Increasing tillage intensity and greenhouse gas emissions under the growing weed pressure in the U.S. corn-soybean cropping system

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Short Title: Emerging weed resistance alters tillage and GHGs

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Abstract

Tillage is a common agricultural practice for soil preparation and weed controls in crop production. However, it remains unknown how tillage intensity evolved and affected the net greenhouse gas (GHG) emissions. Using multi-source data and modeling approaches, we examined the change of tillage intensity across the U.S. corn-soybean cropping systems over the past two decades and its impacts on soil GHG emissions. We found that the trend of tillage intensity had shifted from decreasing to increasing since 2008, which is strongly correlated with the adoption of herbicide-tolerant crops and emerging weed resistance. The GHG mitigation benefit (-5.5 ± 4.8 Tg CO_2 eq/yr) of decreasing tillage intensity before 2008 has been more than offset by tillage re-intensification under growing pressure of weed resistance, which increased GHG emissions by 13.8 ± 5.6 Tg CO_2 eq/yr. As weed resistance persists or grows, tillage intensity is anticipated to continue increasing, likely enhancing GHG emissions.

Introduction

Greenhouse gas (GHG, such as CO_2, CH_4, and N_2O) emissions from agriculture (cultivation of crops and livestock) and deforestation accounted for about a quarter of global total GHG emissions (*1*). In the U.S., agriculture contributed ~10% of total GHG emissions in 2018, and it has increased by 10% since 1990, a substantial increase compared with the national total GHG emission increase of 3.7% in the same period (*2*). The agriculture sector provides significant GHG mitigation potential, but doing so requires a deep understanding of the sector's GHG flux dynamics and their key environmental drivers including human management practices (*3*).

Tillage is an important cropping practice that helps prepare the soil and remove weeds. Although various definitions of tillage types exist in literature, for our purposes tillage practices can be grouped into three types, namely conventional tillage, conservation tillage, and no-till, which differ by degrees of soil disturbance and residue retention. Conventional tillage leaves less than 15% residual on the soil surface, while conservation tillage has at least 30% residue left and no-till keeps the soil covered 100% of the time (*4*, *5*). Various tillage practices have different impacts on the physical, hydrological and biogeochemical processes in the soil. For example, conventional tillage practices (such as disk plowing), not only promote soil organic carbon oxidation and decomposition but also accelerate soil erosion by increasing soil exposure to wind and rain (*6*). On the other hand, no-till and conservation tillage (, such as strip till and mulch till) have been widely adopted by farmers to conserve soil and water (*7*). However, the no-till system has contributed less than what is often assumed to agricultural sustainability as it may retard springtime soil warming, increase weed, pest, and disease pressures, and lead to crop yield loss (*8*–*11*).

There are many reasons why tillage intensity has mostly declined on the U.S. cropped acres in the past century. Reduced tillage has been widely adopted to suppress soil erosion, preserve moisture, and reduce crop production cost in the use of fuel, labor and machinery (*7*, *12*). The advent of herbicide-tolerant (HT) crops, commencing in the late 1990s, has made it possible to spray herbicide over the growing crops and further reduced reliance on tillage (*13*). But the benefit of HT crop adoption in reducing tillage might not be sustainable in the long run as weed resistance has emerged to the main chemical used, glyphosate (*14*). Evidence to date suggests that partial reversion to conventional tillage has resulted (*15*, *16*). For example, a recent study (*16*) reveals that the shares of conservation tillage and no-till in soybean fields declined by 3.9% and 7.6%, respectively, when eight glyphosate-resistant weed species are identified, despite little initial effect of first emergence of weed resistance on tillage practices. However, the consequences of the changing tillage intensity in soil GHG fluxes during this period remain unclear.

In the U.S., a wide variety of studies have been conducted to quantify the GHG mitigation potential in the agriculture sector (*17–19*). More recent efforts have involved seeking policy and market solutions that promote additional mitigation practices (*20–23*). Nonetheless, most existing tillage-related assessment and prediction activities either lack data to characterize the spatiotemporal patterns of tillage practices and their intensity changes or focus on the resultant fluxes of single GHG. This limits the explicit characterization of system responses and hinders us from identifying and adopting sustainable management practices. Although USGS has developed tillage intensity maps during 1989-2004 by aggregating county-level survey into the 8-digit hydrologic unit (HU) watersheds (*24*), little is known about how tillage practices in the

U.S. changed in more recent years, especially given increasing concerns about herbicide-resistant weeds (*12*, *15*, *25*).

In addition, there is still limited understanding as to how tillage decisions are driven by environmental stressors such as herbicide and herbicide-resistant weeds, and how they together have affected GHG mitigation outcomes during recent decades. There is substantial evidence that using more intensive tillage is a coping strategy for many farmers faced with herbicide resistant weeds and this raises concerns about negative environmental impacts (*15*, *16*). Here, we use a process-based land ecosystem model, a long-term farmers survey, and time-series gridded data of environmental changes to test the hypothesis that genetically engineered HT crop adoption and the emergence of weed resistance to herbicide have influenced farmers' decisions in tillage practices, which altered net GHG fluxes in the agricultural lands (Figure 1). Our study in the U.S. could provide insightful information for other agricultural regions in the world that are impacted by growing weed pressure, herbicide resistance, intensifying tillage, and the diminished GHG mitigation potential.

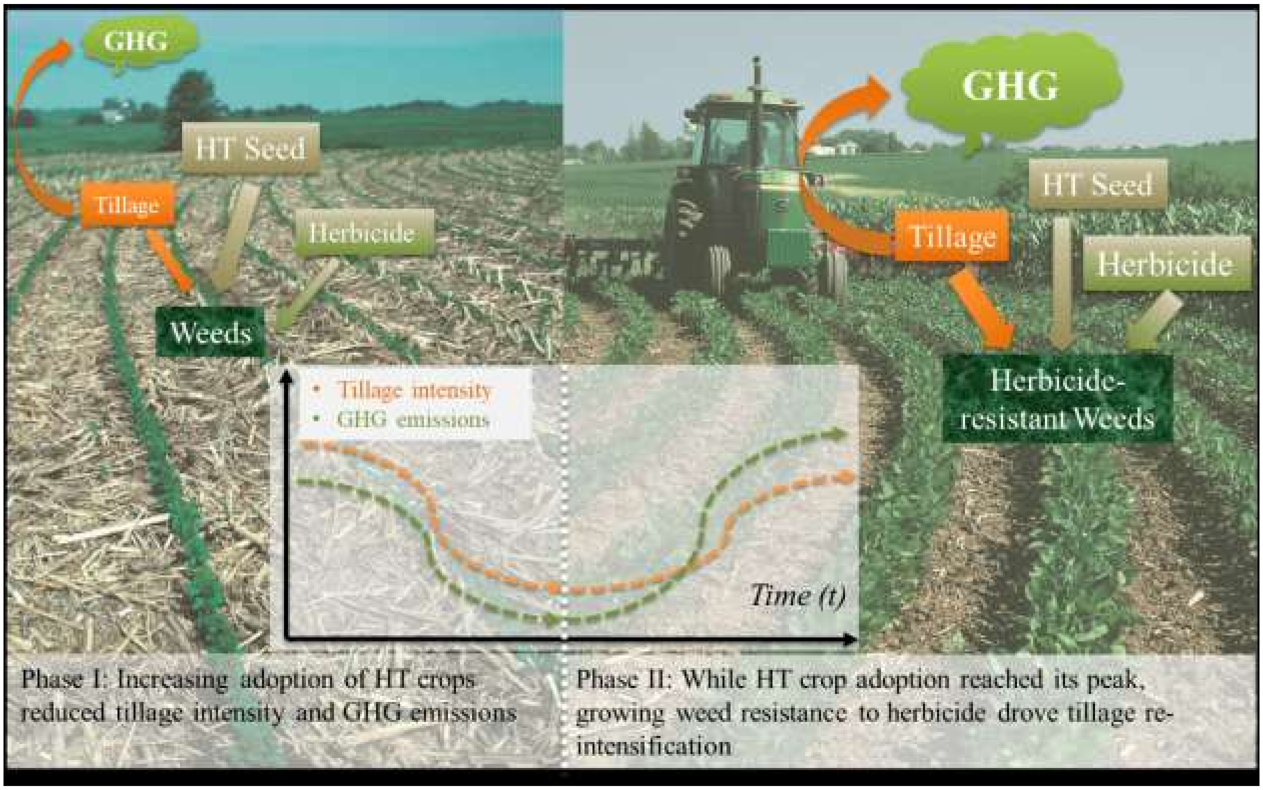

Figure 1 Conceptual depiction of the hypothetical GHG fluxes in response to tillage intensity changes affected by herbicide-tolerant (HT) crop adoption and emergence of herbicide-resistant weeds. Arrow thickness and box sizes indicate the intensity of tillage practice, herbicide use, and seed varieties in controlling weeds. The conditions in phase I and II represent the tillage intensity shift before and after 2008 in the US, respectively, and the tillage-affected GHG fluxes that are examined in this study. (The background photo is credit to the USDA photo gallery, https://photogallery.sc.egov.usda.gov/photogallery/#/)

A key data source of our study is a commercial survey of farmer choices regarding corn and soybean seed varieties, pesticide choices (including herbicide, insecticide, and fungicide), and intensity of tillage practices (*16*). These data allowed us to develop time-series gridded maps to characterize the location and intensity of tillage practices in the U.S. corn-soybean cropping systems during 1998-2016. We explored the reasons that were likely to shape the changes in tillage intensity across the country by examining the relationships between the state-level adoption rate of genetically engineered, herbicide-tolerant crops, the number of herbicide-resistant weed species, and corn-soybean acreage under different tillage practices. Furthermore, we used the annual tillage intensity maps to drive a land ecosystem model, Dynamic Land Ecosystem Model (DLEM), to distinguish and quantify how tillage practice changes in the U.S. corn-soybean cropping system have affected net fluxes of CO_2 and N_2O during 1998-2016. We examined the GHG fluxes under tillage practices in the pre- and post-2008 time intervals because tillage intensity in both corn and soybean-planted lands was found to be the lowest in 2008. In these experiments, except for tillage practices, all the rest of the environmental drivers including climate variability, atmospheric composition, land use and cover change, crop rotation, fertilizer use, and tile drainage are prescribed by time-series gridded data at a resolution of 5-arc min by 5-arc min. More details can be found in the Methods section and Supplementary Material.

Results

Tillage intensity change, HT crop adoption, and weed resistance

We adopted a unit-less index to represent the national and state-level tillage intensity by standardizing the acreage ratio of intensive to less-intensive tillage practices (e.g., acreage ratio of conventional to conservation tillage, conservation to no-till, and conventional to no-till) into a value between 0 and 100% (see Methods). Our analysis indicates that tillage intensity in the U.S. corn-soybean cropping systems declined substantially during 1998-2008, but shifted to an increasing pattern after 2008 (blue line in Fig 2c-2d). The farmers' survey data indicate that corn and soybean acreage under no-till practice increased by 5.2 Mha and 6.8 Mha during 1998-2008, respectively. However, this increase was followed by a no-till cropland acreage decline, composing of 0.2 Mha from corn and 2.4Mha from soybean, in the period 2009-2016 (Fig 2a-

2b). No-till was used on 20%-33% (range of min to max) of national corn acreage, but it had a much larger share (34%-55%) on soybean-planted lands over the study period (Figure S1 in Supplementary Material). This supports the statement in Livingston (*26*) that soybean production is more reliant on herbicide and less on tillage than is corn production. However, the no-till shares estimated in our study only reflect the annual percentage of corn- and soybean-planted areas under no-till according to the surveyed farm operators, without separating continuous or intermittent no-till. By using the same definition of no-till (defined as the absence of any tillage operation from harvest of the previous crop to harvest of the current crop), we found that the acreage shares of no-till reported by our data were close to the three most recent field-level crop-specific production practice surveys conducted by USDA Agricultural Resource Management Survey (ARMS, i.e., 23%-27% of total corn acreage was under no-till in 2005, 2010, 2016, and 35-45% of total soybean acreage in 2002, 2006, 2012) (*5*).

Corn acreage under conventional tillage showed annual fluctuations around the zero line (no change), while areas receiving conservation tillage first declined and then increased from 1998-2016. Soybean acreage under conservation and conventional tillage changed with a similar pattern first declining until 2007 and then increasing with the 2016 level close to or above the initial level of 1998. Increases in no-till crop acreage before 2008 predominantly occurred in the Mississippi River Basin, the Corn Belt and Lower Mississippi Alluvial Valley in particular, and small areas along the U.S. east coast (Figure S2 in the Supplementary Material). Accordingly, the acreage of conservation and conventional tillage decreased in these areas. However, the no-till area declines after 2008 were mainly found in the Southern US and the southern part of the Midwest, while intensifying tillage centered in the central and northern part of the Midwest where a large amount of fertilizer has been applied to boost crop growth (*27*). The spatial heterogeneity of tillage practice changes explained the faster GHG responses in Phase II shown by conceptual diagram (Figure 1) and in our model estimations. Among states, the central (e.g., Illinois, Indiana, and Iowa) and western Corn Belt states (e.g., Nebraska, North Dakota, and Minnesota) had large variations of different tillage practices over the years in corn and soybean acreage (Figure S3-S4 in the Supplementary Material).

We examined the relationships among tillage intensity, crop seed varieties, and weed resistance since 1998. Our analysis demonstrates that the early-stage (1998-2008) reduction in tillage intensity was strongly correlated with the increases in national adoption rate of genetically engineered HT corn and soybean varieties. The latter included seeds that had herbicide-tolerant gene only, as well as stacked genes (i.e., with both herbicide-tolerant and insect-tolerant traits). Nationally, the adoption rate of HT crops has substantially increased since the beginning of the study period, and then reached a level above 90%, or close to 100% in some states during the 2000s (Figure S5-S6 in the Supplementary Material). The same survey data reveal that the national average share of HT varieties in all the planted corn grew from 11% in 1998 to ~90% after 2008, while HT soybean varieties increased from 61% in 1998 to ~95% since 2004. The percentage of HT crops in soybean production started increasing earlier than that in corn production, and reached the peak a few years earlier as well. The share of HT varieties in both crops leveled off in the early- to mid-2000s, and thus had no significant relationship ($p > 0.1$) with the post-2008 increases in tillage intensity. Nonetheless, we find that the increasing number of herbicide-resistant weed species was closely correlated to the rising tillage intensity after 2008 (with a correlation coefficient of 0.81 in corn and 0.87 in soybean, $p < 0.01$, Fig 1c-1d). Likewise, weed resistance to herbicide was more prevalent in the U.S. soybean production than in corn production, with accumulative number of species up to 220 and 166, respectively, in the year of 2016. It may be caused by more herbicide usage and less reliance on tillage in soybean production than in corn production. Similar results were reported by Livingston (*26*), in which 5.6% of corn acres in 2010 and 40% of soybean acres in 2012 were identified as being infested by glyphosate-resistant weeds or declines in glyphosate effectiveness. Our results demonstrate the historical role of HT crop adoption and growing weed pressure in shifting of tillage intensity across the U.S. It also implies that, in the future, farmers are likely to adopt tillage practices on more cropped acres to control weeds given that tillage won’t promote herbicide resistance.

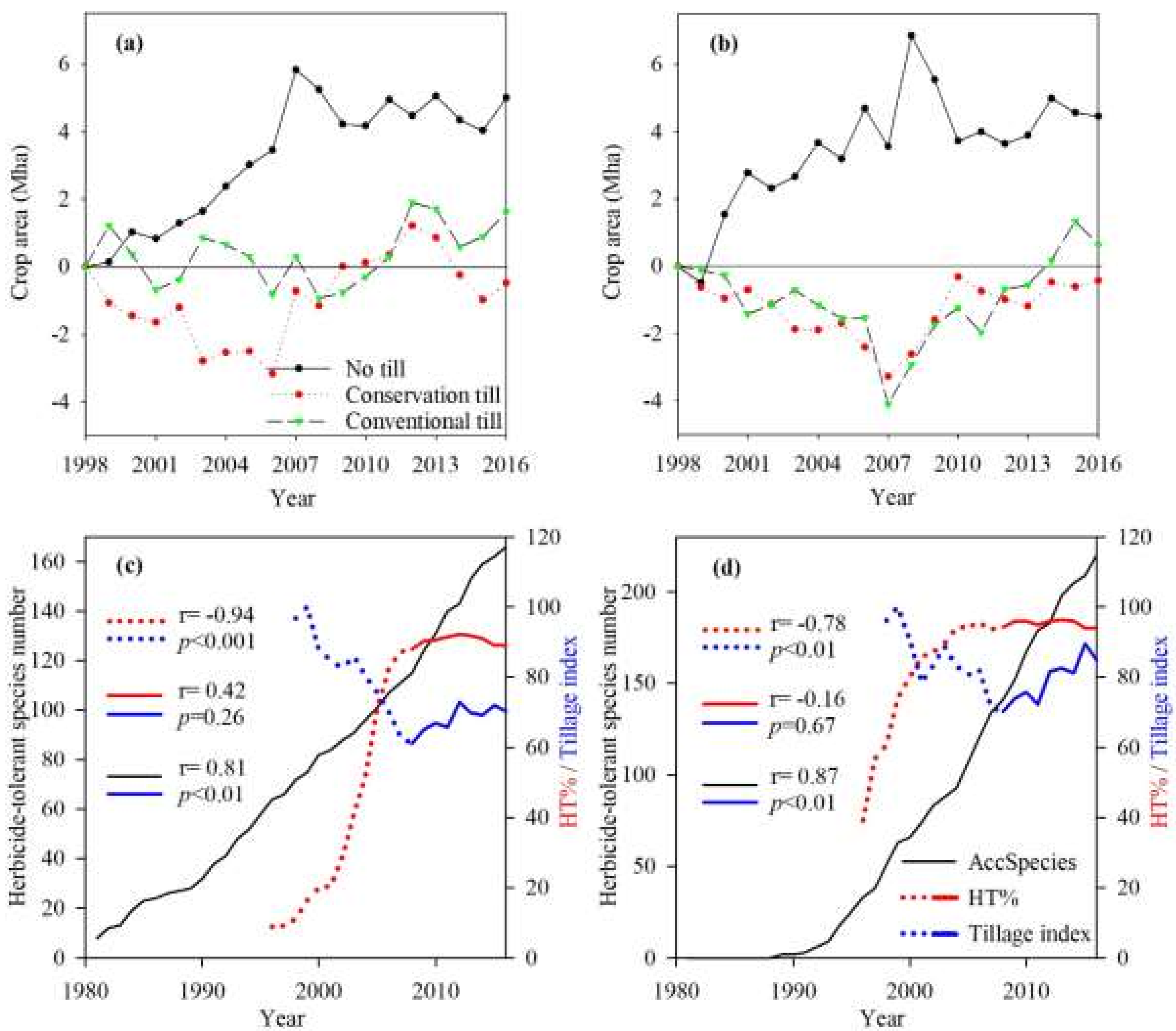

Figure 2. Annual changes of crop acreage under each tillage practice since 1998 for corn (a) and soybean (b) in the lower 48 states of the U.S., and relationships between tillage intensity index (*Tillage index*), accumulated species number (*AccSpecies*) of weeds that are resistant to herbicides, and herbicide-tolerant crop planted percentage (*HT%*) for corn (c) and soybean (d). Dotted and solid lines in figure c & d indicate the period before and after 2008, respectively. Correlation coefficients indicate the relationship between the two lines specified.

Tillage impacts on GHG fluxes

We set up a series of simulation experiments using DLEM to distinguish between and quantify the impacts of historical tillage practices and tillage intensity change (TIC) on soil GHG emissions. The former is estimated as the difference between the experiment driven by historical tillage practices vs no-till scenario, while the latter reflects the differences between experiments under varied vs fixed tillage practices (see Methods). Model simulation results show that historical tillage practices during 1998-2016 resulted in net GHG emissions at a rate of 64.3 ± 20.0 Tg CO_2 eq/yr (mean ± SD, SD indicating inter-annual variability of GHG estimates). This **is close to direct N_2O emission from national synthetic fertilizer uses** (i.e., 63.6 Tg CO_2 eq/yr in 2016 reported by EPA (*28*)), but with larger inter-annual variations (SD is 31% of mean). Nearly half of the tillage impact was attributed to tillage-induced CO_2 emission from soils, and the rest from direct soil N_2O emissions. In the context of multi-factor environmental changes, tillage impacts were estimated to range from 32.9 Tg CO_2 eq/yr in 2009 to 102.8 Tg CO_2 eq/yr in 2012 (Fig 3). The highest tillage-induced GHG emissions we found in 2012 was likely caused by crop mortality in the summer drought which limited crop N demand and provided more substrate for decomposition and denitrification (*29*). The max-min GHG difference resulting from tillage practices on the U.S. corn-soybean system was equivalent to 5-23% of the global GHG mitigation potential of crop management (0.3-1.5 Pg CO_2 eq/yr (*30*)). This difference suggests a sizeable GHG mitigation potential in tillage management, if the tillage decision can be made with consideration of crop N demand/supply balance and impacts of climate extremes.

Our estimation shows that tillage-induced GHG emissions declined at an annual rate of 4.6 Tg CO_2/yr during 1998-2008, and then increased by 2.7 Tg CO_2 eq/yr during 2009-2016 (Figure 3). Regardless of change direction, the changing trends were at a similar level or higher than the reported trend of annual GHG emissions from the U.S. Agriculture sector during 1990-2016 (including CO_2, CH_4 and N_2O emissions from agricultural soil management, rice cultivation, livestock and manure management, liming, and field burning of agricultural residues, 2.3 Tg CO_2 eq/yr (*28*)).

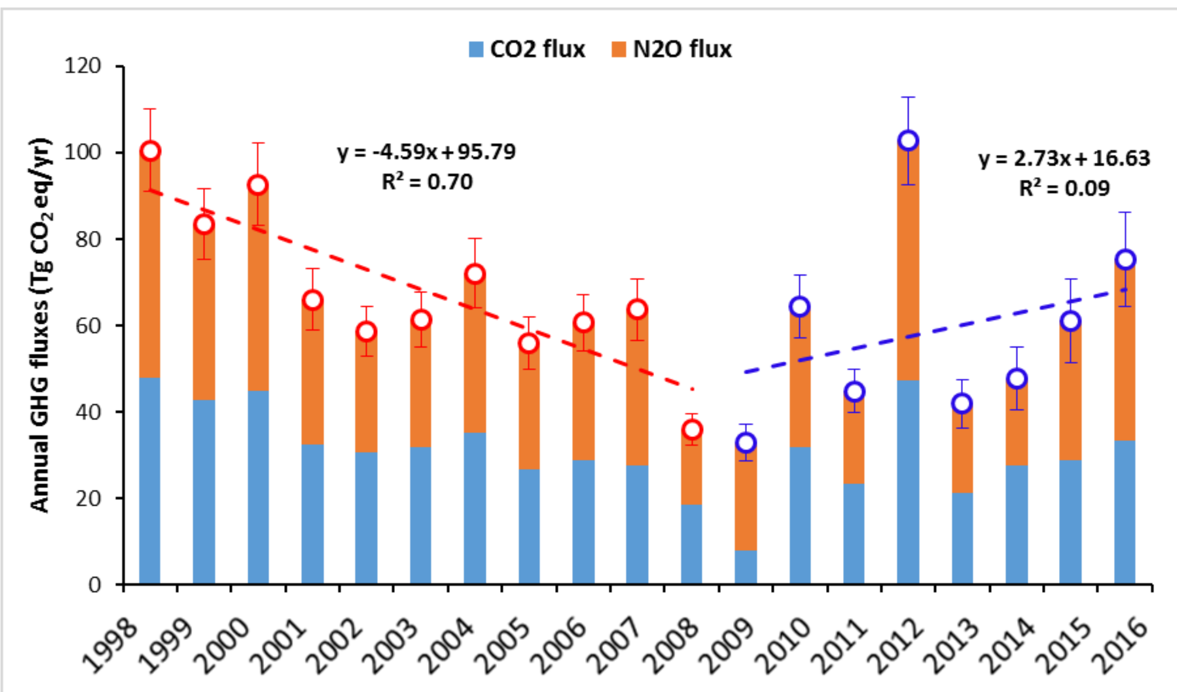

Figure 3. Model estimated impacts of tillage practices on GHG emissions in the U.S. corn-soybean cropping system during 1998-2016. Error bar denotes modeled uncertainty, which is the standard deviation calculated from multiple model runs with various values of key parameter sets

(details of uncertainty estimation and simulation experiments can be found in the Supplementary Material). Note: The lowest tillage-induced GHG emission is not found in 2008 when national tillage intensity was the lowest, because the complex interactions between tillage practices and other environmental changes within managed croplands, as well as legacy effects of residual removal, are also included in model estimations.

Impacts of tillage intensity change on net GHG fluxes

Tillage impact on GHG emissions first declined during 1998-2008, and then increased afterward, which was predominantly determined by tillage intensity change across the nation. The GHG mitigation rate from tillage reduction alone in the period 1998-2008 (-5.5 ± 4.8 Tg CO_2 eq/yr, 1998-2008, Fig 4a) could offset the annual GHG emission increase from the entire US agriculture sector (*28*) over the same period, but this mitigation benefit disappeared after 2008, and the tillage impact shifted to accelerating GHG emissions. We estimated that the tillage intensity increase during 2009-2016 resulted in a net GHG source of 13.8 ± 5.6 Tg CO_2 eq/yr, more than doubled the GHG mitigation rate due to reduced tillage intensity in the preceding decade.

We find that the declining tillage intensity cumulatively reduced GHG emissions by 61.0 Tg CO_2 eq during 1998-2008, while increased GHG emissions of 110.0 Tg CO_2 eq were caused by intensifying tillage in the post-2008 period (Fig 4b). The cumulative impacts of tillage practice change shifted from a net GHG sink to a net source in 2013. During the past ~two decades (1998-2016), cumulative GHG emissions due to tillage intensity change in the U.S. corn-soybean cropping system was estimated as 49.1 Tg CO_2 eq. This change was equivalent to 1.2 fold of the net GHG emission increase from the whole U.S. agriculture sector during the same period (annual increase rate of 2.18 Tg CO_2 eq/yr for 19 years, 41.4 Tg CO_2 eq in total

(*28*)). The model estimates in the U.S. corn-soybean system reveal that the tillage intensity changes over the past two decades are large enough to shape the dynamics of national agricultural soil GHG fluxes.

Our work implies that the benefit of HT crop adoption in reducing tillage has reached its peak, while the emerging weed resistance is found to contribute to intensifying tillage practices. As weed resistance persists and grows, tillage intensity is anticipated to continue to rise, which would further increase GHG emissions and contribute to global warming.

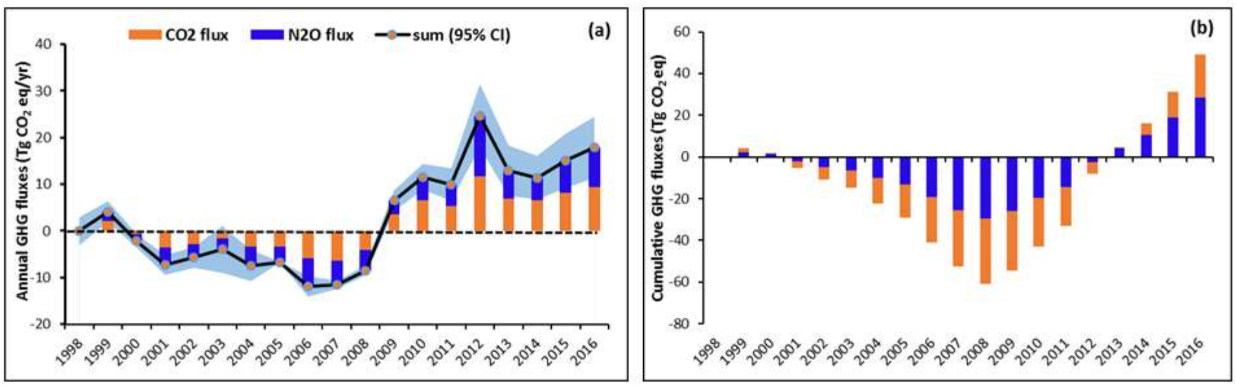

Figure 4 Annual average (a) and accumulated (b) CO_2 and N_2O fluxes (both in the unit of CO_2 equivalent) resulted from tillage intensity change relative to the year 1998 (for the period 1998-2008) and the year 2008 (for the period 2009-2016). We selected 2008 as a benchmark year for the post-2008 assessment because national tillage intensity started to increase from this year. The cumulative GHG fluxes in Figure b reflects how soon the GHG mitigation during 1998-2008 has been offset by the increased GHG emissions after 2008. The shaded area in panel (a) stands for a 95% confidence interval as calculated from multiple simulation experiments with prescribed parameter values.

Spatial patterns of tillage and tillage practice change impacts

Our model estimations indicate a substantial impact of historical tillage adoption on GHG fluxes, equivalent to the role of agricultural fertilizer input. Still, there exist large inter-annual variations due to tillage intensity changes and their interaction with other factors such as climate variability and crop resource use efficiencies. Spatially, the highest tillage-induced GHG emissions are found to center in the Corn Belt area in 1998, the prairie pothole region in particular, including northern Iowa and southwestern Minnesota (Fig 5). Due to the decline in tillage intensity, GHG emissions in 2008 were reduced, which was consistent with the spatial shift of tillage intensity across the region (Figure S2 and S9 in the Supplementary Material). However, GHG emissions due to tillage rebounded in 2016, with a pattern similar to the year of 1998 but wider source areas (Fig 5). The reduced GHG emissions under tillage practices (shown by greenish colors in Fig 5) reflect more weight on the mechanisms that tillage can reduce denitrification rate and residue retention in these areas.

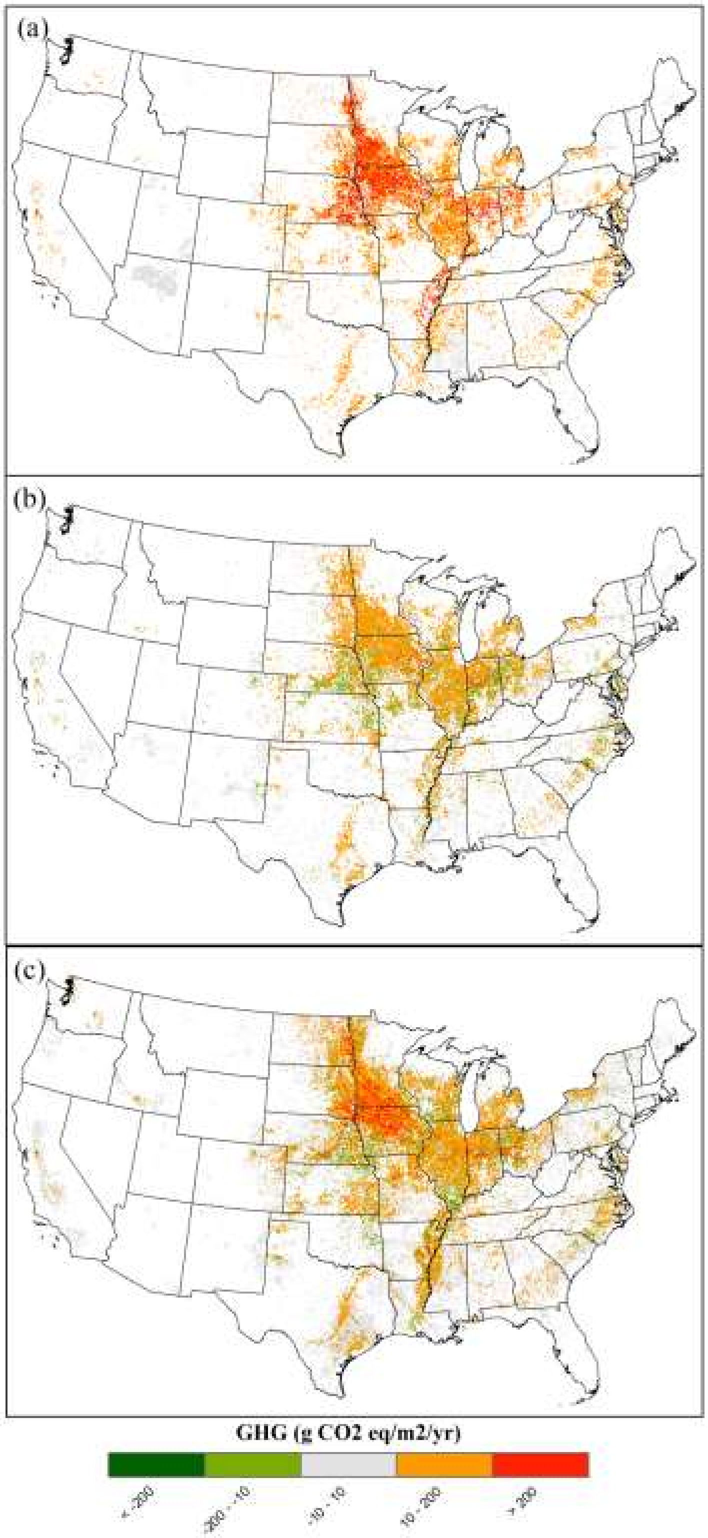

Figure 5. Model estimated GHG fluxes due to the historical use of tillage in the year of 1998 (a), 2008 (b), and 2016 (c) across the US corn-soybean cropping system

In terms of the impacts of tillage intensity changes, we find the spatial distribution and magnitude for the accumulated CO_2 are similar to those of N_2O fluxes before and after 2008 (Fig 6). However, the spatial coverages of tillage affected areas differ between these two periods. The considerable spatial heterogeneity in the GHG flux responses (i.e., a mixture of negative and positive of values) are primarily caused by the variations in local climate, soil properties, and cropping system mixed with tillage intensity changes across the country (Fig 6, Fig S2 in the Supplementary Material). The areas with increased GHG emissions due to intensifying tillage after 2008 covered the entire Corn Belt, Lower Mississippi Alluvial Valley. In particular, the western Corn Belt including the Dakotas and part of Minnesota stood out with high emission rate, in which corn and soybean cropping systems expanded in the most recent decade (*31–33*). They are found to be larger than the pre-2008 GHG mitigation areas that resulted from reducing tillage, which are concentrated in the central Corn Belt, Lower Mississippi Alluvial Valley, and the U.S. east coast.

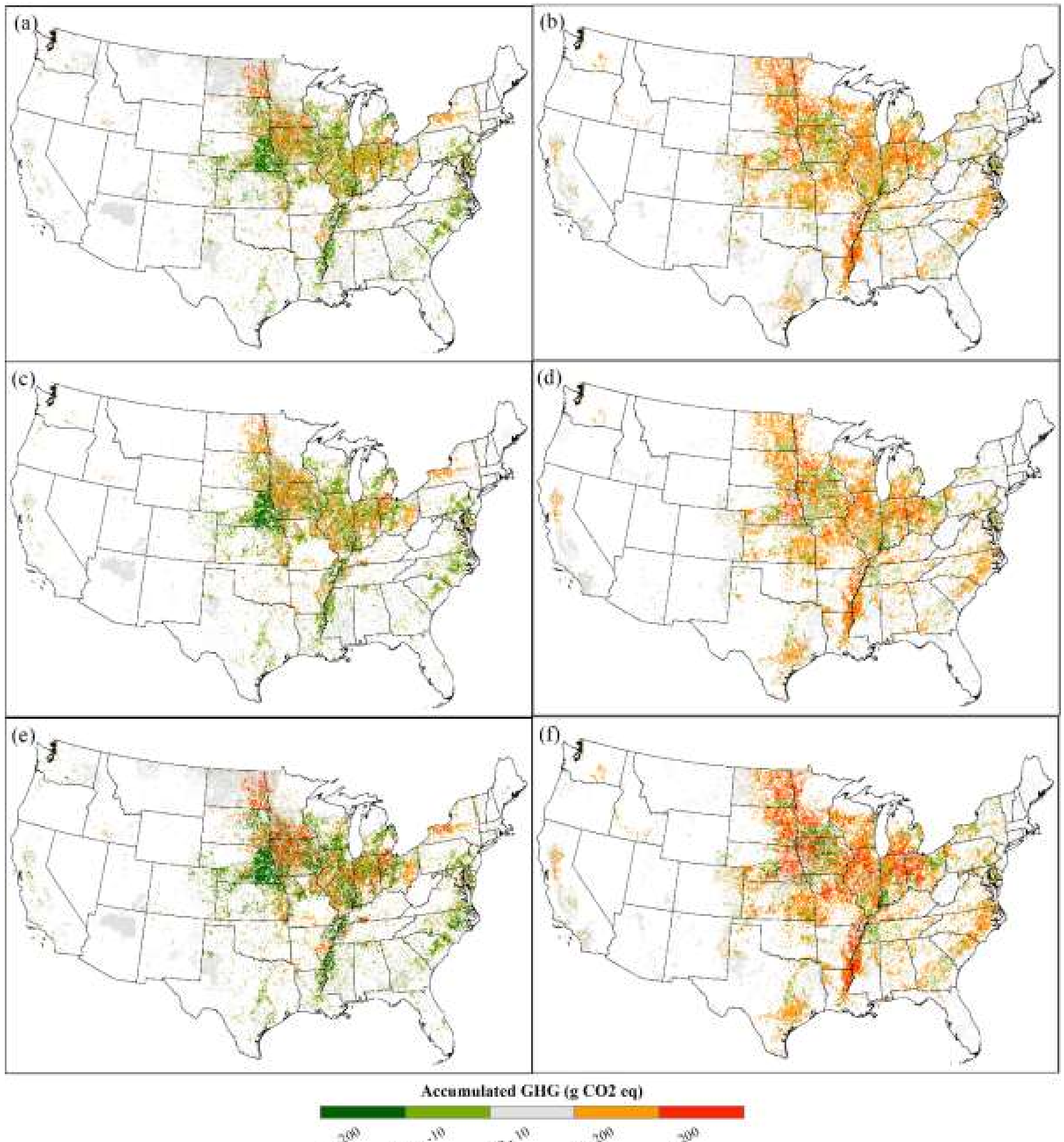

Figure 6. Accumulated GHG fluxes (g CO_2 eq/m^2) due to tillage intensity changes across the U.S. corn-soybean cropping system during 1998-2008 (accumulated in 11 years, left panel) and 2009-2016 (accumulated in 8 years, right panel): fluxes of CO_2 (a, b), N_2O (c, d), and their sum (e, f).

Uncertainties with fall tillage practice considered

Most tillage is implemented in spring. It should be noted that fall tillage may be adopted before and in addition to spring tillage on some farmlands, but we do not exactly know where and when the double tillage was implemented across the country. Considering both spring and fall tillage, our model predicted that historical tillage practices could lead to a net GHG emission of 92.4 ± 22.0 Tg CO_2 eq/yr (mean ± SD) during the study period. This prediction shows an upper bound of estimated tillage impacts, approximately 44% higher than the estimation considering spring tillage only. Assuming that all corn and soybean fields under tillage were tilled twice a year (in both spring and fall), we estimate that the increased tillage intensity in the period 2009-2016 increased GHG emissions by 20.5 ± 7.2 Tg CO_2 eq/yr, while the reduced tillage intensity before 2008 caused a reduction in GHG emissions by 7.0 ± 6.6 Tg CO2 eq/yr. As a result, the corresponding tillage intensity change-induced accumulated GHG flux changes during 1998-2016 were found to be approximately 78% higher than the estimates driven by spring tillage only (i.e., 87.5 Tg CO_2 eq under tillage twice a year versus 49.1 Tg CO_2 eq under spring tillage only). Despite the uncertainty caused by the lack of detailed tillage frequency data, our estimates provide a lower and an upper bound on tillage practice impacts, which strengthened our conclusion that there is substantial GHG mitigation potential through managing tillage practices.

The spatially explicit annual tillage maps used to drive the model simulation in this study was developed by combining time-series crop type and distribution maps, soil erodibility ranking maps, and the Crop Reporting District (CRD)-level farmers survey during 1998-2016. Due to limited information, we assume that the no-till practice has the highest likelihood of being adopted on the highly erodible lands in each CRD. Our data show that the continuous no-till areas account for 10% of total corn and soybean acreage during 1998-2016, with an additional

5% of corn and soybean acreage under tillage only once since 1998. These numbers are lower than but comparable to the values reported in a four-year survey conducted by USDA ARMS, which shows 18% of corn-planted area under continuous no-till/strip-till in 2016 and the three years preceding the survey year, and 21% for soybean in 2012 and three years before that (*5*). The reasons for lower proportion of continuous no-till in our spatial tillage maps include: 1) these data cover longer time period; 2) no-till in our data are defined as the absence of tillage practice and where strip-till is excluded. The long-term survey data we rely on to develop tillage maps in this study have multi-year survey records for some farms (e.g., area percentage under no-till, conservation and conventional tillage in each year), but plot-level arrangement may change over time and remain difficult to track. Even though our data have a lower share of continuous no-till than those reported by the four-year survey, we may still overestimate the no-till share over a ~two-decade time frame considering the spatial tillage arrangement within a farm. The assumption that we made to always assign no-till to highly erodible lands first may have slightly underestimated the historical tillage-induced GHG emissions across the US corn-soybean cropping system, while overestimating GHG mitigation due to tillage intensity change during 1998-2008 and underestimating TIC-induced GHG emissions during 2009-2016. The uncertainty in the estimated GHG consequences of tillage practices indicates the importance of implementing a long-term survey and identifying the places and duration of continuous no-till practices across the U.S.

Tillage intensity changes can affect GHG emission beyond field, among which CO_2 emission from agricultural machinery is an GHG source to be considered. Due to the lack of data, we used two extreme-case scenarios to estimate the amount of machinery CO_2 emissions associated with tillage practice changes. We assume that 1) machinery change from decreasing tillage intensity was all attributed to the shift from conventional tillage to no-till, and vice versa for increasing tillage intensity, and 2) increasing no-till areas were all converted from conventional tillage and reducing no-till areas were all converted to conventional tillage. The tillage conversion area was counted repetitively every year after the conversion occurred to estimate the fuel-derive CO_2 emissions. Based on our data, the no-till practice implemented on additional corn and soybean acreage were found to be 55.6 Mha, cumulatively, during 1998-2008; while the reduced no-till acreage summed to 29 Mha during 2009-2016. Using machinery emission data obtained from Adler et al (*34*) (i.e., 17.01 Kg C/ha from plow vs 0 from no till), such assumption will result in a reduced GHG emission at 0.315 Tg CO_2 eq/yr for the period of 1998 to 2008, and an additional GHG source of 0.226 Tg CO_2 eq/yr for the period of 2009 to 2016. Both scenarios show a minor contribution from the changed machinery emissions, compared with soil GHG emissions driven by tillage intensity changes.

Outlook

This study demonstrated a shift in national tillage intensity for the corn-soybean system during 1998-2016, and examined the role of tillage practices and their intensity changes in affecting GHG emissions from the U.S. corn-soybean planted soils. The findings suggest that the GHG mitigation benefit gained from the tillage intensity reduction during 1998- 2008 have been offset by tillage practice re-intensification since 2008. Without an effective strategy to control weeds, tillage intensity is expected to continue growing and undermine the GHG mitigation achievements from other activities or other sectors. On the other hand, this study implies that the farmers' choices in managing glyphosate resistance, such as not applying glyphosate during consecutive growing seasons, using glyphosate during fewer years, and combining it with other herbicides (*13*), may help mitigate agricultural GHG emissions.

While we assessed our estimation uncertainties caused by model assumptions, limited data about tillage practices, and key parameter values, there remain knowledge gaps that hinder us from accurately predicting the consequences of tillage intensity changes. For example, it remains uncertain how sensitive crop growth, terrestrial carbon and nitrogen cycling, as well as GHG fluxes are to different tillage practices with a combination of environmental stressors including climate and emergence of herbicide-resistant weeds (*29*, *35*). In addition, the environmental impacts differ between simplified and diversified cropping systems (*36*, *37*). Research has also been very limited on how land conversion, crop rotation, and tillage practices interact in affecting agricultural GHG balance and climate mitigation. This increases uncertainty in accounting for both carbon debt (*38*, *39*), soil carbon storage change (*40*, *41*), and GHG balance as indicated in this work. We therefore suggest future research to examine the previously overlooked patterns and drivers responsible for rotation and crop-specific tillage intensity change through data analysis and modeling, and to improve our understanding of responses and feedback between agroecosystem management and climate system.

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Author contributions

C.L., D.A.H., and H.F. conceived and designed the research. C.L. and Y.Z. developed tillage data sets, carried out model simulations, analyzed the model results, and wrote the manuscript. D.A.H. and H.F. synthesized and interpreted the farmers survey data and contributed to the tillage data development. H.T., and D.H. helped with model validation, result interpretation and discussion. All co-authors reviewed and contributed to the manuscript.

Competing interests

The authors declare no competing interests.

Methods

Data Information

The database we used to characterize corn and soybean tillage practice intensity and HT crop adoption rate was mainly from a nationwide survey of farmer choices at the field (i.e., plot) level of analysis. The data were purchased from Kynetec, the most prominent commercial surveying company in U.S. agriculture. Coverage purchased was for the 1998-2016 crop years. Farmers were queried about cultivation practice intensity, including no-till, conservation tillage (e.g., ridge till, mulch till), and conventional tillage (e.g., moldboard plow, chisel plow, disk harrow) in each USDA Crop Reporting District (CRD). Although location is available at the county level, data collection procedures are intended to establish representativeness at USDA Crop Reporting District (CRD) level of disaggregation. A CRD is comprised of about nine contiguous counties that are also similar in cropping conditions. For each of the corn and soybean crops and for each year over the period, about 4,000-4,500 independent farm operators were paid to complete the survey. Respondents were identified by various means, including through federal information regarding participation in government programs. Data used in this manuscript were collected primarily through telephone calls where multiple attempts will be made in order to ensure high participation rates and so representativeness. The company implements rigorous protocols to ensure that interviewers and interview supervisors are trained to implement consistent, standardized procedures for data collection, quality screening and subsequent data transcription/processing.

The 1998-2011 section of these data have been used elsewhere to inquire into how glyphosate tolerant soybean seed has influenced tillage practices (*13*), genetically engineered crops have affected pesticide use (*42*) and confusion in herbicide choices (*43*). The soybean part of these data have been recently used to examine the relationship of between the widespread of glyphosate-resistant weeds and reduction in the conservation tillage in soybean production (*16*). As far as we know, no alternative data source on actual annual tillage choices exists in the United States that covers the period 2005-2016, a critical time in light of seed technology innovations.

From this database we obtained the annual information of seed varieties, including state-level adoption of HT crops, and annual percentage of tillage types at the CRD level. Weed species data were obtained from http://www.weedscience.org/. To demonstrate the comprehensive dynamics of acreage changes under different tillage practices, we use a unit-less indicator to represent national and state-level tillage intensity (*TI*) by considering the area share of no-till, conservation and conventional tillage. First, we identified the max tillage intensity from sum of the three ratio during the period of 1998 to 2016 for each state or entire country. Second, we normalized the weight of acres under intensive tillage practice to those under less intensive tillage groups. Note that the index was normalized by the max tillage intensity in a given area (i.e. state or entire US), which depicts the temporal changes of tillage intensity in each specific region and it was not comparable between regions.

$$TI_{max} = max\ (A\_Till_{CV,i,j}/A\_Till_{CS,i,j} + A\_Till_{CV,i,j}/A\_Till_{NT,i,j} + A\_Till_{CS,i,j}/A\_Till_{NT,i,j})$$

$$TI_{i,j} = \frac{(A\_Till_{CV,i,j}/A\_Till_{CS,i,j} + A\_Till_{CV,i,j}/A\_Till_{NT,i,j} + A\_Till_{CS,i,j}/A\_Till_{NT,i,j})}{TI_{max}} \times 100\%$$

where A_Till_{CV}, A_Till_{CS}, and A_Till_{NT} stand for corn or soybean acreage under conventional tillage, conservation tillage, and no till, respectively. Subscript *i* denotes corn or soybean, and subscript *j* denotes year.

We harmonized 1-km time-series gridded cropland distribution and type maps for the contiguous U.S. (*44*, *45*) with the CRD-level percentage data of corn/soybean acreage that adopted the three tillage types to spatialize the annual tillage-specific area data (*46*). The annual maps of various tillage practices have been used to force the model to assess their impacts on GHG fluxes. More details on tillage intensity change can be found in Figure S1-6 in the Supplementary Material.

Modeling Approach

We adopted a process-based land ecosystem model, DLEM (Dynamic Land Ecosystem Model), to assess the impacts of tillage practices on net fluxes of CO_2 and N_2O from the agricultural soils in the U.S. Corn-soybean cropping system. The DLEM is unique in incorporating multiple environmental drivers, grid-to-grid connectivity through river systems, and simultaneous estimation of CO_2, CH_4 and N_2O fluxes (*47–49*). Its agricultural module has been intensively calibrated and validated in upland and lowland croplands across countries and the entire world, and has been widely used to quantify the contributions of multi-factor environmental changes to ecosystem functions (*32*, *49–54*). We have validated the DLEM's performance in simulating soil organic carbon content and tillage impacts on SOC dynamics across the U.S. in our previous work (*31*, *45*, *46*). In this study, we implemented additional model validation by comparing model estimates with measured N_2O fluxes under no-till and conventional tillage practice in a corn-planting site in Tennessee (Fig S7 in the Supplementary Material).

To distinguish the impacts of tillage practice change from other environmental drivers and human activities, we set up a series of simulation experiments by turning on and off tillage practice changes at a few time points (more details in section 3.4 in the Supplementary Material). To characterize other natural environmental changes and human practices and to force the model, a number of time-series gridded data sets have been developed at the same resolution spanning from 1850-2016. In addition to tillage practice, the model input data include daily climate condition (max, min and mean temperature, precipitation, shortwave solar radiation, and relative humidity), monthly atmospheric N deposition, air CO_2 concentration, annual land use and cover change, and major agricultural management practices (such as crop-specific N fertilizer use, manure N application, tile drainage, crop rotation). More details regarding the input data can be found in section 3.3 in the Supplementary Material.

Our analysis focused on the period of 1998-2016, during which consistently collected annual tillage practice data for the corn-soybean cropping system were available. In Experiment I, the model was driven by historically varying tillage intensity and other historical input drivers including daily climate, atmospheric composition (e.g., CO_2 concentration, N deposition), land use and cover changes, and agricultural management practices (such as nitrogen fertilizer uses, crop rotation, tile drainage etc.) for the contiguous U.S. at the resolution of 5 arc-min × 5 arc-min. This experiment provided our "best estimates" of biogenic greenhouse gas fluxes in the U.S. corn-soybean cropping systems which were comparable to observations.

Experiments II and III fixed the location and cropland area under conservation and conventional till at the level of 1998 and 2008, respectively. The difference between these two experiments and Experiment I can be used to quantify the impacts of tillage intensity change (TIC) on GHG fluxes during the period 1998-2008 and 2009-2016, respectively. We set up Experiment IV to represent a hypothetical case in which the no-till practice was adopted in all the cropland area since 1998. The difference between Experiment I and IV represented the impact of the historical tillage practice pattern in the corn-soybean system (Table S1 and Figure S8 in the Supplementary Material).

We calculated CO_2 fluxes as the year-by-year SOC changes excluding DOC leaching and CH_4 fluxes. Because the CO_2 assimilation into crop biomass will be eventually consumed somewhere else, we only counted CO_2 emission from soils in this study. Likewise, only soil direct N_2O emissions were included for estimating the net GHG emissions here. Methane (CH_4) fluxes were not included in the calculation of net GHG balance because its total amount was negligible in the corn/soybean-planted areas. We used 100-year global warming potential to convert the fluxes of CO_2 and N_2O from gram C and gram N into gram CO_2 eq (*1, 49*).

$$F_{CO2^i} = (SOC_{i-1} - SOC_i) - F_{DOC_{leaching}{}^i} - F_{CH4^i}; \qquad \textit{eq. (1)}$$

$$E_{CO2^i} = F_{CO2^i}/12 \times 44; \qquad \textit{eq. (2)}$$

$$E_{N2O^i} = (F_{N2O^i}/28) \times 44 \times 265; \qquad \textit{eq. (3)}$$

$$E_{net^i} = E_{CO2^i} + E_{N2O^i}; \qquad \textit{eq. (4)}$$

in which F_{CO2^i} and F_{N2O^i} are fluxes of CO_2 and N_2O in the unit of Tg C/yr and Tg N/yr, respectively, and E_{CO2^i} and E_{N2O^i} are emissions of CO_2 and N_2O in the unit of Tg CO_2 eq.

Negative values represent GHG uptake from the atmosphere, while positive values stand for GHG emissions from soils. In eq. (1), we approximated CO_2 flux as the between-year SOC storage change minus DOC leaching and CH_4 emissions. We estimated the annual net fluxes of CO_2 and N_2O in each simulation experiment, and the impacts of historical tillage practices and tillage intensity change were quantified as the differences between experiments as described above.

For our "best-estimate" simulations, tillage was implemented in spring when corn or soybean was planted. Generally, previous-year fall tillage may also be adopted before spring tillage in part of the study areas, but it remains uncertain where they are and how often farmers have undertaken more than one tillage practices a year (*55*). Therefore, we designed two types of experiments to quantify the impacts of with- and without-fall tillage practice following the protocol described in our previous study (*46*). More specifically, fall tillage was assumed to have been implemented two weeks after harvest. In this study, we used simulations driven by spring-tillage as our 'best-estimate', while the experiments with corn-soybean land tilled twice annually (i.e. both fall and spring tillage) represented more intensive soil disturbance scenarios and provided the upper bound on tillage impact estimations.

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