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Using the DNDC model to compare soil organic carbon dynamics under different crop rotation and fertilizer strategies

Lan Mu[1,2], Yinli Liang[1,2]*, Quingwu Xue[3], Chen Chen[2] and Xingjun Lin[1]

[1] *Institute of Soil and Water Conservation. Chinese Academy of Sciences and Ministry of Water Resources. Yangling. Shaanxi 712100, China.* [2] *Institute of Soil and Water Conservation. Northwest A&F University. Yangling. Shaanxi 712100, China.* [3] *Texas AgriLife Research-Amarillo. 6500 Amarillo Blvd W. Amarillo. TX 79106, USA*

Abstract

Soil organic carbon (SOC) plays a vital role in determining soil fertility, water holding capacity and susceptibility to land degradation. On the Chinese Loess Plateau, a large amount of crop residues is regularly removed; therefore, this agricultural area mainly depends on fertilizer inputs to maintain crop yields. This paper aims to use a computer simulation model (DeNitrification and DeComposition, or DNDC) to estimate the changes of SOC content and crop yield from 1998 to 2047 under different cropping systems, providing some strategies to maintain the SOC in balance and to increase crop yields. The results demonstrated that: (i) single manure application or combined with nitrogen fertilizer could significantly enhance the SOC content and crop yield on the sloped land, terraced field and flat land; and (ii) in contrast to sloped land and terraced field, the SOC content and crop yield both continuously increased in flat fields, indicating that the flat field in this region is a good soil surface for carbon sequestration. These results emphasize that application of manure combined with nitrogen fertilizer would be a better management practice to achieve a goal of increasing soil carbon sequestration and food security.

Additional key words: Loess Plateau; soil organic carbon; crop yield; fertilization; croplands.

Introduction

Soil organic carbon (SOC) plays a role in improving soil and water quality and hence sustains food production (Han *et al*., 2010). The total SOC pool is estimated to be 1400-1500 Pg C, which is approximately two times greater than the atmospheric pool (750 Pg C) (Shi *et al*., 2010). Even small changes in SOC may potentially add up to significant changes in large-scale carbon (C) cycling (Fang *et al*., 2001). In farming systems the SOC content may be increased by agricultural practices such as reduced tillage, improved fertilization management, irrigation, and increased vegetation covers (Entry *et al*., 2002; Fortuna *et al*., 2003; Ratnayake *et al*., 2011). These measures can be important means to achieve both high rates of C sequestration in terrestrial ecosystems and sustainable agricultural development (Smith, 2004; Moshki & Lamersdorf, 2011). Therefore, understanding SOC contents and changes is necessary to further understanding of C cycling in productive soils, to assess the responses of agroecosystems to fertilizer management and to aid policy makers in making land use management decisions.

Soil C sequestration in croplands is deemed to be one of the most promising greenhouse gas mitigation options for China's agriculture. Increasing agricultural soil C stocks has been suggested as a way to sequester CO_2 from the atmosphere in order to help reducing atmospheric CO_2 concentrations. It has been estimated that 0.4-0.9 Pg C year^{-1} can be sequestered within global agricultural soils (Paustian *et al*., 1998). Estimations of changes in the SOC content of cropland soils in China have been made under both short-term and long -term scenarios (Qiu *et al*., 2005; Tang *et al*., 2006). Other studies have focused on the characteristics of the C pool accumulated in ecosystems (Pan *et*

* Corresponding author: liangly@ms.iswc.ac.cn
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Abbreviations used: C (carbon); CF (chemical fertilizer application); CK (un-mulched); DNDC (DeNitrification and DeCompositi on model); E (relative error); M (manure amendment); MAE (mean absolute error); MN (combined fertilizer and manure application); N (nitrogen); RMSE (root mean square error); SOC (soil organic carbon).

al., 2003) and farm management effects on SOC (San José & Montes, 2001; Manna *et al.*, 2005). However, little attention has been paid to the effect of fertilization on soil C sequestration in China's Loess Plateau. The Loess Plateau region is a typical rain-fed agricultural area in China. The region has infertile soil and severe water shortages, which seriously hinder agricultural production and sustainable development. Therefore, increasing crop yield by improving soil fertility as well as increasing SOC sequestration has been a challenge (Smith, 2004).

Recently, research has been carried out to estimate SOC change from agro-ecosystems using a SOC model (DeNitrification and DeComposition, DNDC model) (Smith *et al.*, 1997; Tang *et al.*, 2006). The DNDC model applies a generic agro-ecosystem model for predicting crop growth, C sequestration and water use efficiency for both upland and wetland crops (Zhang *et al.*, 2006). The DNDC model simulates the biogeochemical C and N cycles of agricultural systems based on land use and activity data (crops, tillage, fertilization, manure application, grazing), soil variables (texture, soil organic matter, pH, bulk density, hydraulic properties) and daily temperatures and precipitation. DNDC integrates crop growth and soil biogeochemical processes on a daily time step and simulates N and C cycles in plant-soil systems (Smith *et al.*, 2010). The total C and N fluxes from each site were calculated by summing up crop-area-weighed fluxes from each crop rotation. Reported changes in SOC, thus represent the loss or gain in SOC over a one-year crop rotation, based on initialization of SOC pools from available soil data (Li *et al.*, 2003). At present, the modified DNDC model (version 9.1) performs well based on seven long-term experiments selected from the Global Change and Terrestrial Ecosystem Soil Organic Matter Network (GCTE SOMNET). These experiments represented three different land uses, a range of climatic conditions within the temperate region, and different treatments (Tang *et al.*, 2010).

Consequently, the objectives of this study were: (1) to validate and evaluate the DNDC model performance by comparing the observed and simulated SOC content and crop yields from 1998 to 2007; (2) to use the modified DNDC model to simulate the SOC content and crop yield changes in sloped, terraced and flat lands under different fertilization treatments in hilly and gully areas of the Loess Plateau in next 50 years; (3) to estimate the potential contributions of different croplands to SOC sequestration.

Material and methods

Description of the study area

A multi-year field study was conducted in three experimental sites at the Ansai Experimental Station, The Institute of Soil and Water Conservation, Chinese Academy of Sciences. The study was initiated in 1995, and SOC and crop yields were measured over a period of 10 years (1998 -2007). The field sites were located in the northern Shaanxi Province of the Loess Plateau (36° 51' N 109° 19' E). The study area belongs to a typical semiarid continental monsoon climate with annual mean rainfall of 535 mm. Approximately 60% of rain falls in storms during the summer months (July to September) when severe soil erosion often occurs. The mean annual air temperature is 8.8°C and the growing degree days (based on > 10°C) is 3114 degree-C-day. The geomorphic type is the typical hilly and gully area and the gully density is 8.1 km km^{-2}. Soils in the study area originated from parent material of calcareous loess and the SOC concentration of the soil in the study area is less than 10 g kg^{-1}. These belong to the Calcic Cambisol group according to the FAO/UNESCO soil classification system (Chen *et al.*, 2007). Much of the region is subjected to severe soil erosion (Shi & Shao, 2000). Land degradation, desertification, soil erosion and low soil fertility threaten the environment, and severely limit crop yields. Sloping land (site A), terraced fields (site B), and flat fields (site C) are three common cropping land surfaces in the hilly and gully areas. The rotations used in the experiment are a continuation of the long-term management at each site. Cropping systems differ depending on land surface due to differences in soil moisture and fertility levels. Generally, one crop was planted and harvested per year and farmers mainly harvested crops in autumn in the study area. Before planting and after harvest, the soil properties and SOC content were measured every year from 1998 to 2007. Furthermore, we calculated crop yields when harvested in autumn. The fertilizer application rates keep the same every year for the different croplands. The detailed information and the soil nutrient content of each land surface site are listed in Tables 1 and 2.

Site A: sloping land

The sloping experimental site was situated in a hilly-gully slope which faced north, with a slope of 19°. The

Table 1. The DNDC model input variables of climate, soil properties and management conditions for the experiment sites of cropland set in 1998

Croplands		Site A (sloped land)				Site B (terraced field)				Site C (flat feld)			
Treatment factor	**Variables**	**CK**	**CF**	**M**	**MN**	**CK**	**CF**	**M**	**MN**	**CK**	**CF**	**M**	**MN**
Soil data	SOC content (g kg^{-1})	2.46	2.5	3.1	3.2	2.28	—	2.59	2.89	4.89	4.87	5.3	5.97
	Total N content (g kg^{-1})	0.34	0.4	0.4	0.42	0.22	—	0.32	0.31	0.57	0.59	0.6	0.65
	Soil texture	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sandy loam	—	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sandy loam
	pH	8.6	8.7	8.6	8.6	8.5	—	8.6	8.7	8.6	8.5	8.7	8.6
	Bulk density (g cm^{-3})	1.38	1.4	1.4	1.38	1.38	—	1.38	1.38	1.38	1.38	1.4	1.38
Climate data	Annual mean air temperature (°C)	8.8	8.8	8.8	8.8	8.8	—	8.8	8.8	8.8	8.8	8.8	8.8
	Annual mean precipitation (mm)	450	450	450	450	450	—	450	450	450	450	450	450
Faming management	Crop yields (kg ha^{-1})	258	370	716	465	532	—	395	842	1,314	1,350	1,348	1,562
	Crop residue returned rate (%)	15	15	15	15	15		15	15	15	15	15	15
	Crop rotation system	Broomcorn millet → Millet →				Soybean → Millet →				Soybean → Maize →			
	Crop rotation system	→ Buckwheat → Millet				→ Broomcornmillet → Millet				→ Maize			

Treatments: CK, without fertilizer application; CF, chemical fertilizer application, 212 kg ha^{-1} (46% N); M, 7,500 kg manure ha^{-1} (15.9% organic matter and 1.3% N); MN, combination of N + Manure (1:1).

site was a long-term experimental field which started in autumn, 1983. The plot size was 4 m long and 5 m wide and there were four treatments including: (1) M, farmyard manure amendment at 7500 kg ha^{-1} containing 15.9% organic matter and 1.3% nitrogen, (2) CF, application of 212 kg ha^{-1} of chemical fertilizer (urea) containing 46% N, (3) MN, application of 412.3 kg ha^{-1} of a combination of fertilizer (urea) and manure (at a ratio of 1 kg of manure per kilogram of fertilizer), and (4) CK, without fertilizer application (control). A completely random block design with four treatments and three replications was used. The field was successively planted (Table 1) with broomcorn millet (*Panicum miliaceum* L.), millet [*Setaria italica* (L.) Beauv.], buckwheat (*Fagopyrum esculentum* Moench) and millet rotation.

Site B: terraced field

The terraced field was located on a mountain terrace and the site was a long-term experimental field which started in autumn, 1992. Each of the plots was 30 m^2 and there were three different treatments: M,

Table 2. The DNDC model input parameters of different crops grown in the study area

Parameters	Soybean	Maize	Millet	Broomcorn millet	Buckwheat
Maximum crop yield (kg ha^{-1})	2,570	11,300	2,100	2,450	1,100
Portion of crops					
Portion of harvest part	0.25	0.44	0.33	0.26	0.43
Portion of shoot	0.67	0.5	0.56	0.65	0.46
Portion of root	0.08	0.06	0.11	0.09	0.11
C/N ratio of harvest part	10	34	25.44	25	20
C/N ratio of shoot	79	78	58.78	55	65
C/N ratio of shoot	68	80	67.1	70	75
N fixation index	1.5	1	1	1	1
TDD/(°C)	1,500	2,550	1,750	1,150	1,250
Water requirement (kg kg^{-1})	541	250	331	258	450
Maximum LAI	3	4.5	3	1.7	2.8

The data come from Ansai Research Station of Soil and Water Conservation, Chinese Academy of Sciences. TDD: temperature degree days. LAI: leaf area index.

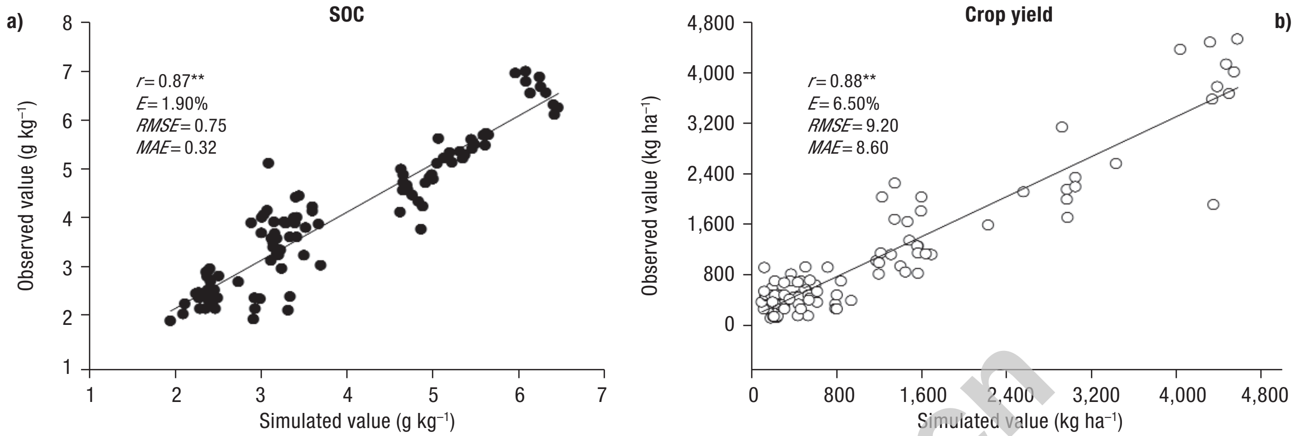

Figure 1. Comparison between the simulated and observed (a) soil organic carbon content (g kg^{-1}) and (b) crop yield (kg ha^{-1}) values from 1998 to 2007 on sloped, terraced and flat land. *r*: sample correlation coefficient. *E*: relative error. *MAE*: mean absolute error. *RMSE:* root mean square error.

MN and CK. Each treatment had four replications, the total being 3 treatments × 4 replicates = 12 plots. The crop rotation was soybean (*Glycine max* L.) → millet → broomcorn millet → millet, where the soybean was utilized as "green manure".

Site C: flat field

The site was a long-term experimental field which started in autumn, 1995. Each plot area was 14 m^2 and the fertilizer treatments were M, CF, MN and CK. Each treatment hadthree replications and the total plots were 4 treatments × 3 replications = 12 plots. The experimental field was planted with a soybean → maize (*Zea mays* L.) → maize rotation.

As a typical rainfed agricultural area in this region, the crops were never irrigated and the crop growth all depended on the rainfall. The fertilizer treatments for the three different croplands were: (i) for the millet, broomcorn millet and buckwheat, 20% of the N fertilizer (urea) applied at planting as a basal fertilizer and 80% of N applied at the stem elongation stage; (ii) in the maize growing season, 20% of N applied at planting as a basal fertilizer and the rest (80%) of N applied between internode elongation and tasseling; (iii) to soy bean, N fertilizer applied before sowing (20% N, urea) and at the budding stage (80% N, urea). Farmyard manure of 7,500 kg ha^{-1} was applied before seeding in each crop.

Soil sampling and analysis

Soil was sampled in September every year from 1998 to 2007 after cop harvesting. Five soil samples per plot were collected at depths of 0-30 cm layer and 0-100 cm layer (for measured SOC stock). The samples were mixed by hand and a 2-kg composite sample was obtained from each plot. SOC concentration was measured by the Walkley Black method (Nelson & Sommers, 1982); total N by the Kjeldahl procedure; soil bulk density was measured by the ring tube method; and pH was measured by electronic pH-meter (ISS, 1978).

DNDC model

The DeNitrification-DeComposition (DNDC, version 8.2) model was originally developed for predicting carbon (C) and N biogeochemical cycles in USA agro-ecosystems (Li *et al*., 1992a, 1992b). The DNDC version 9.1 was used in this study to simulate the biogeochemical C and N cycle of agricultural and based on land use and activity data (crops, tillage, fertilization, manure application, grazing), soil variables and daily temperatures at a regional scale to study the agricultural soils of China. The DNDC version 9.1 has reasonable data requirement and is suitable for simulation at appropriate and spatial scales (Tang *et al*., 2006, 2010; Zhang *et al*., 2012). Clear description of the model simulation process was given by Smith *et al.* (1997). The model contains six interacting sub-models:

(1) Soil climate and thermal-hydraulic sub-models. These sub-models use soil physical properties, air temperature and precipitation data to calculate soil temperature and moisture profiles and soil water fluxes through time. The results of the calculations are input to the other sub-models.

(2, 3) Nitrification component and denitrification sub-models, which calculate hourly denitrification rates and N_2O, NO, and N_2 production during periods when the soil redox potential (Eh) decreases due to rainfall, irrigation, flooding, or soil freezing.

(4) Decomposition sub-models. This sub-model simulates decomposition of each SOC pool, *i.e.,* calculates daily decomposition, nitrification, ammonia volatilization processes, and CO_2 production from soil microbial respiration.

(5) A plant growth component, which calculates daily root respiration, water, and N uptake by plants, and plant growth.

(6) A fermentation module, which calculates daily methane production and oxidation (Li *et al*., 2004).

The effects of cropping practices on C and N dynamics are also considered in the model.

Data input

In order to run the DNDC model, different datasets were compiled to parameterize the DNDC model. The soil datasets consist of soil attributes, including bulk density, organic matter content, texture and pH and clay content, etc. The soil properties were annually measured from 1997 to 2008 for the three types of croplands (Table 1).

DNDC model required data of daily precipitation, and maximum and minimum air temperatures. From 1997 to 2008, the weather data were acquired from the weather station in Ansai Experimental Station of Soil and Water Conservation, the Chinese Academy of Sciences, which was 100 meters away from our experimental site. And the future climate parameters from 2007 to 2047 were predicted according to the Synthesis Report (IPCC, 2007), which reported that the temperature would increase at a rate of about 0.2°C each 10 years. So 0.02°C was added to both maximum and minimum air temperatures each year from 1998 to 2047. And the precipitation in the future years was set at the increasing rate of 3.9 mm per year. The CO_2 concentration was calculated based on the increasing rate of 1.9 ppm per year. The crop dataset included physiological data for the different croplands of different plants species (Table 2). The agricultural management dataset contained sowing acreage, N fertilizer application rates, livestock, planting and harvest dates, and crop residue incorporation. Farming practices were compiled based on global assumptions as follows (Qiu *et al*., 2005; Tang *et al*., 2006): (i) 15% of straw was returned to the soil; (ii) 20% of livestock wastes and 10% human wastes were added as manure to the soil and with no other fertilization; (iii) tillage was applied twice (20 cm before harvest and 15 cm after harvest).

Model validation and statistical analysis

In order to confirm the reliability, the DNDC model was tested against measured data from loess soil of the hilly and gully region of the study area, which is the same area examined here. This study compares simulation results with the 10-year measured data from the autumn of 1998 to the autumn of 2007 under different fertilizer application in the croplands.

The error in the total difference between simulation and measurement was determined by the sample correlation coefficient (*r*), the relative error (*E*), the mean absolute error (*MAE*) and the root mean square error (*RMSE*), using the following equations (Smith *et al*., 1997):

$$E = \frac{100}{n} \times \sum_{i=1}^{n} \frac{V_{oi} - V_{pi}}{V_{oi}} \quad [1]$$

$$r = \frac{\sum_{i=1}^{n}\left(V_{oi} - \overline{V_{oi}}\right)\left(V_{pi} - \overline{V_{pi}}\right)}{\left[\sum_{i=1}^{n}\left(V_{oi} - \overline{V_{oi}}\right)^2\right]^{1/2}\left[\sum_{i=1}^{n}\left(V_{pi} - \overline{V_{pi}}\right)^2\right]^{1/2}} \quad [2]$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_{oi} - V_{pi})^2} \quad [3]$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} ABS(V_{oi} - V_{pi}) \quad [4]$$

where V_{oi} are the measured values, V_{pi} are the simulated values, $\overline{V_{oi}}$ is the mean of the measured data, $\overline{V_{pi}}$ is the mean of the simulated data, and *n* is the number of the measured and simulated data pairs. In general, if the absolute value of *E* is < 5%, indicates that the modeling results are good (Smith *et al.,* 1997). An *r*-value closest to 1 indicates that the model matches the pattern of the observations. And the smaller *RMSE* or *MAE* value is, the greater prediction accuracy is. One way analysis of variance (ANOVA) was used to analyze the differences of SOC stock between the three croplands. Subsequently, least significant difference (LSD) test was used to identify statistically significant differences ($p < 0.05$) among the mean values of SOC stock within each cropland.

Results

Comparison of observed and simulated SOC content and crop yield

The SOC contents for the surface layer (0-30 cm) and crop yields were measured under different fertilization treatments from 1998 to 2007 for the three sites of croplands. The variation range of observed SOC was 1.87 to 6.24 g kg^{-1} in the three croplands. And the observed crop yield ranged from 90 to 4521 kg ha^{-1} in the croplands. By comparison, the simulated SOC varied from 1.95 to 6.47 g kg^{-1}; meanwhile, the crop yield ranged from 92 to 4,586 kg ha^{-1} for the croplands, and the simulated values of SOC and crop yield were generally within the range of observed values.

Thus, the range of simulated SOC and crop yield was consistent with the measured values from 1998 to 2007. Furthermore, Fig. 1 depicts that the correlation coefficients (r) between simulated and measured SOC levels were 0.87 ($p < 0.001$) and the r values for crop yield were 0.88 ($p \leq 0.001$). The relative errors (E) were 1.90% and 6.50% for the SOC and crop yield, respectively. In addition, the small values of *MAE* and *RMSE* for SOC data were 0.32 and 0.75 and for crop yields data were 8.60 and 9.20. Meanwhile, changes in SOC and crop yield over time showed the same trends: (i) application of manure increased SOC content as a result of increasing crop production as well as the direct addition of organic matter into the soil under the sloped land, terraced field and flat field, respectively (Figs. 2a, b, c); (ii) Each cropland (sloped land, terraced field and flat field; Figs. 2d, 2e and 2f, respectively) had specific farming management practices, however, their crop yields generally all increased after applying a certain amount of manure.

SOC content and crop yield changes using the DNDC model: 1998-2047

Effects of different fertilization treatments on the SOC content and crop yield in different types of cropland: years 1998-2007

Figs. 3a,b,c show that the SOC simulated results, over the 10-yr period (from 1998 to 2007), gain with either the single manure application or combined application in the sloped land, terraced field and flat field, respectively. Differently, under the single chemical N fertilizer management, SOC content decreased by 6.36% from 1998 to 2007 under the sloped land, while slightly increased by 2.87% from 1998 to 2007 under the flat field. Without fertilization, SOC was lower in 2007 than in 1998 under the sloped land and flat field, while it was higher in 2007 than in 1998 under the terraced field.

As expected, the crop yield decreased by 58.83% for terraced field, 42.64% for sloped land and 8.52% for flat field (Figs. 3d, e, f) from 1998 to 2007 under no fertilizer application. For sloped land the crop yield was lower in 2007 than in 1998 under the M fertilizer management while it was higher in 2007 than in 1998 under the MN application. Meanwhile, the yield decreased in 2007 under all the fertilization applications for site B. On the contrary, the crop yields for type C continually increased in all the different fertilizations from 1998 to 2007, which reflected higher productivity and C inputs on flat fields.

Effects of different fertilization treatments on the SOC content and crop yield in different type of croplands: prediction using DNDC for 2007-2047 years

Figs. 3a, 3b and 3c indicate that SOC content and crop yield continuously will decline from 2007 to 2047 under sloped land and flat field, while will increase for terraced field when no fertilization (CK) is applied. The SOC content data also predicted trends under sloped land that were similar with that under terraced field when only manure was applied. The overall trend was that there was a weak loss in SOC content from 2007 to 2027 under the sloped land and the terraced field, but later on (2027-2047) SOC gains under both the sloped land and terraced field. In contrast, the rate of SOC content continuously increasing occurred in either the period 2007-2027 or in the period 2027-2047 under flat field. Predictions show that until 2047, SOC content continuously will increase in sloped, terraced and the flat field under MN application, indicating that this is the best fertilizer treatment among those investigated for increasing SOC in this region.

The results also showed that the crop yield predicted under the treatment with manure fertilizer from 2007 to 2027 increased by 7.6%, 8.6% and 43.6%, while in the latter years (2027-2047) the increasing rates were 5.4%, 1.5% and 3.0% for sloped, terraced and flat

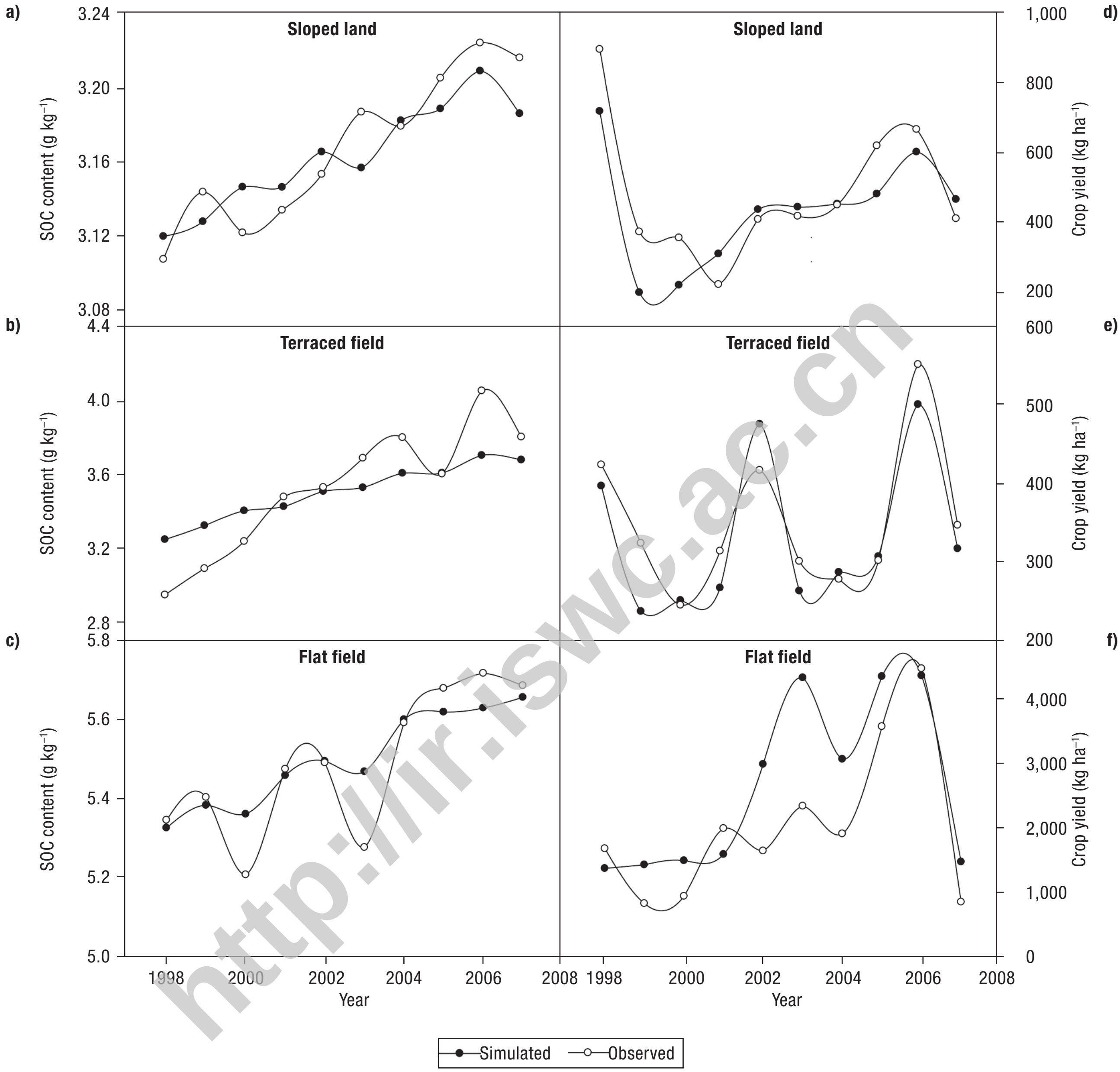

Figure 2. Changes of observed (0-30 cm) and DNDC model simulated soil organic carbon (left) and crop yield (right) over time, from 1998 to 2007 under single manure fertilization (7,500 kg ha^{-1} farmyard manure containing 15.9% organic matter and 1.3% N) in sloped land (a, d), terraced field (b, e) and flat field (c, f).

land, respectively (Figs. 3d,e,f). For MN fertilizer management, the yields in the previous periods (2007 to 2027) were predicted to be higher, 2.1%, 0.6% and 31.6% than in the latter periods (2027 to 2047) under the sloped land, terraced field and flat field, respectively. However, the predicted yields in the MN treatments were higher than in the M application in all the croplands mentioned above, providing a useful measure for farmers to achieve sustainable crop productivity.

Effects of different fertilization treatments on soil organic carbon sequestration

Changes in SOC stock under different fertilization managements

Fig. 4 shows that from 1998 to 2007 the SOC stock was at a situation of net loss under no fertilizer application (by 1.6%) and only N management (by 0.3%).

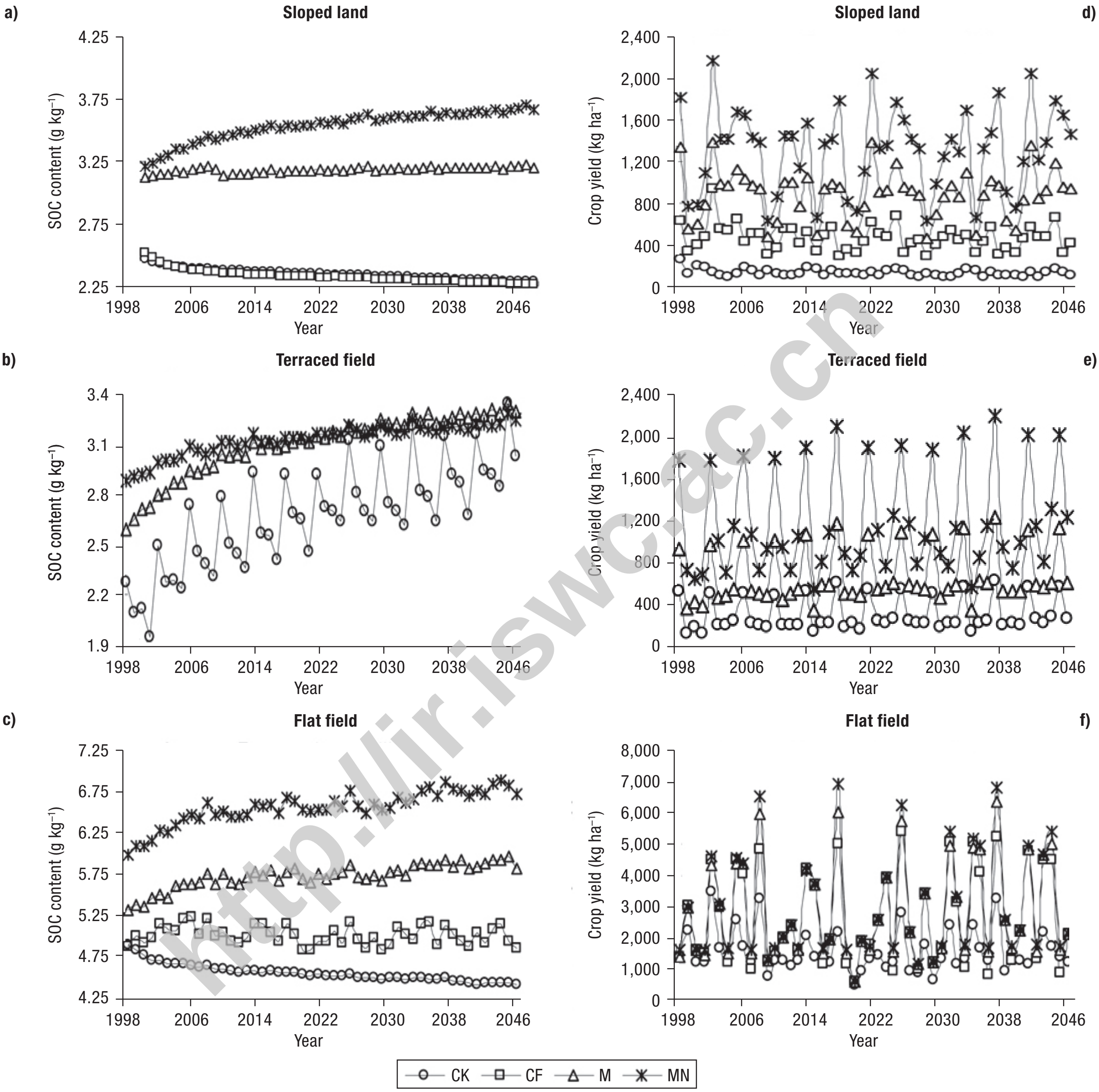

Figure 3. Effects of different fertilization treatments (CK, without fertilizer application; M, manure amendment; CF, chemical fertilizer; MN, combined chemical fertilizer and manure application) on simulated soil organic carbon content (left) and crop yield (right) of sloped (a, d), terraced (b, e) and flat land (c, f) for the period 1998-2047.

In contrast, the SOC stock increased under either the M or MN treatments, which indicated a continuous increasing in SOC equal to 15.3% and 15.8% respectively during the 10 years. Interestingly, the trends in SOC stock changes under the terraced field (Fig. 4) were similar to those under the sloped land from 1998 to 2007, but the rates and magnitudes of change differed. The overall trend under the terraced field was a slight loss (1.5%) in the no-fertilization (CK) treatment but gains in both the M (9.5%) and MN (8.3%) management. Fig. 4 also showed a higher reduction (about 5.7%) in SOC stocks from 1998 to 2007 in the flat field, which had higher initial SOC under the control (CK) compared with the other two treatments.

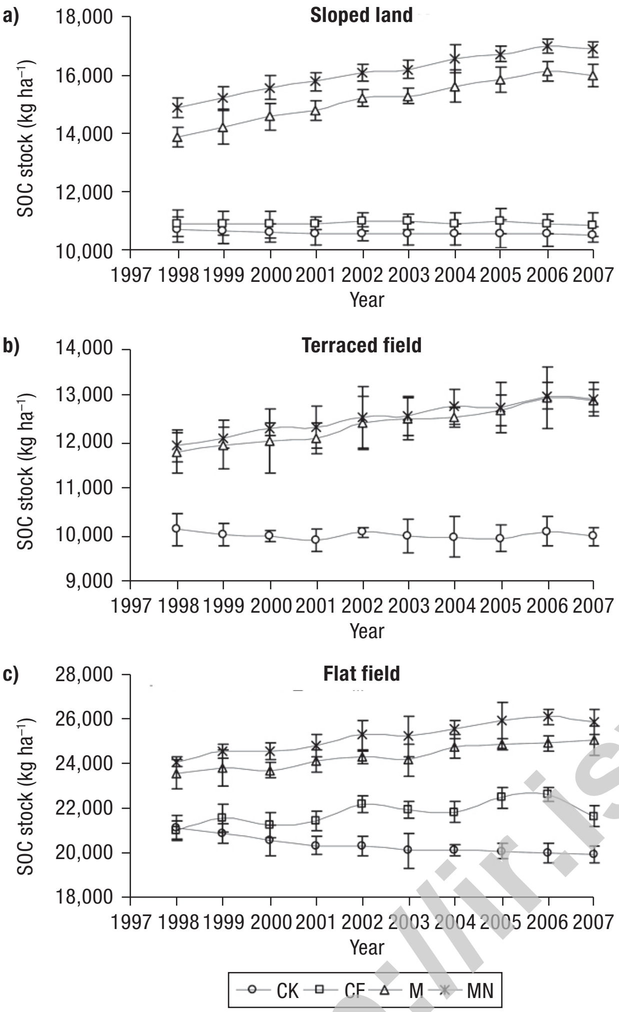

Figure 4. Soil organic carbon stock measured (0-100 cm) under different fertilization treatments (CK, without fertilizer application; CF, chemical fertilizer; M, manure amendment; MN, combined chemical fertilizer and manure application) and under different croplands: sloped land (a), terraced field (b), and flat field (c) for 10 years (1998-2007).

Status of SOC stock under different cropland uses in the same fertilization

The status of SOC stocks was compared among the three major cropland use classes. As shown in Table 3, the mean SOC stock values for the three land-use-based groups were significantly different ($p < 0.01$), being highest for flat field, intermediate for sloped land and lowest for terraced field regardless of four fertilization treatments. Fig. 5 indicates that under the M and MN managements, the SOC in the flat field increased less (6.3% and 7.5%) than that in the sloped land (15.3% and 15.8%) and the terraced field (9.5% and 8.3%). On the contrary, the control in the flat field had the highest decrease (5.68%).

Table 3. Differences of measured SOC stock at 0-100 cm (kg ha^{-1}) in the three types of croplands (sloped land, terraced field, and flat field) under different fertilizer managements

Croplands	CK	CF	M	MN
Site A (sloped land)	10,548.3[b]	10,893.1[b]	15,138.1[b]	1,6079.5[b]
Site B (terraced field)	10,006.0[c]	—	12,380.70[c]	12,517.0[c]
Site C (flat field)	20,575.3[a]	22,018.0[a]	24,534.0[a]	25,403.9[a]

CK: without fertilizer application. M: manure amendment. CF: chemical fertilizer. MN: combined chemical fertilizer and manure application. Data are mean values ($n = 10$) from 1998 until 2007. Values followed by the same letters in each column are not statistically different at the 1% level of significance.

Discussion

Effects of different fertilization treatments on the simulated SOC content and crop yield in different types of cropland

Our results predicted that, from 1998 until 2007, the SOC in the no fertilizer treatments decrease under sloped land and flat field, but increase for terraced field. However, the crop yields are lower for all the three crop-

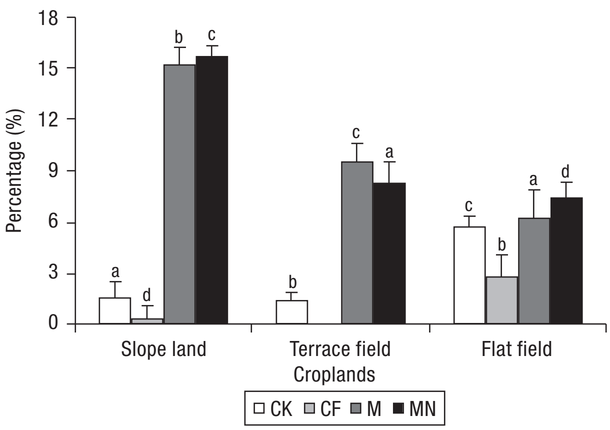

Figure 5. Percentages (%) of the increase or decrease on measured SOC stock within 10 years (from the beginning of year 1998 to the end of year 2007) under different croplands (sloped land, terraced field, flat field) and fertilization treatments. Error bars indicate the standard error of the mean (n = 3). Lower case letter indicate statistically significant differences among the croplands under each fertilizer application.

lands under no fertilizer management. Any changes in either the amount of fertilizer or the kinetics that affect conversion of fertilizer to available C will directly or indirectly alter crop yield and SOC content. It was the accumulation of residue biomass from the green manure (soybean) under terraced field that enhanced the SOC sequestration. In contrast with manure management, the pattern of combined application of manure and chemical fertilizers could significantly provide crops with the N direct for use or activates the soil microorganisms as well as improve soil fertility, providing crops with more nutrients. Therefore, it increased crop residues and root biomass so that the SOC sequestration increased (Han *et al*., 2008). As also pointed out in other studies (Fließbach *et al*., 2006; Wu & Cai, 2007; Chen *et al*., 2010) the combined application could enhance the SOC content. Hao *et al.* (2012) found that the combination of manure and chemical fertilization significantly decreased the total NH_3 volatilization, with the fertilization pattern being economic benefit-significantly, feasibility-strongly and environment-friendly. So the MN fertilization was identified as the best carbon sequestration and crop yields increasing in the region.

We also found that the modeled SOC and yields increased during the period 2007-2047. In general, its differences may result from increased temperature and precipitation. The Synthesis Report (IPCC, 2007) estimates future climate change in a series of Special Report on Emissions Scenarios (SRES), predicting that temperature will increase at a rate of about 0.2°C in 10 years, from 2007 until 2027. Microorganisms may become more active under the constantly increased temperatures, which would accelerate the decomposition of soil organic matter. Meanwhile, under MN treatment the prediction was a crop yield increase of 74.9% from 2007 until 2047. This is probably because the MN fertilization supplies extra N and may promote a "priming effect", which activates the soil microbial activity to release more nutrients (Kuzyakov *et al*., 2000; Fontaine *et al*., 2003). Besides, long-term application of MN can maintain soil nutrient levels and simulate different aspects of soil fertility, because MN ensures the largely constant presence of active microorganisms and the regular dynamics of biomass carbon (Nardi *et al*., 2004). Consequently, from a long-term development viewpoint, MN combined application should be better than a single manure application to achieve soil carbon sequestration and food security goals.

Estimate the impact of SOC content and different fertilization treatments on crop yields

The relationship between the SOC contents and crop yields varied with fertilization. However, we did not find a relationship between SOC and crop yield. In the treatment without fertilization, crop roots and root exudates were the only source of organic input into the soils because aboveground biomass was removed from the field. Roots exudates would contribute significantly to increasing SOC content. Thus, the increase in SOC by increasing crop yields along is lower than by inputting organic materials such as fertilization and crop residues. Meanwhile, with the improvement of soil fertility, many uncertain factors such as temperature, precipitation, evaporation and original soil properties (Wan *et al*., 2011) may affect the crop yield and production. In general, higher CO_2 levels in the atmosphere, resulting from global human activities, also could increase growth and yield, mainly through their effect on the crop's photosynthetic processes (higher levels of CO_2 meant that plants absorb more CO_2) – a process known as CO_2 fertilization (Hendrey & Kimball, 1994). Liang *et al.* (2011) stated that there may be a higher dependence on N fertilizer for soybean → maize → maize rotation system while a lower dependence on N fertilizer under the MN management, which would improve soil fertility by accumulation of manure.

Effects of different fertilization treatments on soil organic carbon sequestration

SOC content and crop yield had similar trends under four fertilizer treatments, SOC stock also steadily increased in the three types of cropland under the MN fertilizer management (Fig. 3). Therefore, the model clearly suggests that a higher proportion of M returned to the soil can significant increase SOC stock, which may provide a powerful measure for increasing SOC sequestration at hilly and gully areas of Loess Plateau. The measures would possibly make alterations within the structure of the recent farming systems to convert these soils from carbon sources to net sinks under different croplands. This information is helpful with regard to the design of an explicit policy for soil fertility improvement.

Nevertheless, the rate of increasing or decreasing on SOC stock for the three types of cropland was different in the same fertilization treatment. The reason could be that factors such as different initial SOC levels, different cropping rotations, the climate, soil erosion and human activities affect the sloped land and the terraced field more than the flat field in Loess Plateau. Under the sloped land, the organic matter will flow down with the rainfall and diminish due to decomposition, especially in the upper slope (McNab, 1993). The leguminous rotation induced biological N fixation under terraced field that enhanced the SOC sequestration. SOC stock would be relatively higher in flat fields even without human influence because of the favorable soil and water conditions (Liu *et al*., 2011). In our croplands, the initial C level was important for SOC sequestration, probably because soils with higher initial C contents tend to lose more C later following land surface disturbances and climate warming (Tan *et al*., 2006). But the risk of net C loss may increase with increasing SOC density when the sequestration of input C does not balance the carbon losses via soil respiration or other events such as runoff and soil erosion.

Therefore, management through combined fertilizer and manure application could be better than other fertilizer applications to achieve a win-win goal of increasing soil carbon sequestration and maintaining food security.

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References

Chen C, Gong J, Fu BJ, Huang ZL, Huang YL, Gui LD, 2007. Effect of land use conversion on soil organic carbon sequestration in the loess hilly area, loess plateau of China. Ecol Res 22: 641-648.

Chen C, Liang YL, Wu RJ, Peng Q, Jia WY, Huang ML, 2010. A preliminary study on the change of soil organic carbon and carbon cycling of Loess Hilly Region sloped land. J Nat Res 25: 668-676. [In Chinese, with English Abstract].

Entry JA, Sojka RE, Shewmaker GE, 2002. Management of irrigated agriculture to increase organic carbon storage in soils. Soil Sci Soc Am J 66: 1957-1964.

Fang JY, Piao SL, Zhao SQ, 2001. CO_2 missing carbon sink and carbon pool in the land ecosystem with medium latitude in the Northern Hemisphere. J Plant Ecol 25: 594-602. [In Chinese, with English abstract].

Fließbach A, Oberholzer HR, Gunst L, Mader P, 2006. Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. Agr Ecosyst Environ 118: 273-284.

Fontaine S, Mariotti A, Abbadie L, 2003. The priming effect of organic matter: a question of microbial competition. Soil Biol Biochem 35: 837-843.

Fortuna AR, Harwood K, Kizilkaya, Paul EA, 2003. Optimizing nutrient availability and potential carbon sequestration in an agroecosystem. Soil Biol Biochem 35: 1005-1023.

Han FP, Hu W, Zheng JY, Du F, Zhang XC, 2010. Estimating soil organic carbon storage and distribution in a catchment of Losee Plateau, China. Geoderma 154: 261-266.

Han SJ, Dong YS, Cai ZC, Song CC, 2008. Chinese terrestrial ecosystem carbon cycle and biogeochemical processes. Science Press, Beijing. pp: 258-320. [In Chinese, with English abstract].

Hao XY, Gao W, Wang YY, Jin JY, 2012. Effects of combined application of organic manure and chemical fertilizers on ammonia volatilization from greenhouse vegetable soil. China Agr Sci 45: 4403-4414.

Hendry GR, Kimball BA, 1994. The FACE program. Agric. Forest Meteorol 70: 3-14.

IPCC, 2007. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC WGI Fourth Assessment Report: 12.

ISS, 1978. Physical and chemical analysis methods of soils. Institute of Soil Science, Chinese Academy of Science, Shanghai Sci Technol Press, Shanghai. pp: 7-59.

Kuzyakov Y, Friedel JK, Stahr K, 2000. Review of mechanisms and quantification of priming effects. Soil Biol Biochem 32: 1485-1489.

Li CS, Frolking S, Frolking TA, 1992a. A model of nitrous oxide evolution from soil driven by rainfall events I. Model structure and sensitivity. Geophys Res 97: 9759-9776.

Li CS, Frolking S, Frolking TA, 1992b. A model of nitrous oxide evolution from soil driven by rainfall events II. Model application. Geophys Res 97: 9777-9783.

Li CS, Mosier A, Wassmann R, Cai Z, Zheng X, Huang Y, 2004. Modeling greenhouse gas emissions from rice-based production systems: sensitivity and upscaling. Glob Biogeochem Cycles 18: 1-19.

Li CS, Zhuang YH, Frolking S, 2003. Modeling soil organic carbon change in croplands of China. Ecol Appl 13: 327-336.

Liang YL, Chen C, Xue QW, Lin XJ, Peng Q, 2011. Long term soil organic carbon and crop yield dynamics on cropland in hilly and gully areas of Loess Plateau. J Agron 10: 40-47.

Liu ZP, Shao MA, Wang YQ, 2011. Effect of environmental factors on regional soil organic carbon stocks across the Loess Plateau region, China. Agr Ecosyst Environ 142: 184-194.

Manna MC, Swarup A, Wanjari RH, Ravankar HN, Mishra B, 2005. Long-term effect of fertilizer and manure application on soil organic carbon storage, soil quality and yield sustainability under sub-humid and semi-arid tropical India. Field Crops Res 93: 264–280.

McNab WH, 1993. A topographic index to quantify the effect of mesoscale landform on site productivity. Can J For Res 23: 110-117.

Moshki A, Lamersdorf NP, 2011. Growth and nutrient status of introduced black locust (*Robinia pseudoacacia* L.) afforestation in arid and semi arid areas of Iran. Res J Environ Sci 5: 259-268.

Nardi S, Morari F, Berti A, Tosoni M, Giardini L, 2004. Soil organic matter properties after 40 years of different use of organic and mineral fertilizer. Eur J Agron 21: 357-367.

Nelson DW, Sommers LE, 1982. Total carbon, organic carbon and organic matter. In: Methods of soil analysis, Part 2, 2nd ed. (Page AL *et al.,* eds). Agron Monogr ASA SSSA, Madison, WI, USA. pp: 102-129.

Pan GX, Li LQ, Wu LS, Zhang XH, 2003. Storage and sequestration potential of topsoil organic carbon in China's paddy soils. Glob Change Biol 10: 79-92.

Paustian K, Cole CV, Sauerbeck D, Sampson N, 1998. CO_2 mitigation by agriculture: an overview. Clim Change 40: 135-162.

Qiu JJ, Wang LG, Tang HJ, Li H, Li CS, 2005. Studies on the situation of soil organic carbon storage in croplands in northeast of China. Agric Sci China 4: 594-600. [In Chinese, with English abstract].

Ratnayake RR, Seneviratne G, Kulasooriya SA, 2011. The effect of cultivation on organic carbon content in the clay mineral fraction of soils. Int J Soil Sci 6: 217-223.

San Jose JJ, Montes RA, 2001. Management effects on carbon stocks and fluxes across the Orinoco savannas. For Ecol Manage 150: 293-311.

Shi H, Shao MA, 2000. Soil and water loss from the Loess Plateau in China. J Arid Environ 45: 9-20.

Shi XZ, Yang RW, Weindorf DC, Wang HJ, 2010. Simulation of organic carbon dynamics at regional scale for paddy soils in China. Climatic Change 102: 579-593.

Smith P, 2004. Carbon sequestration in croplands: The potential in Europe and the global context. Eur J Agron 20: 229-236.

Smith P, Powlson DS, Smith JU, Elliot ET, 1997. A comparision of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma 81: 153-225.

Smith WN, Grant BB, Desjardins RL, Worth D, Li CS, Boles SH, Huffman EC, 2010. A tool to link agricultural activity data with the DNDC model to estimate GHG emission factors in Canada. Agr Ecosyst Environ 136: 301-309.

Tan Z, Lal R, Liu S, 2006. Using experimental and geospatial data to estimate regional carbon sequestration potential under no-till management. Soil Sci 171: 950-959.

Tang HJ, Qiu JJ, Eric VR, Li CS, 2006. Estimations of soil organic carbon storage in cropland of China based on DNDC model. Geoderma 134: 200-206.

Tang HJ, Qiu JJ, Wang LG, Li CS, Van Ranst E, 2010. Modeling soil organic carbon storage and its dynamics in croplands of China. Agr Sci China 9: 704-712.

Wan YF, Lin Erda, Xiong W, Li YE, Guo LP, 2011. Modeling the impact of climate change on soil organic carbon stock in upland soils in the 21st century in China. Agr Ecosyst Environ 141: 23-31.

Wu LZ, Cai ZC, 2007. Estimation of the change of topsoil organic carbon of croplands in China based on long-term experimental data. Ecol Environ 16: 1768-1774. [In Chinese, with English abstract].

Zhang F, Li CS, Wang Z, Wu H, 2006. Modeling impacts of management alternatives on soil carbon storage of farmland in Northwest China. Biogeosci 3: 451-466.

Zhang LM, Yu DS, Shi XZ, Xu SX, Wang SH, Xing SH, Zhao YC, 2012. Simulation soil organic carbon change in China's Tai-Lake paddy soils. Soil Till Res 121: 1-9.