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Simulation of Soil Organic Carbon Dynamics in Oasis Farmland in Xinjiang based on DNDC model

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Abstract: This paper reports a study of long-term fertilization impacts on soil organic carbon (SOC) dynamic using DNDC (denitrification-decomposition) model to simulate the related experimental parameters in Manas Country, Xinjiang province. RMSE, M, R^2 and r values were used verification the DNDC model. Meanwhile, the simulation predicted that fertilizer (N+P+K)+S (S, plant residue returned) treatment under the trend of SOC in the different soil types, and analysis of corresponding of △SOC and the initial value in soil chemical and physical properties. In addition, based on GIS the spatial distribution was calculate by SOC content, bulk density, depth, density of soil carbon conversion (SOCD). Results showed that through DNDC model simulation SOC increased 1.9g kg^{-1} from 2011 to 2041 year; soil carbon density ranges from 0.012kg C m^{-2} yr^{-1} to 0.021 kg C m^{-2} yr^{-1}. Soil carbon sequestration rate ranges from 207 kg C ha^{-1} yr^{-1} to 121kg C ha^{-1} yr^{-1}. Carbon density of the Manas country farmland was increasing. Moreover, high SOC content has higher sequestration rate than low SOC content.

***Keywords:** Soil organic carbon; DNDC model; GIS; Grey desert soil; Manas country*

1. Introduction

Soil organic carbon (SOC) is one of the most important terrestrial pools for C storage [1-2]. Even very small local changes of the SOC pool may potentially add up to significant changes in large-scale carbon (C) cycling [3]. It is estimated that the total SOC pool is about 1400-1500 Pg C (1Pg=10^{15}g), which is approximately two times greater than the atmospheric pool (750 Pg C) [4-6]. SOC is one of the key factors that affect agricultural production, nutrient availability, soil stability and the flux of greenhouse gases between land surface and atmosphere [7]. SOC represents a major pool of carbon within the biosphere, and acts both as a source and a sink for carbon. Variation of SOC reflects the net result of additions of carbon and the carbon loss. Loss of SOC may cause soil degradation, which does not only undermine sustainable agricultural development but also affects environmental health [7]. Consequently, improved management practices should aim to increase SOC accumulation, as these practices affect both world food security and global climate change [8-9].

Estimates from the IPCC Second Assessment Report suggested that 400-800 Tg (1Tg=10^{12}g) C per year could be sequestered in global agricultural soils, with the finite capacity saturating after 50-100 years [10]. Sun [11] suggested that the potential of SOC sequestration in China was estimated to be 2-2.5 Pg C, which could be achieved by the 2050s if crop production and field management are improved. Smith [12] reported the biological potential for carbon storage in European (EU15) cropland to be 90-120 Tg C per year with the available management options including reduced and zero tillage, set-aside (i.e., land that farmers are not allowed to use for any agricultural purpose), and the more efficient use of organic amendments. Sperow [13] further projected that U.S. cropland has the potential to increase soil C sequestration by an additional 60-70 Tg C yr^{-1} over the rate of 17 Tg C yr^{-1} in the early 2000s.

Over the past 30 years, crop yields in China have approximately doubled as a result of the adoption of modern cultivars, the increased use of fertilizer, improved field management, and expanded irrigation [11]. Zhang [14] reported that the changes of fertilizer quantity used in Xinjiang for 15 years have been analyzed, the contributions of fertilizer using to main crops in Xinjiang were studied and the important problems of using fertilizer were discussed.

The vast majority of the changes in the SOC are believed to occur in the top 20 cm of soil [15-17], the changes within an additional 0-20 cm depth are well understood, which may result in an appropriate assessment of the soil carbon sequestration.

The spatial and temporal characteristics of soil C describe are difficult to determine with limited field experiments. Therefore, it is required to establish a comprehensive process-based model of simulating such a complex process and deriving management practices to soil C describe [18]. A list of the most widespread models to simulate SOC storage and loss from cropland under global warming scenarios were as follows: NCSOIL [19], CENTURY [20], ROTHC [21], LEACHM [22] and DNDC [23-24]. The DNDC model is one of the few models developed including both a site-specific mode and a regional mode, simulating carbon biogeochemistry in agro-ecosystems, is used to study the agricultural soils of China. Moreover, the DNDC model has been validated throughout the world by using long-term and short-term experimental data, testing the modeling behavior and sensitivity of the carbon biogeochemical process in agricultural soils [25-27]. Nowadays, the DNDC model has been modified and improved by adding new function. Meanwhile, DNDC was also reported to a good performance models by using fertilization experiments representing oasis land-uses, a range of climatic conditions within the arid region, and fertilization treatments [28-29].

Xinjiang province in northwest China is a unique region with strong geographical heterogeneity and complex meteorological systems [30-33]. In Xinjiang, several studies have reported SOC on a local scale agricultural [34-35]. Nationwide studies have been conducted by analyzing the large number of different soil profiles found in the literature. However, several limitations exist: these records generally result from observations made with data obtained from various sources; the values obtained in samplings done in different years are mixed; and the data obtained from different approaches have led to wide variations. In the present work, we assess SOC, bulk density (BD) and stoniness spatial variability as edaphic attributes in Xinjiang soils.

This paper presents an approach to estimate the carbon density in Manasi country, Xinjiang province using soil quality data (71 study plots) and a simple geostatistical technique for evaluation purposes. The objectives of this study were to: (1) quantify current SOC and soil organic carbon density (SOCD) in Manas country, Xinjiang; and (2) generate fine-resolution estimates of surface soil SOC stocks from 2011 to 2041, reveal the spatiotemporal pattern of the regional C pools, and assess the best reasonable fertilization factors mainly in the grey desert soil at the arid or semi-arid regions of Northwest China.

2. Materials and Methods

2.1. Study Area

The study area is located in northwest China, Manas country, Xinjiang province, (N43°28′-45°38′, E85°34′-86°43′) covering about an agricultural acreage of 1700km^2 (Fig.1).

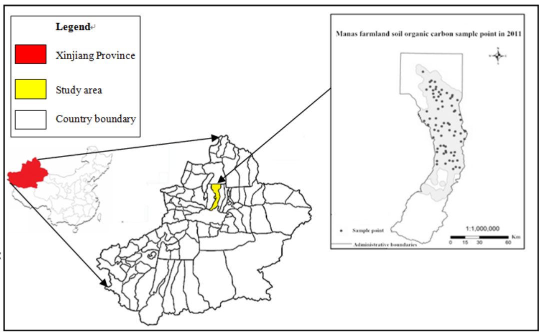

Fig. 1 *Location of the study area in China and monitoring sites and County in the study area.*

The climate is arid or semi-arid with full of sunshine. Annual average rainfall is 173.3 mm, with a mean temperature of 7.7 °C. There is a rotation of corn-wheat-cotton (i.e., corn and cotton cropping for one year and wheat cropping for next two year) in the local. Corn was seeded during late April to early May for the mono-cropping system. Spring wheat was seeded in mid-April and winter wheat in late September in the same year. Cotton was seeded in May in the year. According to farmer surveys in 2011, chemical fertilizer was commonly used as its application is less laborious than that of manure. In the wheat growing season, nitrogen fertilizer was commonly applied before sowing. Similar applications of nitrogen fertilizer were used for cotton before sowing. In the corn growing season, nitrogen fertilizer was commonly applied in the days between node elongation and tasseling. Drip irrigation was widespread. Wheat fields were commonly irrigated three to four times, corn fields one or two times, and cotton was commonly irrigated two to three times. General characteristics of the sites are shown in Table 1.

Table.1 *Basic soil information (mean±S.D.) of the topsoil samples*

Soil types	No. of samples	Area (10^4ha)	Mean initial SOC (g kg^{-1})	Bulk density (gcm^{-3})	pH values
Meadow Soil	7	1.64	6.98±0.35	1.34	8.38
Gray desert soil	27	6.92	7.31±0.74	1.46	8.43
Moisture soil	12	3.22	8.73±1.26	1.23	8.48
Aeolian sandy soil	7	1.38	4.24±0.67	1.41	8.33
Irrigated desert soils	2	0.27	6.24±0.73	1.44	8.18
Desert solonchak	6	1.28	8.21±1.22	1.34	8.61
Shruby meadow soils	2	0.41	7.86±0.11	1.39	8.28

Alluvial soils	2	0.33	10.18±0.5!	1.29	8.37
Solonchak	6	1.14	6.87±0.59	1.38	8.59
All/Mean	71	16.59	7.40±0.69	1.36	8.41

2.2. Soil Sample and Analyses

In August and September 2012, based on the practical conditions and employing Global Position System (GPS), 71 sampling points were located with every three random topsoil (0-20cm) samples from each sampling point mixed together for chemical analysis. Soil samples were stored in cloth bags, transported to the laboratory and air dried at room temperature. Then the soils were crumbed, and passed through a 2 mm mesh to remove visibly identifiable plant residues, fauna, and debris. Generally, the soils were nearly stone free and we did not measure soil stone content. A small fraction of each sample was ground and passed by a 0.25 mm mesh for analyses of SOC concen trations. SOC was determined using the $K_2Cr_2O_7$-H_2SO_4 oxidation method [36]. Soil bulk density (BD) of sampling site was measured using the core method described by Blake and Hartage [37]. Soil BD samples were dried at 105 °C until a constant mass and weighed to calculate BD by dividing by soil volume. The pH (soil-water suspensions, 1:2.5) was measured using the PHS-3C instrument (INESAS Scientific Instrument Co., Ltd). Particle size distribution, one of the basic physical properties of soil, can be used to calculate other characteristic parameters of the soil. Though time consuming, the densimeter method is the common way to determine particle-size distribution of fine-grain soils [38]. Soil total N (TN) and Soil total P (TP) contents were determined by the micro-Kjeldahl digestion procedure [39].

2.3. Data Analysis

Where individual replicate values were not available, other tests were used. After Loague and Green [40], between the simulated and the measured values, the total difference was calculated as the root mean square error (Smith et al., 1997), RMSE:

$$\mathrm{RMSE} = \frac{100}{\bar{O}}\sqrt{\frac{\sum_{i=1}^{n}(Si - Oi)^2}{n}} \quad (1)$$

In the following equations, Oi are the observed values, Si are the predicted (simulated) values, $\bar{O}$ is the mean of the observed data, is the mean of the predicted (simulated) data, and n is the number of paired values [28]. The RMSE is a measure of the deviation of the simulated values from observations, and is scaled relative to the units of measurement [41].

$$M = \frac{\sum_{i=1}^{n}(Oi - Si)}{n} \quad (2)$$

The nature of the bias was further examined using the mean difference, M [28]; meanwhile, the mean difference between measured and simulated values gives an indication of the bias in the simulation.

To assess whether simulated values follow the same pattern as measured values, the sample correlation coefficient, r, can be calculated [28]:

$$r = \frac{\sum_{i=1}^{n}(Oi - \bar{O})(Si - \bar{S})}{\sqrt{\sum_{i=1}^{n}(Oi - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(Si - \bar{S})^2}} \quad (3)$$

This statistic can be useful in assessing how well the shape of the simulation matches the shape of the measured data. However, if it is no clear trend in the measured data to give a spread of paired measured and simulated data values, the correlation coefficient is of only limited use in determining how well a model simulates the measured data, meanwhile, an r value closest to 1 indicates the model matches the pattern of the observations.

There is a soil organic carbon density (SOCD) is the soil organic carbon content, soil bulk density and soil depth, which the product of for soil profile is divided into n layers. The calculation method of soil organic carbon density (C kg soil m^{-2}) C is as follows:

$$\mathrm{SOCD} = \sum_{i=1}^{n}(1 - \theta i\%) \times Pi \times Ci \times Ti/100 \quad (4)$$

Where SOCD is soil organic carbon density of a profile, θi is gravel (>2mm) content in horizon i (%), Pi is soil bulk density in horizon i (soil g cm^{-3}), Ci is organic carbon content in horizon i (soil organic carbon g soil kg^{-1}), Ti is the thickness of horizon i (cm), and n is the numbers of horizons involved [42]. Depths involved in calculation are usually recorded during the field observations with the maximum depth for calculation limited to 20cm. Meanwhile, a GIS was used to link records in the Attributes Database to the Spatial Database based on soil samples (using the ArcGIS 9.3). The assignment is done according to the principles of soil parent material identity, soil type identity and similarity. Thereafter, a SOCD (kg m^{-2}) vector map of Manas was compiled by linking SOC density data of soil profiles calculated with the soil spatial database.

$$V = (Ct - Co)/T \quad (5)$$

Where V is carbon sequestration rate, Ct is SOC content in 2041, Co is SOC content in 2011 and T is 30 year.

2.4 Model Inputs

In this study, the main input data used for the DNDC model include climate, soil, farming management and crop yield (Table 2).

Table.2 *Main input data for running the DNDC model.*

Category	Item (Unit)
Climate	Daily maximum and minimum

	temperature(℃), precipitation (mm)
Soil properties	Land-use, Top soil texture, Bulk density, pH, SOC (g kg^{-1}) at surface soil
Farming management and crop yield	crop planting and harvesting dates, the rate and timing of fertilizer application, tillage, weeding, and irrigation

The daily climate data (i.e., maximum and minimum temperature, precipitation in 1980-2010) were collected from China meteorological data sharing service system (http://www.escience.gov.cn). These datasets are constructed by applying spatial interpolation algorithms to historical climate data from approximately 752 observations across China. There are approximately 56 observations in Xinjiang province. Moreover, input soil properties include the concentrations of organic carbon and total nitrogen, bulk density, clay and sand fraction, and pH in the topsoil to 20 cm depth.

There is a rotation of corn-wheat-cotton in Manas cropland. Corn was seeded during late April to early May for the mono-cropping system. Spring wheat was seeded in mid-April and winter wheat in late September in the same year. Cotton was seeded in May in this year. Fertilizers were applied at N, P_2O_5 and K_2O in Manas cropland (Table.3). Drip irrigation was widespread. Wheat fields were commonly irrigated three to four times, corn fields one or two times, and cotton was commonly irrigated two to three times.

Table.3 *Average annual nutrient input from different source during 1980-2011*

Treatment	Chemical fertilizer (kg hm^{-2})			Straw (t hm^{-2})
	N	P	K	
NPKS	89.4[a]/216.7[b]	24.5/50.8	16.9/42.3	4.5[c]/9[d]

a:annual rate of fertilizer between 1980-1990;
b:annual rate of fertilizer between 1990-2011;
c:wheat straw, d:maize straw

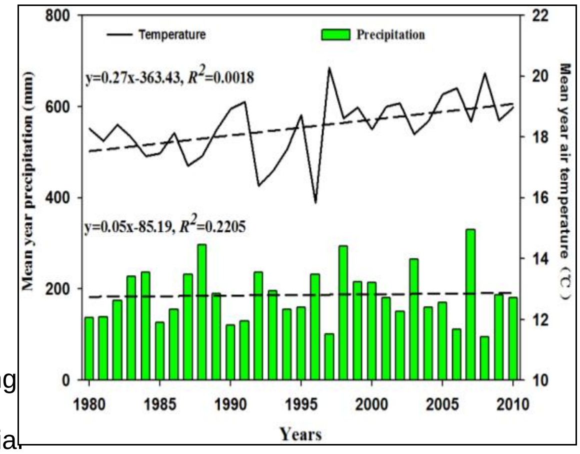

Fig.2 *Mean year precipitation (mm) and mean year air temperature (℃) from 1980 to 2010*

Figure 3 showed a change of SOC (1:1 line) during 30 years as simulated by the 9.5DNDC, linear is simulation values (g kg^{-1}) in 2011, and dot is observation values (g kg^{-1}) in 2011. Statistical analysis of the model is conducted by comparing model simulations (Sim) and field observations (Obs) over the course of simulation. Next, we runned our model using forecast the 30 year that SOC content in different of types (2011-2041, Table.1 and Fig.5). For model validation, we assessed goodness of fitting between simulated and observed SOC content using statistical metrics.

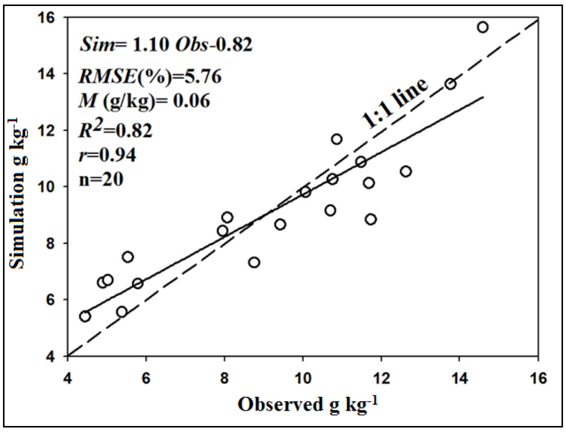

Fig.3 *Modeled vs. observed SOC at the validation sites.*

2.5 Model Validation

The SOC contents in the analysis was obtained from the Second National Soil Survey in 1980, the soil in Urumqi district, comprising Manas County, was sampled, analyzed and mapped. The sites information for 1980, including cropping systems, soil types, fertilization schemes Meanwhile, the climate was listed in Figure 2, were also considered in our database.

We validation DNDC to simulate SOC content in the soil using the 1980 year (20 simples, Fig.3) of our data set. The DNDC was calibrated by testing the full range of possible parameter values for the r, RMSE, M and R^2, which was emphasized in the validation.

3. Results and Analysis

3.1 SOC density in Manas

Statistics based on the soil polygon for the SOCD (kg m^{-2}) vector map of Manas (Fig.4) show that SOC density in polygons varied dramatically, with the lowest SOC density of 1.44 kg m^{-2}, and the highest of 3.33 kg m^{-2} in 2011(Fig.4a). Meanwhile, results of through simulation of 30 year show that the lowest SOC denisty of 2.03 kg m^{-2}, and the highest of 3.69 kg m^{-2} in 2041 (Fig.4b). The soil organic carbon content increased range from 0.38 g kg^{-1} to 0.59 g kg^{-1} during 2011 and 2041(Fig.4c).

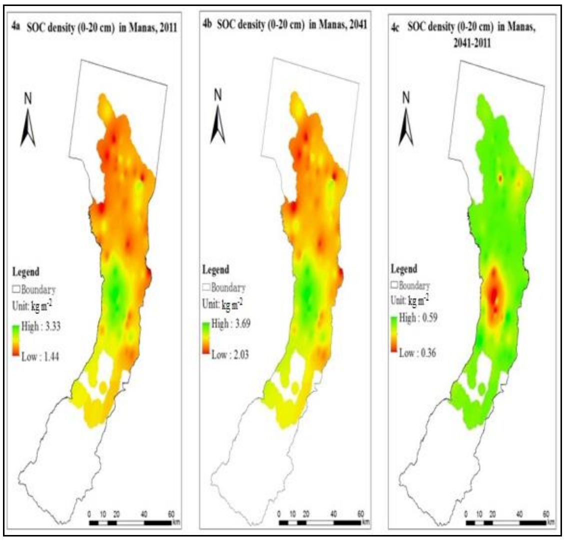

Fig.4 *Map of Soil organic carbon density in Manas (2041-2011).*

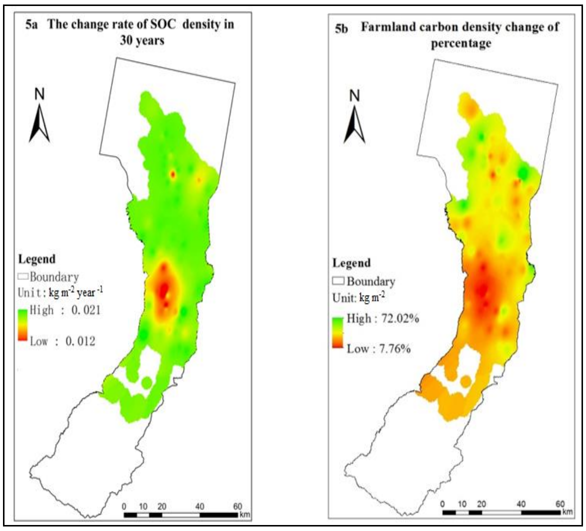

Fig.5 *Manas County farmland soil carbon rate and soil carbon balance in 2011 and 2041years*

Estimates of SOC content and density in China derived from available studies varied greatly. Among published figures, 2009 the analysis of the period from 1998 to 2017 by Liu [43] show that SOC storage could be effectively improved by NPKS in Yujiang country (North, China). Cited from the second general soil survey, the soil organic carbon density and storage of Shandong province (East, China) were estimated by taking soil type as unit. Soil organic carbon density changed from 38.50 to 0.77 kg m^{-2} with average of 6.00 kg m^{-2}, which is lower than the average of China [44]. Meanwhile, Liu's result showed that the SOC density of sandy soil, loess soil in north Shaanxi, and litho soil in Shangluo was the lowest (less than 4 kg m^{-2}), whereas the highest SOC density was mainly presented in Guanzhong Plain and Qinling Mountains (up to or even more than 30 kg m^{-2}) [45]. The paper(Northwest, China) showed that through DNDC model simulation SOC increased 1.9 g kg^{-1} from 2011 to 2014 year, soil carbon density ranges from 0.012 kg C m^{-2} yr to 0.021 kg C m^{-2} yr. Soil carbon sequestration rate ranges from 207 kg C ha^{-1} yr^{-1} to 121 kg C ha^{-1} yr^{-1}, average was 164 kg C ha^{-1} yr^{-1}.

3.2 Soil organic Carbon Change of Rate

In accordance with the Manas farmland soil carbon density and fertilizer application show that the relationship between chemical fertilizer and straw returned makes the soil carbon density (2041-2011) increased (Fig. 5a). Meanwhile, the soil carbon density additional rate ranges were 0.012 kg m^{-2} yr^{-1} from 0.021 kg m^{-2} yr^{-1}. In the next 30 years, the maximun rate of the soil carbon density is 207 kg hm^{-2} yr^{-1}, the minimum rate is 121 kg hm^{-2} yr^{-1}, and the average rate is 164 kg m^{-2} yr^{-1} (Fig. 5b). From 2011 to 2041, soil carbon density ranges from 7.76% to 72.02%, and the Manas farmland soil carbon density shows a trend of increase.

Based on a review of SOC density data from the agricultural literature published before 1960, it has been shown that there have been SOC losses across wide ranges of ecosystems of China [46]. Furthermore, when using the DNDC model, it suggested that soil SOC storage has been continuously reducing since the 1950s, and amounting to 70Tg (1Tg=10^{12}g) since the 1970s [47], when using the DNDC model. These reports have internationally acknowledged, however, dry-land ecosystems are particularly sensitive to environmental stresses. Despite their importance to the global carbon cycle, responses of the Central Asian dry-land to the rapid climate change in recent decades are still unclear. Using DNDC, a newly developed, spatially explicit process model for dry-land ecosystems, a case study was conducted in Xinjiang, a 9154.48 km^2 dry-land cultivation area. The goal was to assess the impacts of future changes on the topsoil regional C dynamics from 2011 to 2041. The results indicated that Xinjiang acted as a C sink of 164 kg hm^{-2} yr^{-1}, 93% of which was contributed by increasing NPK+S in the next three decades. The C dynamic overall was dominated by the CO2 fertilization effect, which resulted in the addition of soil carbon density from 0.012 kg hm^{-2} yr^{-1} to 0.021 kg hm^{-2} yr^{-1} with the increase time from 2011 to 2041.

3.3 SOC Changed in the Different Types

The C content of the soil in a 10 ha field can be measured precisely, and the error in the measurement defined using replicates, whereas for applications at larger scale, the soil C content is often determined for 1 km^2 grid cells, with the C content estimated from typical or averaged soil C values for the major soil types identified in the cell [48].

The uncertainty due to the structural and input errors can be quantified by evaluating the model at field scale, but using only input drivers that are available at the larger scale. In order to represent the uncertainty, a range of sites across the whole area to be simulated should be included in this field-scale evaluation. Good model performance is indicated statistically by simulations and measurements that are both coincident (indicating a close fit) and associated (indicating the trends in measurements are replicated) [49]. The degree of coincidence can be used to represent the size of the uncertainty in the simulations.

Where measurements are replicated, the coincidence between simulated and measured values can be expressed as the 'lack of fit' statistic, if a data set is not replicated, the degree of coincidence can instead be determined by calculating the total error as the root mean squared error and the bias in the error as the relative error [40]. The structural and input errors should be calculated separately to allow the source of errors to be understood and reduced, but the combined errors are then used to determine the accuracy of the model simulations at large scale.

The simulated results showed that SOC content increased by 21.68%, 23.49%, 23.56% and 20.76% over that in Gray desert soil, Meadow soil, Solonchaks and Shruby meadow soils, respectively. In addition, the SOC content also increased by 16.99%, 17.48%, 23.56% and 14.01% over that in Moisture soil, Desert solonchaks and Alluvial soils, respectively. But the SOC content increased by 33.12% and 26.35% in Aeolian sandy soil and irrigated desert soils in the future 30 years, respectively (Fig6).

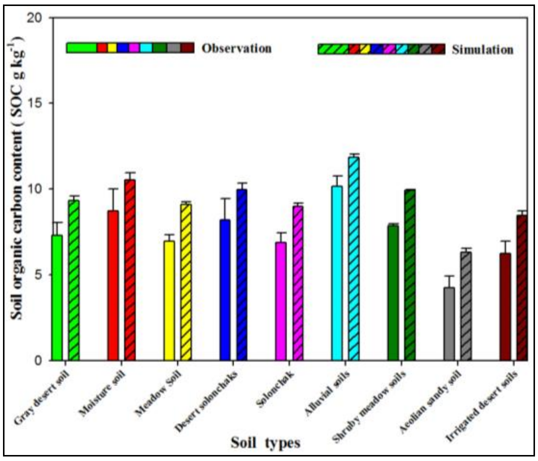

***Fig.6** Simulated SOC content by DNDC model from 2011to 2041 under different soil types*

3.4 Corresponding of ΔSOC and the initial value in soil chemical and physical properties

The changes in the SOC concentration (ΔSOC) follow a normal distribution with an arithmetic mean of 1.98 g kg^{-1}. ΔSOC is the different between final and initial measurements (Simulation 2041 and Observation 2011). The SOC content maybe mainly attributed to an increase in crop production, residue and manure management [11].

SOC is one of the key factors that affect agricultural production, nutrient availability, soil aggregate and the flux of greenhouse gases between land surface and atmosphere [7]. Our results showed that the relationship between the ΔSOC and the TN showed negative correlations (P<0.01), the regressive equations for TN was y= -2.33x^2+2.02x+1.78 (Fig.7A). The relationship also in compliance with ΔSOC and the TP (P<0.01), the regressive equations for TP was y=-3.72x^2+4.01x+1.08 (Fig.7B). In addition, the relationship between the ΔSOC and sand (%) or ΔSOC and clay (%) also showed negative correlations (P<0.05), respectively (Fig.7C and D). ΔSOC and SOC (P<0.01) showed regressive equations was y=-0.0177x^2+0.1715x+1. 81 (Fig7E) and ΔSOC and SOCD (P<0.01) was y= -0.2224x^2+0.6083x+1. 81 (Fig7F).

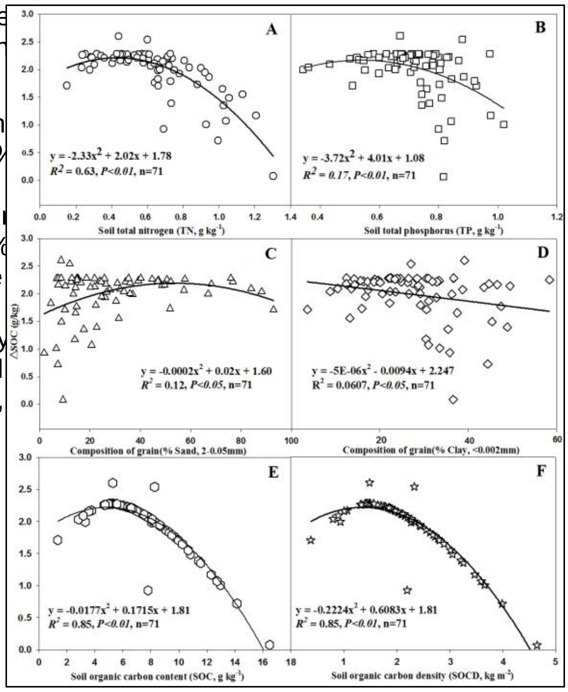

***Fig.7** Corresponding of ΔSOC and the initial value in soil chemical and physical properties*

No-burning harvest systems have several benefits: for instance, higher crop longevity and lower costs for renewing areas; recycling and gradual release of nutrients by straw decomposition; decrease in gas emissions; and less nutrient losses [50]. Increasing soil carbon provides carbon and energy to support microbial activity provides a reservoir of organic N, P and other nutrients for plant productivity and creates more physically cohesive soil to resist soil losses by physical erosion and by protecting occluded organic matter within the larger aggregates [51]. Carbon that enters soil is removed from the atmosphere; any gains in soil carbon mitigate greenhouse gas emissions, with caveats about impacts on the N cycle and N_2O production and the production of CH_4 from the anaerobic decomposition of organic carbon in waterlogged soils [52].

4. Conclusion

Fertilizer application has played an important role in improving the total SOC in the topsoil, demonstrating that NPK+S were better than single chemical fertilizers in ensuring greater accumulation of organic C. This study showed that Manas farmland soil carbon density additional ranges were 0.012 kg m^{-2} yr^{-1} from 0.021 kg m^{-2} yr^{-1}. The next 30 years, the maximum rate of the soil carbon density 207 kg m^{-2} yr^{-1}, the minimum rate of 121 kg m^{-2} yr^{-1}, the average rate of 164 kg m^{-2} yr^{-1}. From 2011 to 2041, soil carbon density ranges from 7.76% to 72.02%, the Manas farmland soil carbon density showed a trend of increase. In Northwest China, straw and fertilizer application practices have a positive effect on the soil C sequestration in farmland. Therefore, straw and fertilizer application in dry-land farming soil has been promoted as a "win-win strategy" for the sustainable food production and mitigation of greenhouse gas emissions through soil C sequestration. This result has rather significant implications for SOC sequestration potential in semi-arid agro-ecosystems of northwest China.

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