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Long-term Soil Organic Carbon and Crop Yield Dynamics on Cropland in Hilly and Gully Areas of Loess Plateau

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Abstract: Soil Organic Carbon (SOC) is one of the key factors affect agricultural production, nutrient availability, soil stability and the flux of greenhouse gases. The comparison of simulated and observed data of SOC and yields for the period 1998-2008 were conducted in hilly and gully areas of loess plateau. Denitrification-Decomposition (DNDC) model was validated using SOC content and crop yield data collected from long-term experimental sites on Loess Plateau in China. The results showed that DNDC was capable of quantifying SOC and crop yield in the agro-ecosystems in this region. In addition, the DNDC model was used to investigate effects of different fertilization managements on SOC content and crop yield dynamics on the three major croplands for 11 years. Simulated results showed that single manure application or combined with nitrogen fertilizer application could significantly enhance the SOC content and crop yield on all three types of cropland (3.16 or 3.53 g C kg^{-1}, 425.04 or 437.08 kg C ha^{-1} on the slope land, 3.10 or 3.14 g C kg^{-1}, 366.86 or 517.3 kg C ha^{-1} on the terraced field and 5.72 or 6.55 g C kg^{-1}, 2808.36 or 2940.40 kg C ha^{-1} on the flat field, separately). No application of any fertilizer neither contributed to enhancing soil fertility nor increased crop yield. Single nitrogen fertilizer application could increase crop yield 333.84 kg C ha^{-1} on the slope land and 2616.36 kg C ha^{-1} on the flat field but could not significantly increase the fertility level of top soil. Sometimes, the single nitrogen fertilizer application even decreased 0.02 g C kg^{-1} on the slope land. Therefore, the application of manure combined with a certain amount of nitrogen fertilizer would be a better management practice to achieve a goal of increasing soil carbon sequestration and food security.

Key words: DNDC model, loess plateau, manure, nitrogen fertilizer, soil organic carbon, crop yield

INTRODUCTION

A number of studies have indicated that Soil Organic Carbon (SOC) is one of the key factors affect agricultural production, nutrient availability, soil stability and the flux of greenhouse gases (Yerokun *et al*., 2007; Wardle *et al*., 2004; Doran *et al*., 1999; Brahim *et al*., 2010). The SOC pool represents a carbon dynamic equilibrium of gains and losses (Wang *et al*., 2008; Bouajila and Gallali, 2008), acting as a source and a sink for carbon and nutrient. Even small changes of SOC may potentially add up to significant changes in large-scale carbon cycling (Brahim *et al*., 2011; Fang *et al*., 2001). Furthermore, SOC is relatively dynamic and can be greatly influenced by agricultural practices (Olson and Ebelhar, 2009; Ratnayake *et al*., 2011; Onweremadu, 2008). A number of researchers in many countries have paid attention to carbon sequestration and mitigation of SOC loss by optimizing farming managements (Abunyewa *et al*., 2007). The carbon loss may be prevented or reversed by improved agricultural management, including measures such as reduced tillage, improved fertilization management and irrigation as well as increased vegetation covers (Follett, 2001; Entry *et al*., 2002; Fortuna *et al*., 2003; Lal, 2004a). These measures can be considered as an important means to achieve both high rates of carbon sequestration in terrestrial ecosystems and sustainable agricultural development (Lal, 2004b; Smith, 2004; Moshki and Lamersdorf, 2011). Increase in SOC storage in cropland soils benefits soil productivity and environmental health, thus it is recognized as a win-win strategy (Lal, 2004a; Qiu *et al*., 2009).

China as a large agricultural country has about 120 million hectares of cultivated land, accounting for 7% of

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the world's arable land (Qiu *et al*., 2009). With such small area of cropland, Chinese agriculture has supported approximately 22% of the world's population and has been responsible for the growing population's food security (Pan and Zhao, 2005). Meanwhile, agriculture is also an essential industry supporting China's economic development and even profoundly influences social and economic stability. The Loess Plateau region, a typical rain-fed agricultural area in China, has infertile soil and severe water shortage that seriously hinder agricultural production and sustainable development. Currently, increasing crop yield by improving soil fertility while maintaining or increasing SOC have been a challenge in agricultural production in the region (Lal, 2004a; Smith, 2004; Yusuf *et al*., 2009).

The Denitrification-Decomposition (DNDC) is a simulation model that can quantify soil carbon dynamics and crop yields. The modified DNDC has been independently tested and utilized in several studies for estimating soil carbon sequestration in China (Liang and Xu, 2000; Li *et al*., 2003, 2010; Qiu *et al*., 2005, 2009; Zhang *et al*., 2006; Wang *et al*., 2008; Chen *et al*., 2010; Giltrap *et al*., 2010). These tests demonstrated that DNDC is capable of capturing basic patterns and magnitudes of SOC variations across climate zones, soil types and management regimes. However, the utilizations of DNDC have not been tested in the hilly and gully areas of the Loess Plateau.

The objectives of this study were to (1) evaluate the DNDC model for simulating SOC and crop yields in three types of cropland; (2) investigate effects of fertilization managements on long-term SOC and crop yields in hilly and gully areas of the Loess Plateau. The overall goal is to improve current fertilizer management practices for enhancing SOC storages and increasing crop productivity.

MATERIALS AND METHODS

DNDC model: The Denitrification-Decomposition (DNDC) model was originally developed for predicting carbon (C) and nitrogen (N) biogeochemical cycles in agroecosystems of U.S.A. (Li *et al*., 1992, 1994, 1997). More international researchers involved in the modeling SOC during the past decade. DNDC has been substantially enhanced and becomes a generic agro-ecosystem model for predicting crop growth, C sequestration, greenhouse gases missions, nitrate leaching and water use efficiency for both upland and wetland crops (Zhang *et al*., 2006).

The study area: This study was conducted in field sites at Ansai Soil and Water Conservation Experimental Station of the Chinese Academy of Sciences (Latitude 36°51'N, Longitude 109°19'E), located in the northern Shaanxi Province in the center of Loess Plateau (Xu *et al*., 2006), with typical semiarid continental climate conditions (mean annual precipitation of 535 mm, mean annual temperature of 8.8°C. The local soil is loess soil (sand loamy soil) which classified as Gelisols in the USDA classification system (Soil Survey Staff, 1999) characterized by low SOC content, nitrogen and phosphorus but rich in potassium. This region has been one of the most severely eroded areas in the world. The local environmental conditions with frequent droughts and lack of irrigation water severely limited the crop yield as well the litter production. Generally, cropping systems is one harvest per year in the area. Slope land, terraced field and flat field are three common types of cropland in the hilly and gully areas. In this study, three long-term SOC content and crop yield datasets were collected across typical agricultural ecosystems in this region.

Case 1: Slope land: Long-term (11 years) measurements on SOC and crop yield were taken at an experimental field in hilly and gully areas of the Loess Plateau from 1997 to 2007. The experimental field was planted with broomcorn millet (*Panicum miliaceum* L.)-millet (*Setaria italica* (L.) Beauv.)-buckwheat (*Fagopyrum esculentum* Moench)-millet rotation under four different treatments: (1) manure amendment (M) at 7500 kg ha^{-1} containing 29.73% organic matter and 1.33% nitrogen, (2) chemical fertilizer (N) application of 114.13 kg ha^{-1} containing 46% nitrogen, (3) combined fertilizer and manure application (MN) and (4) without fertilizer application (control, CK).

Case 2: Terraced field: The tested field had a single-cropping system with soybean (*Glycine max* L.)-millet-broomcorn millet-millet rotation under three treatments: (1) manure amendment (M), (2) combined chemical fertilizer and manure application (MN) and (3) without fertilizer application (control, CK). The manure-treated plots received farmyard manure of 7500 kg ha^{-1} containing 15.92% of organic matter and 0.58% of nitrogen. The fertilizer-treated plot received nitrogen of 97.5 kg ha^{-1}.

Case 3: Flat field: The experimental field was planted with soybean-maize (*Zea mays* L.)-maize rotation. Treatments included (1) manure amendment with 7500 kg ha^{-1} farmyard manure containing 16.04% organic matter and 0.79% nitrogen (M), (2) chemical fertilizer application of 211.96 kg ha^{-1} containing 46% nitrogen (N), (3) combined fertilizer and manure application (MN) and (4) without fertilizer application (control, CK). For the millet, broomcorn millet and buckwheat, 20% of the N fertilizer was applied at planting as base fertilizers and 80% of N fertilizer was amended in the stem elongation stage. In the maize growing season, 20% of nitrogen fertilizer was applied at planting as base fertilizers and the rest 80% of nitrogen fertilizer was applied in the days between internodes elongation and tasseling. Similar application of nitrogen fertilizer was used for soybean before sowing and at the budding stage. Farmyard manure of 7500 kg ha^{-1} was applied before the seeding date of each crop.

The statistical analysis: The measured SOC values (1997-2007) with other data (e.g., climate, soil properties, crop type and rotation, cropping practices etc.) from the three experimental sites were utilized for DNDC validations. The details information about the sites is listed in Table 1 and 2. The three experimental sites were initiated in 1995 and the 11-year data from the autumn of 1997 to the autumn of 2007 was selected to test DNDC model under the same climate background. At first, set up data-base about diurnal rainfall, diurnal mean air temperature and then run DNDC, in put soil properties, crop type and rotation, cropping practices etc. (Li *et al*., 1997), out put SOC values, crop yield and so on. In this study simulated SOC values and yield were utilized to compare with measured SOC values and yield. The relationship between SOC and crop yield were analyzed.

Table 1: Geographic and crop information in each experimental site*

Croplands	Location	Altitude	Rotation systems (beginning with 1998)
Slope land	E109°14' N 36°44'	1070 m	Broomcorn millet (*Panicum miliaceum* L.)→Millet [*Setaria italica* (L.) Beauv.] →Buckwheat (*Fagopyrum esculentum* Moench)→Millet
Terraced field	E109°19' N36°51'	1200 m	Soybean (*Glycine max* L.)→Millet→ Broomcorn millet→Millet
Flat field	E109°19' N36°51'	1032 m	Soybean→Maize (*Zea mays* L.)→Maize

*The information come from Ansai research station of soil and water conservation, chinese academy of sciences

Table 2: Soil characteristics at 0-15 cm soil layer in the autumn of 1997*

Croplands	Treatments**	SOC content (g C kg^{-1})	Total Nitrogen content (g N kg^{-1})	Bulk density (g cm^{-3})
Slope land	CK	2.46	0.34	1.379
	N	2.51	0.35	1.379
	M	3.06	0.43	1.379
	MN	3.20	0.42	1.379
Terraced field	CK	2.28	0.22	1.378
	N	-	-	-
	M	2.59	0.32	1.379
	MN	2.89	0.31	1.379
Flat field	CK	4.89	0.57	1.377
	N	4.87	0.59	1.377
	M	5.34	0.56	1.377
	MN	5.97	0.65	1.377

*The data come from Ansai research station of soil and water conservation, chinese academy of sciences. **Slope land: CK-without fer* The information come from Ansai Research Station of Soil and Water Conservation, Chinese Academy of Sciences. izer application. N-N fertilizer 114.13 kg ha^{-1} containing 46% nitrogen. M-manure 7500 kg ha^{-1} containing 29.7% organic matter and 1.33% nitrogen. MN-combined N fertilizer and manure. Terraced field: CK-without fertilizer application. M-manure 7500 kg ha^{-1} containing 15.92% organic matter and 0.58% nitrogen. MN-combined N fertilizer and manure. Flat field: CK-without fertilizer application. N-N fertilizer 211.96 kg ha^{-1} containing 46% nitrogen. M-manure 7500 kg ha^{-1} containing 16.04% organic matter and 0.79% nitrogen. MN-combined N fertilizer and manure

RESULTS AND DISCUSSION

Model validation: In this study, model simulations were conducted with the single manure application (M) scenarios for the three type of cropland. The model captured the trends of SOC dynamics and crop yield very well as compared to the observed data at the three sites (R^2 = 0.7424 on the slope land, R^2 = 0.6962 on the terraced field, R^2 = 0.6551 on the flat field). with statistical values (Fig. 1). The simulated results indicated that: (1) application of manure increased SOC content through increasing crop production as well directly adding organic matter into the soil on all three types of cropland (Fig. 1) (2) although, the slope land (Fig. 1d), terraced field (Fig. 1e) and flat field (Fig. 1f) each had specific farming management practices, crop yield generally increased after applying a certain amount of manure.

In summary, DNDC model is capable of quantifying SOC and crop yield dynamics in the agroecosystems across the hilly and gully areas of the Loess Plateau. This results support the conclusions reported by other researchers (Zhang *et al*., 2006; Chen *et al*., 2010). In this study, the well-tested model to estimate the impacts of fertilization managements on SOC and crop yield dynamics across the major cropland in this region was used.

The effects of long-term fertilization on the SOC content of different croplands: The SOC contents on the three types of croplands continuously increased during the simulated 11 years under the single manure application and combined application (Table 3). Over the years, SOC values in the 2 treatments increased 0.82 and 1.19 g C kg^{-1} on the slope land. SOC values increased 0.42 and 0.44 g C kg^{-1} on the terraced field and increased 1.18 and 2.01 g C kg^{-1} on the flat field, respectively.

Under the single fertilizer management conditions, simulated SOC dynamics showed decrease trends across the tested sites that represented two types of cropland in hilly and gully areas of the Loess Plateau. During the simulated 10 years, the SOC content on the slope land continuously increased by 7.23%. On the flat field, SOC

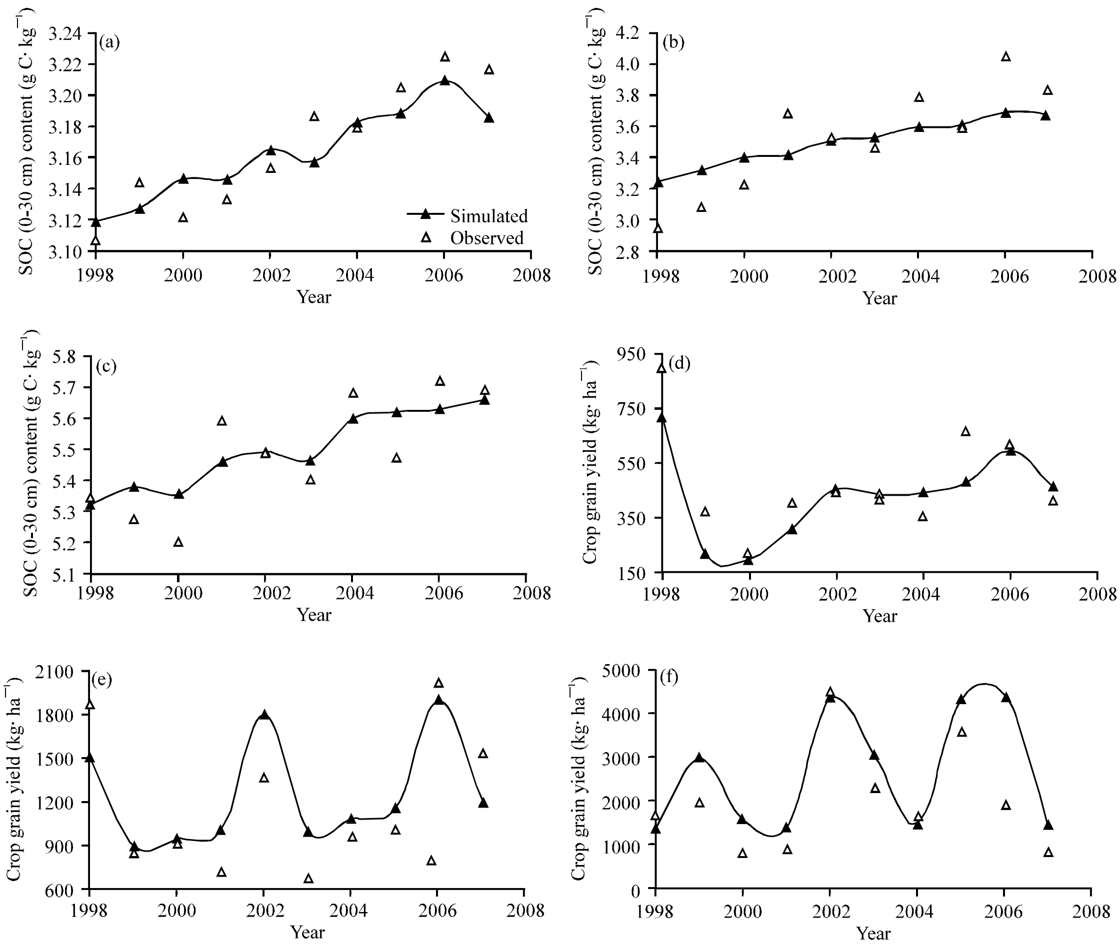

Fig. 1 (a-f): Comparison between observed and the DNDC model simulated SOC (a, b, c) and crop yield (d, e, f) on different croplands, slope land (a, d), terraced field (b, c), flat field (c, f)

Table 3: The effects of long-term fertilization on the SOC content and grain yield of different croplands

	Average SOC content (g C kg^{-1})			Average grain yield (kg C ha^{-1})		
Treatments	Slope land	Terraced field	Flat field	Slope land	Terraced field	Flat field
CK**	2.34B*	2.68B	4.54D	132.1C	295.76C	1516.92B
N	2.32B	-	5.01C	333.84B	-	2616.36A
M	3.16C	3.10A	5.72B	425.04A	366.86B	2808.36A
MN	3.53A	3.14A	6.55A	437.08A	517.3A	2940.4A

*Different letters in the same column represented the significant difference at $p<0.05$. **Slope land: CK-without fertilizer application. N-N fertilizer 114.13 kg ha^{-1} containing 46% nitrogen. M-manure 7500 kg ha^{-1} containing 29.7% organic matter and 1.33% nitrogen. MN-combined N fertilizer and manure. Terraced field: CK-without fertilizer application. M-manure 7500 kg ha^{-1} containing 15.92% organic matter and 0.58% nitrogen. MN-combined N fertilizer and manure. Flat field: CK-without fertilizer application. N-N fertilizer 211.96 kg ha^{-1} containing 46% nitrogen. M-manure 7500 kg ha^{-1} containing 16.04% organic matter and 0.79% nitrogen. MN-combined N fertilizer and manure

increased in the first decade, then decreased in the subsequent years and finally decreased by 0.45%.

Under no fertilizer application condition, the SOC on the slope land and flat field continuously decreased during the simulated 50 years by 7.23 and 9.72%, respectively. Meanwhile, the four-year soybean-millet-broomcorn millet-millet rotation on the terraced field would enhance SOC storage by 32.95%.

The effects of long-term fertilization on crop yield of different croplands: By varying the fertilization managements, we tested the effects of different fertilizations on crop yield. The simulated data indicated that the fertilization had significant ($p<0.01$) effect on the crop yield dynamics on all the tested sites during the simulated 11 years and the ranking of yield-increasing rate was MN>M>N (Table 3). The total crop yield changed

Inverted S and changed greatly between years in the terraced field (Fig. 1e), flat field (Fig. 1f) compared to the slope land (Fig. 1d).

On the three types of cropland, the crops totally depended on soil fertility to maintain production under no fertilizer conditions. Every year the crops could transfer lots of carbon into the soil, such as root exudates during the annual growing season, crop residues and stubble after harvest, even though it was far from being able to maintain the SOC balance and the remained SOC could be exhausted. Wu and Cai (2007) had the same conclusion after they researched the SOC Flieβbach *et al*. (2006) found that the SOC decreased most in the unfertilized treatment. Zhang *et al*. (2006) and our early research Chen *et al*. (2010) had the same results under control in this region. Meanwhile, no fertilizer application not only reduced crop yields but also decreased organic material inputs (e.g., crop residues, microbial biomass, etc.) back to soil which made it more difficult to increase SOC. Several studies had shown that the single fertilizer application could increase crop yields but the increase of surface soil fertility was not significant (Li, 2007) and soil fertility was even reduced (Wu and Cai, 2007; Jin *et al*., 2008). On the three types of cropland, single manure application or combined application of manure and chemical fertilizer could enhance the SOC content steadily. Several studies had similar results (Gami *et al*., 2001; Yadvinder-Singh *et al*., 2004; Flieβbach *et al*., 2006; Wu and Cai, 2007; Chen *et al*., 2010).

On the slope field and flat field, NM combined application had always been better than the M treatment. The combined nitrogen fertilizer either provides crops with the N elements for the direct use or activates the microorganism, so that the decomposition of soil organic matter is accelerated (Han *et al*., 2008), providing crops with more nutrient. The application of the chemical nitrogen fertilizer might lead to priming effect; which activates the soil microbial activity to release more nutrients. The NM management increased the crop yield 74.91% but single manure application only increased yield by 24.04%. However, Yadvinder-Singh *et al*. (2004) showed that organic manure can be as effective as chemical fertilizer for increasing crop yields. Nevertheless, from the long-term development viewpoint, NM combined application should be better than single manure application to achieve soil carbon sequestration and food security goal.

Relationship between the SOC content and grain yield under different long-term fertilization managements on different croplands: On the slope land (Table 4), there was significant correlation ($p<0.01$) between the SOC content and grain yield under no fertilization conditions, suggesting that crops were highly sensitive to the change of soil fertility. It was perhaps due to crops only reliance on soil to meet their nutrient requirements under no fertilization conditions. However, there was no significant correlation between SOC and yield in M and MN managements. Single nitrogen fertilizer application reduced the soil fertility continuously but increased crop yields which indicated that crop yields increase at the expense of the soil fertility, not consistent with the goal of agricultural sustainable development.

Table 4: Coefficients between the SOC content and crop yield on three types of cropland under long-term different fertilization

	Croplands		
Treatments	Slope land	Terraced field	Flat field
CK	0.420**	0.605**	0.197
N	0.128	—	0.796**
M	0.189	0.282*	0.272
MN	0.137	0.222	0.389**

*: $p<0.05$, **: $p<0.01$

On the terraced field (Table 4), there was also highly significant correlation ($p<0.01$) between the SOC content and grain yield under no fertilizer conditions. The significantly correlation ($p<0.05$) occurred in the M management. Apparently, long-term application of manure had greatly improved soil fertility and made it possible for crops to achieve high-yield. Meanwhile, the release of manure nutrient restricted the crop yield to increase further, resulting from the reliance on microbial activity. Under the MN management condition, the extra nitrogen fertilizer led to the priming effect which accelerated the degradation and mineralization of soil organic nutrients and increased crop use of these nutrients; therefore, its SOC content was lower than that of the M management. From the long-term development viewpoint, combined application of manure and chemical fertilizer should be better than single manure application.

On the flat field (Table 4), the highly significant correlation ($p<0.01$) between the SOC content and grain yield occurred in N and MN treatments, showing the SOC content changes could affect the crop yield significantly and N application was more related to crop yield. That may be related to a higher dependence on nitrogen fertilizer for soybean-maize-maize rotation system in the N treatment while a less dependence on nitrogen fertilizer in the MN management, for the long-term accumulation of manure would improve its soil fertility. The application of manure could significantly affect the correlation coefficient r between SOC and yield. For example, r was 0.796 in N treatment but was reduced to 0.389 in MN treatment. On contrary, there was no significant correlation between the SOC content and grain yield under no fertilizer condition which suggested that crop yield, could not show a decrease trend corresponding to continuous reduction of SOC content. Root nodules of soybeans could fix biological nitrogen, reduce C/N ratio of root and residue, improve soil fertility and promote the growth of the following crops, as a result of increasing decomposition, soil microbial biomass and nitrogen (Yusuf *et al*., 2009). In addition, although M treatment had enhanced the SOC content, it is always difficult to meet the crop growth demand since the nutrient release was subjected to activities of soil microorganisms. However, when brought it into soil with amount of nitrogen fertilizer, the nitrogen fertilizer was either available to crops, meeting their growth needs, or to micro-organisms, promoting their activities and accelerating the degradation of manure and soil organic matter (Han *et al*., 2008).

Correlation analysis indicated that, the crop production in no fertilizer application treatment was constrained by soil fertility to a larger extent on the slope land and terraced field than on flat field. That could be explained as: the necessary fertilization measures would not only enhance soil fertility in the barren soil but also play a very significant role in increasing crop yields which is consistent with the findings of Han *et al*. (2008). However, when soil fertility is improved, other factors would become the limiting factors for crop production. For example, annual precipitation and annual mean temperature had been becoming the most significant limiting factors in the M and MN treatments on the slope fields. On the flat field in the soybeans-maize-maize rotation, the root nodules of the soybean could fix biological nitrogen; however, the 1/3 of required N still need to be supplied from soil. While maize is a high N demand crop, both soybean and maize relied on soil nitrogen supply which could explain why there were the highly significant correlations ($p<0.01$) between the SOC content and crop grain yield in N and MN treatments.

CONCLUSIONS

Based on the feasibility of DNDC model in hilly and gully areas of Loess Plateau, the effects of different fertilization managements on the SOC content and crop yield dynamics on the three major croplands were simulated for 10 years. The simulated results showed that no fertilizer application decreased soil fertility due to soil nutrition deficiency and reduced crop yields on the slope land and flat field. Planting leguminous crop soybean promoted the accumulation of soil fertility on the terraced field. Single nitrogen fertilizer application could ensure crop production on the slope land and flat field but could not significantly increase the fertility of top soil. Occasionally, single nitrogen application even decreased soil fertility. To achieve a win-win goal of soil carbon sequestration and high yield on the three types of cropland, single manure application or NM combined application could significantly increase SOC content and crop yield for long term. No matter which type of cropland was cultivated, the NM combined application should be better than single manure application to achieve the goal of increasing soil carbon sequestration and maintaining food security.

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