over the predictive period (2014–2033) used in the simulation scenarios that took in account historical crop yield trends in the United States.

Crop	Tillage	Aboveground biomass input for crops									
		Year									
		Baseline†	2016	2018	2020	2022	2024	2026	2028	2030	2033
		Mg ha^{-1}									
Corn	CnT	14.4	15.0	15.1	15.2	15.3	15.3	15.4	15.5	15.6	15.6
	CvT	14.0	15.0	15.1	15.1	15.2	15.3	15.4	15.4	15.5	15.6
Soybean	CnT	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
	CvT	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
Cotton	CnT	4.1	4.1	4.1	4.1	4.1	4.2	4.2	4.2	4.2	4.2
	CvT	4.2	4.1	4.1	4.2	4.2	4.2	4.2	4.2	4.3	4.3
Wheat‡	CnT	3.0	4.1	4.2	4.3	4.4	4.5	4.6	4.8	4.9	5.0
	CvT	3.0	4.1	4.2	4.3	4.4	4.5	4.6	4.8	4.9	5.0
Rye§	CnT	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
	CvT	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1
Sorghum	CnT	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
	CvT	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8

† Baseline values were determined from the 2002–2013 study period, unless stated otherwise.

‡ The baseline, aboveground wheat, and sorghum biomass were estimated from average yield in the United States (1998–2013) by taking in account the relationship between US and South Carolina yield data over 1944–1997.

§ Rye yield was not projected to increase based on US yield data over 1940–2014.

Statistical Procedures

Mean square deviation (MSD) and linear regression were used to compare observed and simulated SOC values over the experimental period and to evaluate the overall CQESTR model performance. The MSD, which measures bias of the model, is the square of root mean square deviation (RMSD). It was partitioned into three components—lack of correlation (measures the scatter); nonunity slope (measures the degree of rotation of the regression line), and squared bias (measures the inequality between the arithmetic means of the *X* and *Y* values) —which are distinct, additive, and provide insight into the model performance and ANOVA interpretations (Kobayashi and Salam, 2000; Gauch et al., 2003). Pearson correlation (PROC CORR) was also used to determine the correlation between the simulated and observed response in SOC over the experimental period, as well the correlation between average annualized biomass inputs (treatment specific) and the change in SOC over the entire predictive period (SAS Institute, 2014). Residuals were used to compare the simulated with observed SOC values.

Results and Discussion

CQESTR Model Performance

There were 19 pairs of simulated and observed SOC values for the CvT and CnT treatments spanning 2002 to 2013 (Table 3, Fig. 1). Regression analysis of those pairs had an r^2 of 0.70 and a slope of 1.23, with a *P*-value of <0.0001. The overall MSD value [2.58 (Mg SOC ha^{-1})^2] had components of 1.05 for lack of correlation, 1.41 Mg SOC ha^{-1} for nonunity slope, and 0.12 Mg SOC ha^{-1} for square bias (Fig. 2). The lack of correlation component accounted for 59% of the MSD, indicating that deviations in the simulated and observed SOC values were largely due to scatter, presumably associated with inherent spatial and temporal SOC variability, as indicated by large SDs of the measured SOC values (Fig. 3 and 4). The residuals for the tillage systems were relatively small and were on average ∼2.0%, except for the 2002 sampling in the CnT and three sampling years (2002, 2004, and 2010) in the CvT treatments. In 2002, CQESTR overpredicted measured SOC value by 3.8 Mg SOC ha^{-1} in the CnT, and by 2.3 and 2.7 Mg SOC ha^{-1} for the 2002 and 2004 sampling in CvT, respectively, while underpredicting SOC by 2.78 Mg SOC ha^{-1} for 2010 sampling (Table 3). This could be related to different sampling protocols used at different sampling periods, as evidenced by differences in the SD error bars for each sampling period (Fig. 3 and 4).

Table 3. Residual difference between observed and estimated soil organic carbon (SOC) stocks (expressed as percentage of observed) under conventional tillage (CvT) and conservation tillage (CnT) for each sampling period.

Tillage	Soil sampling year	△SOC		
		Observed	Simulated	Residual
		Mg kg^{-1}		%
CvT	2002	17.42	19.68	13
	2004	17.97	20.66	15
	2005	20.81	20.91	0
	2006	19.27	20.77	8
	2007	22.19	21.51	3
	2008	20.04	21.72	8
	2009	22.03	21.96	0
	2010	24.65	21.86	11
	2011	23.18	22.11	5
	2012	22.40	21.91	2
CnT	2002	19.08	22.52	18
	2005	24.73	23.87	3
	2006	22.33	23.87	7
	2007	25.83	24.91	4
	2008	25.41	25.10	1
	2009	24.93	25.43	2
	2010	25.01	25.29	1
	2011	27.42	25.63	7
	2012	23.79	25.39	7

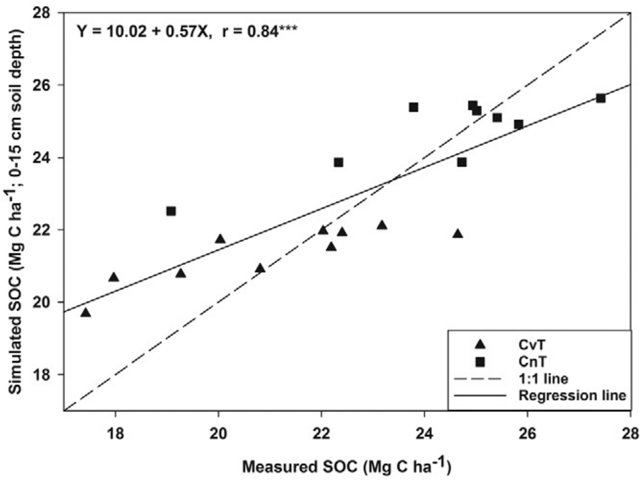

Fig. 1. Simulated and observed soil organic carbon (SOC) stocks within the top 15 cm for a Norfolk loamy sand soil in conventional (CvT) and conservation (CnT) tillage. The dotted line represents equal values for simulated and observed data. The solid line is the linear fit of simulated vs. observed SOC stocks.

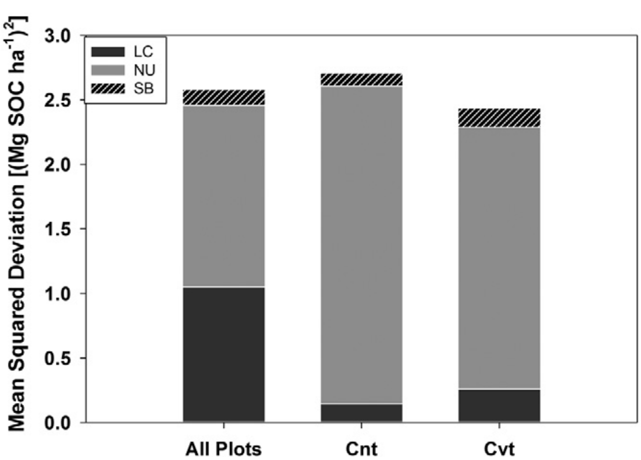

Fig. 2. Comparison of mean square deviations (MSD) for CQESTR simulations of soil organic carbon changes for all the simulated and each tillage system separately at Clemson University, Pee Dee Research Center. The scatter (lack of correlation, LC) component of MSD gives a measure of the scatter in the data. The translation (squared bias, SB) component of MSD is a measure of the inequality of the means. The rotation (nonunity, NU) component contributes to the MSD when the slope of the regression line between simulated and observed values is ≠ 1. CnT, conservation tillage; CvT, conventional tillage.

Baseline Scenario: Crop Rotations and Tillage Effects

The simulated change in SOC at the 0- to 15-cm soil depth during the 2014 to 2033 predictive period for the SG-CT and C-SB w/Rye rotations ranged from −3.18 to 3.79 Mg C ha^{-1}, respectively, when averaged for CnT and CvT treatments (Table 4). The wide range in SOC stocks was strongly correlated (r = 0.99, P < 0.0001, data not presented) with annualized biomass inputs (Table 5). The SG-CT rotation had the least (5.1 Mg ha^{-1}) and C-SB w/Rye had the greatest (22.5 Mg ha^{-1}) average biomass for CnT and CvT treatments. These simulation results are consistent with multiple long-term field studies that have reported a positive correlation between the amount of crop residue added and SOC content (Paustian et al., 1997; Kong et al., 2005). Furthermore, the average biomass N content for the SG-CT rotation was 15.4 g kg^{-1}. This was the highest among all the crop rotations studied, excluding SG/WW-SB in CnT. Since the rate of SOM decomposition is commonly reported to increase with N content of residue (Cochran et al., 2006), the SG-CT may have also induced a greater loss of SOC compared with rotations with lower biomass N content, such as corn.

The CQESTR simulations do not factor in soil erosion. Therefore, the predicted increases (or decreases) in SOC from either the winter cover crop or the double-cropping scenario were a function of biomass input (Table 5). Simply incorporating a rye cover crop into either C-CT or C-SB rotations during the 20-yr period was projected to increase SOC by 2.26 (358%) and 2.55 Mg C ha^{-1} (271%), respectively, averaged across the tillage treatments. These predictions were similar to findings reported in a review by Causarano et al. (2006), which showed that SOC content in southeastern US fields can be doubled when cover crops are combined with CnT.

The addition of winter wheat as a double crop was predicted to increase SOC within the 0- to 15-cm layer by 1.26 Mg C ha^{-1} (142%) with the C/WW-SB rotation and to reduce SOC loss by 22% with the SG/WW-SB rotation in CvT by 2033 (Table 4, Fig. 3). The addition of double-cropped winter wheat had less impact on SOC than the annual rye cover crop (2.15 vs. 3.19 Mg C ha^{-1}). However, it is important to note that the predicted response was not a function of reduced biomass production with winter wheat. It was instead due to the fact that winter wheat was planted biannually, versus an annual planting of rye.

Soil organic C decreased when corn was replaced with sorghum in the rotation (Table 4, Fig. 3). Under nondrought conditions, the quantity of crop residue provided by sorghum is often significantly less than for corn (Johnson et al., 2006). Therefore, replacing corn with sorghum in rotations would likely have a negative impact on long-term regional SOC stocks, especially when combined with cotton, which also has a low residue input to the soil (Causarano et al., 2006). The CQESTR simulations further illustrated the importance of including corn, a winter cover crop, and/or double cropping with winter wheat to offset low residue production associated with cotton or sorghum. This would provide enough residue to significantly increase SOC stocks.

Differences in annual biomass input between CvT and CnT for the 12-yr field study were minimal (0.0–0.7 Mg ha^{-1}) for all crop rotations (Table 5). However, the model predicted that CnT would increase SOC content 10 to 45% in the 0- to 15-cm layer by 2033 for six of eight crop rotations. All of these included corn and/or double-cropped wheat (Table 4). Adoption of CnT in the southeastern United States often increases SOC compared with CvT (Causarano et al., 2006; Franzluebbers, 2010), but it is not always clear whether the response is due to reduced soil disturbance, decreased residue incorporation, increased biomass input, or lower SOC decomposition (Franzluebbers, 2004). Since biomass inputs between CnT and CvT were similar and the CQESTR model simulations do not factor in soil erosion, the predicted response in SOC to tillage was solely a function of reduced residue incorporation into the soil and lower rates of SOM decomposition. These model predictions support findings from around the southeastern United States that report SOC increases for CnT compared with CvT (Franzluebbers, 2005, 2010; Causarano et al., 2006). Small reductions in SOC within the top 15 cm by 4 and 9% for the SG-CT and SG-SB rotations were predicted in CnT compared with CvT for 2014 through 2033. A possible explanation for this was that the SG-SB and SG-CT rotations had the lowest

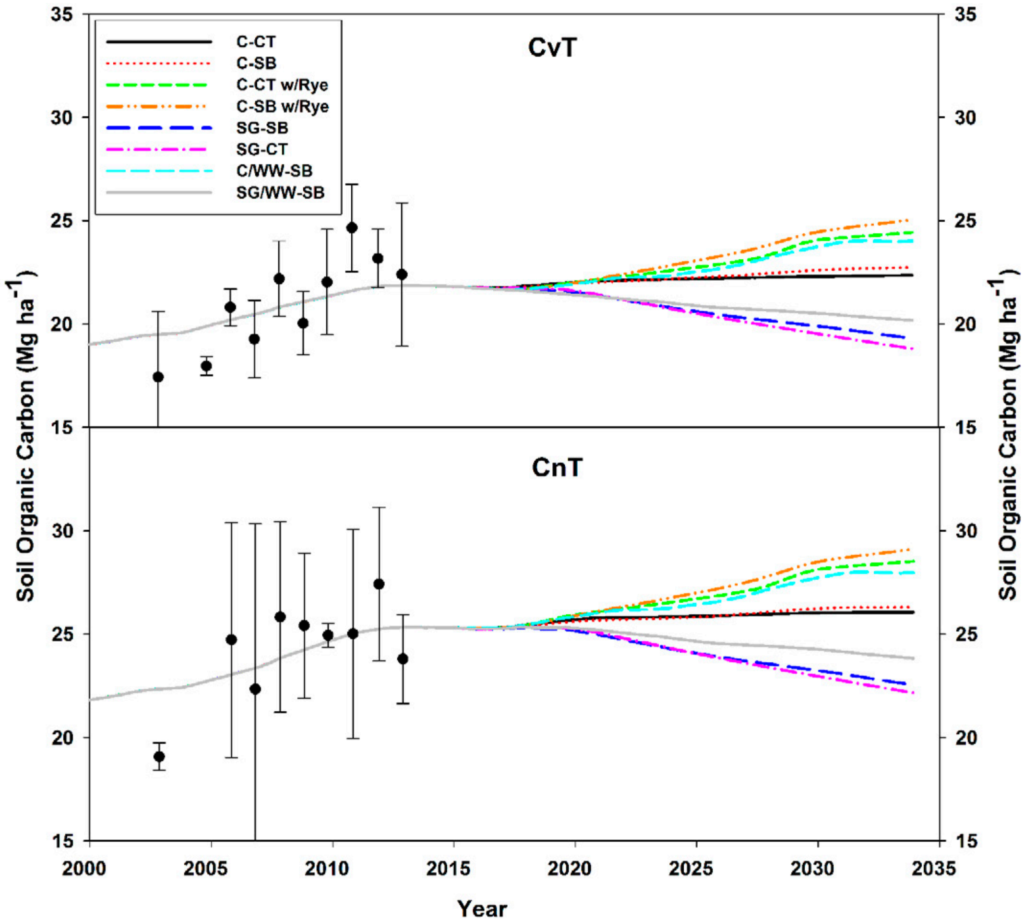

Fig. 3. Baseline scenario simulated (lines) and observed (circles) soil organic carbon (SOC) at the 0- to 15-cm soil depth for crop rotations (corn–cotton [C-CT], corn–soybean [C-SB], corn–cotton with rye cover [C-CT w/Rye], corn–soybean with rye cover [C-SB w/Rye], sorghum–soybean [SG-SB], sorghum–cotton [SG-CT], corn/winter wheat–soybean [C/WW-SB], sorghum/winter wheat–soybean [SG/WW-SB]) with conventional (CvT) and conservation (CnT) tillage at the Clemson University, Pee Dee Research Center. The baseline scenario assumed that climate and crop biomass production after 2013 remained at the 2002 to 2013 study average. Bars on the observed SOC values represent the SDs (*n* = 3).

average annual biomass inputs (5.1–8.0 Mg ha^{-1}) among the eight crop rotations evaluated. Therefore, these model predictions indicated that when crop production differences between CnT and CvT are minimal, the response in SOC will vary according to the amount of residue returned to the soil due to the crop rotation in this loamy sand soil.

Unlike many C models, CQESTR includes a soil C saturation factor (Stewart et al., 2007). As a result, the rate of SOC accumulation was predicted to decrease around 2030 with the highest residue-providing cropping systems (i.e., C-CT w/Rye, C-SB w/Rye, and C/WW-SB) for both tillage systems (Fig. 3). The model indicated that soil C saturation, which is an upper limit for the stabilization of the added organic material by silt and clay particles, within the top 15 cm may be reached soon after 2030. Therefore, gains in SOC due to management that simply maximizes biomass inputs may have limited impact after 2030. This suggests that soil C saturation in the 5- to 15-cm depth has not been reached, but supports conclusions of Novak et al. (2007) that C saturation within the surface 5 cm had already been reached with CvT in 2002. Both of these predictions suggest that increasing SOC in sandy loam soil in the US southeastern Coastal Plains by simply using best management practices and CnT may be limited if only the top 15 cm of soil are considered.

Climate Change-Only Scenario: Rotations Effects Modified by Climate

The climate change-only simulations predicted a small decrease in SOC of −7 to −15% in the top 15 cm between 2013 and 2033 for all eight crop rotations, indicating little impact of climate change-only relative to crop rotation management (Table 6, Fig. 4). A possible cause was that a small increase in temperature and precipitation resulted in an increased SOM decomposition rate, which agrees with previous research (Schimel et al., 1994). The greatest impact of climate change on SOC stocks in the southeastern United States will presumably occur indirectly through reduced crop production and residue input (Neenu et al., 2013). However, significant reductions in most major crops grown in the region (because of climate change) will likely not occur by 2033 based on the current climate, climate change predictions, and the optimum temperature ranges reported for crops grown in the region (Hatfield et al., 2008).

The addition of a winter cover crop (double-cropped winter wheat or annual rye) was predicted to minimize SOC loss through 2033 by counteracting an increased rate of SOM decomposition through increased residue inputs (Table 4, Fig. 4). Climate change interaction with crop rotation resulted in minimal loss of SOC at the 0- to 15-cm soil depth in the following order: C-CT = C-SB ~ C-CT w/Rye = SG-CT = SG-SB

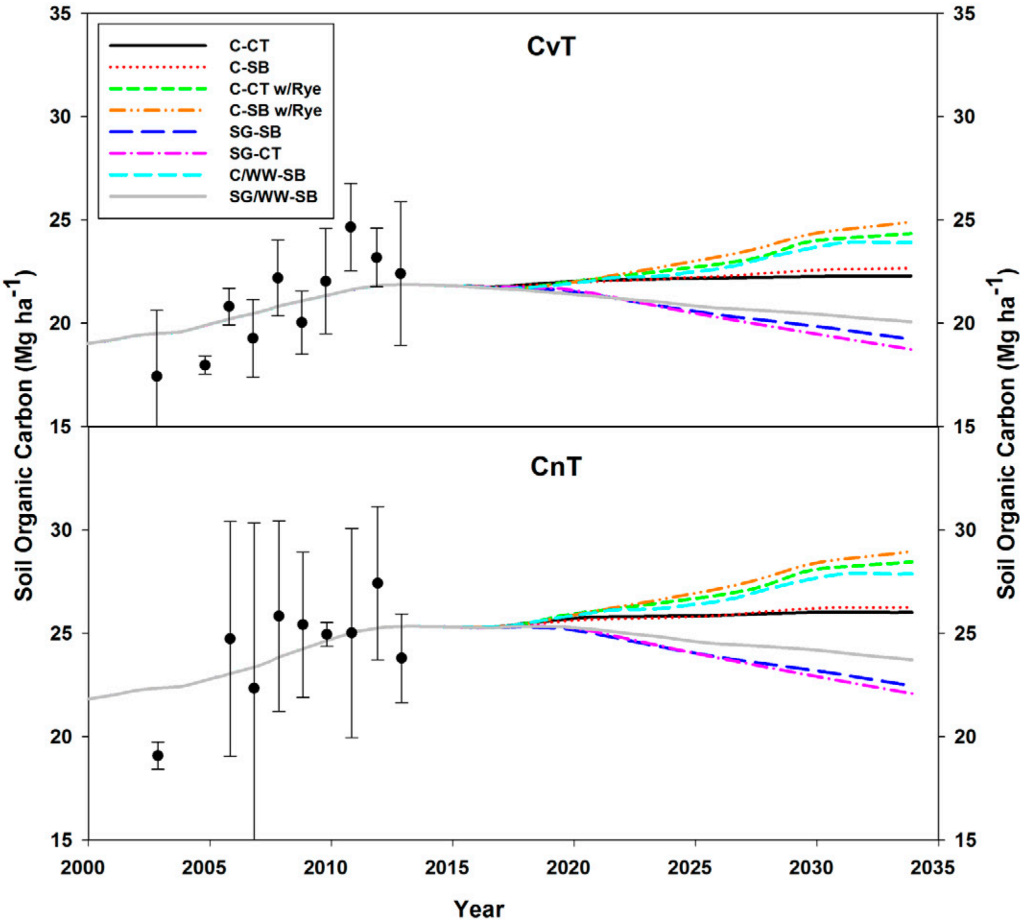

Fig. 4. Climate change scenario simulated (lines) and observed (circles) soil organic carbon (SOC) at the 0- to 15-cm soil depth for crop rotations (corn–cotton [C-CT], corn–soybean [C-SB], corn–cotton with rye cover [C-CT w/Rye], corn–soybean with rye cover [C-SB w/Rye], sorghum–soybean [SG-SB], sorghum–cotton [SG-CT], corn/winter wheat–soybean [C/WW-SB], sorghum/winter wheat–soybean [SG/WW-SB]) with conventional (CvT) and conservation (CnT) tillage at the Clemson University, Pee Dee Research Center. Climate change assumed that crop biomass production after 2013 remained at the 2002 to 2013 study average with an increase in average increase in temperature of 0.5°C and a 2.1% increase in precipitation by 2033. Bars on the observed SOC values represent the SDs (*n* = 3).

< C/WW-SB = SG/WW-SB < C-SB w/Rye. The predicted responses indicate that adding winter crops (winter wheat or rye) to traditional crop rotations such as C-CT or C-SB may be an effective management practice to minimize the negative impact that climate change may have on SOC stocks through 2033.

Yield Trend Scenario: Rotation Effects Modified by Crop Yield

In addition to climate change, crop yield trends and the subsequent impact on biomass inputs are important factors when predicting SOC changes due to crop rotation and tillage. The yield trend CQESTR simulations, which accounted for yield growth trends, predicted a greater 20-yr SOC response within the top 15 cm than the climate change scenarios (Table 6, Fig. 5). On the basis of current yield trends, SOC accumulation was projected to stay at the current value for SG-CT or increase up to 0.28 Mg C ha^{-1} for all rotations that included corn and/or a winter crop, when compared with the baseline simulations. Furthermore, as predicted by the baseline simulations, CnT was predicted to increase SOC accretion by 9 to 46% when compared with CvT for rotations other than SG-SB or SG-CT. There was no apparent tillage × yield interaction for these cropping systems at this site. Technological advances in plant breeding and management such as pesticides, herbicides, tillage practices, and planting equipment have increased crop production and are currently outpacing negative impacts of rising temperatures, continuing positive yields trends for most major crops (Reilly and Fuglie, 1998; Lobell and Field, 2007). Recent data show that corn, soybean, soft red winter wheat, and cotton (seed) yields are increasing at rates of 117, 26, 50, and 9 kg ha^{-1} yr^{-1}, respectively, although US rye and sorghum yields have remained stagnant over the period of 1975 to 2014 (USDA-NASS, 2014; USDA-ERS, 2015a, 2015b, 2015c, 2017). Except for corn (Hatfield et al., 2008), climate change predictions through 2033 for South Carolina do not exceed the reported optimum temperature ranges for crops being grown in the region. Therefore, it is plausible that crop yield trends can remain at current rates through 2033 if technological advancements continue at a similar rate.

Climate + Yield Scenario

The effect of climate + yield was minimal. This resulted in a net change similar to the baseline scenario (Table 7). According to CQESTR predictions, climate change effects would have to increase the prevalence and severity of drought to the point that corn production would be drastically reduced for sorghum to be a viable alternative that still maintains SOC stocks. Soil organic C stocks with SG-SB and SG-CT rotations were predicted to decrease up to 1% because of limited yield growth of sorghum

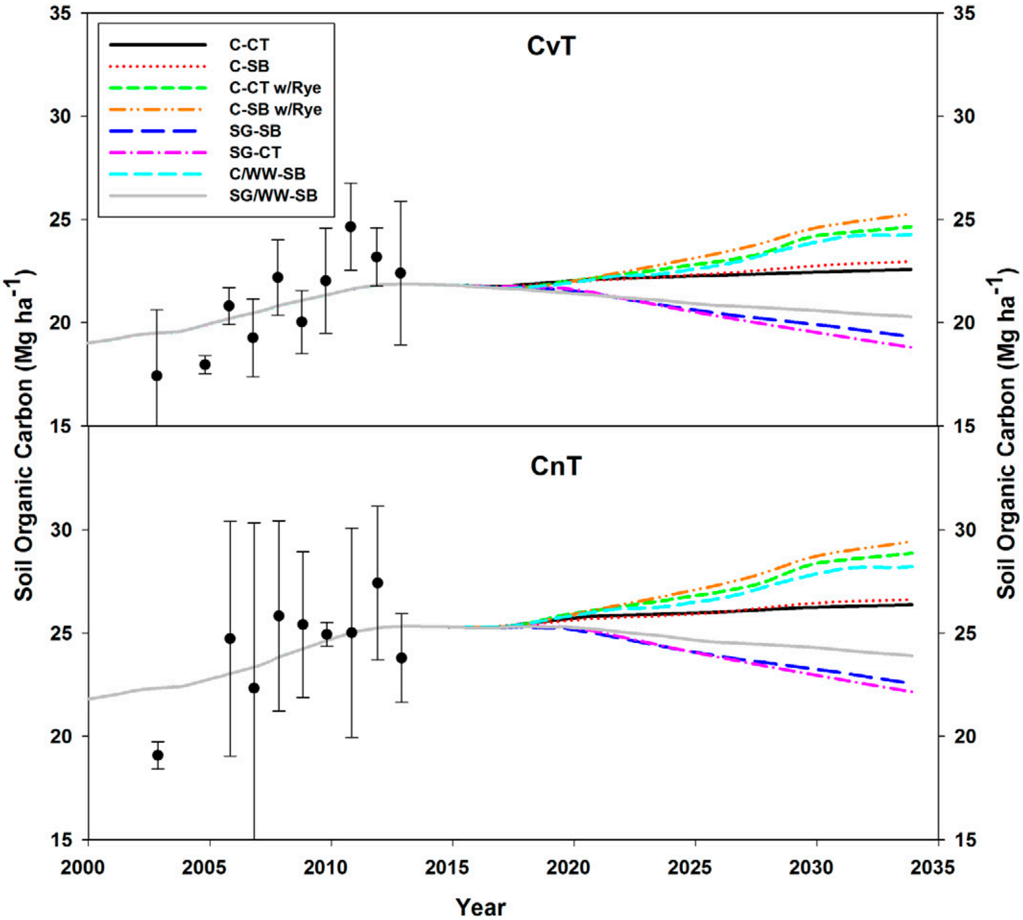

Fig. 5. Yield trend scenario simulated (lines) and observed (circles) soil organic carbon (SOC) at the 0- to 15-cm soil depth for crop rotations (corn–cotton [C-CT], corn–soybean [C-SB], corn–cotton with rye cover [C-CT w/Rye], corn–soybean with rye cover [C-SB w/Rye], sorghum–soybean [SG-SB], sorghum–cotton [SG-CT], corn/winter wheat–soybean [C/WW-SB], sorghum/winter wheat–soybean [SG/WW-SB]) with conventional (CvT) and conservation (CnT) tillage at the Clemson University, Pee Dee Research Center. Yield trend scenario factored in changes in biomass inputs due to crop yield trends. Bars on the observed SOC values represent the SDs (*n* = 3).

and cotton. However, sorghum is drought tolerant and may become a viable alternative to corn in the southeastern United States if water stress becomes prevalent (Assefa et al., 2010). Furthermore, despite a 26-kg ha^{-1} yr^{-1} yield increase for soybean, biomass inputs were not predicted to increase significantly with yield based on the yield–biomass relationship calculated using the 12-yr observed data (Table 5). Morrison et al. (1999) and Bender et al. (2015) also reported that recent yield growth of soybean has been due to an increased harvest index. This indicates that although crop yield growth could play a major role in increasing future SOC stocks, selecting crops that have biomass/grain yield ratios that are closer to 1:1 will maximize the SOC response. Simulation results indicated that CnT will be more effective than CvT in increasing SOC stocks in simple rotations (i.e., C-CT and C-SB) or rotations that include corn with rye cover crop or winter wheat (i.e., C-CT w/Rye and C/WW-SB) rather than with sorghum in the rotation.

In addition to climate change, crop yield trends and the subsequent impact on biomass inputs are important factors when predicting SOC changes due to crop rotation and tillage. The greatest impact of climate change on SOC stocks in the southeastern United States will presumably occur indirectly through

Table 4. The CQESTR simulated change in soil organic C (SOC) at the 0- to 15-cm soil depth during 2014 to 2033 in response to tillage and crop rotation in baseline scenarios.

Scenario	Tillage†	Depth	ΔSOC							
			Crop rotation‡							
			C-CT	C-SB	C-CT w/Rye	C-SB w/Rye	SG-SB	SG-CT	C/WW-SB	SG/WW-SB
		cm	Mg C ha^{-1}							
Baseline§	CvT	0–15	0.51	0.89	2.57	3.19	−2.56	−3.05	2.15	−1.68
Baseline	CnT	0–15	0.74	0.99	3.21	3.79	−2.79	−3.18	2.66	−1.51

† CvT, conventional tillage practices comprised annual disking and in-row subsoiling and paratillage; CnT, conservation tillage comprised of annual in-row subsoiling and paratillage only.

‡ C-CT, corn–cotton; C-SB, corn–soybean; C-CT w/Rye, corn–cotton with rye cover; C-SB w/Rye, corn–soybean with rye cover; SG-SB, sorghum–soybean; SG-CT, sorghum–cotton; C/WW-SB, corn/winter wheat–soybean; SG/WW-SB, sorghum/winter wheat–soybean.

§ Baseline scenario assumed that climate and crop biomass production after 2013 remained at the 2002–2013 study average.

reduced crop production and residue input (Neenu et al., 2013). However, significant reductions in most major crops grown in the region (because of climate change) will likely not occur by 2033 based on the current climate, climate change predictions, and the optimum temperature ranges reported for crops grown in the region (Hatfield et al., 2008). Yield growth assumptions are a major source of variation in future SOC stock projections (Donigian et al., 1994). Predicted SOC changes were very similar between scenarios that factored in yield growth trends, with or without climate change. This further indicates that yield growth may be a more important factor than climate change for regional SOC accretion over the next 20 yr.

Conclusions

High-residue-producing crop rotations, such as those that include corn and/or winter crops, will likely result in the greatest accumulation of SOC in the 0- to 15-cm soil depth by 2033. Under current production levels with existing cultivars, sorghum

Table 5. Average annualized biomass inputs and N content, averaged during 2002 to 2013 at Clemson University, Pee Dee Research Center for each crop rotation used as the baseline inputs in the CQESTR model simulations.

Crop rotation†	Tillage‡	Annualized biomass input			Biomass N content§
		Aboveground	Root	Total	
		Mg ha^{-1}			g kg^{-1}
C-CT	CvT	9.1	4.7	13.8	9.9
	CnT	9.3	4.6	13.9	9.4
C-SB	CvT	10.8	5.9	16.7	10.1
	CnT	11.0	5.8	16.8	9.9
C-CT w/Rye	CvT	13.2	6.0	19.2	10.9
	CnT	13.9	6.0	19.9	11.1
C-SB w/Rye	CvT	14.9	7.2	22.1	10.9
	CnT	15.6	7.2	22.8	11.2
SG-SB	CvT	5.7	2.4	8.1	13.8
	CnT	5.7	2.3	8.0	14.2
SG-CT	CvT	4.0	1.1	5.1	15.4
	CnT	4.0	1.1	5.1	15.4
C/WW-SB	CvT	12.3	6.8	19.1	11.4
	CnT	12.5	6.7	19.2	11.3
SG/WW-SB	CvT	7.2	3.2	10.4	15.4
	CnT	7.2	3.2	10.4	15.8

† Sorghum and winter wheat biomass and N concentration values were estimated based on US crop yields, South Carolina crop yields, and literature. C-CT, corn–cotton; C-SB, corn–soybean; C-CT w/Rye, corn–cotton with rye cover; C-SB w/Rye, corn–soybean with rye cover; SG-SB, sorghum–soybean; SG-CT, sorghum–cotton; C/WW-SB, corn/winter wheat–soybean; SG/WW-SB, sorghum/winter wheat–soybean.

‡ CvT, conventional tillage practices comprised annual disking and in-row subsoiling and paratillage; CnT, conservation tillage comprised of annual in-row subsoiling and paratillage only.

§ Biomass N content was calculated for crop rotations by factoring in biomass contributions by individual crops in each rotation.

Table 6. Twenty-year CQESTR simulated soil organic C (SOC) changes at the 0- to 15-cm soil depth in response to climate change (CC), yield trend (YT) for each crop rotation, and their comparison with the baseline (BL) simulation scenarios, averaged across conventional and conservation tillage systems during the predictive period (2014–2033).

Crop rotation†	ΔSOC				
	Scenario				
	BL‡	CC§	Difference BL to CC	YT¶	Difference BL to YT
	Mg C ha^{-1}				
C-CT	0.63	0.56	−0.07	0.89	+0.26
C-SB	0.94	0.87	−0.07	1.21	+0.27
C-CT w/Rye	2.89	2.81	−0.08	3.17	+0.28
C-SB w/Rye	3.49	3.34	−0.15	3.77	+0.28
SG-SB	−2.68	−2.76	−0.08	−2.66	+0.02
SG-CT	−3.12	−3.20	−0.08	−3.12	+0.00
C/WW-SB	2.41	2.30	−0.11	2.65	+0.24
SG/WW-SB	−1.60	−1.71	−0.11	−1.50	+0.10

† C-CT, corn–cotton; C-SB, corn–soybean; C-CT w/Rye, corn–cotton with rye cover; C-SB w/Rye, corn–soybean with rye cover; SG-SB, sorghum–soybean; SG-CT, sorghum–cotton; C/WW-SB, corn/winter wheat–soybean; SG/WW-SB, sorghum/winter wheat–soybean.

‡ BL, baseline scenario assumed that climate and crop biomass production after 2013 remained at the 2002 to 2013 study average.

§ CC, climate change scenario factors in climate predictions for the Florence, SC after 2013 but assumed that the crop biomass production remained at the 2002 to 2013 study average.

¶ YT, yield trend scenario factors in future changes in biomass inputs based on US crop yield trends and the yield and biomass regression equations calculated from data from the study site but assumed that the climate conditions remained at the 2002 to 2013 study average.

Table 7. Twenty-year CQESTR simulated soil organic C (SOC) changes at the 0- to 15-cm soil depth in response to climate + yield trend for each crop rotation under conventional (CvT) or conservation (CnT) system and their comparison with the baseline simulation scenarios during the predictive period (2014–2033).

Scenario	Tillage†	Depth	ΔSOC Crop rotation‡ C-CT	C-SB	C-CT w/Rye	C-SB w/Rye	SG-SB	SG-CT	C/WW-SB	SG/WW-SB
		cm	Mg C ha^{-1}							
Baseline§	CvT	0–15	0.51	0.89	2.57	3.19	−2.56	−3.05	2.15	−1.68
Baseline	CnT	0–15	0.74	0.99	3.21	3.79	−2.79	−3.18	2.66	−1.51
Climate + yield¶	CvT	0–15	0.65	1.03	2.69	3.27	−2.62	−3.13	2.30	−1.68
Climate + yield	CnT	0–15	0.99	1.23	3.45	3.96	−2.86	−3.26	2.79	−1.54

† CvT, conventional tillage practices comprised annual disking and in-row subsoiling and paratillage; CnT, conservation tillage comprised of annual in-row subsoiling and paratillage only.

‡ C-CT, corn–cotton; C-SB, corn–soybean; C-CT w/Rye, corn–cotton with rye cover; C-SB w/Rye, corn–soybean with rye cover; SG-SB, sorghum–soybean; SG-CT, sorghum–cotton; C/WW-SB, corn/winter wheat–soybean; SG/WW-SB, sorghum/winter wheat–soybean.

§ Baseline scenario assumed that climate and crop biomass production after 2013 remained at the 2002 to 2013 study average.

¶ Climate + yield scenario factored in both climate change predictions and changes in biomass inputs due to crop yield trends.

is not a viable option to replace corn in rotation, when SOC accumulation is the primary goal. Simulation predictions indicate that soil C saturation may be reached soon after 2030 in high-residue cropping systems. Therefore, increasing SOC deeper in the soil profile will be required for long-term SOC accretion beyond 2030 in the sandy loam soils of the southeastern Coastal Plains. Soil organic C is predicted to increase with the adoption of CnT, even though crop production may be similar between CnT and CvT. The combination of high residue crop rotations with CnT is the best management option to increase long-term SOC accretion, because accumulation of SOC with CnT was predicted to increase with annualized biomass inputs.

Increasing air temperatures would likely facilitate SOC loss by increasing the rate of SOM decomposition. However, climate change may not significantly affect crop production in South Carolina by 2033 based on current climate, climate change predictions, and optimum temperature ranges for crops grown in the region.

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