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Global Pattern and Change of Cropland Soil Organic Carbon during 1901-2010: Roles of Climate, Atmospheric Chemistry, Land Use and Management

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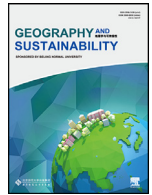Wei Ren, Kamaljit Banger, Bo Tao, Jia Yang, Yawen Huang, and Hanqin Tian

Article

Global pattern and change of cropland soil organic carbon during 1901-2010: Roles of climate, atmospheric chemistry, land use and management

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HIGHLIGHTS

- Century-scale dynamics in global cropland soil organic carbon (SOC) were simulated
- Storage and density of global cropland SOC largely increased during 1901-2010
- Increased SOC from land management partially offset SOC losses caused by climate change

GRAPHICAL ABSTRACT
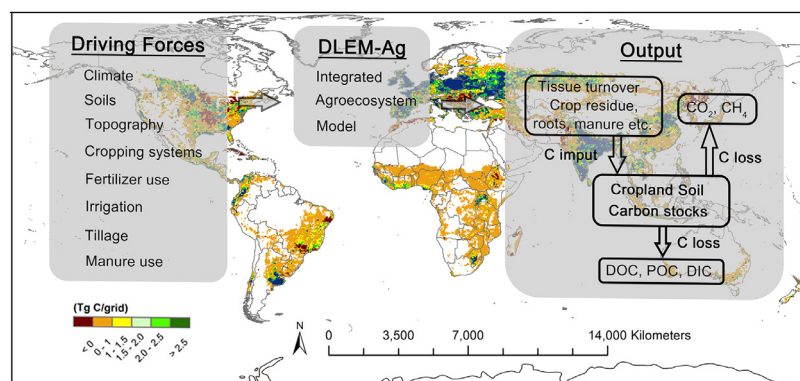
ABSTRACT

Soil organic carbon (SOC) in croplands is a key property of soil quality for ensuring food security and agricultural sustainability, and also plays a central role in the global carbon (C) budget. When managed sustainably, soils may play a critical role in mitigating climate change by sequestering C and decreasing greenhouse gas emissions into the atmosphere. However, the magnitude and spatio-temporal patterns of global cropland SOC are far from well constrained due to high land surface heterogeneity, complicated mechanisms, and multiple influencing factors. Here, we use a process-based agroecosystem model (DLEM-Ag) in combination with diverse spatially-explicit gridded environmental data to quantify the long-term trend of SOC storage in global cropland area during 1901-2010 and identify the relative impacts of climate change, elevated CO_2, nitrogen deposition, land cover change, and land management practices such as nitrogen fertilizer use and irrigation. Model results show that the total SOC and SOC density in the 2000s increased by 125% and 48.8%, respectively, compared to the early 20th century. This SOC increase was primarily attributed to cropland expansion and nitrogen fertilizer use. Factorial analysis suggests that climate change reduced approximately 3.2% (or 2,166 Tg C) of the total SOC over the past 110 years. Our results indicate that croplands have a large potential to sequester C through implementing better land use management practices, which may partially offset SOC loss caused by climate change.

1. Introduction

Soil organic carbon (SOC) represents the largest terrestrial C pool (Jobbágy and Jackson, 2000) and a small change in its magnitude

can provide significant feedbacks to atmospheric CO_2 concentration (Jobbágy and Jackson, 2000; Smith et al., 2008; Tian et al., 2015). The croplands account for approximately 10% of the global total SOC, as estimated at a range of 128-165 Pg C (1 Pg C = 10^{15} g) (Watson et al., 2000). Generally, average SOC values are relatively lower in croplands than in natural ecosystems as a result of biomass removal/harvest and some land management practices such as tillage (Drewniak et al., 2015). Improving levels of organic C and fostering C sequestration in cropland soils could have significant implications not only for food security and soil health (Six et al., 2004; Six et al., 2002), but also for achieving the less than 1.5°C global target of the Paris Climate Agreement. It has been estimated that global croplands could sequester 0.90-1.85 Pg C/yr, equivalent to 26-53% of the soil carbon sequestration target of 3.5 Pg C/yr that the 4p 1000 Initiative has established for climate mitigation (Zomer et al., 2017). Sustainably managing SOC might be a primary means for achieving climate-smart agriculture, which aims to ensure food security, mitigate, and adapt to climate change with minimal adverse environmental effects (Bai et al., 2019; Branca et al., 2011; Huang et al., 2018; Lipper et al., 2014; Ren, 2019). Therefore, it is urgent to advance our current understanding of the magnitude and patterns of cropland SOC as well as their environmental drivers, which is a prerequisite for achieving the dual benefits of meeting increasing food demand and mitigating future climate change (Lal, 2004; Lal et al., 2007; Paustian et al., 1997) .

Cropland SOC storage is mainly determined by the balance between C inputs in the form of residues and outputs from microbial respiration (Davidson and Janssens, 2006; Paustian et al., 1997). This balance in the C inputs and outputs is modified by changing climate, land-use, and various agronomic management practices (Davidson and Janssens, 2006; Regnier et al., 2013; Tian et al., 2016). For instance, changing climatic factors (e.g., temperature, precipitation, heatwave) reduce cropland productivity and stimulate microbial activity, which may result in net SOC loss (Lobell et al., 2014; Tian et al., 2015). While increasing CO_2 concentration enhances above and below ground plant biomass (de Noblet-Ducoudré et al., 2004; Jastrow et al., 2005; Norby et al., 2004) and is likely to promote cropland SOC storage (de Noblet-Ducoudré et al., 2004; Jastrow et al., 2005; Lobell et al., 2014; Norby et al., 2004; Ren et al., 2012; Tian et al., 2015). Unlike natural ecosystems, agronomic management (such as nitrogen fertilizer use, irrigation management, and tillage operations) may substantially change cropland SOC storage by altering the biomass production and C entering into the soil (Banger et al., 2015a; Leff et al., 2004; Ren et al., 2012; Tian et al., 2016). For example, Buyanovsky and Wagner (1998) reported that cropland SOC storage increased during the 20th century primarily due to higher-yielding crop varieties and agronomic management that improved crop residues entering into the soils. Realistically quantifying changes in cropland SOC necessitates considering both natural factors (e.g., climate change) and human activities (e.g., cropland expansion and management practices), and interactions among them, which act simultaneously in reality.

Over past decades, global cropland SOC has been investigated using a range of approaches, such as inventory-based method, empirical modeling, and process-based modeling. However, the magnitude and patterns of global cropland SOC are far from well constrained due to high land surface heterogeneity, complicated mechanisms, and multiple influencing factors. Large discrepancies were shown in estimates of the magnitude and variations from various approaches (Jandl et al., 2014; Ogle Stephen et al., 2010). Recent rapid development in soil observations/measurements, high-resolution regional/global soil compiling, big-data assimilation, and process-based modeling provides an opportunity to further examine changes in cropland SOC and the relative contributions of various environmental factors at a large extent and over a long period (Luo et al., 2009; Smith et al., 2019; Tian et al., 2015). Here we use a process-based agroecosystem model (DLEM-Ag) in combination with diverse gridded environmental data sources to quantify the magnitude and tempo-spatial patterns of SOC storage in

global croplands during 1901-2010. Specific objectives are to 1) investigate the magnitude of and long-term changing trend in SOC storage; 2) quantitatively examine the relative contributions of climate change and land use/management practices in the context of global changes; and 3) identify uncertainties and future needs. This study is built on our previous efforts that quantified C dynamics in croplands at regional scales (such as China, India, and the United States, see the model description section).

2. Methodology: model, input data and simulation protocol

2.1. The Dynamic Land Ecosystem Model and Its Agriculture Module

The Dynamic Land Ecosystem Model (DLEM) is a highly integrated, process-based ecosystem model that couples major biogeochemical cycles, water cycle, and vegetation dynamics to make spatially-explicit estimates of water, C, and nitrogen fluxes in terrestrial ecosystems at multiple temporal and spatial scales (Tian et al., 2010a; Tian et al., 2010b). It consists of five core components, i.e., biophysics, plant physiology, soil biogeochemistry, vegetation dynamics, and land use and management. The DLEM model has been widely applied in investigating dynamic responses of terrestrial water, C and nitrogen cycling to multiple global change factors such as climate, atmospheric composition (atmospheric CO_2, nitrogen deposition, and tropospheric ozone), land use change, and agriculture management practices (e.g., harvest, rotation, irrigation, and fertilizer use) at regional (such as China (Lu et al., 2012; Ren et al., 2007; Ren et al., 2012; Tian et al., 2011), India (Banger et al., 2015a; Banger et al., 2015b), Monsoon Asia (Tian et al., 2011a), tropical Asia (Tao et al., 2013), the United States (Chen et al., 2012; Ren et al., 2016; Yang et al., 2015b), and North America (Tian et al., 2015a; Xu et al., 2012; Xu et al., 2010) and global scales (Pan et al., 2014; Tian et al., 2015; Yang et al., 2015a; Zhang et al., 2016).

The DLEM-Ag was built on the framework of the DLEM for investigating changes in terrestrial biogeochemical processes in diverse agricultural ecosystems and their interactions with other ecosystems (Ren et al., 2012; Ren et al., 2016). It combines the features of crop models and biogeochemical land ecosystem models and is characterized by coupled biogeochemical cycles in an integrated atmosphere-crop-soil system, feedbacks/interactions between agroecosystems and other natural systems, multiple spatial-temporal scales, and multiple environmental driving forces. The DLEM-Ag is capable of simulating SOC, plant productivity, crop yield, greenhouse gas emissions, and other hydrological and biogeochemical (e.g., C, nitrogen, and phosphorus) processes in agroecosystems (e.g., Banger et al., 2015a; Banger et al., 2015b; Ren et al., 2011; Ren et al., 2012; Tao et al., 2013; Tian et al., 2016; Zhang et al., 2016). It simulates crop growth, soil decomposition, soil water, temperature, and nutrient flows in agroecosystems at a daily time step; and meanwhile simulates the exchange of C, nitrogen, water, and energy between agroecosystems and other natural systems.

Soil organic matter (SOM) dynamics in croplands are simulated using the classic first-order decomposition algorithm (Parton et al., 1994). The SOM in the DLEM-Ag consists of dissolved organic matter (DOM), four litter pools, three microbial pools, and two slow SOM pools. Litter pools receive biomass from tissue turnover and crop residue. The C outfluxes from cropland soil include C losses by microbial respiration and removal by soil erosion and leaching through time. The decomposition rate of each SOC pool in agroecosystems is influenced by soil temperature, texture, water content, and nutrient availability. As shown in the general conceptual framework of process-based agroecosystem models, DLEM-Ag aims to simulate SOC dynamics in croplands as influenced by direct, interactive, and long-term factors derived from natural and anthropogenic disturbances (Fig. 1). The detailed description of how the model simulates the above-mentioned processes could be found in our previous studies (Pan et al., 2014; Ren et al., 2012; Tian et al., 2010b). Here, we provide a brief introduction of soil C decomposition, dissolved organic C (DOC), and CH_4 fluxes related simulation processes.
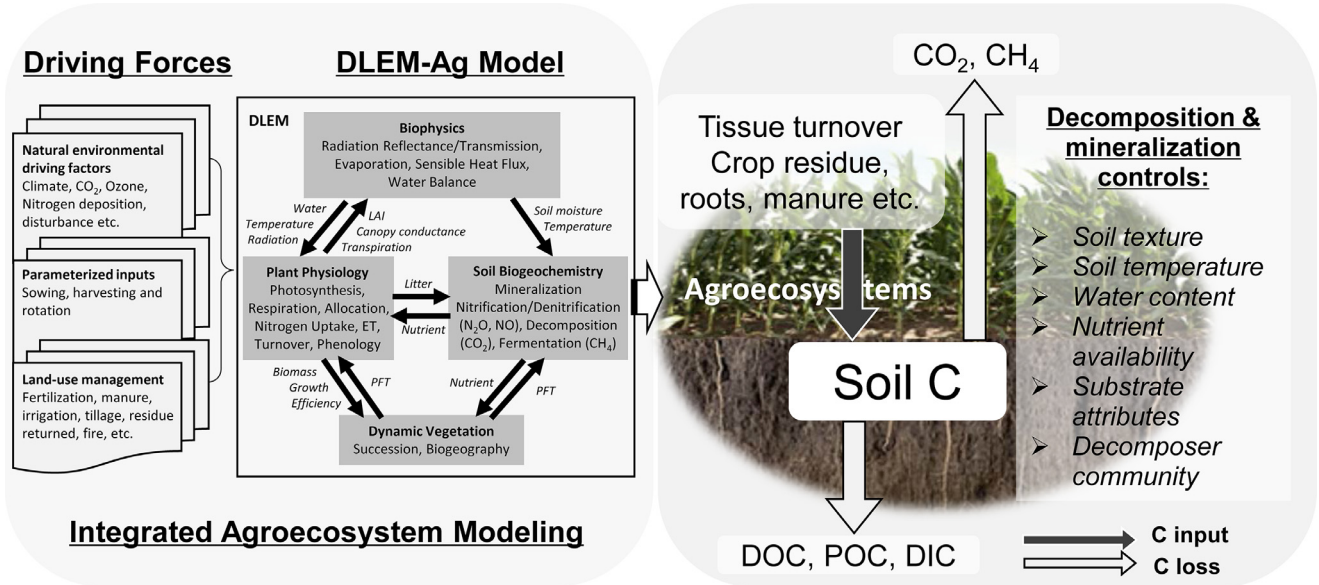
Fig. 1. Conceptual framework of crop soil carbon dynamics as influenced by long-term, interactive, and direct controls under natural and anthropogenic disturbances

2.1.1. Soil carbon decomposition

The sizes of soil C pools and the C fluxes transferred between pools determine the source and loss of soil organic and inorganic C. There are seven soil C pools (three microbial pools; two slow soil organic matter pools, namely, native organic matter and passive soil organic matter; one dissolved organic matter pool; and one dissolved inorganic pool); one woody detritus pool; and two litter pools. All organic C input, received from tissue turnover, manure, crop residue, and branch fragmentation, are totally allocated to litter pools according to a carbon/nitrogen ratio. Then the C fluxes are transferred between pools through biological decomposition, physical adsorption and desorption, and leaching. The equations to estimate soil and litter decomposition use first-order decay rate constants (k_{C_Pool}) (Liu et al., 2005; Parton et al., 1993; Petersen et al., 2005). Generally, heterotrophic respiration is a critical process that largely determines the generation of soil DOC. In the DLEM, the decomposition rate of each SOC pool is influenced by soil temperature, soil water content, nutrient availability, and soil texture:

$$k_{C\_Pool} = Kmax/365 \times f(T) \times f(W) \times f(N) \times f(clay) \quad (1)$$

$$f(T) = 4.89 \times e^{-3.432 + 0.1 \times T \times (1 - 0.5 \times T/36.9)} \quad (2)$$

$$f(W) = \begin{cases} \frac{1 - e^{-\theta/\theta_{sat}}}{1 - e^{-\theta_{fc}/\theta_{sat}}} & \theta \le \theta_{fc} \\ 1.0044 - \frac{0.0044}{e^{-5\frac{\theta/\theta_{sat} - \theta_{fc}/\theta_{sat}}{1 - \theta_{fc}/\theta_{sat}}}} & \theta > \theta_{fc} \end{cases} \quad (3)$$

$$f(clay) = 1 - 0.75 P_{clay}/100 \quad (4)$$

$$f(NM) = \begin{cases} 1 - \frac{avn - avn_{opt}}{avn_{opt}} & avn > avn_{opt} \\ 1 & avn_{opt}/2 \le avn \le avn_{opt} \\ 1 + \frac{0.5avn_{opt} - avn}{avn_{opt}} & avn \le avn_{opt}/2 \end{cases} \quad (5)$$

$$f(NI) = 0.8 + 0.2avn/avn_{opt} \quad (6)$$

where $Kmax_i$ is the maximum decay rate (year^{-1}); $f(T)$ is the average soil temperature scalar; $f(W)$ is the soil moisture scalar; $f(clay)$ is the soil texture scalar; $f(NM)$ and $f(NI)$ are different calculations of nitrogen scalar $f(N)$ in mobilization and immobilization, respectively. θ is soil water content (mm); T is air temperature (Celsius degree); θ_{sat} is soil water content at field capacity (mm); θ_{fc} is soil water content at field capacity at wilting point (mm); P_{clay} is the percentage of clay in soil (%); avn is the available soil nitrogen (g N/m^2); avn_{opt} is the optimum available soil nitrogen (g N/m^2).

2.1.2. DOC leachate production

In the DLEM, litter and soil organic matter are the sources of DOC leachate (Chantigny, 2003). Leaching of DOC is simulated with the following equations:

$$R_{lchdoc} = SDOC \times fflow \times \frac{DOCC}{DOCC + lchb_{doc}} \quad (7)$$

$$DOCC = \frac{SDOC}{W_{soil}} \quad (8)$$

$$SDOC = C_{dec} \times f_{doc-dec} \quad (9)$$

$$fflow = \frac{q_{srun} + q_{drain}}{\theta + q_{srun} + q_{drain}} \quad (10)$$

where R_{lchdoc} is the leaching rate of dissolved organic C (g C/m^2/day); $lchb_{doc}$ is the soil desorption coefficient for DOC (g C/g soil); $DOCC$ is the concentration of dissolved organic C (g C/g soil); $SDOC$ is the total amount of dissolved organic C in soil (g C/m^2); C_{dec} is the total amount of decomposed organic C for litter and all the SOC pools (g C/m^2/day); $f_{doc-dec}$ is the fraction of decomposed organic C that is dissolvable (%); W_{soil} is the weight of soil from 0 to 0.5m (g); $fflow$ is the runoff coefficient for leaching; q_{srun} is the surface runoff (mm); q_{drain} is the drainage runoff (mm).

In the DLEM, CH$_4$ production, consumption, and transport processes are considered to estimate the land-atmosphere gas exchange. Dissolved organic carbon is the only CH$_4$ production substrate considered in the DLEM. The DOC comes from gross primary productivity (GPP), and decomposition byproducts from soil organic matter and litters, which are indirectly controlled by environmental factors including soil pH, temperature and soil moisture content. CH$_4$ oxidation is determined by CH$_4$ concentrations in the air or pore space of soil, as well as soil moisture, pH, and temperature. We consider three pathways for CH$_4$ transport from soil to the atmosphere (i.e., ebullition, diffusion, and plant-mediated transport) (Tian et al., 2010c). It is assumed that methane-related biogeochemical processes only occur in the top 50 cm of the soil profile. Overall, the net CH$_4$ exchange between the atmosphere and soil is calculated by the following equation:

$$F_{CH4} = F_P + F_D + F_E - F_{air,\ oxid} - F_{trans,\ oxid} - F_{soil,oxid} \quad (11)$$

Where F_{CH4} is the flux of CH$_4$ between soil and the atmosphere (g C/m^2/day); F_P is plant-mediated transport from soil pore water to the atmosphere (g C/m^2/day); F_D is the diffusive flux of CH$_4$ from

water surface to the atmosphere (g C/m^2/d); F_E is the ebullitive CH$_4$ emission to the atmosphere; $F_{air,\,oxid}$ is atmospheric CH$_4$ oxidation rate (g C/m^2/day); $F_{trian,\,oxid}$ is the CH$_4$ oxidation during plant-mediated transport (g C/m^2/day); $F_{soil,\,oxid}$ is the CH$_4$ oxidation rate in soil pore water.

2.2. Model Driving Forces

Spatially-explicit 0.5° gridded datasets at various time steps (daily to annual) were developed to drive the DLEM-Ag model. These datasets include climate, atmospheric CO$_2$, nitrogen deposition, cropland distribution, and land management practices (such as irrigation, nitrogen fertilizer, and rotation) for the period of 1901-2010. Daily climate data, including maximum/minimum/mean temperature, precipitation, relative humidity, downward shortwave radiation, were derived from 6-hourly CRU-NCEP data set version 7 that combines the monthly CRU climate data and the daily NCEP/NCAR Reanalysis products (Wei et al., 2014).

A dynamic cohort approach is adopted to represent land use and land cover changes at the grid level based on multiple land use/cover datasets, such as global water mask (Carroll et al., 2009), time-series cropland distribution obtained from North American Carbon Program Multi-scale Synthesis and Terrestrial Model Intercomparison Project (Wei et al., 2014) (derived from Synergetic Land Cover Product (SYNMAP) (Jung et al., 2006) and land conversion datasets (Hurtt et al., 2011), global potential vegetation map (Ramankutty and Foley, 1999), global C4 percentage map (Still et al., 2003), and the Global Lakes and Wetlands Database (GLWD) (Lehner and Döll, 2004). We assume that each grid cell is initially covered by undisturbed potential vegetation and other land cover types (i.e., bare land, glacier, river, lake, and ocean, etc.). When cropland expansion or shrinkage occurs (e.g., from forest/grassland to cropland and vice versa), a new cohort is formed, and the disturbed land area within the grid cell is then proportionally subtracted from the undisturbed potential vegetation. Land management practices data (e.g., cropping system, nitrogen fertilizer use, and irrigation) were developed to examine biogeochemical processes in cropland as well as their interactions with other vegetation types. Global cropping system was categorized into nineteen types (e.g., wheat, corn, soybean, cotton, groundnuts, millet, barley, sorghum, and rice). The distribution of main crop types was identified according to the global crop geographic distribution map at a 5min spatial resolution (Leff et al., 2004) and country-level FAOSTAT agricultural census as well as the regional-level census in China and India (Banger et al., 2015a; Banger et al., 2015b; Ren et al., 2012; Ren et al., 2011; Tian et al., 2011). The phenology information and rotation types (single, double, and triple harvesting) were obtained from MODIS (Moderate Resolution Imaging Spectroradiometer) LAI product calibrated against census data and site-level observations (Banger et al., 2015a; Ren et al., 2012; Xu et al., 2012). Nitrogen fertilizer amount data were estimated based on FAOSTAT country-level data as well as more detailed data (e.g., county-level) in China, India, and North America (Banger et al., 2015a; Ren et al., 2012; Xu et al., 2012). The irrigation distribution was developed by incorporating a global irrigation map and historical crop geographic distribution map, and agricultural census (Klein Goldewijk et al., 2011; Leff et al., 2004; Siebert et al., 2013).

Other datasets (such as atmospheric CO$_2$ concentration, nitrogen deposition, soil properties, and topographic information) were the same as those used in our previous studies (Pan et al., 2014; Tian et al., 2015; Zhang et al., 2016).

2.3. Model Calibration and Performance Evaluation

In the previous studies, our model has been extensively calibrated and validated against substantial field observations/measurements in typical ecosystems, such as forests, grassland, wetland, and croplands (e.g., Banger et al., 2015a; Liu et al., 2013; Ren et al., 2012;
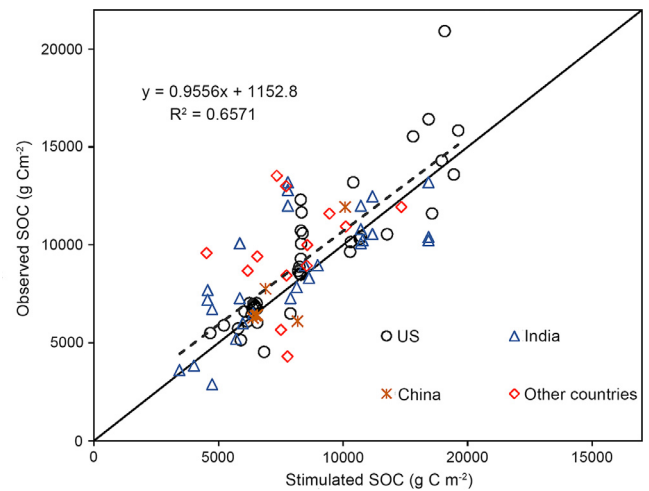
Fig. 2. Comparisons of the model estimated and observed soil organic carbon (SOC) for major cropping systems across the world (dashed line is the regression of observed data and modeled results, and the solid line is the 1:1 line. More details of observations can be found in Supporting Information)

Tian et al., 2010a; Tian et al., 2011; Zhang et al.,2015). In particular, model simulated C fluxes (e.g., NPP) and pools (e.g., SOC) in croplands have been calibrated and evaluated using site-level datasets in China (Ren et al., 2012; Ren et al., 2011; Tian et al., 2011), India (Banger et al., 2015a; Banger et al., 2015b), and the United States (Chen et al., 2012; Tian et al., 2010a), and the detailed data source of parameters can be found in the published papers (Banger et al., 2015a; Ren et al., 2012; Tao et al., 2013; Tian et al., 2011). Given we used different model driving forces from previous regional studies, we, therefore, put a specific effort on calibrating and validating the simulated cropland SOC by collecting a series of site-level SOC observations across the globe (Fig. 2, Table S1). Generally, the model-simulated SOC showed a good agreement with the field observations. However, relatively large discrepancies occurred in some sites because the background information (such as time-series climate records and rotation and management information) was incomplete and we had to use alternative datasets (e.g., deriving gridded global datasets) for driving the model.

We also compared model-simulated cropland SOC with the estimates from other studies (Table 1). For example, our simulated crop SOC storage is 115.0 ± 2.0 Pg C in the 2000s in the 50 cm soil profile. Jobbágy and Jackson (2000) estimated that cropland SOC in the 40 cm and 60 cm depth approximately accounts for 64% and 79% of total SOC in the top 1 m soil profile. Therefore, our estimated total SOC is equivalent to 141-175 Pg C in the 1m soil depth, which falls within the reasonable range (128-165 Pg C) reported by IPCC (Watson et al., 2000), and is comparable with estimates from IGBP-DIS (Global Soil Data Task, 2014), Jobbágy and Jackson (2000), and Harmonized World Soil Database (FAO et al., 2012), but lower than ISRIC SoilGrids (Hengl et al., 2014) and Zomer (for 30cm soil profile) (Zomer et al., 2017). A recent study used the process-based model to simulate the cropland SOC change in the global main cereal cropping systems during 1961-2014, and estimated a continuous increasing trend in cropland SOC storage at an annual sequestration rate of 0.48 Pg C under the designed C input rate (Wang et al., 2017). This result agrees well with our estimated annual sequestration rate of 0.65 Pg C during 1901-2010 and an average rate of 0.42 Pg C from 1961 to 2010, respectively. Comparisons show that our estimated total cropland SOC is generally comparable to those from inventory, process-based modeling, and empirical modeling, although discrepancies exist due to differences in the study domain, data sources, model structure, and assumption.

Table 1

Comparisons of results estimated by inventory and empirical/process-based modeling at the global level: soil organic carbon (SOC) storage, density, and change.

SOC storage (Pg C)	SOC density (kg/m²)	SOC change (Pg C/yr)	Area (Mha)	Period	Method	Data source
157	11.2 ± 7.7		1400	1990s	Empirical model	Jobbágy and Jackson (2000)
164	10.8		1518	1996	Inventory	IGBP-DIS (Global Soil Data Task, 2014)
149	10.23		1448	Recent decades	Inventory	Harmonized World Soil Database v 1.2 (FAO et al., 2012)
194	11.2		1730	Recent decades	Inventory	SoilGrids (Hengl et al., 2014)
128 - 165	8.0		1600	Recent decades	Inventory	IPCC, 2000 (Watson et al., 2000)
115.0 ±2.0	6.9		1667	2001-2010	Process-based modeling	This study
		0.65		1901-2010		
		0.42		1961-2010		
140.28	8.5	0.48	1400	1961-2014	Process-based modeling	Wang et al.[2017]
149.84 – 168.87	9.6 – 10.8	0.9 – 1.85	1631	2014 -2024	Geospatial modeling	Zomer et al.[2017]

Note: Jobbágy and Jackson 2000, SOC storage at 1m profile; IGBP-DIS soil Data Product, SOC storage at 1m profile. Wang et al., 2017, SOC change at the top 30 cm soil layer. Zomer et al., 2017, SOC storage and change at the top 30 cm soil layer (current and after 20 years under medium and high increase scenarios)

2.4. Simulation Experiment Design

In this study, we designed eight simulation experiments for assessing the magnitude and spatiotemporal patterns of global cropland SOC over the past 110 years, and for analyzing the relative contribution of the single environmental factor (Table 2). An equilibrium run that used 30-year (1901-1930) mean climate datasets was performed to develop the simulation baselines for C, N, and water pools, in which the equilibrium state was reached when the year-to-year changes in C, nitrogen, and water pools in each grid were less than 0.1 g C m^{-2}, 0.1 mm H$_2$O, and 0.1 g N m^{-2}, respectively. After the equilibrium run, the model was run for another 1000 years for the spin-up to remove system fluctuations caused by the shift from equilibrium to transient mode. During this stage, the time series of driving forces were randomly selected within the 30 years from 1901 to 1930. To examine model fluctuation resulting from internal system dynamics, we first performed a baseline simulation (**Reference**) driven by all factors remained constant at 1900 levels through 1901-2010. The simulation experiment **All** aims to examine the combined effects of the multiple driving factors in this study including climate change (*CLM*), CO$_2$ (*CO$_2$*), nitrogen deposition (*Ndep*), land conversion (*LC*), and management practices (*LMPs* such as nitrogen fertilization, irrigation, harvest, and rotation).

To attribute the relative contributions of these factors to annual variations of SOC, we then designed six factorial simulation experiments: climate [**CLM**], land-cover and land-use change [**LCLUC**], atmospheric CO$_2$ [**CO$_2$**], nitrogen deposition [**Ndep**], land conversion [**LC**], and land management [**LMPs**]). In each factorial experiment, the single factor was allowed to change over time, while other factors were kept constant at the level of 1900, to determine the relative importance of the climate, atmospheric CO$_2$, nitrogen deposition, land conversion, and land management practices (Table 2). We used a simulated attribution analysis approach (Ren et al., 2016) to calculate the relative contributions of these factors. The overall change in SOC (ΔSOC_{all}) caused by multiple environmental factors was calculated as the difference between the **All** simulation and the **Reference** baseline simulation; and the change due to each factor ($\Delta SOC_{factori}$) as the difference between the factor-specific experiment and the baseline.

3. Results and Discussion

3.1. Global environmental changes in global cropland during 1901-2010

The global croplands have experienced substantial changes in climate (i.e., temperature and precipitation), atmospheric CO$_2$ concentration, nitrogen (NO$_x$ and NH$_3$) deposition, and agronomic management during 1901-2010 (Fig. 3). Mean annual air temperature showed significant inter-annual variations with a long-term increasing trend since the late 1970s. North America experienced the highest increase in the annual air temperature while the lowest increase occurred in Asia over the past 110 years. Annual precipitation slightly increased in the global croplands (0.58 mm yr^{-1}) and varied across regions during 1901–2010. For instance, mean annual precipitation decreased by 103.9 mm yr^{-1} in Africa and 148.4 mm yr^{-1} in Australia, respectively, in the 2000s compared to the 1900s, On the other hand, South America, North America, and Asia experienced an increase in annual precipitation, ranging from 25.8 mm yr^{-1} to 129.6 mm yr^{-1}. The atmospheric CO$_2$ concentration increased from 296 ppm to 385 ppm during 1901-2010.

During the study period, cropland areas have expanded due to the conversion of natural ecosystems across the entire globe (Figs. 3c, 4). Spatially, substantial crop expansion happened in East and Southeast Asia, India, the Midwest US, Mexico, the southern part of South America, and parts of Europe. While decreases in croplands occurred in Eastern US, parts of Central China, and Northern Europe. In addition to changes in the total areas, global croplands experienced nitrogen enrichment due to nitrogen fertilizers and atmospheric deposition (Fig. 3). For instance, the nitrogen deposition rate increased nearly two folds from

Table 2
Simulation experiment design.

Numerical experiments	Climate change	CO_2 change	Nitrogen deposition	Land use change	
				LC	LMPs
Reference	1900	1900	1900	1900	1900
All	1901-2010	1901-2010	1901-2010	1901-2010	1901-2010
CLM	1901-2010	1900	1900	1900	1900
LCLUC	1900	1900	1900	1901-2010	1901-2010
CO₂	1900	1901-2010	1900	1900	1900
Ndep	1900	1900	1901-2010	1900	1900
LC	1900	1900	1900	1901-2010	1900
LMPs	1900	1900	1900	1900	1901-2010

Note: Simulation experiments include (1) ***Reference:*** all environmental factors keep unchanged in 1900; (2) ***All***: climate, carbon dioxide (***CO₂***), Nitrogen deposition (***Ndep***), and land-cover and land-use (***LCLUC***) change during 1901-2010; (3) ***Climate(CLM)*** - in which only climate changes during 1901-2010 while other factors are kept constant in 1900; (4) ***LC*** and (5) ***LMPs*** only land cover and land management practices (fertilizer, irrigation, etc.) change, respectively, while others factors are kept constant in 1900.
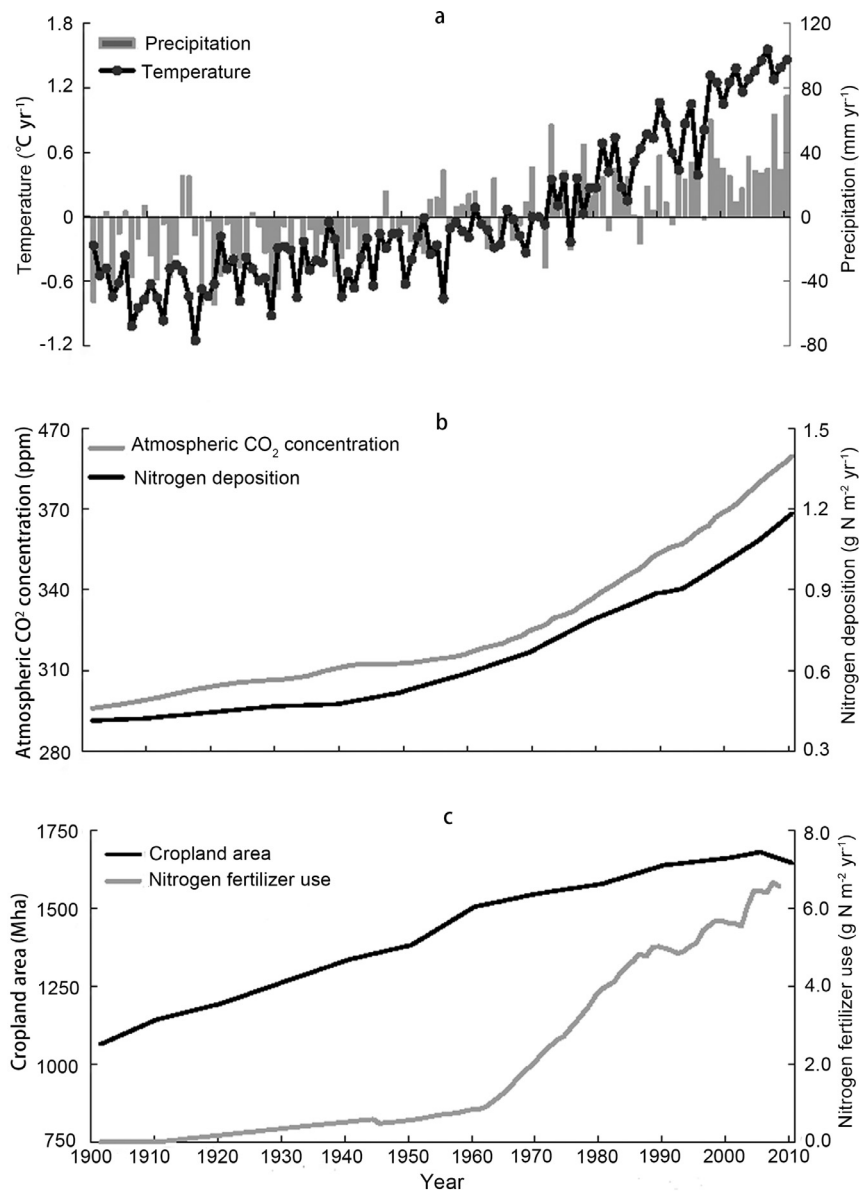

Fig. 3. Temporal changes in global climate, atmospheric CO_2, nitrogen deposition, land use and nitrogen fertilizer use during 1901-2010

Table 3

The decadal mean of annual SOC, SOC change and accumulated SOC during 1901-2010 at continental and global scales.

Region	North America	South America	Africa	Asia	Australia	Europe	Global	Mean SOC (g C/m²)
Time period	Decadal mean of the total SOC (Pg C/yr)							
1900s	13.1 ± 1.0	8.7 ± 0.2	2.2 ± 0.1	9.7 ± 0.6	0.4 ± 0.1	17.0 ± 1.1	51.2 ± 3.1	4,632±163
1950s	21.4 ± 0.1	11.9 ± 0.3	5.4 ± 0.4	21.0 ± 1.5	2.2 ± 0.2	24.9 ± 0.9	86.9 ± 3.4	5,988±76
1990s	23.9 ± 0.4	15.4 ± 0.2	7.9 ± 0.1	34.1 ± 1.7	3.7 ± 0.1	26.6 ± 0.3	111.7 ± 2.0	6,759±95
2000s	24.1 ± 0.3	15.8 ± 0.1	8.3 ± 0.2	37.4 ± 0.2	3.5 ± 0.1	25.8 ± 0.2	115.0 ± 2.0	6,895±80
Changing rate	0.100**	0.074**	0.066**	0.275**	0.035**	0.101**	0.65**	
	Total accumulated SOC (Pg C)							
1901-2010	11.9 (17.8%)	7.1 (10.7%)	5.8 (8.8%)	28.5 (42.8%)	3.1 (4.6%)	10.2 (15.3%)	66.6 (100%)	

** $p<0.01$
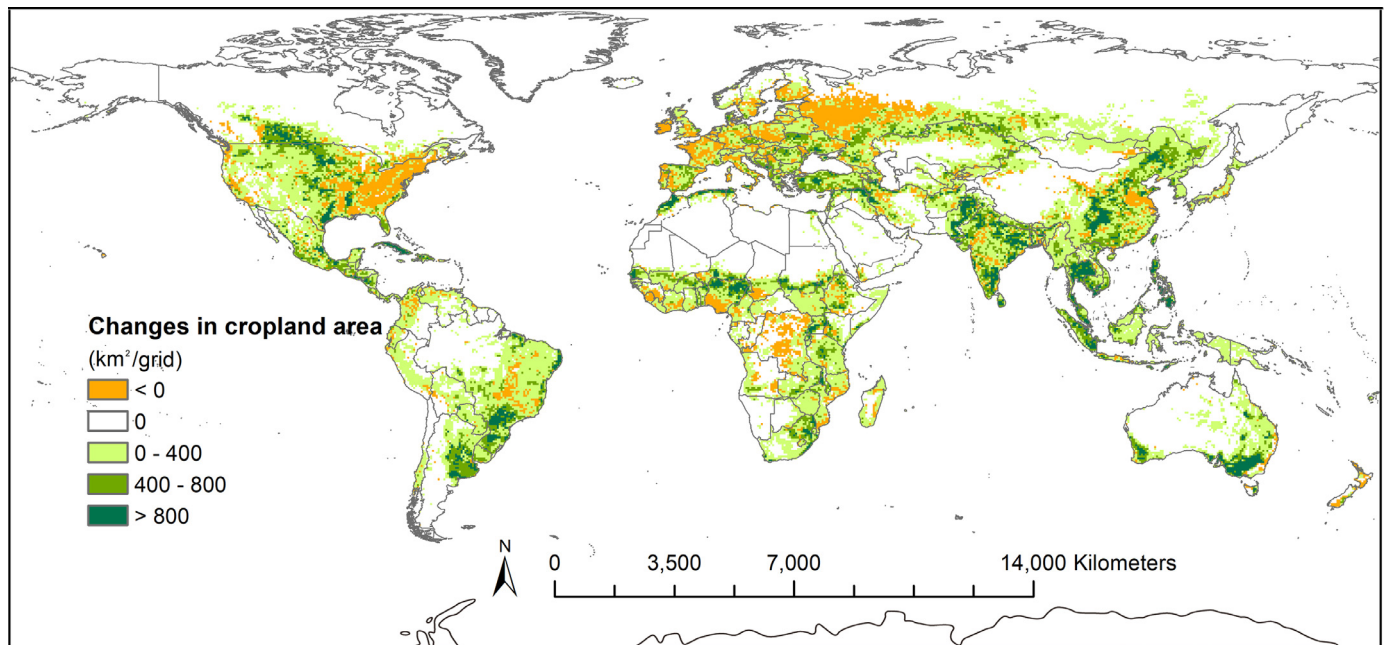
Fig. 4. Spatial distribution of changes in global cropland area during 1901-2010

563 to 1020 mg N m^{-2} yr^{-1} during 1961-2010 (Fig. 3b) because of immensely increased human activities (Galloway et al., 2003). The average nitrogen fertilizer use rate in global croplands has increased from nearly 0 g N m^{-2} yr^{-1} in the 1900s to approximately 8 g N m^{-2} yr^{-1} in the 2000s (Fig. 3c). Across the globe, Asia and Europe experienced relatively higher increases in nitrogen fertilizer use while other regions such as Africa have seen few increases. These changes were far from uniform, resulting in different problems among regions—excessive fertilizers were used in some regions, while insufficient nutrient inputs failed to provide adequate food production in others (Board on Sustainable development, Policy Division, National Research Council, 2000).

3.2. Global cropland SOC storage and its long-term changes

The DLEM-Ag simulated results show that significant long-term increases in SOC storage across the global cropland have occurred over the past 110 years (Table 3, Fig. 5) (Mann-Kendall trend test, $p < 0.001$). Decadal mean SOC was 51.2 ± 3.1 Pg C in the 1900s, which increased more than two folds to 115.0 ± 2.0 Pg C in the 2000s under the combined influence of multiple environmental factors (Table 3, Fig. 6a). Similar to the magnitude, mean SOC density increased by 48.8% from 4632 ±163 g C m^{-2} yr^{-1} in the 1900s to 6895±80 g C m^{-2}·yr^{-1} in the 2000s (Table 3).

3.2.1. Crop expansion and management practices impacts

Our results suggest that the cropland expansion has contributed to 89.7% of the increase in SOC storage across the global croplands

(Fig. 6b). To meet food demands for the growing human population, cropland areas have significantly increased at the expense of natural ecosystems such as shrublands and forests (Figs. 3c, 4). Cropland use changes reflected the magnitude and spatio-temporal patterns of the global cropland SOC storage. For instance, Asia, where cropland areas increased by 258.1 Mha, accumulated 28.5 Pg C, equivalent to 42.8% of increased cropland SOC storage during the study period. In contrast, increased SOC was less than 6.0 Pg C in Australia and Africa over the 110 years although the SOC magnitude in the 2000s was 4–9-folds greater than that in the 1900s. Our simulation results show that most global cropland areas gained SOC during 1901–2010, with higher increases (> 2.5 Tg C/grid) in India and Northern Europe. Some regions experienced cropland SOC loss during the study period, including the Midwestern United States, Southern Europe, Northeast China, Northwest India, and Southeast Brazil. The spatial patterns of SOC change (Fig. 5) appeared to coincide with those of cropland area change (Fig. 4). The temporal variations in the SOC storage (Fig. 6) were also in line with the changes in the cropland areas (Fig. 3c). For example, rapid crop expansions caused sharp increases in SOC in the 1950s, while the shrinkge in cropland resulted in a SOC reduction in the 2000s, particularly in North America and European regions.

In the LMPs simulation experiment, we examined the relative importance of land management practices by excluding effects of crop expansion and natural environmental factors. During 1901-2010, LMPs contributed to 7.5% of the total increase in global cropland SOC. Interestingly, we found the overall effects of land management prac-
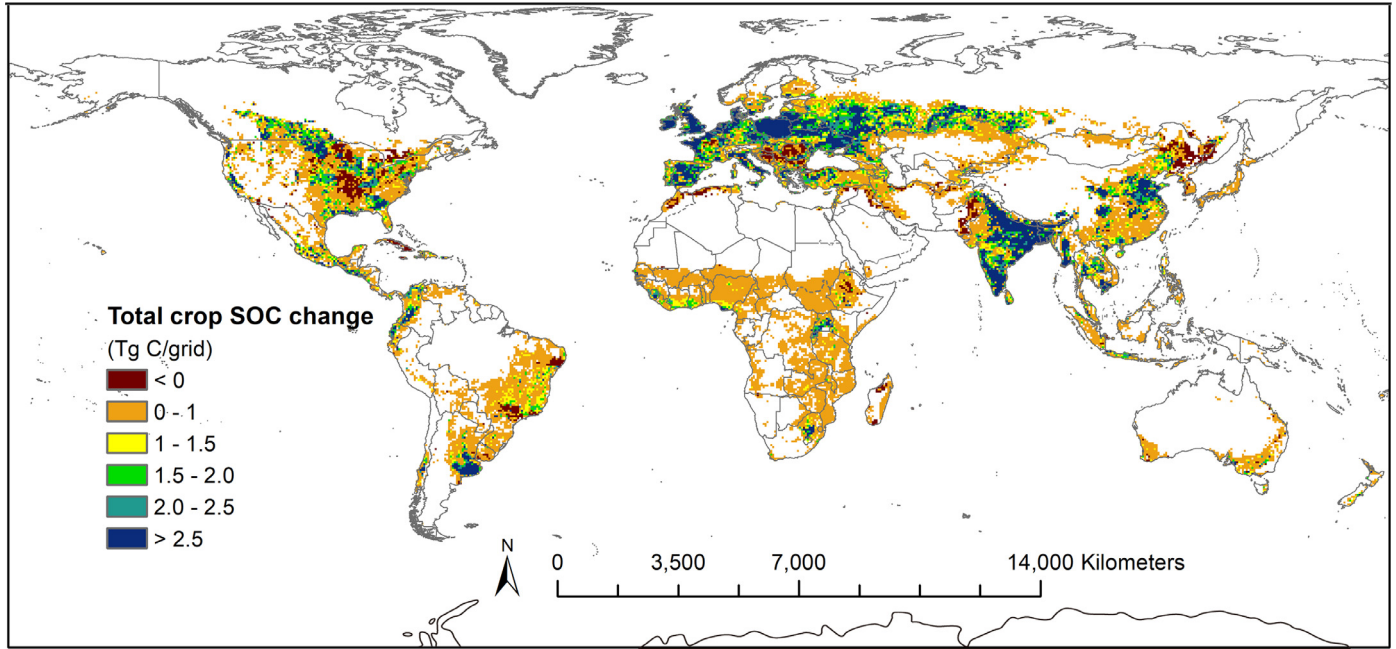
Fig. 5. Spatial distribution of changes in global cropland soil organic carbon (SOC) during 1901 - 2010
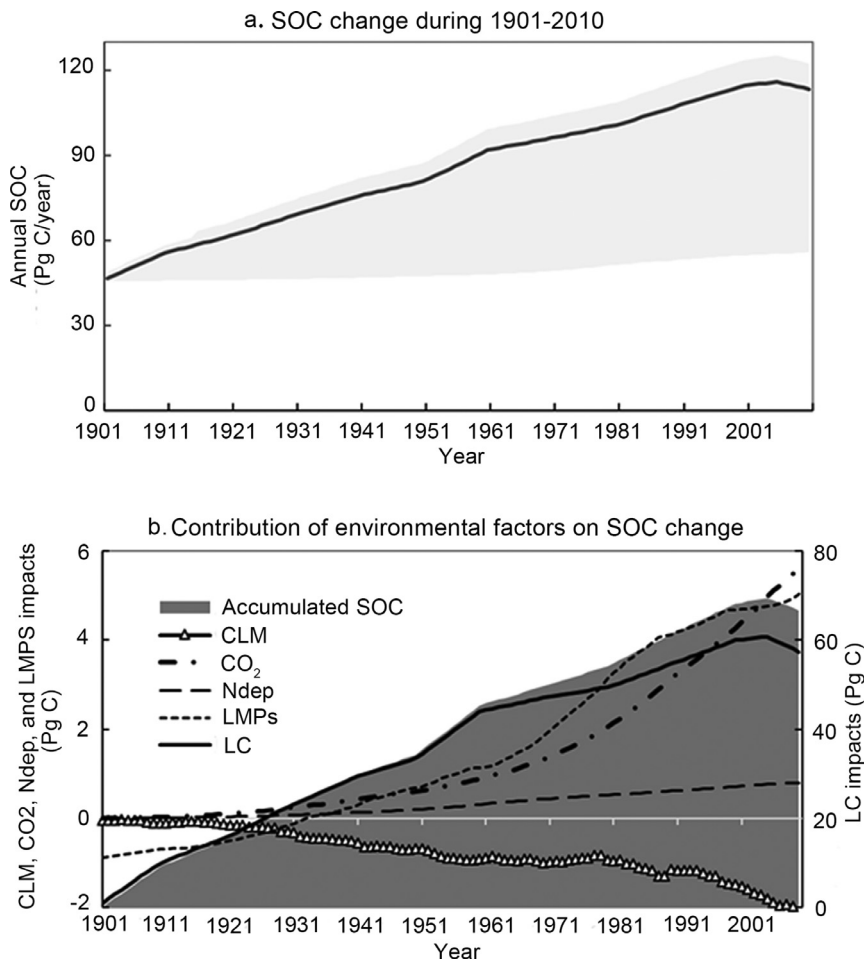

Fig. 6. Temporal changes in global cropland soil organic carbon (SOC) simulated by the DLEM-Ag model. Blackline and light grey area represent simulated estimations of crop SOC from different simulation experiments. The line represents the estimation of simulation experiment *ALL*, which considers all environmental factors including climate, atmospheric CO_2, nitrogen deposition, land cover and land management practices (a). Temporal changes in accumulated crop SOC as influenced by multiple global changes in climate (CLM), atmospheric CO_2 (CO_2), nitrogen deposition (Ndep), land management practices (LMPs: nitrogen fertilizer, irrigation, harvest, rotation, etc.) and land conversion (LC) from forests, grassland, wetland, etc. to croplands. Dark grey area means the accumulated SOC storage in global croplands during 1901-2010 (b)
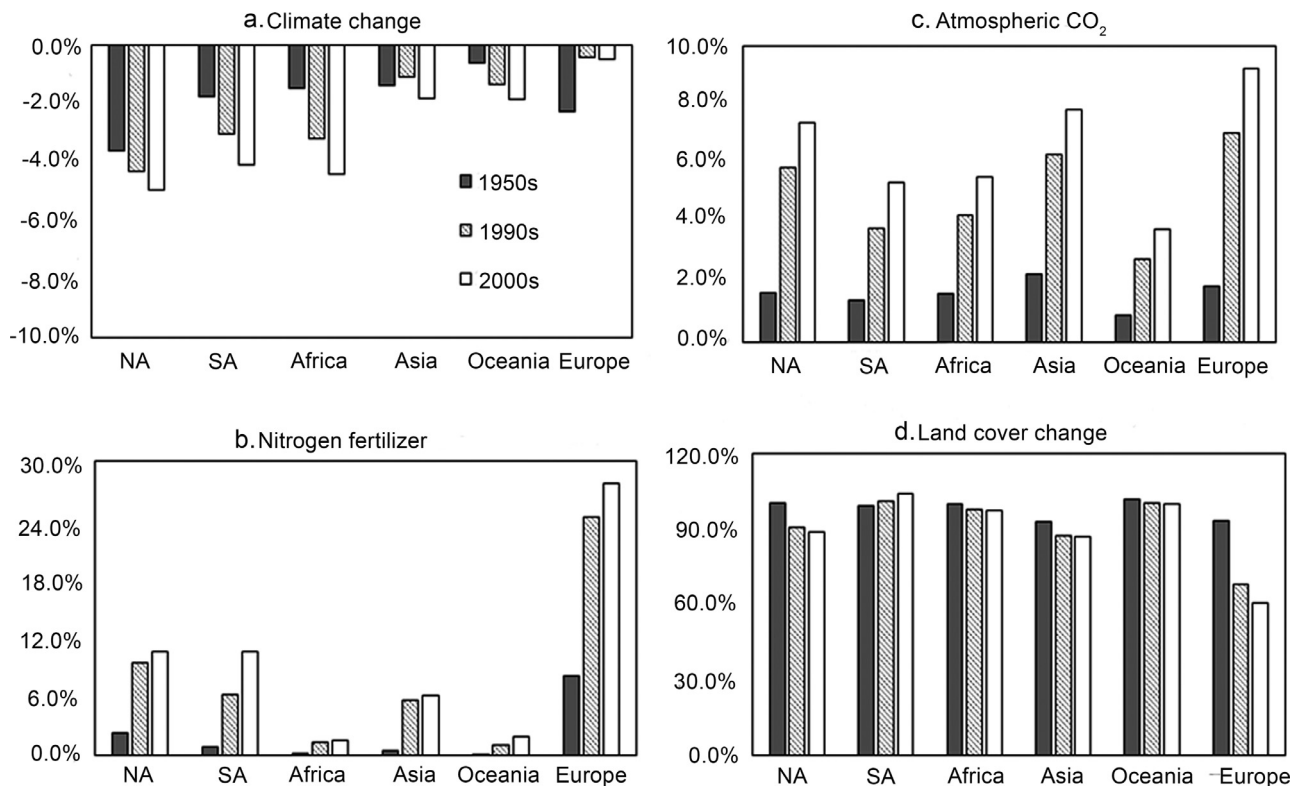
Fig. 7. Relative contributions (%) of climate, atmospheric CO_2, nitrogen fertilizer, and land cover change to the total changes in crop soil organic carbon (SOC) at the continental level

tices (e.g., harvesting, straw return, fertilization) led to a small decrease in SOC storage before the middle 1930s. This decrease might be partially attributed to removed crop biomass and nutrients (e.g., nitrogen) during the harvest, which led to the insufficient biomass and nutrient return to soils, thus lower crop production and further soil degradation, especially when the nitrogen fertilize use rate was much lower than the current level. Since the late 1930s, the overall effects of LMPs showed a rapidly positive contribution to SOC accumulation as the nitrogen fertilizer use largely increased, particularly after the early 1960s (Fig. 3c). These changes are consistent with previous studies, which show that nitrogen fertilizers enhance SOC storage by improving crop productivity and residues (Banger et al., 2010; Han et al., 2016; Mandal et al., 2007; Wang et al., 2017). In our model simulations, C inputs through residue return were dynamically enhanced as the harvest index and crop production increased during 1901-2010. Using the RothC model, Wang et al. (2017) also reported that global SOC density largely increased under different scenarios of crop residue retention.

3.2.2. Atmospheric CO_2 concentration and climate change impacts

In the global croplands, elevated atmospheric CO_2 concentration has sequestered C by 5.6 Pg C, accounting for 8.4% of the total increase in cropland SOC storage (ranging from 5.4% to 9.3% at the continental scale) (Figs. 6b and 7b). The elevated CO_2 concentration stimulates the plant photosynthesis, thus increases above and belowground biomass (Jastrow et al., 2000; Morgan et al., 2004). A meta-analysis by Jastrow et al. (2005) found that SOC storage increased by 5.6% over 2 to 9 years due to the higher belowground biomass return to the soils. Our model results have provided global estimates of SOC storage due to rising CO_2 concentration at a century time scale.

Our DLEM-Ag simulated results suggest that climate variability and change (**CLM** experiment) reduced SOC storage by 2.2 Pg C during 1901-2010, partially offsetting the benefits from the elevated CO_2 concentration. Regional-scale studies have shown that net primary productivity

reduces with rising temperature and climatic extremes (Lobell and Gourdji, 2012; Lobell et al., 2011; Pan et al., 2014; Tian et al., 2016), resulting in decreased biomass that entered into the soil. Furthermore, higher temperature increases soil respiration (Davidson and Janssens, 2006) and thereby decreases the SOC storage. This warming-induced carbon loss was evident in North Amercica, which experienced the rapid warming trend (0.015 °C yr^{-1}) and largest decreases in the total SOC storage (0.62 Pg C) during 1901-2010 as simulated in this study. Our simulation results also indicate that drought played an important role in reducing SOC storage during the study period. For example, in contrast to other continents, Australia and Africa saw decreasing trends in annual precipitations and experienced larger reductions in SOC density under the **CLM** simulation experiment, with approximately 969 g m^{-2} and 447 g m^{-2} C loss, respectively.

Through assessing the overall SOC dynamics in the context of multiple global changes (Table 2) and quantifying the relative contributions of the major factors (Fig. 7), this study indicates that the vulnerability of cropland soils to climate change might have been obscured by intensive management pracitces (e.g., nitrogen fertilizer use) in some regions. For example, historical climate change caused a large reduction in SOC storage in North America (NA) since the 1950s (Fig. 7a), while increased nitrogen fertilizer use rates largely offset the negative effects of climate change (Fig. 7c). On the other side, this study suggests that further climate change (e.g., temperature and precipitation) would greatly weaken soil carbon sequestration if no appropriate land management practices and other adaptation strategies were applied to improve climate resilience and soil health. For example, in Africa, insufficient nitrogen fertilizer inputs exhibited a relatively lower contribution to the SOC storage while climate change significantly enhanced soil C losses (Fig. 7a, c). Applying more fertilizer (e.g., nitrogen and phosphorus) might serve as one of the potential climate adaption strategies for increasing crop production and crop residue and accordingly enhancing SOC storage in Africa. However, this strategy should be used with caution to avoid potential environmental

problems, such as eutrophication, soil acidification, and atmospheric pollution.

4. Uncertainty and Future Needs

To our best understanding, this study offers the first attempt to report on the century-scale SOC dynamics in global cropland using a process-based agroecosystem model. Our results provide an understanding of the relative importance of the major environmental factors, such as climate and land-use change in controlling long-term trend and spatial variability in cropland SOC. The simulated total cropland SOC falls within the reasonable ranges of existing estimates from inventory-based, process-based model, and empirical approaches. We acknowledge that, however, some uncertainties exist in input data sets and model parameterization, which need to be addressed in future research. For example, our land use and land cover maps cannot reflect some recent cropland use change (such as cropland losses due to reforestation in China), which potentially over-estimated total SOC. We greatly simplified land management practices without the consideration of some traditional and innovative agronomic practices (e.g., manure application and cover crops) and natural disturbances (e.g., pest outbreaks). We also simply assumed that nitrogen fertilizer use during the growing season remains the same daily input rate, which influences the C assimilation, allocation, input into, and loss from soils due to the carbon-nitrogen interactions. In addition, we did not consider changes in crop varieties limited by spatially explicit datasets, which brought uncertainties into crop yield and SOC simulations. These factors do affect SOC through changing the physical environment and altering the plant growth and C, water, and nutrient cycles that occur daily, seasonally and inter-annually, and thus have enormous century-scale biological consequences. Therefore, more cropland management practices (including those for future climate adaptation and mitigation) are needed to be integrated into the assessment of cropland SOC dynamics. To accurately evaluate and predict cropland soil C dynamics, we calls for an integrated system framework that considers feedbacks and interactions within and beyond agroecosystems (e.g., legacy impacts on SOC due to land conversions between natural systems and croplands). In the context of multiple global changes, an assessment of soil C dynamics should consider the interplay of changes in environmental, socio-economic, and political processes at local, national, and international levels.

5. Conclusions

Process-based agroecosystem models offer an effective tool to quantitatively understand SOC dynamics in croplands as influenced by natural and anthropogenic factors at diverse space and time scales. Our study demonstrates that the DLEM-Ag model is capable of simulating the magnitude and spatiotemporal patterns of SOC storage in global croplands, and quantifying the relative contributions of multiple influencing factors. The simulated increases in the total cropland SOC were mainly attributed to the rapid expansion of cropland during the study period. Land management practices such as the nitrogen fertilizer use have enhanced the SOC density over the past 20th century. While climate change led to a reduction of approximately 3.2% (or 2,166 Tg C) in global cropland SOC. In spite of uncertainties above-mentioned, the century-scale responses of soil C dynamics to climate change and human activities are helpful for further understanding of SOC's vulnerability and resilience to climate change in the context of global changes. The findings provide a quantitative view of global patterns and controls of SOC dynamics in croplands. The estimated increases in SOC due to nitrogen fertilizer use illustrate that climate resilience could be promoted by improving nutrient use efficiency and choosing appropriate management practices. Due to highly heterogeneous climatic and soil conditions, diverse cropping systems, optimizing management practices for building a climate-resilience system is highly region-specific. We, therefore, call for further site-level controlled experiments and modeling studies into this issue.

Declaration of Interest

The authors declare no conflict of interest.

Acknowledgments

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