Simulated Soil Organic Carbon Changes in Maryland Are Affected by Tillage, Climate Change, and Crop Yield


Abstract
The impact of climate change on soil organic C (SOC) stocks in no-till (NT) and conventionally tilled (CT) agricultural systems is poorly understood. The objective of this study was to simulate the impact of projected climate change on SOC to 50-cm soil depth for grain cropping systems in the southern Mid-Atlantic region of the United States. We used SOC and other data from the long-term Farming Systems Project in Beltsville, MD, and CQESTR, a process-based soil C model, to predict the impact of cropping systems and climate (air temperature and precipitation) on SOC for a 40-yr period (2012–2052). Since future crop yields are uncertain, we simulated five scenarios with differing yield levels (crop yields from 1996–2014, and at 10 or 30% greater or lesser than these yields). Without change in climate or crop yields (baseline conditions) CQESTR predicted an increase in SOC of 0.014 and 0.021 Mg ha\(^{-1}\) yr\(^{-1}\) in CT and NT, respectively. 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% led to SOC decreases between 2 and 8% compared with 2012 levels. Increasing crop yield by 10 and 30% was sufficient to raise SOC 2 and 7%, respectively, above the climate-only scenario under both CT and NT between 2012 and 2052. Results indicate that under these simulated conditions, the negative impact of climate change on SOC levels could be mitigated by crop yield increases.

Core Ideas
- Soil organic C was greater in a no-till than a conventional tillage system.
- CQESTR model-simulated soil organic C increased under both systems.
- CQESTR-simulated soil organic C decreased under climate change.
- Simulated soil organic C decreased under climate change when yields were reduced.
- Simulated soil organic C increased under climate change when yields were increased.

Soil Organic Matter (SOM), which is ~58% C, is the foundation of soil quality and soil function. It is critical to the development and stabilization of soil aggregates (Tisdall and Oades, 1982; Six et al., 2000), which, in surface soils, are correlated with reduced soil erosion and reduced sediment and nutrient losses (Albers and Moldenhauer, 1981; Lal, 1997). Soil organic matter contributes substantially to a soil’s water-holding capacity, water infiltration rate, fertility, and biological activity and improves soil aeration, root penetration, and pH buffering (Allison, 1973; Janzen, 2006).

Cultivation has resulted in the loss of 30 to 50% of soil organic C (SOC) present in native ecosystems for many soils in the United States (Kucharik et al., 2001; David et al., 2009). Although factors such as artificial drainage have contributed to these losses (David et al., 2009), tillage is an important factor. Tillage accelerates SOM decomposition by placing residues in the soil, where decomposition conditions are often more favorable than on the soil surface, and by exposing physically protected SOC when soil structure is disrupted (Douglas et al., 1980; Christensen, 1986; Roberts and Chan, 1990; Reicosky and Lindstrom, 1993). In addition, tillage increases SOC losses via soil erosion and runoff (Paustian et al., 1995). In the US Southeast, SOC loss due to cultivation has been estimated at 36%, which is higher than for many regions of the United States due to relatively high rainfall and air temperatures, which favor high soil erosion and SOC decomposition rates (Franzluebbers, 2005; Franzluebbers and Follett, 2005). Increasing SOC to improve soil function is therefore especially important in the US Southeast, an area that encompasses the southern Mid-Atlantic states of Maryland, Delaware, Virginia, and North Carolina.

Soil organic matter also has implications for the global climate. Since the world’s soils are the largest terrestrial pool of C, containing 2344 Gt of C in the form of SOM, 1500 Gt of which is within 1 m of the surface, small changes in this pool can affect the atmospheric concentration of CO\(_2\), the dominant greenhouse gas (Schlesinger, 2000; Stockmann et al., 2013). Although fossil fuel combustion is the largest source of the increasing atmospheric concentration of CO\(_2\), loss of SOM from soils has also contributed to ~19% of this increase (Lal, 2003; Houghton).
et al., 1983). On a global scale, reversing SOM losses in agricultural soils by sequestering C could offset up to 5 to 15% of fossil fuel CO₂ emissions (Lal, 2004), although recent analyses suggest that gains, if any, might be substantially lower (Powolson et al., 2014; VandenBygaart, 2016).

No-till (NT) agriculture has been promoted as an important means of sequestering C (Paustian et al., 1997; Lal, 2003; Sperow et al., 2003; Pacala and Socolow, 2004; Lal et al., 2007). Many, though not all, studies have shown that NT management increases SOM compared with conventional tillage (CT), especially in the top 20 cm of soil (Kern and Johnson, 1993; Paustian et al., 1995; Angers et al., 1997; Six et al., 2002; West and Post, 2002; Alvarez, 2005; Franzluebbers, 2005; Franzluebbers and Follett, 2005). In the United States, some of the greatest C sequestration rates for NT versus CT systems have been found in the Southeast (Franzluebbers and Follett, 2005). Franzluebbers (2005) reported rates of 0.42 ± 0.46 Mg C ha⁻¹ yr⁻¹ after 10 ± 5 yr, whereas Dell and Novak (2012) reported a value of 0.50 Mg C ha⁻¹ yr⁻¹ from more recent studies in the eastern United States. On average, SOC under NT was 16% greater than under CT in the US Southeast (Franzluebbers, 2005). Higher SOM under NT management results in increased water-stable aggregates and maintenance of larger aggregates than in CT soils (Bear et al., 1994; Six et al., 2000; Green et al., 2005; Grandy et al., 2006).

No-till also increases water infiltration and reduces runoff and erosion (Laflen and Tabatabai, 1984; Pesant et al., 1987; Ghidey and Alberts, 1998; Rhoton et al., 2002).

On a per-area basis, states in the southern Mid-Atlantic region have among the highest rates of NT adoption. Although 35% of US cropland acres were under NT management in 2012, rates in Maryland and Delaware were higher than in any other state (55 and 50%, respectively; USDA NASS, 2014). North Carolina and Virginia had the 6th and 10th highest adoption rates at 40 and 32% (Doberstein, 2014; USDA NASS, 2014).

Since NT management can increase soil water infiltration rate and water-holding capacity, NT is often considered an important means of adapting to the altered rainfall patterns associated with climate change (Powolson et al., 2014). However, the impact of climate change on the SOC stocks in NT that contribute to this adaptation potential is poorly understood (Pan et al., 2010; van Groenigen et al., 2014; Maas et al., 2017). Mechanistic process-based models of SOC dynamics can be used to evaluate these changes (Paustian et al., 2016). A number of models (e.g., CENTURY, NCSoil, Environmental Policy Integrated Climate [EPIC], and RothC) are available for these analyses, but most require large amounts of data and/or the C pools are difficult if not impossible to measure (Liang et al., 2009). CQESTR was developed to address these concerns, as it uses readily available input data and C pools are depicted as a continuum (Rickman et al., 2001; Liang et al., 2009), as described by Lehmann and Kleber (2015). However, CQESTR does not predict crop yield (although it contains a crop growth algorithm) because of the complex interaction among plant growth, climate, soil, and biotic factors such as disease and insect and microbial infestations.

The CQESTR model has been shown to reliably predict SOC very well for a variety of agricultural management practices, including CT and NT, within long-term agroecological research sites in North America that represent a wide range of climates, soil textures, and drainage classes ($r^2 \geq 0.94$, $P \leq 0.0001$, slopes not different than one between measured and CQESTR predicted SOC stocks; Liang et al., 2008, 2009; Gollany et al., 2011). These validations indicate that the CQESTR model is a robust tool to evaluate the expected impacts on SOC levels of climate change over time (Liang et al., 2009).

Climate change impacts on crop yields are highly uncertain. While the $\sim$0.4°C increase in annual global temperatures between 1981 and 2000 has resulted in a loss of 2 to 3% of corn (Zea mays L.) and wheat (Triticum aestivum L.) yields at a global scale, technological yield gains over the same time period resulted in net yield increases of $\sim$40 to 50% (Lobell and Field, 2007). Parsing the trajectory of future crop yields, however, is much more difficult, since the effects of improvements in crop genetics, management innovations, or farmer adaptability are unknown and may not reflect historical patterns (Alexandrov and Hoogenboom, 2000; Crane et al., 2011). In addition, there is considerable geographical variation in crop responses to multiple factors (Lobell and Field, 2007). Models using current crop varieties indicate that rainfall and corn yields could decrease by $\sim$6 to 20% and up to 14%, respectively, under climate change in the US Southeast; soybean [Glycine max (L.) Merr.] yields, however, are predicted to increase by up to 44% (percentages estimated from graphs in Alexandrov and Hoogenboom, 2000). The objective of this study was to simulate the impact of projected climate change on SOC in the southern Mid-Atlantic region for a 40-yr period (2012–2052) using the CQESTR model, SOC, and other data from the long-term Farming Systems Project (FSP), in Beltsville, MD. Since future crop yields are uncertain (Crane et al., 2011), we ran simulation scenarios at five crop yield levels: crop yields from 1996 to 2014, and at 10 or 30% greater or lesser than 1996 to 2014 yields.

**Materials and Methods**

**Site Description and Management Practices**

The data used in this modeling study were obtained from the FSP, a long-term agroecological research site located at the Beltsville Agricultural Research Center in Beltsville, MD (39°01'N, 76°53'W). The study site is at the western edge of the Atlantic Coastal Plain and was in NT production for at least 11 yr prior to research plots being established in 1996. The soil types at the field site were predominantly Christiana (fine, kaolinitic, mesic Typic Paleudults), Keyport (fine, mixed, semi-active, mesic Aquic Hapludults), Matapeake (fine-silty, mixed, semiactive, mesic Typic Hapludults), and Mattapex (fine-silty, mixed, active, mesic Aquic Hapludults) silt loams (Cavigelli et al., 2005). Weather data collected at the field site from 1997 to 2013 and from a nearby location in 1996 were used as the baseline weather conditions for the model simulations. The average annual precipitation for the modeling period was 1005 mm, and average annual temperature was 13.1°C, with monthly average daily temperature minimum and maximum occurring in January (1.3°C) and July (24.6°C), respectively.

Data from 1996 to 2014 for four replications of two management systems were used in the model simulations. Both systems followed the same 3-yr crop rotation: corn–rye (Secale cereale L.)/soybean–winter wheat/soybean. The rye served as a cover crop. One system was a continuous NT treatment, and the other was a CT system with a chisel plow used for primary
tillage followed by disking, field cultivating, and cultipacking to prepare a seedbed for corn and full-season soybean (planted after the rye cover crop). Disking served as the primary tillage operation for the winter wheat crop. Rye and double-cropped soybean (planted after winter wheat harvest) were direct-seeded using a NT drill. Although cropping systems that use a chisel plow for primary tillage are sometimes considered conservation tillage systems, we refer to this system as CT because <30% of crop residues were left on the soil surface after seedbed preparation. Corn and soybean residues were returned to the soil, but wheat residue was harvested in both systems. Management in both systems followed University of Maryland recommendations for fertilizer and herbicide application rates and timing. Until 2000, both treatments followed a 2-yr corn–winter wheat/soybean rotation; in 2001, rotations were expanded to include a rye cover and a full-season soybean crop after the corn phase of the rotation. The experimental design is a split plot with cropping system as the main plot and crop rotation entry point as the split. Detailed descriptions of the field site, agricultural management practices, and experimental design can be found in previously published research (Cavigelli et al., 2008, 2009).

**Soil Sampling and Analyses**

Soils were sampled to a depth of 50 cm in 1996, 2006, and 2011 from one rotation entry point of the CT and NT treatments. Two cores were taken in 1996 (diameter = 5.0 cm), and four cores were taken in 2006 (diameter = 4.4 cm) and 2011 (diameter = 5.5 cm) along a transect in each replicated block to minimize differences in soil type, slope, aspect, and other soil properties between the two treatments. Samples were oven dried and stored until analyzed (in duplicate) for total C in 2016 using the dry combustion method (Sollins et al., 1999) with a Leco TruMac CN instrument. Prior to analysis, representative subsamples were hand ground with a mortar and pestle, oven dried at 60°C overnight, and weighed. Bulk density was measured by weighing oven-dried samples of known volume. Total C was considered equivalent to organic C, since earlier analyses showed no inorganic C at this site (data not shown). Percentage soil C was converted to megagrams C per hectare to a depth of 50 cm by multiplying by bulk density and appropriate multiplication factors. Student’s t test was used to compare SOC values between CT and NT in 1996, 2006, and 2011 and to compare changes in SOC between 1996 and 2011 using SAS 9.4 (SAS Institute, 2014).

**Description of the Model**

A process-based soil C model, CQESTR, which has been calibrated across North America to simulate the effects of management practices and climate change (Liang et al., 2009), was used to simulate the effect of FSP management practices. The CQESTR model operates on a daily time step, and each organic residue addition along with its placement is tracked independently (Liang et al., 2008, 2009). The rate of crop residue decomposition depends on soil texture, drainage class, soil temperature, water content, residue N content, and whether or not residue is incorporated into the soil. The inputs needed for the model simulation are aboveground biomass and N content of the biomass, root biomass, planting and harvest dates, organic amendment inputs, soil bulk density, soil texture, drainage class, initial SOC content, and mean monthly air temperature and precipitation. For each soil disturbance event (i.e., tillage and planting), the depth and percentage soil disturbance, as well as the percentage of residue remaining on the surface, were accounted for in the CQESTR simulations. Model input values used in the simulations (entire simulation [1996–2052], fitting period [1996–2011], and predictive period [2012–2052]) were obtained from 19 yr of field experiment data and published research and organized into crop management files associated with the e-factor file of the Revised Universal Soil Loss Equation (RUSLE, Version 1; Renard et al., 1996).

**Model Simulation Scenarios**

The fitting period of the model (1996–2011) used annual grain yield, biomass additions of winter cover crops, soil bulk density, and SOC content measured in 1996, 2006, and 2011. Model inputs such as biomass N content and the amount of aboveground and root biomass added to the soil were estimated using literature values. The aboveground biomass additions for grain crops (corn, soybean, and winter wheat) were estimated by multiplying field site grain yield data by harvest index obtained from literature (corn = 0.53, soybean = 0.46, winter wheat = 0.45) (Johnson et al., 2006). Root biomass for every crop was estimated based on root/shoot ratios obtained from the literature (corn = 0.42, soybean = 0.37, winter wheat = 0.31, annual rye = 0.31) (Bray, 1963; Sainju et al., 2005; Gray et al., 2014). The biomass N content values reported in Meisinger and Randall (1991) were used in the simulations.

The predictive period (2012–2052) was defined as the period of time that model input values required assumptions, since field data were not available. Six climate and crop yield scenarios were simulated for both cropping systems based on the inclusion or exclusion of climate change and five rates of crop yield increase or decrease over the predictive period. This is similar to the approach used by Gollany (2016). The baseline scenario assumed that crop yields and biomass inputs remained at the 1996 to 2014 average and that climate (mean monthly air temperature and precipitation) remained at the 2005 to 2014 average. A climate-only scenario assumed that biomass inputs remained at the 1996 to 2014 average, whereas midcentury climate predictions (mean monthly air temperature and precipitation) were used to alter the 2005 to 2014 average climate values over the predictive period. Four “climate and yield” scenarios factored in climate change but also included changes to the average biomass input values proportional to crop yield changes of 10 and 30% less and more than the 1996 to 2014 average. Thus, these four scenarios are termed “climate with x% yield” where x is 70, 90, 110, and 130 in the four separate scenarios.

The midcentury climate predictions used in the simulations were obtained from the North American Regional Climate Change Assessment Program (NARCCAP). The Canadian Regional Climate Model (CRCM) with boundary conditions from the Coupled Global Climate Model (CGCM3) developed by the Canadian Centre for Climate Modeling and Analysis was selected from 11 models because of its best representing the mean in the range of climate change predictions (Mearns et al., 2014). Climate change predictions were made in 3-mo periods (December to February, March to May, June to August, and September to November), and temporal response in the climate change predictions were accounted for in the CQESTR model. According to the climate model prediction, annual air temperature increased...
Carbon inputs were similar in CT and NT (Table 2), reflecting similar crop yields in the two systems (for corn and soybean: Teasdale and Cavigelli, 2017; for wheat: Cavigelli et al., 2008, unpublished data, 2017). In a review article, Franzluebbers (2005) also found no differences in corn, soybean, and wheat grain yields under NT and CT management in the US Southeast. Since crop rotations were identical in the two FSP systems, N concentration of inputs was also very similar in CT and NT systems (Table 2). Thus, the primary difference in factors affecting SOC between the two FSP systems was tillage. After 15 yr, SOC to a depth of 50 cm was greater in NT (60.1 Mg C ha$^{-1}$) than CT (53.0 Mg C ha$^{-1}$) ($P < 0.01$). This is consistent with results reported for the US Southeast, where 90% of 96 comparisons showed greater SOC under NT than CT (Franzluebbers, 2005; Franzluebbers and Follett, 2005), and for the eastern United States (Dell and Novak, 2012). At the FSP, differences were observed only in the top 10 cm of soil (data not shown), which is also consistent with results from other studies (Kern and Johnson, 1993; Angers and Eriksen-Hamel, 2008). Changes in SOC values between 1996 and 2011 were not significant due to the large variability in 1996 data (Fig. 1a and 1b).

### Effect of Tillage on Soil Organic Carbon

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### Table 1. Residual difference between observed and predicted soil organic C stocks (expressed as percentage of observed) under no-till and conventional tillage cropping systems at the USDA-ARS Farming Systems Project in Beltsville, MD.

<table>
<thead>
<tr>
<th>Cropping system</th>
<th>Year</th>
<th>Soil organic C</th>
<th>Observed</th>
<th>Predicted</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>—— Mg ha$^{-1}$ ——</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No-till</td>
<td>1996</td>
<td>54.5</td>
<td>60.6</td>
<td>11.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>57.6</td>
<td>60.1</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2011</td>
<td>60.1</td>
<td>60.1</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Conventional tillage</td>
<td>1996</td>
<td>61.3</td>
<td>57.2</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>53.3</td>
<td>56.4</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2011</td>
<td>53.0</td>
<td>56.8</td>
<td>7.2</td>
<td></td>
</tr>
</tbody>
</table>

### Results and Discussion

#### Performance of the CQESTR Model

The CQESTR simulated and measured SOC values at the 0- to 50-cm depth of the two cropping systems were used to evaluate the CQESTR model performance. Predictive performance of CQESTR is illustrated by the small calculated residuals for the two cropping systems (Table 1, Fig. 1a and 1b). The residuals for the three soil sampling times at the two FSP cropping systems were relatively small, averaging <5.9%, except for the 1996 sampling in the NT. In 1996, CQESTR overpredicted the measured SOC value in NT by 6.1 Mg SOC ha$^{-1}$ (Table 1). This could be related to differences in soil bulk density during the sampling time or because of different sampling protocols used at different sampling periods at the FSP.

#### Climate Change and Crop Production Effects on Soil Organic Carbon

Under baseline conditions (no change in climate or crop yields), CQESTR predicted an increase in SOC of 0.014 and 0.021 Mg ha$^{-1}$ yr$^{-1}$ in CT and NT, respectively (Table 3). The relatively low rate of increase in NT compared with other values reported for the eastern and southeastern United States (Franzluebbers, 2005; Dell and Novak, 2012) probably reflects that the NT system had been in place for at least 27 yr in 2012. The mean time in NT in studies reported by Franzluebbers (2005) is 10 ± 5 yr. Soil organic C accrual rates decrease exponentially with time under NT management and reach a new steady state level within 15 to 20 yr, on average (West and Post, 2002; West and Six, 2007). Thus, it is reasonable that SOC accrual rates would be lower between 27 and 67 yr after NT adoption (2012–2052). The small increase in SOC under CT 16 to 56 yr after establishment suggests that the CT system is also approaching a new steady-state level. Thus, results presented below reflect expected changes under climate change for relatively mature cropping systems.

Predicted climate change alone resulted in a 10-fold decrease in the rate of SOC increase predicted by CQESTR in NT, to only 0.002 Mg ha$^{-1}$ yr$^{-1}$, and led to a decrease in SOC of 0.017 Mg ha$^{-1}$ yr$^{-1}$ in CT (Table 3). Thus, climate change led to a substantially greater decrease in SOC levels compared with baseline values in the CT (0.031 Mg ha$^{-1}$ yr$^{-1}$) than in the NT system (0.009 Mg ha$^{-1}$ yr$^{-1}$). Since the climate change scenario used in this analysis included a 2.0°C increase in annual temperature but no change in annual precipitation, results suggest that soil managed using NT methods is better protected against temperature-induced SOC degradation than soil managed using CT methods.

Crop yield declines of 10% under the climate change scenario led to SOC decreases of 2 (0.030 Mg ha$^{-1}$ yr$^{-1}$) and 4% (0.050 Mg ha$^{-1}$ yr$^{-1}$) in NT and CT, respectively, between 2012 and 2052. With crop yield declines of 30%, SOC decreased 7 (0.099 Mg ha$^{-1}$ yr$^{-1}$) and 8% (0.116 Mg ha$^{-1}$ yr$^{-1}$) in NT and CT, respectively (Table 3). A decrease in crop yields at FSP under an increased temperature scenario is consistent with a recent study indicating that corn, and to a lesser extent soybean, varieties used from 1996 to 2014 were negatively affected by increased air temperatures during reproductive growth phases (Teasdale and Cavigelli, 2017). Recent modeling efforts in the US Southeast also predict decreased corn and wheat yields under increased temperatures due to a decrease in the number of days to maturity; soybean yields, however, are predicted to increase (Alexandrov and Hoogenboom, 2000). Since corn and wheat produce crop residues more resilient to decomposition than soybean, and corn produces substantially more residue than soybean (Paustian et al., 1997), yield decreases in corn and wheat, regardless of increases in soybean yields, would likely lead to decreases in SOC in crop rotations that include these three crops.

Increasing crop yield by 10 or 30% under the climate change scenario was sufficient to raise SOC above baseline levels under both NT and CT between 2012 and 2052. Soil organic C gains were in proportion to crop yield increases such that a 10% yield increase resulted in 2.4 and 1.2% (0.036 and 0.016 Mg ha$^{-1}$ yr$^{-1}$) increases in SOC, and a 30% yield increase resulted in 7 and 6% (0.101 and 0.083 Mg ha$^{-1}$ yr$^{-1}$) increases in SOC in NT and CT, respectively, during the 40-yr time period. Under this climate
change scenario, the negative impact of climate change on SOC levels was mitigated by crop yield increases.

Given the large impact of crop yields on results, what are likely crop yield trajectories in the southern Mid-Atlantic region? Although models using current crop varieties indicate that corn and wheat yields will decrease under climate change in the US Southeast, crop genetics or management changes such as altered planting dates or irrigation that could improve crop performance were not included in this analysis (Alexandrov and Hoogenboom, 2000). The importance of crop genetics is...
Table 2. Average annualized biomass inputs and nitrogen concentration, averaged during 1996 to 2014, used as inputs in the CQESTR model simulations for no-till and conventional tillage corn/rye–soybean/winter wheat–soybean rotations at the USDA-ARS Farming Systems Project in Beltsville, MD.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Simulation scenario</th>
<th>Baseline§</th>
<th>Climate only</th>
<th>Climate and 70% yield</th>
<th>Climate and 90% yield</th>
<th>Climate and 110% yield</th>
<th>Climate and 130% yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-till</td>
<td>0–50 cm 2012</td>
<td>60.12</td>
<td>60.12</td>
<td>60.12</td>
<td>60.12</td>
<td>60.12</td>
<td>60.12</td>
</tr>
<tr>
<td>No-till</td>
<td>0–50 cm 2022</td>
<td>59.94</td>
<td>59.91</td>
<td>59.64</td>
<td>59.81</td>
<td>60.05</td>
<td>60.31</td>
</tr>
<tr>
<td>Conv-till</td>
<td>0–50 cm 2012</td>
<td>56.82</td>
<td>56.82</td>
<td>56.82</td>
<td>56.82</td>
<td>56.82</td>
<td>56.82</td>
</tr>
<tr>
<td>Conv-till</td>
<td>0–50 cm 2022</td>
<td>56.34</td>
<td>56.26</td>
<td>55.83</td>
<td>56.12</td>
<td>56.40</td>
<td>56.69</td>
</tr>
<tr>
<td>Conv-till</td>
<td>0–50 cm 2032</td>
<td>56.55</td>
<td>56.21</td>
<td>54.54</td>
<td>55.65</td>
<td>56.76</td>
<td>57.87</td>
</tr>
<tr>
<td>Conv-till</td>
<td>0–50 cm 2042</td>
<td>56.67</td>
<td>55.98</td>
<td>53.16</td>
<td>55.04</td>
<td>56.93</td>
<td>58.80</td>
</tr>
<tr>
<td>Δ40-yr SOC</td>
<td>0–50 cm 2052</td>
<td>57.38</td>
<td>56.15</td>
<td>52.17</td>
<td>54.82</td>
<td>57.48</td>
<td>60.12</td>
</tr>
</tbody>
</table>

Table 3. Changes in soil organic C (SOC) at the 0- to 50-cm soil depth during 2012 to 2052 simulated with the CQESTR model in response to tillage and a predicted climate change scenario at various crop yields for no-till and conventional tillage (Conv-till) corn/rye–soybean/winter wheat–soybean rotations at the USDA-ARS Farming Systems Project in Beltsville, MD.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Depth</th>
<th>Year</th>
<th>Simulation scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-till</td>
<td>0–50</td>
<td>2012</td>
<td>Baseline§</td>
</tr>
<tr>
<td>No-till</td>
<td>0–50</td>
<td>2022</td>
<td>Climate only</td>
</tr>
<tr>
<td>No-till</td>
<td>0–50</td>
<td>2032</td>
<td>Climate and 70% yield</td>
</tr>
<tr>
<td>No-till</td>
<td>0–50</td>
<td>2042</td>
<td>Climate and 90% yield</td>
</tr>
<tr>
<td>Conventional tillage</td>
<td>0–50</td>
<td>2052</td>
<td>Climate and 110% yield</td>
</tr>
<tr>
<td>Δ40-yr SOC</td>
<td>0–50</td>
<td>2052</td>
<td>Climate and 130% yield</td>
</tr>
</tbody>
</table>

† Yield increases or decreases are relative to average yield data from 1996 to 2014, beginning in 2015.
‡ Biomass nitrogen concentration.
§ Baseline used averaged yield from 1996 to 2014.

illustrated in an analysis of global crop yields that shows that corn and wheat yields were negatively affected by the ~0.4°C increase in annual global temperatures between 1981 and 2000, but that technological yield gains over the same time period outweighed these losses (Lobell and Field, 2007). In addition, farmer adaptation to a changing climate is a socially embedded dynamic process that is not represented in biophysical models (Crane et al., 2011). Therefore, the specific trajectory of crop yields in the southern Mid-Atlantic region remains uncertain, and running CQESTR at various crop yield trajectories is warranted. Our results clearly indicate that crop yield increases will be necessary to counteract the negative impacts of changing climate alone on SOC, with or without tillage. In addition, NT provides more buffering from SOC losses with climate change than does CT.

Greater SOC in NT than CT provides a number of agronomic and environmental benefits, regardless of any climate impacts. At FSP, the NT compared with the CT system has greater aggregate stability (0.74 vs. 0.40 mm mean weight diameter), macroaggregates (0.62 vs. 0.35 g g⁻¹), and aggregate-associated C, N, and P (66–70 vs. 59–60%) and lower soil bulk density (1.37 vs. 1.53 Mg m⁻³) in the top 5 cm (Green et al., 2005). Improved surface soil quality resulted in lower modeled soil erosion, from 64 Mg ha⁻¹ yr⁻¹ in CT to only 8.5 Mg ha⁻¹ yr⁻¹ in NT, along with commensurate decreases in C, N, and P losses via sediment transport (Green et al., 2005). In addition, ponded water infiltration was also greater in NT than CT (Cavigelli et al., unpublished data, 2007). Others have shown similar soil health and function improvements in NT compared with CT in soils in the eastern United States (Dell and Novak, 2012, and citations therein). Our CQESTR results suggest that better soil function under NT than CT will be maintained under climate change. A recent analysis of the impacts of climate change in the Mississippi River Basin further supports the benefits of NT under climate change. Although increases of 9 to 12% in sediment and P loads were predicted in tilled systems under climate change, converting to NT management resulted in 20 to 47% decreases in these environmental impacts with climate change (Yasare et al., 2017).
Finally, our results reflect benefits accrued from a continuous NT system. However, NT is rarely practiced continuously (Grandy et al., 2006). In Virginia, for example, corn and soybean are often NT planted, but soil is often tilled prior to planting a small grain (wheat or barley [Hordeum vulgare L.]). In addition, many NT fields in Virginia are periodically tilled to incorporate organic amendments, alleviate soil compaction, or remove tire ruts resulting from harvesting equipment (Spargo et al., 2008). One expert estimated that <10% of American farmers practice continuous NT (VandenBygaart, 2016). The impact of noncontinuous NT on results presented here is not clear, but we suggest that even greater yield increases would be needed to maintain SOC at a given level in noncontinuous than in continuous NT management.

Conclusions

The impact of climate change on SOC stocks in NT and CT agricultural systems is uncertain. We used SOC and other data from the long-term FSP in Beltsville and CQESTR, a process-based soil C model, to predict the impact of tillage, climate change, and crop yield on SOC to 50-cm soil depth for grain cropping systems in the southern Mid-Atlantic region of the United States. Without change in climate or crop yields (baseline conditions), CQESTR predicted small increases in SOC in CT and NT systems (0.014 and 0.021 Mg ha\(^{-1}\) yr\(^{-1}\), respectively). Predicted climate change alone resulted in a very small increase in SOC in NT (0.002 Mg ha\(^{-1}\) yr\(^{-1}\)) and a small decrease in CT (0.017 Mg ha\(^{-1}\) yr\(^{-1}\)). Crop yield decreases of 10 and 30% led to more substantial SOC decreases—between 2 and 8% compared with 2012 levels. On the other hand, increasing crop yield by 10 and 30% raised SOC levels 2 and 7%, respectively, above the climate-only scenario under both CT and NT between 2012 and 2052. Results indicate that increases in crop yields, which are not guaranteed, will be necessary to mitigate the negative impact of climate change on SOC levels under these simulated conditions.

References


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