Agricultural Systems 197 (2022) 103355

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Research Paper

Simulating no-tillage effects on crop yield and greenhouse gas emissions in Kentucky corn and soybean cropping systems: 1980–2018

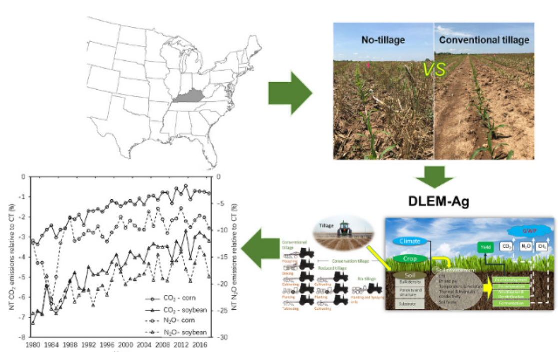
Yawen Huang [a], Bo Tao [a], Yanjun Yang [a], Xiaochen Zhu [b], Xiaojuan Yang [c], John H. Grove [a], Wei Ren [a,*]

[a] Department of Plant and Soil Sciences, College of Agriculture, Food, and Environment, University of Kentucky, Lexington, KY 40546, USA
[b] School of Applied Meteorology, Nanjing University of Information Science and Technology, Nanjing, Jiangsu, China
[c] Environmental Science Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA

HIGHLIGHTS

- Whether NT mitigates climate change through reducing greenhouse gas emissions at the regional scale needs to be explored.
- We quantified the long-term effects of NT on crop yield and GHG emissions in Kentucky through agro-ecosystem modeling.
- No-tillage reduced CO_2 and N_2O emissions and showed minor effects on crop yield in Kentucky corn and soybean cropland.
- Increased air temperature diminished NT benefits in reducing GHG emissions, while high clay soils boosted such benefits.
- Findings suggested NT can enhance agricultural production stability and mitigate climate change in the Kentucky region.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Guillaume Martin

Keywords:
Crop yield
Greenhouse gas emissions
No-tillage
Agroecosystem model

ABSTRACT

CONTEXT: No-tillage (NT) is a conservation practice that aims to minimize soil disturbance and improve crop production. However, NT effects on crop production remain controversial due to the spatial heterogeneity of climate and soil conditions. Some studies argued that NT might offset its greenhouse gas (GHG) mitigation potential in agriculture by promoting soil N_2O emissions.
OBJECTIVE: This study used a process-based agroecosystem model (DLEM-Ag) along with spatially explicit environmental datasets to quantify the long-term effects of NT on crop yield and GHG emissions in corn and soybean cropping systems in the state of Kentucky (USA) from 1980 to 2018.
METHODS: The DLEM-Ag was used to quantify the long-term effects of NT on crop yield and GHG emissions in corn and soybean cropping systems in the state of Kentucky. Three spatiotemporal tillage scenarios, i.e., historical varying tillage, consistent conventional tillage (CT), and consistent NT, were adopted to simulate changes in crop yield and GHG emissions.

* Corresponding author.
E-mail address: wei.ren@uky.edu (W. Ren).

https://doi.org/10.1016/j.agsy.2021.103355
Received 20 October 2021; Received in revised form 13 December 2021; Accepted 16 December 2021
Available online 26 December 2021

RESULTS AND CONCLUSIONS: Overall, our results showed that NT could reduce soil CO_2 (−1.6% for corn and −4.53% for soybean) and N_2O emissions (−10.5% for corn and −19.6% for soybean) in Kentucky, as compared to CT, although corn and soybean yields with NT were not significantly different from those with CT. Our further analysis suggested that air temperature and soil clay content were the two main factors influencing NT advantages in reducing GHG emissions. The increased temperature decreased the benefits of mitigating GHG emissions, while high clay content soils had less N_2O emission under NT.
SIGNIFICANCE: This study represents one of few attempts to quantify the effects of NT on crop yield and soil GHG emissions at the regional scale using an agroecosystem modeling approach. The findings from this study provide insights into how NT can enhance agroecosystem production stability and support climate change mitigation. This information may be used by the scientific community and policymakers working on practical technologies to mitigate climate change from agriculture.

1. Introduction

The challenge of modern farming, in a context of population growth and climate change, is to simultaneously improve crop yield and reduce greenhouse gas (GHG) emissions. Among the portfolio of management options for climate change adaptation and mitigation, conservation soil management practices, such as no-tillage (NT), have been promoted to reduce environmental side effects (e.g., soil erosion and degradation) while ensuring long-term agricultural productivity (Lal, 2013). However, NT effects on crop yield and GHG emissions vary widely among current studies (Pittelkow et al., 2015; Huang et al., 2018). With the growing worldwide adoption of NT, controversy still is whether NT can effectively enhance food security and mitigate GHG emissions under climate change (Powlson et al., 2014; VandenBygaart, 2016).

No-tillage soil management minimizes soil disturbance and leaves crop residues on the soil surface. The NT system can benefit soil function and quality of soil in many situations and, therefore, crop production (Blanco-Canqui and Ruis, 2018; Skaalsveen et al., 2019). For example, compared to conventional tillage (CT), NT reduces the risks of soil degradation from erosion (Montgomery, 2007; Derpsch et al., 2010). Therefore, NT soils can hold more soil organic carbon (SOC) and water to maintain or improve soil quality (Huggins and Reganold, 2008). These mechanisms are especially important in areas like the southeastern U.S., where tilled soil is more vulnerable to water erosion in a climate characterized by heavy and intense rainfall (Triplett and Dick, 2008; USDA, 2015). This region has witnessed rising adoption of NT in recent decades (Claassen et al., 2018). No-tillage accounts for more than 68% of Kentucky's total cropland acreage, according to the 2017 USDA Agricultural Resource Management Survey (USDA, 2019).

Many studies have reported positive yield responses to NT for rainfed crops in dry climates (Pittelkow et al., 2015; Huang et al., 2018) or under humid conditions with moderately well-drained to well-drained soils (DeFelice et al., 2006; Triplett and Dick, 2008). However, in more mesic climates or with poorly drained soils, the yield responses are more variable. No-tillage management can benefit soil water conservation and retention under water-limited conditions (Farooq et al., 2011). Still, the potential for soil waterlogging and delayed soil warming in spring can be detrimental to crop growth (Licht and Al-Kaisi, 2005). While studies in Kentucky have generally reported improved productivity with NT at several sites (Blevins et al., 1971; Díaz-Zorita et al., 2004; Grove et al., 2009), NT yield outcomes have not been well quantified at the state level.

No-tillage can reduce soil CO_2 emissions primarily due to: 1) less soil disturbance, which keeps SOC unexposed (Rastogi et al., 2002); 2) improved soil aggregate stability that protects SOC from microbial attack (Abdalla et al., 2013); and 3) a lower soil temperature (Lu et al., 2016). However, greater soil moisture availability with NT could also enhance microbial activity, thus increasing CO_2 emissions (Plaza-Bonilla et al., 2014). A recent global meta-analysis suggested that reduced CO_2 emissions under NT could diminish with the increasing duration of NT management as the system reaches a new equilibrium at higher SOC stocks (Huang et al., 2018).

Because NT soil water status and bulk density are usually higher compared to tilled soils, there have been suggestions that higher N_2O emissions occur with NT (Smith et al., 2001). In contrast, NT soils may have a slower N mineralization rate than tilled soils, leading to lower NH_4^+ and NO_3^- concentrations and, therefore, lower N_2O emissions (Dick et al., 2008; Almaraz et al., 2009). In the long-term, NT adoption substantially modifies soil physical properties with improved soil aggregation and aeration status, consequently reducing N_2O emissions (Six et al., 2004; van Kessel et al., 2013).

Generally, climate conditions, soil texture classes, and NT management duration are the major factors that affect agricultural systems responses to NT management (Pittelkow et al., 2015; Blanco-Canqui and Ruis, 2018; Cusser et al., 2020). However, a knowledge gap exists regarding NT effects on crop yield and GHG emissions at large spatial scales. Field experiments are invaluable, and have great credibility, in revealing management practice impacts on agronomic and environmental variables (Plaza-Bonilla et al., 2018). However, there are limitations when interpreting and applying site-specific findings to a larger area because of the unique environment (e.g., climate and soil) and management conditions (e.g., cropping system) of each study site. Although statistical tools such as meta-analysis are helpful in testing the linear relationship between site-specific conditions and crop yield or GHG emissions, meta-analysis cannot assess variate spatiotemporal magnitudes and patterns as affected by management practices. Process-based models provide an opportunity to overcome these limitations (Lutz et al., 2019) and can help guide management decisions (Ludwig et al., 2011). The objective of this study was to: 1) assess NT effects on crop yield and GHG emissions from Kentucky cropland for the 1980–2018 time period using an agroecosystem model (DLEM-Ag); and 2) examine the environmental factors (i.e., climate and soil) that regulate the NT effects.

2. Materials and methods

2.1. Description of the study area

Kentucky lies in the east-central United States. The Ohio River forms a northern border and the Mississippi River a western border. Kentucky experiences a humid subtropical climate with an oceanic climate in the highlands of the southeast. Hot summers and cold winters typically occur, with a gradual increase in warmth in the southern regions. Kentucky receives good rainfall, with an average of 1143 mm of annual rainfall, increasing from the north to the south. Soybean and corn are the two major row crops grown in Kentucky, accounting for about 55% of cropland area.

2.2. Input driving data

2.2.1. Climate, CO_2, and nitrogen deposition data

The daily climate data were derived from the Daymet Version 3 model output data at a resolution of 1-km × 1-km, covering Kentucky from 1980 to 2018 (Thornton et al., 2016), including maximum and

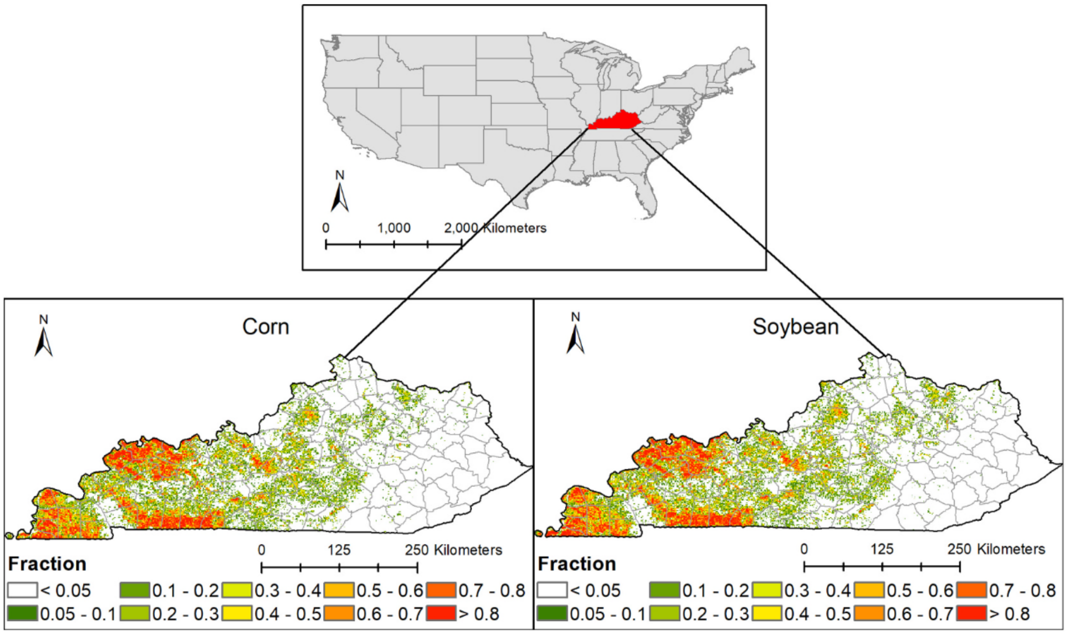


Fig. 1. Location of Kentucky and fractional distribution of corn and soybean in Kentucky.

minimum temperature, precipitation, shortwave radiation, and vapor pressure. The historical CO_2 concentration dataset was retrieved from NOAA/GML (www.esrl.noaa.gov/gmd/ccgg/trends/). Gridded N deposition maps were adapted from the North American Climate Integration and Diagnostics – Nitrogen Deposition Version 1 (NACID-NDEP1) dataset (Hember, 2018). All data sets were compiled to drive the model at a resolution of 1-km × 1-km according to the climate data set.

2.2.2. *Crop distribution map*

The crop distribution map used in this study was generated by using the USDA-NASS Cropland Data Layer (CDL) datasets. Using the available CDL datasets for Kentucky (2008–2018), we firstly estimated the maximum distribution of corn and soybean between 2008 and 2018 using the 30-m layers. Then, we calculated the fractions of corn and soybean, respectively, for each 1-km pixel based on the 30-m layers (Fig. 1). The crop distribution maps were generated on the ArcGIS platform. First, we created a binary mask map based on the CDL data set, in which a value of 1 represented corn or soybean pixels, and a value of 0 represented other land use/cover types. Second, we calculated the sum of values at a 33 by 33 (i.e., 990-m × 990-m;; approximately 1-km) block using the BlockSum function in the ArcGIS. Third, we resampled the map to a 990-m × 990-m resolution and estimated the percentage of corn/soybean in each 990-m pixel by dividing 1089. Lastly, we used the Project Raster function to transfer the map generated from Step 3 into a new map with the same projection and cell size as the Daymet climate data. We eliminated grids with less than 5% of corn or soybean area during the model simulation and assumed that corn and soybean had the maximum cultivated area during the simulation period.

2.2.3. *Tillage and other agricultural management practices*

We obtained county-level tillage information from the Conservation Technology Information Center's (CTIC; https://www.ctic.org/) National Crop Residue Management Survey (CRM). The tabular data provides the acreages and percentages of five tillage types implemented for all crops, including corn and soybean. For simplification, we grouped the five major tillage types into three categories, i.e., no-tillage (NT), reduced tillage (RT, including ridge tillage, mulch tillage, and reduced tillage), and conventional tillage (CT). We used county acreages in combination with the CDL-derived cropland layer to estimate the spatial distribution of conventional and conservation tillage fractions for corn and soybean, assuming each pixel within a county has the same portion of each tillage-specific area. We reconstructed annual tillage maps from 1989 to 2011 based on the CRM dataset and made the assumptions that the tillage maps for other years are similar to the nearest year. In addition, we also generated two ideal tillage maps (all NT vs. all CT), with all the corn/soybean under a tillage regime, for a scenario analysis. Crop-specific N fertilizer use data at the state level were derived from USDA ERS statistics on fertilizer use (https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx), covering the 1960–2018 period. The irrigation map was reconstructed at a 1-km resolution based on the MODIS irrigated agriculture dataset for the United States (MIrAD-US) (Pervez and Brown, 2010).

2.3. *Model description*

The agricultural module of the Dynamic Land Ecosystem Model (DLEM-Ag) is a highly integrated process-based agroecosystem model. The model is capable of simulating the daily crop growth and exchanges of trace gases (CO_2, CH_4, and N_2O) between agroecosystems and the atmosphere; and quantifying fluxes and storage of carbon, water, and nitrogen within agroecosystem components as affected by multiple factors such as climate, atmospheric CO_2, nitrogen deposition, tropospheric ozone, land use and land cover change, and agriculture management practices (e.g., harvest, rotation, irrigation, and fertilizer use). This model has been extensively used to study crop production, SOC, exchanges of trace gases between the agroecosystems and the atmosphere. The detailed structure and processes have been well documented in previous work (e.g., Tian et al., 2010; Ren et al., 2011, 2012, 2016; Zhang et al., 2018).

A tillage sub-module was recently incorporated in the DLEM-Ag model (Huang et al., 2020, 2021). The implementation of tillage mainly focuses on two processes directly affected by tillage: 1) the redistribution of surface residues with tillage practice and subsequent effects on soil water properties and water-related processes; 2) the increased residue decomposition rates. The tillage effects are implemented in combination with residue management, as these management practices are often interrelated (Strudley et al., 2008). Tillage incorporates surface residues into the soil, altering the residue coverage at the soil surface. Crop residues left on the soil surface intercept rainfall,

Table 1
Experimental designs used in this study.

Experiment	Abbr	Drivers used: Tillage	Drivers used: Others[a]
Historical varying tillage	S1	1980–2018	Varying
Conventional tillage	S2	1980[b]	Varying
No tillage	S3	1980[c]	Varying

[a] Others include climate data (e.g., air temperature, precipitation, and radiation from 1980 to 2018), agricultural N fertilizer (i.e., N fertilizer from 1980 to 2018), and atmospheric conditions (i.e., CO_2 and N deposition from 1980 to 2018).
[b] Tillage intensity across Kentucky for the entire period was consistently conventional tillage (CT).
[c] Tillage intensity across Kentucky for the entire period was consistently no-tillage (NT).

facilitating water infiltration. Surface residues also serve as a barrier that reduces water losses to the atmos (evaporation). Therefore, residues help maintain or improve soil moisture. Soil moisture affects plant primary production by regulating the amount of available water for plants, and in turn, plant water uptake also changes soil moisture. The tillage sub-module does not consider the direct effect of tillage on soil thermal properties due to the scarcity of studies on soil thermal properties under different tillage regimes (Blanco-Canqui and Ruis, 2018; O'Brien and Daigh, 2019). However, as soil thermal properties are intimately associated with soil hydraulic properties in the DLEM-Ag, the tillage sub-module indirectly affects soil temperature by changing soil water content.

2.4. Model experiment design

In this study, we designed three simulation experiments to assess the magnitudes in, and spatiotemporal patterns for, crop yield and GHG emissions under different tillage systems from 1980 to 2018 (Table 1). The model simulation began with an equilibrium run using 30-year (1980–2009) mean climate datasets to develop the simulation baseline, in which the yearly variations in carbon, nitrogen, and water for each grid were less than 0.1 g C/m^2/yr, 0.1 mm H_2O/yr, and 0.1 g N m^2/yr, respectively. Before the transient run, the model was run for another 100 years for the spin-up to remove system fluctuations caused by the shift from equilibrium to transient mode, using climate data randomly selected from the 1980–2008 time period. The first simulation (S1) was designed to produce the near-real crop yield/GHG emissions and their changes in Kentucky, driven by historical varying tillage types and other input drivers (e.g., climate, CO_2, N deposition, fertilizer use, irrigation). In the second and third simulations (S2 – S3), we assumed that a specific tillage practice was applied to all the croplands over the study period. Comparing the three scenarios provides potential yield and GHG emission changes to NT implementation in the corn and soybean production.

3. Results and discussion

3.1. Historical climate changes in Kentucky

The climate in Kentucky was generally becoming warmer and wetter between 1980 and 2018. Overall, the air temperature increased at 0.02 °C/year (R^2 = 0.11, p = 0.04) in Kentucky (Fig. 2c). The most significant temperature increases occurred in the west and east regions of Kentucky (Fig. 2a). Similarly, annual precipitation exhibited a significant increasing trend (7.05 mm/year, R^2 = 0.15, p = 0.02) across the state (Fig. 2d), with relatively greater increases in Kentucky's north-central regions (Fig. 2b). The decadal mean annual precipitation increased from about 1226 mm in the 1980s to 1448 mm in the 2010s. Compared to other areas, most corn and soybean cropland located in western and central regions have experienced a moderately warmer and wetter climate. There were four relative droughts (e.g., significant increases in temperature and decreases in precipitation) that occurred in 1987, 1999, 2005, and 2012 and six abnormally wet periods (significant increases in precipitation with fewer temperature changes) in 1989, 1996, 2003, 2009, 2011, and 2018.

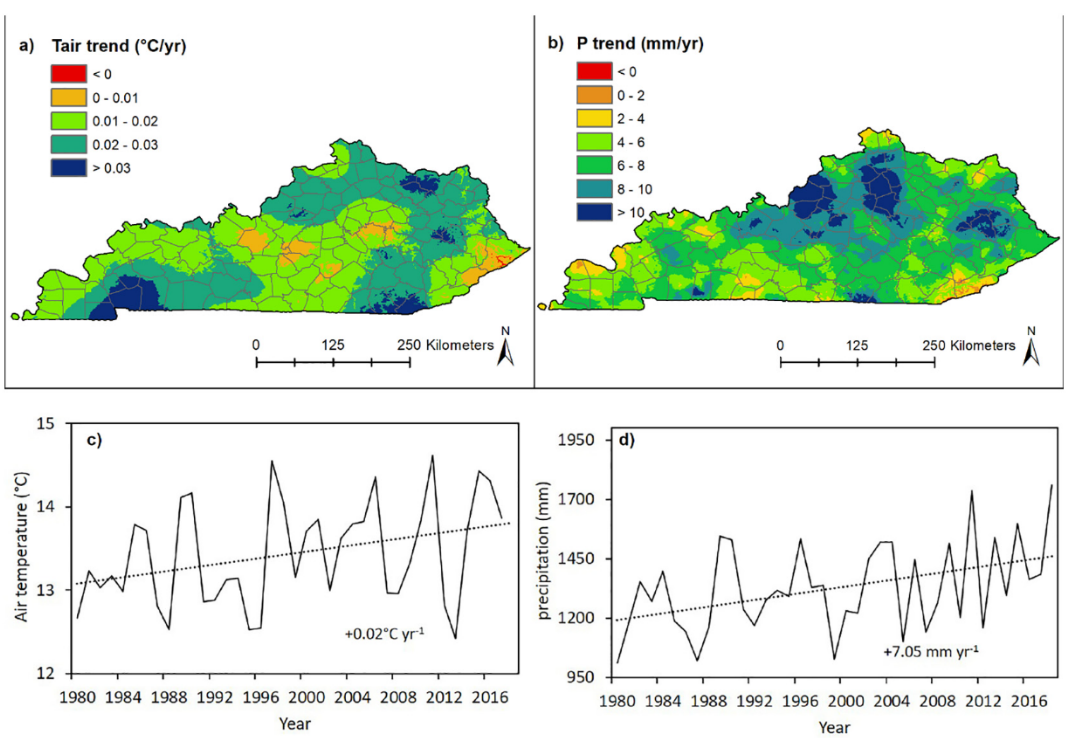


Fig. 2. Spatial and temporal change in annual air temperature (a, c), and precipitation (b, d) in Kentucky between 1980 and 2018.

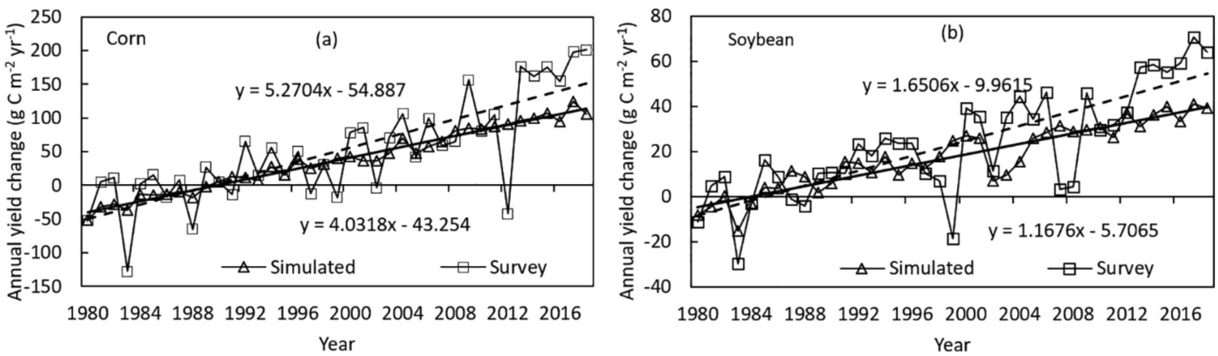


Fig. 3. Changes in annual crop yield (relative to the average for 1980–1989) of Kentucky's corn (a) and soybean (b) estimated by the DLEM-Ag model and the USDA-NASS survey (the solid and dashed lines are linear trends for simulated and survey yield, respectively).

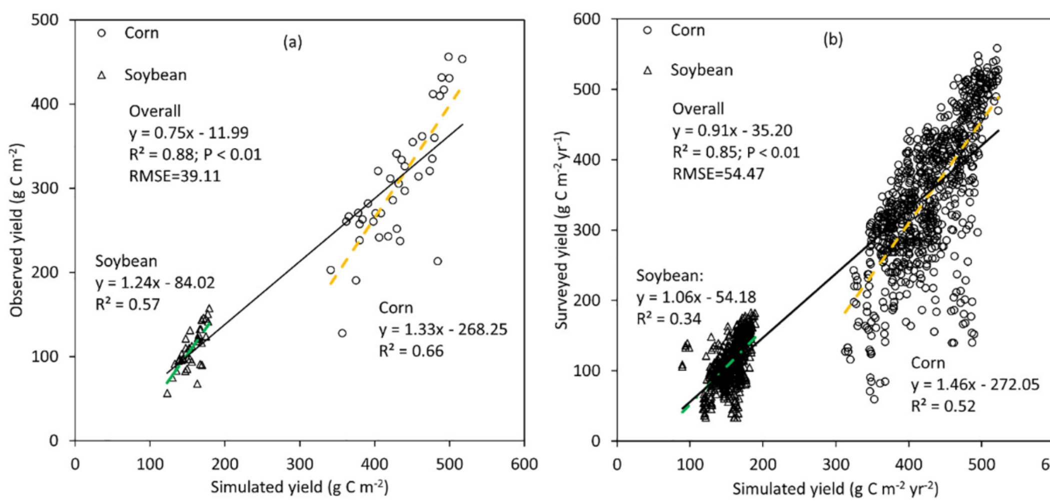


Fig. 4. Comparison between the DLEM-Ag simulated crop yields and the USDA-NASS survey estimated crop yields for corn and soybean from 1980 to 2018 at (a) state- and (b) county-level (counties are randomly selected).

3.2. Evaluation of DLEM-Ag simulated results

We first compared the model simulated crop yields against the USDA reported state-level crop yields for corn and soybean from 1980 to 2018 (Figs. 3 and 4a). A carbon content factor was used to convert the dry biomass to carbon (450 g C/kg). The simulated results well captured the increasing trends in corn and soybean yields during the study period, with slightly lower rates of increase than those determined from the USDA data (4.03 g C m^{-2} $year^{-1}$ vs. 5.27 g C m^{-2} $year^{-1}$ for corn, 1.17 g C m^{-2} $year^{-1}$ vs. 1.65 g C m^{-2} $year^{-1}$ for soybean, Fig. 3). As presented in Fig. 4a, the simulated yields by DLEM-Ag agreed well with the USDA crop yield ($R^2 = 0.88$). We also compared the simulated results with the estimated crop yields from USDA inventory at the county level during 1980–2018 (Fig. 4b). The county-level comparisons also showed high correlation coefficients ($R^2 = 0.85$). The calibration procedure used is responsible for this good agreement.

Simulated state-level crop yields also well captured the temporal patterns in the survey data, with a correlation coefficient of 0.81 and 0.75 for corn and soybean, respectively (Fig. 3). Although changes in production technology (improved crop genetics and management practices) were mainly responsible for the upward trend in crop yields (Egli, 2008; Fischer et al., 2014), environmental factors, such as seasonal weather, were likely responsible for the annual variations (Hatfield et al., 2011). Some have suggested that the trends in increased crop yield were also associated with changes in rainfall and temperature (Anderson et al., 2001; Lobell and Asner, 2003). The simulated yield results exhibited similar interannual variation but showed less variance than the survey yield data. The reason could be due to uncertainties in climate data. Limited by the data availability, tillage distribution maps were constructed based on the county-level surveys, therefore associated tillage practices were proportionally allocated to corn/soybean pixels; and data during 1980–1998 and 2012–2018 were assumed to be the same as the year of 1989 and 2011, respectively. These assumptions could also result in uncertainties in estimating yield interannual variations. In addition, the model simulation assumed that corn and soybean were planted in late-April in western Kentucky and early May in central and eastern areas throughout the study period, which represented the optimal planting period for Kentucky (Lee et al., 2007). Compared to the large variations in planting dates, the relatively stable and optimal planting dates used in the model could lead to lower simulated interannual variations in crop yields.

3.3. Tillage effects on crop yield and GHG emissions

In general, our simulations showed that adopting NT slightly increased corn yield (0.2%) and decreased soybean yield (−2.4%) on average (Fig. 5a, b, respectively). These differences suggested that the yield differences between NT and CT are negligible in Kentucky, primarily due to the humid climate and moderately well to well-drained cropland soils. In terms of tillage effects on GHG emission, our simulated results showed that CO_2 emissions were generally reduced by −1.6% for corn and by −4.5% for soybean with NT than with CT (Fig. 5c, d). Switching from CT to NT management decreased N_2O emissions by an average of −10.5% for corn and by −19.6% for soybean

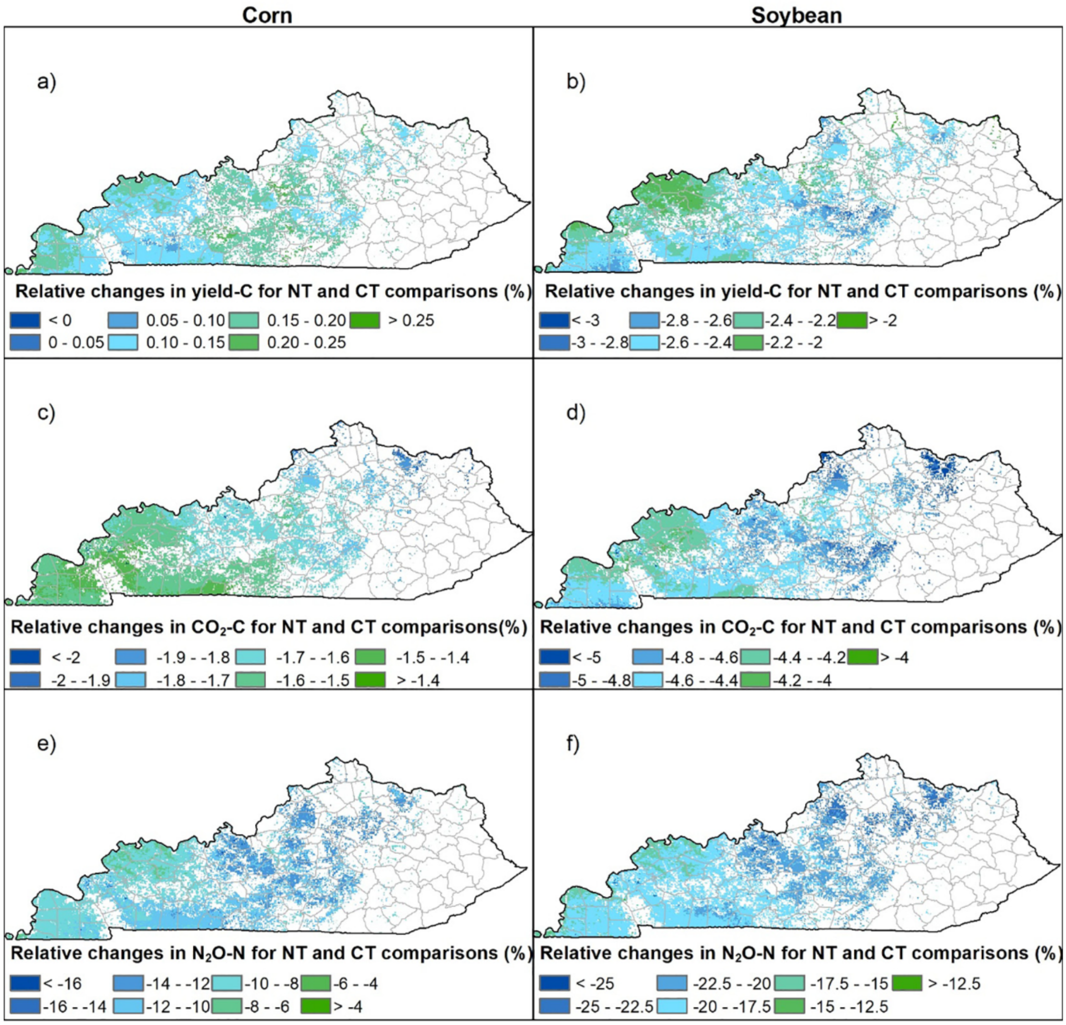


Fig. 5. Relative changes in yield-C (a, b; carbon content of grain yield), emitted soil CO_2-C (c, d; carbon content of CO_2) and emitted N_2O-N (e, f; nitrogen content of N_2O) for NT and CT comparisons for corn (left panel) and soybean (right panel).

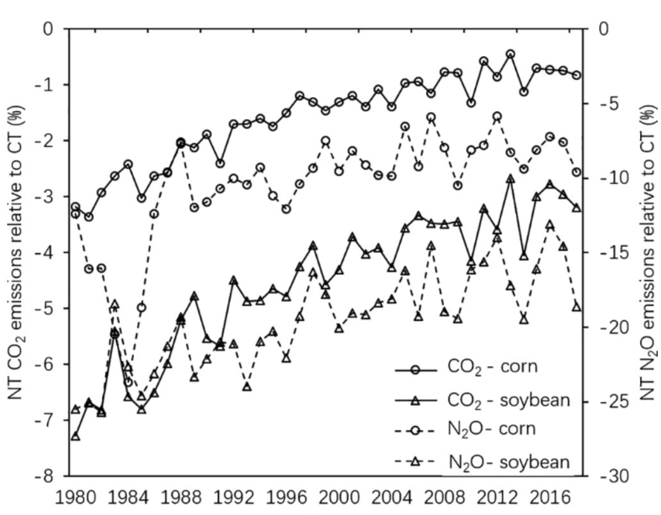


Fig. 6. NT CO_2 and N_2O emissions, relative to CT, in corn and soybean production systems from 1980 to 2018.

(Fig. 5e, f). The spatial patterns for tillage effects on GHG emissions were similar, with the relatively more substantial reductions in CO_2 and N_2O emissions in the central and northern areas and relatively smaller reductions in the western regions.

The decrease in CO_2 emissions with NT, as compared to CT, is consistent with previous findings (ranging from −11.9% to −4.9%; Abdalla et al., 2013; Lutz et al., 2019; Huang et al., 2020), as NT decreases organic matter decomposition rates with less soil disturbance and lower soil temperature (Rastogi et al., 2002; Lu et al., 2016). However, NT effects on reducing CO_2 emissions diminished with the duration of NT (Fig. 6), suggesting that the soil and litter C stocks were increasing, causing rising CO_2 emissions under NT which gradually decrease differences between tillage systems. Huang et al. (2018) reviewed the effects of NT duration and found that NT reduced CO_2 emissions in the short term but the differences decreased with longer NT duration. Similar findings were also reported from a global simulation by Lutz et al. (2019). As soil organic matter accumulated with time, the contribution of older weathered residues to CO_2 emission rose (Oorts et al., 2007). Therefore, the larger soil carbon stocks in long-term NT enabled CO_2 emissions equal to those from the smaller CT soil carbon stock. However, NT duration did not show obvious effects on the reduction in N_2O emissions, probably due to the improvement in soil structure and hydraulic properties in the long term (Blanco-Canqui and Ruis, 2018). Our results of reduced N_2O emissions due to NT agree with some previous studies (Omonode et al., 2011; Yoo et al., 2016; Plaza-

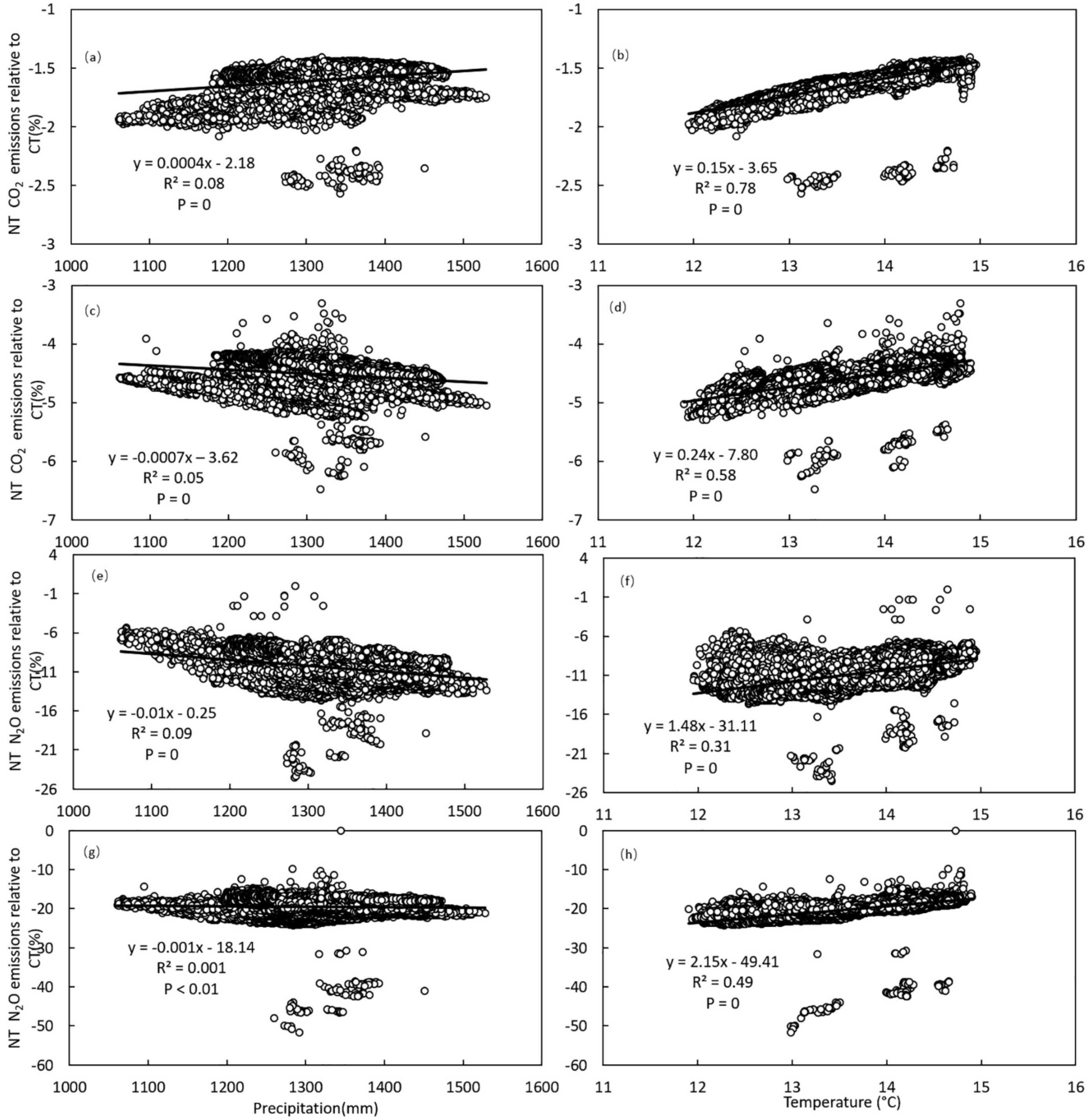


Fig. 7. Linear regression of NT CO_2 (a, b, c, d) and N_2O (e, f, g, h) emissions, relative to CT, against annual precipitation (left panel) and temperature (right panel) in corn (a, b, e, f) and soybean (c, d, g, h) production systems.

Bonilla et al., 2018) but contradicts several literature studies (Huang et al., 2018; Mei et al., 2018; Lutz et al., 2019). The reduction in N_2O emissions may be due to Kentucky's generally well-aerated cropland soils (Rochette, 2008). The sequential nitrification and denitrification responsible for N_2O emissions occur in the optimal soil temperature and moisture conditions under NT (Doran, 1980; Williams et al., 1992). Higher levels of inorganic N could lead to higher N_2O emissions. However, N mineralization rates are often lower under NT than under CT due to the leaving of crop residues on the soil surface (Rice et al., 1986; Franzluebbers et al., 1995; Dick et al., 2008).

3.4. *Climate and tillage effects on GHG emissions*

We examined tillage effects on GHG emissions as affected by spatial climate characteristics (i.e., annual precipitation and temperature) across Kentucky for corn and soybean croplands. Generally, annual precipitation did not significantly influence tillage effects on either CO_2 and N_2O emissions from Kentucky corn and soybean croplands (Fig. 7a, c, e, g). In comparison, differences in GHG emissions between NT and CT tended to decrease with increasing annual temperature in both cropping systems (Fig. 7b, d, f, h). This phenomenon was more pronounced for changes in CO_2 emissions than changes in N_2O emissions. The results

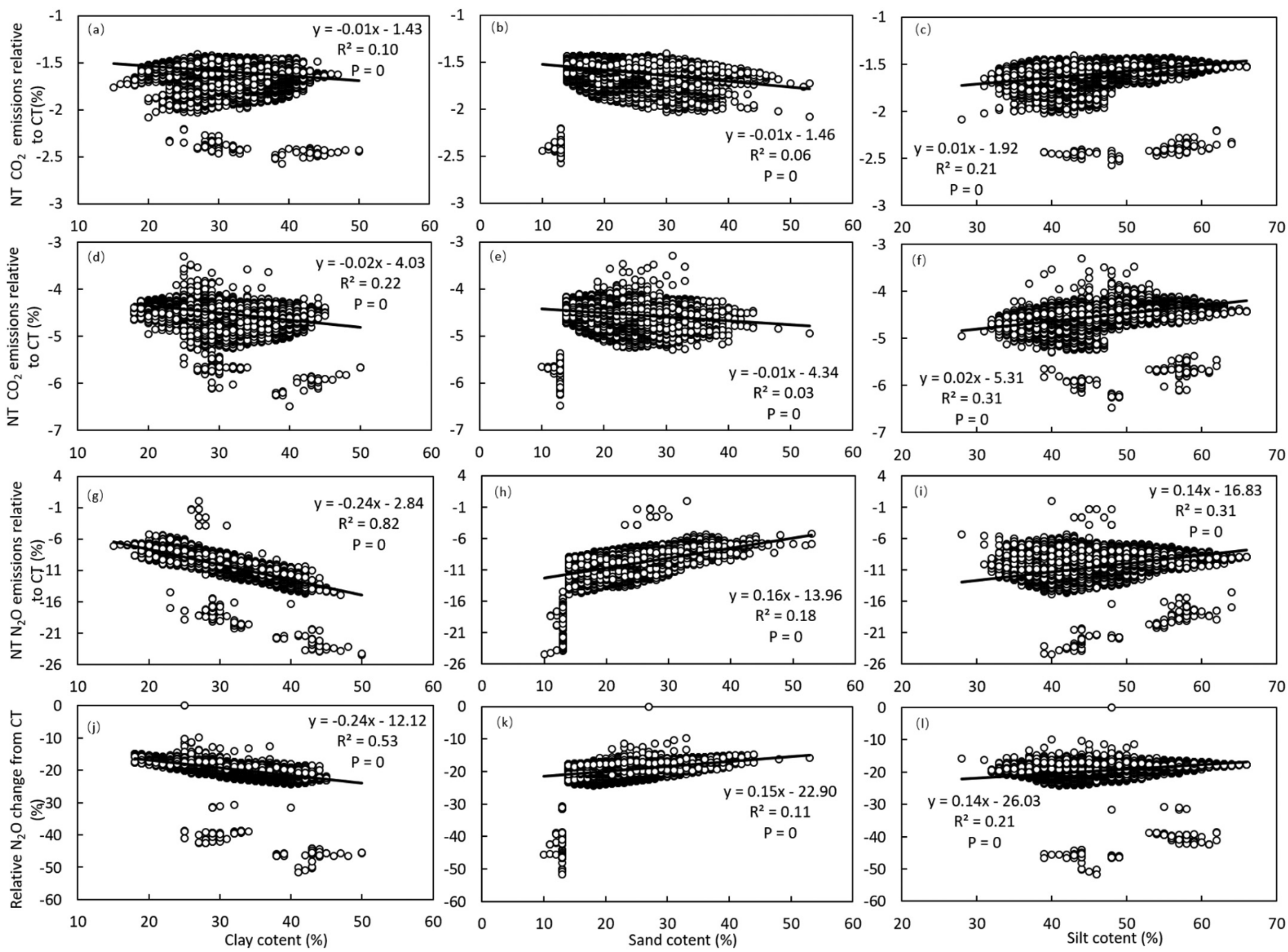


Fig. 8. Linear regression of relative NT CO_2 (a, b, c, d, e, f) and N_2O (g, h, i, j, k, l) emissions, relative to CT, against soil clay (left panel), sand (middle panel), and silt (right panel) contents in corn (a, b, c, g, h, i) and soybean (d, e, f, j, k, l) production systems.

suggest that spatial air temperature patterns, but not precipitation patterns, are the dominant factor affecting the spatial heterogeneity in NT effects on GHG emissions in Kentucky. Relative to CT, NT can reduce GHG emissions more in cooler (i.e., northern Kentucky) than warmer (western and southern Kentucky) regions. These results agreed with our recent site-level study indicating NT effects on SOC were controlled more by temperature than precipitation in northern Kentucky (Huang et al., 2020), as soil GHG emissions and SOC were highly correlated.

3.5. *Soil texture and tillage effects on GHG emissions*

Our simulation results showed that differences in N_2O emissions, relative to CT, significantly increased with the increasing soil clay content (Fig. 8g, j), but tended to decrease with rising sand and silt contents (Fig. 8h-i, k-l). In comparison, CO_2 emissions between NT and CT management were not significantly affected by soil texture (Fig. 8a-f). Clay content in the soil is strongly correlated with SOC (Meersmans et al., 2012). By binding organic matter, clay particles help form and stabilize soil aggregates, imposing a physical barrier between microbial decomposers and organic substrates (Dominy et al., 2002). Compared to CO_2, the production of N_2O in the soil is more sensitive to soil clay content (Miller et al., 2020).

4. Conclusions

This study is one of few attempts to quantify the effects of NT on crop yield and soil GHG emissions at the regional level using a spatially explicit agroecosystem modeling approach. Overall, the model exhibited good performance in the Kentucky region. Oursimulations showed that NT had no significant effect on corn and soybean yield in Kentucky but decreased soil CO_2 (−1.6% for corn and − 4.53% for soybean) and N_2O emissions (−10.49% for corn and −19.64% soybean) as compared to CT. Further analysis suggested that temperature and soil clay content were two crucial factors that governed the effectiveness of NT in reducing soil GHG emissions in the study area. Increased temperature would lead to less impact on the reduction of GHG emissions from NT soils. High clay content soils under NT were associated with more reductions in N_2O emissions. This study illustrated that NT could be a viable management practice towards the building of climate-resilient agriculture in Kentucky. Our findings regarding climate and soil controls in NT systems could be extended to other regions where conservation tillage practices are being widely adopted.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by grants from NSF (no. 2045235), the Alfred P. Sloan Foundation (G-2019-12468), and the National Institute of Food and Agriculture (NIFA-USDA Hatch project 2352437000 and 2021-67013-33616). We thank Dr. Mark S. Coyne and Dr. Ole Wendroth for the comments that improved this manuscript.

References

Abdalla, M., Osborne, B., Lanigan, G., Forristal, D., Williams, M., Smith, P., Jones, M., 2013. Conservation tillage systems: a review of its consequences for greenhouse gas emissions. Soil Use Manag. 29 (2), 199–209.

Almaraz, J.J., Zhou, X., Mabood, F., Madramootoo, C., Rochette, P., Ma, B.L., Smith, D. L., 2009. Greenhouse gas fluxes associated with soybean production under two tillage systems in southwestern Quebec. Soil Tillage Res. 104 (1), 134–139.

Anderson, J.A., Alagarswamy, C.A., Rotz, C.A., Ritchie, J.T., LeBaron, A.W., 2001. Weather impacts on maize, soybean, and alfalfa production in the Great Lakes Region, 1895–1996. Agron. J. 93, 1059–1070.

Blanco-Canqui, H., Ruis, S.J., 2018. No-tillage and soil physical environment. Geoderma 326, 164–200.

Blevins, R., Cook, D., Phillips, S., Phillips, R., 1971. Influence of no-tillage on soil moisture. Agron. J. 63, 593–596.

Claassen, R., Bowman, M., McFadden, J., Smith, D., Wallander, S., 2018. Tillage Intensity and Conservation Cropping in the United States, EIB-197. U.S. Department of Agriculture, Economic Research Service.

Cusser, S., Bahlai, C., Swinton, S.M., Robertson, G.P., Haddad, N.M., 2020. Long-term research avoids spurious and misleading trends in sustainability attributes of no-till. Glob. Chang. Biol. 26 (6), 3715–3725.

DeFelice, M.S., Carter, P.R., Mitchell, S.B., 2006. Influence of tillage on corn and soybean yield in the United States and Canada. Crop Manag. 5 (1), 1–17.

Derpsch, R., Friedrich, T., Kassam, A., Li, H., 2010. Current status of adoption of no-till farming in the world and some of its main benefits. Int. J. Agric. Biol. 3, 1–25.

Díaz-Zorita, M., Grove, J.H., Murdock, L., Herbeck, J., Perfect, E., 2004. Soil structural disturbance effects on crop yields and soil properties in a no-till production system. Agron. J. 96 (6), 1651–1659.

Dick, J., Kaya, B., Soutoura, M., Skiba, U., Smith, R., Niang, A., Tabo, R., 2008. The contribution of agricultural practices to nitrous oxide emissions in semi-arid Mali. Soil Use Manag. 24 (3), 292–301.

Dominy, C., Haynes, R., Van Antwerpen, R., 2002. Loss of soil organic matter and related soil properties under long-term sugarcane production on two contrasting soils. Biol. Fertil. Soils 36 (5), 350–356.

Doran, J., 1980. Microbial changes associated with residue management with reduced tillage. Soil Sci. Soc. Am. J. 44 (3), 518–524.

Egli, D.B., 2008. Comparison of corn and soybean yields in the United States: historical trends and future prospects. Agron. J. 100 (3), S79–S88.

Farooq, M., Flower, K., Jabran, K., Wahid, A., Siddique, K., 2011. Crop yield and weed management in rainfed conservation agriculture. Soil Tillage Res. 117, 172–183.

Fischer, R., Byerlee, D., Edmeades, G., 2014. Crop yields and global food security. In: ACIAR Monograph No. 158. Australian Centre for International Agricultural Research, Canberra. http://aciar.gov.au/publication/mn158.

Franzluebbers, A., Hons, F., Zuberer, D., 1995. Tillage and crop effects on seasonal soil carbon and nitrogen dynamics. Soil Sci. Soc. Am. J. 59 (6), 1618–1624.

Grove, J., Pena-Yewtukhiw, E., Diaz-Zorita, M., Blevins, R., 2009. Does fertilizer N "burn up" soil organic matter? Better Crops 93, 6–8.

Hatfield, J.L., Boote, K.J., Kimball, B., Ziska, L., Izaurralde, R.C., Ort, D., Wolfe, D., 2011. Climate impacts on agriculture: implications for crop production. Agron. J. 103 (2), 351–370.

Hember, R.A., 2018. Spatially and temporally continuous estimates of annual total nitrogen deposition over North America, 1860–2013. Data Brief 17, 134–140.

Huang, Y., Ren, W., Wang, L., Hui, D., Grove, J.H., Yang, X., Tao, B., Goff, B., 2018. Greenhouse gas emissions and crop yield in no-tillage systems: a meta-analysis. Agric. Ecosyst. Environ. 268, 144–153.

Huang, Y., Ren, W., Grove, J., Poffenbarger, H., Jacobson, K., Tao, B., Zhu, X., McNear, D., 2020. Assessing synergistic effects of no-tillage and cover crops on soil carbon dynamics in a long term maize cropping system under climate change. Agric. For. Meteorol. 291, 108090.

Huang, Y., Tao, B., Zhu, X., Yang, Y., Liang, L., Wang, L., Jacinthe, P.A., Tian, H., Ren, W., 2021. Conservation tillage increases corn and soybean water productivity across the Ohio River Basin. Agric. Water Manag. 254, 106962.

Huggins, D.R., Reganold, J.P., 2008. No-till: the quiet revolution. Sci. Am. 299 (1), 70–77.

Lal, R., 2013. Enhancing ecosystem services with no-till. Renew. Agric. Food Syst. 28 (2), 102–114.

Lee, C., Herbek, J., Murdock, L., Schwab, G., Green, J.D., Martin, J., Bessin, R., Johnson, D., Stombaugh, T., 2007. Corn and Soybean Production Calendar. University of Kentucky Cooperative Extension Service, Lexington, KY, USA.

Licht, M.A., Al-Kaisi, M., 2005. Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil Tillage Res. 80 (1–2), 233–249.

Lobell, D.B., Asner, G.P., 2003. Climate and management contributions to recent trends in U.S. agricultural yields. Science 299 (5609), 1032.

Lu, X., Lu, X., Tanveer, S., Wen, X., Liao, Y., 2016. Effects of tillage management on soil CO_2 emission and wheat yield under rain-fed conditions. Soil Res. 54 (1), 38–48.

Ludwig, B., Bergstermann, A., Priesack, E., Flessa, H., 2011. Modelling of crop yields and N_2O emissions from silty arable soils with differing tillage in two long-term experiments. Soil Tillage Res. 112 (2), 114–121.

Lutz, F., Herzfeld, T., Heinke, J., Rolinski, S., Schaphoff, S., Bloh, W.V., Stoorvogel, J.J., Müller, C., 2019. Simulating the effect of tillage practices with the global ecosystem model LPJmL (version 5.0-tillage). Geosci. Model Dev. 12 (6), 2419–2440.

Meersmans, J., Martin, M.P., De Ridder, F., Lacarce, E., Wetterlind, J., De Baets, S., Bispo, A., 2012. A novel soil organic C model using climate, soil type and management data at the national scale in France. Agron. Sustain. Dev. 32 (4), 873–888.

Mei, K., Wang, Z., Huang, H., Zhang, C., Shang, X., Dahlgren, R.A., Xia, F., 2018. Stimulation of N_2O emission by conservation tillage management in agricultural lands: a meta-analysis. Soil Tillage Res. 182, 86–93.

Miller, G.A., Rees, R.M., Griffiths, B.S., Cloy, J.M., 2020. Isolating the effect of soil properties on agricultural soil greenhouse gas emissions under controlled conditions. Soil Use Manag. 36 (2), 285–298.

Montgomery, D.R., 2007. Soil erosion and agricultural sustainability. Proc. Natl. Acad. Sci. 104 (33), 13268–13272.

O'Brien, P.L., Daigh, A.L., 2019. Tillage practices alter the surface energy balance–a review. Soil Tillage Res. 195, 104354.

Omonode, R.A., Smith, D.R., Gál, A., Vyn, T.J., 2011. Soil nitrous oxide emissions in corn following three decades of tillage and rotation treatments. Soil Sci. Soc. Am. J. 75 (1), 152–163.

Oorts, K., Merckx, R., Gréhan, E., Labreuche, J., Nicolardot, B., 2007. Determinants of annual fluxes of CO2 and N2O in long-term no-tillage and conventional tillage systems in northern France. Soil Tillage Res. 95, 133–148.

Pervez, M.S., Brown, J.F., 2010. Mapping irrigated lands at 250-m scale by merging MODIS data and National Agricultural Statistics. Remote Sens. 2 (10), 2388–2412.

Pittelkow, C., Linquist, B.A., Lundy, M.E., Liang, X., van Groenigen, K.J., Lee, J., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015. When does no-till yield more? A global meta-analysis. Field Crop Res. 183, 156–168.

Plaza-Bonilla, D., Cantero-Martínez, C., Bareche, J., Arrúe, J., Álvaro-Fuentes, J., 2014. Soil carbon dioxide and methane fluxes as affected by tillage and N fertilization in dryland conditions. Plant Soil 381, 111–130.

Plaza-Bonilla, D., Álvaro-Fuentes, J., Bareche, J., Pareja-Sánchez, E., Justes, É., Cantero-Martínez, C., 2018. No-tillage reduces long-term yield-scaled soil nitrous oxide emissions in rainfed Mediterranean agroecosystems: a field and modelling approach. Agric. Ecosyst. Environ. 262, 36–47.

Powlson, D.S., Stirling, C.M., Jat, M., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Chang. 4 (8), 678.

Rastogi, M., Singh, S., Pathak, H., 2002. Emission of carbon dioxide from soil. Curr. Sci. 82 (5), 510–517.

Ren, W., Tian, H., Xu, X., Liu, M., Lu, C., Chen, G., Melillo, J., Reilly, J., Liu, J., 2011. Spatial and temporal patterns of CO_2 and CH_4 fluxes in China's croplands in response to multifactor environmental changes. Tellus B 63, 222–240.

Ren, W., Tian, H., Tao, B., Huang, Y., Pan, S., 2012. China's crop productivity and soil carbon storage as influenced by multifactor global change. Glob. Chang. Biol. 18, 2945–2957.

Ren, W., Tian, H., Cai, W.J., Lohrenz, S.E., Hopkinson, C.S., Huang, W.J., Yang, J., Tao, B., Pan, S., He, R., 2016. Century-long increasing trend and variability of dissolved organic carbon export from the Mississippi River basin driven by natural and anthropogenic forcing. Glob. Biogeochem. Cycles 30 (9), 1288–1299.

Rice, C., Smith, M., Blevins, R., 1986. Soil nitrogen availability after long-term continuous no-tillage and conventional tillage corn production 1. Soil Sci. Soc. Am. J. 50 (5), 1206–1210.

Rochette, P., 2008. No-till only increases N_2O emissions in poorly-aerated soils. Soil Tillage Res. 101, 97–100.

Six, J., Ogle, S.M., Conant, R.T., Mosier, A.R., Paustian, K., 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Glob. Chang. Biol. 10 (2), 155–160.

Skaalsveen, K., Ingram, J., Clarke, L.E., 2019. The effect of no-till farming on the soil functions of water purification and retention in North-Western Europe: a literature review. Soil Tillage Res. 189, 98–109.

Smith, P., Goulding, K.W., Smith, K.A., Powlson, D.S., Smith, J.U., Falloon, P., Coleman, K., 2001. Enhancing the carbon sink in European agricultural soils: including trace gas fluxes in estimates of carbon mitigation potential. Nutr. Cycl. Agroecosyst. 60 (1–3), 237–252.

Strudley, M.W., Green, T.R., Ascough II, J.C., 2008. Tillage effects on soil hydraulic properties in space and time: state of the science. Soil Tillage Res. 99 (1), 4–48.

Thornton, P.E., Thornton, M.M., Mayer, B.W., Wei, Y., Devarakonda, R., Vose, R.S., Cook, R.B., 2016. Daymet: Daily Surface Weather Data on a 1-km Grid for North America, Version 3. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1328.

Tian, H., Chen, G., Liu, M., Zhang, C., Sun, G., Lu, C., Chappelka, A., 2010. Model estimates of net primary productivity, evapotranspiration, and water use efficiency in the terrestrial ecosystems of the southern United States during 1895–2007. For. Ecol. Manag. 259, 1311–1327.

Triplett, G., Dick, W.A., 2008. No-tillage crop production: a revolution in agriculture! Agron. J. 100, 153–165.

USDA, 2015. Summary Report: 2012 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology.

USDA, 2019. 2017 Census of Agriculture: Kentucky State and County Data. National Agricultural Statistics Service. https://www.nass.usda.gov/index.php.

van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M., Linquist, B., van Groenigen, K., 2013. Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: a meta-analysis. Glob. Chang. Biol. 19 (1), 33–44.
VandenBygaart, A., 2016. The myth that no-till can mitigate global climate change. Agric. Ecosyst. Environ. 216, 98–99.
Williams, E., Hutchinson, G., Fehsenfeld, F., 1992. NOx and N_2O emissions from soil. Glob. Biogeochem. Cycles 6 (4), 351–388.
Yoo, J., Woo, S.H., Park, K.D., Chung, K.Y., 2016. Effect of no-tillage and conventional tillage practices on the nitrous oxide (N_2O) emissions in an upland soil: soil N_2O emission as affected by the fertilizer applications. Appl. Biol. Chem. 59 (6), 787–797.
Zhang, J., Tian, H., Yang, J., Pan, S., 2018. Improving representation of crop growth and yield in the dynamic land ecosystem model and its application to China. J. Adv. Model. Earth Syst. 10 (7), 1680–1707.