Ecological Complexity 8 (2011) 30–37

Contents lists available at ScienceDirect

Ecological Complexity

journal homepage: www.elsevier.com/locate/ecocom

Using the CENTURY model to assess the impact of land reclamation and management practices in oasis agriculture on the dynamics of soil organic carbon in the arid region of North-western China

Wenqiang Xu [a,b,*], Xi Chen [a,b], Geping Luo [a,b], Qing Lin [c]

[a] Key Laboratory of Oasis Ecology and Desert Environment, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China
[b] XIEG-UCR International Center for Arid Land Ecology, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China
[c] Water Resources Department of Xinjiang, Urumqi 830000, Xinjiang, China

ARTICLE INFO

Article history:
Received 23 April 2010
Received in revised form 10 November 2010
Accepted 25 November 2010
Available online 23 December 2010

Keywords:
Land reclamation
Anthropogenic oasis
Crop rotation
Fertilization
No tillage
CENTURY model

ABSTRACT

Large-scale reclamation of arid land in North-western China over the past 50 years has converted the natural desert landscape into anthropogenic oasis, particularly in the lower part of watersheds. Drastic human activities may have caused the change of soil organic carbon (SOC) in anthropogenic oasis. This study employs the CENTURY model (Version 4.0) to investigate the effects of land reclamation and management practices in oasis agriculture on the dynamic of SOC at the lower part of Sangong river watershed, a typical anthropogenic oasis reclaimed at 50 years ago. Based on field investigation, history of crop rotations, and past farm practices in study area, land management practices were divided into five categories, corresponding five periods, 0–1958, 1959–1984, 1985–1992, 1993–1998 and 1999–2008. The model successfully simulated the SOC dynamics of the top layer soil (0–20 cm) in the different periods. The state of equilibrium of total SOC and the active, slow, and passive carbon pools were built by CENTURY model in 0–1959. Over the 50 years' cultivation (1959–2008), the mean change in total SOC exhibited complex ways. SOC increased rapidly in the first 2 years (1959–1960) after shrubland reclamation, and declined slowly during the period 1961–1984 and then decreased rapidly from 1985 to 1992. Between 1993 and 1998, it remained relatively stable, and climbed rapidly again during 1999–2008. The trend in total SOC showed "N" shape, i.e., increase, decrease, then increase. Finally, total SOC is greater (8.2%) in 2008 than the original level of SOC under the natural desert shrub. The improvements of land management practices such as ploughing being replaced with no tillage, straw being crushed before returning it to soil, and reasonable application of fertilizers, played a key role in the change in total SOC. Especially, soil carbon sequestration was obviously increased since protective management practices were implemented in 1993, such as no tillage, straw returning to soil, and the balanced fertilization technique. The results were different from the conclusions that loss of soil organic carbon would happen due to reclamation and continuous farming in tropical forests, semiarid grasslands of northern China and Nigerian semiarid Savannah.

1. Introduction

Soil organic carbon (SOC) is the largest carbon pool in the terrestrial biosphere and accounts for two-thirds of the total carbon pool in the terrestrial ecosystem (Schlesinger, 2006; Chen et al., 2005; IPCC, 2007). The pool of SOC in the farmland forms about 8–10% of terrestrial carbon pool (Cole et al., 1993). In fact, the pool of SOC is drastically influenced by land use and land cover changes caused by the drastic human activities, especially – as is well known – the conversion of natural vegetation to farmland (Breuer et al., 2006; Kasel and Bennett, 2007). In semiarid Senegal in West Africa, Elberling et al. (2003) reported that up to 24% of SOC in the upper 1 m layer was lost over the 40 years since the Savannah began to be cultivated. In Vertisols of Australia, Grace et al. (1998) observed that 50 years' of cultivation reduced SOC level to 40% of its original level. In the semiarid Horqin sandy steppe of northern China, Su et al. (2004) observed that in the 3 years that a sandy grassland was under cultivation, SOC of the ploughed layer (0–15 cm depth) decreased by 38%. In Nigerian semiarid Savannah, although SOC has declined by 40–65% over the 25 years which the Savannah has been cultivated, about half the losses occurred during the first 3 years of cultivation (Jaiyeoba, 2003). However, the conversion of natural vegetation to

* Corresponding author at: Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China. Tel.: +86 991 7885375; fax: +86 991 7885320.
E-mail address: xuwq@ms.xjb.ac.cn (W. Xu).

1476-945X/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecocom.2010.11.003

farmland does not always result in loss of SOC. In some cases, the SOC may even increase (Thuille et al., 2000), and the conversion of natural desert vegetation to oasis agriculture in the arid regions of North-western China could be one such case. However, changes in SOC in the arid region of North-western China have not been studied adequately.

The Mountain–basin structure, a peculiar physical feature of the arid region of North-western China, owes its origin to the influence of large topographic units including the Altai Mountain, the Junggar Basin (which encloses the Gurbantonggut desert), Tianshan Mountains, Tarim Basin (which encloses the Taklamakan desert, the second largest desert in the world), and Kunlun Mountain (Fig. 1). The surface runoff in the arid region originates from rainfall in the mountains and from melting of glacial snow flowing into the desert. Thus, the characteristic oasis develops under the desert landscape of the arid region. The Mountain–Oasis–Desert ecosystem thus formed has always been part of the arid region of North-western China and differs from other ecosystems of the arid regions of the world including the African Savannah, parts of the North American West, central and Western Australia, and the Middle East area. For the past 50 years, the Mountain–Oasis–Desert ecosystem has been strongly influenced by human activity. Large-scale land reclamation of arid land in North-western China has resulted in expansion of oasis agriculture, especially in Xinjiang, which has been accompanied by changes in spatio-temporal distribution of water and replacement of some natural desert vegetation with crops and trees. The virgin soil has been gradually modified through cultivation, irrigation, and application of fertilizers (Xu et al., 2006; Luo et al., 2008; Fu et al., 2010). However, the effect of land reclamation and management practices on dynamics of SOC has not been studied in depth, and more research is needed to explore the process and mechanism of changes in SOC due to such practices as application of manures and fertilizers, irrigation, and crop rotation.

CENTURY, a biogeochemical ecosystem model that simulates fluxes of C, N, P, and S, has been successfully used in studies of farmlands, grasslands, and forests (Parton et al., 1995; Song and Woodcock, 2003; Foereid and Hogh, 2004; Tornquist et al., 2009). However, in spite of some studies on modelling arid agro-ecosystems, no information is available on the use of mathematical models to assess the impact of land reclamation and management practices in oasis agriculture on the dynamics of SOC in the arid region of North-western China. The objective of the present study was therefore to use the Century model (1) to simulate the dynamics of SOC before and after the large-scale land reclamation and (2) to assess the effect of the land management practices on soil carbon pools.

2. Materials and methods

2.1. Description of study area

The oasis in the watershed of Sangong river, located at the northern foot of the Tianshan Mountains, in Xinjiang, is a typical oasis agriculture ecosystem of the arid region of North-western China. The oasis mainly consists of the Fubei Farm, the Liuyunhu Farm, and the district of Fukang (Fig. 1). The Fubei Farm, developed by reclaiming a part of the desert shrubland at 50 years ago, is a representative of the anthropogenic oasis in the arid region, which made the farm a perfect choice for the study.

The Fubei Farm, spread over approximately 187 km^2, shares its border with the Gurbantunggut desert (Fig. 1). The terrain in the study area is relatively flat with a slope from South-east to North-west with its elevation ranging from 450 m to 480 m above the sea level. The climate is inland arid temperate continental. The annual average temperature is 6.6 °C, precipitation is 164 mm, and potential evaporation is 1817 mm. The soils are predominantly grey desert soils low in soil organic matter and nitrogen but high in potassium.

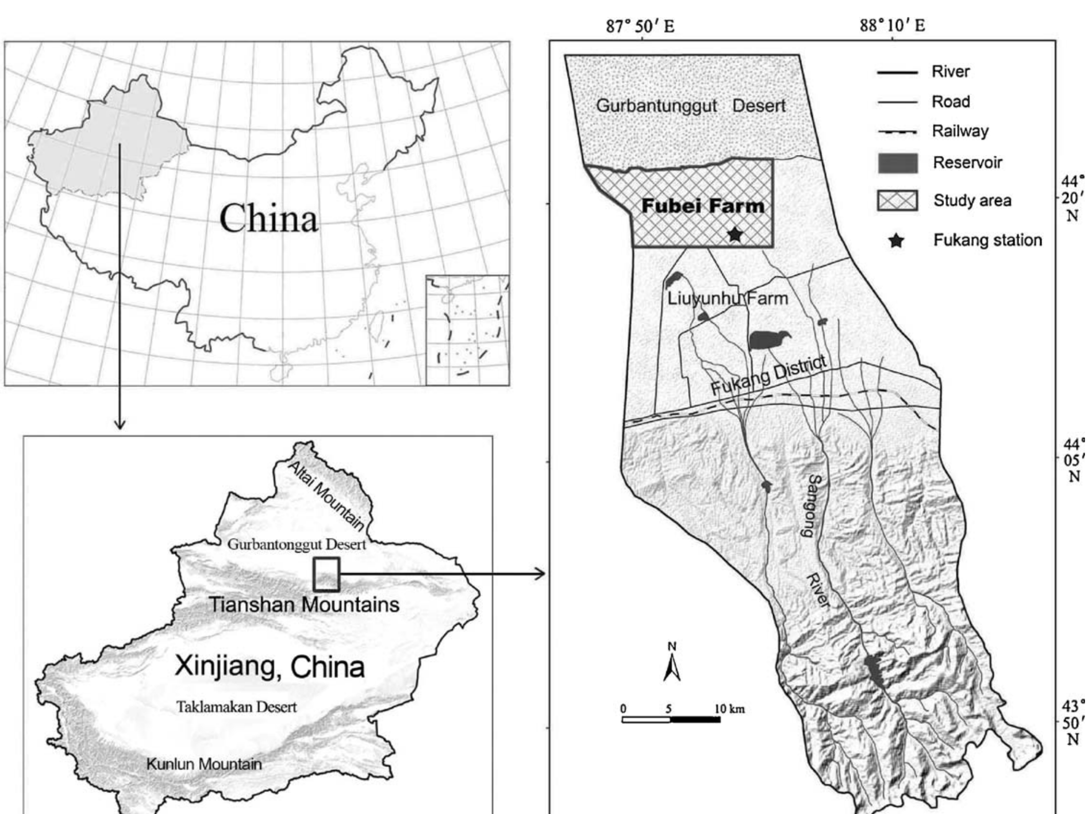

Fig. 1. Sketch map of the Sangong river watershed and the study area.

Fig. 2. The original landscape (a natural desert shrub) before land reclamation. Photo a and b were natural desert landscape around the Fubei Farm dominated by *Tamarix ramosissima* and *Haloxylon ammodendron*, respectively.

The Fubei Farm was established in 1959. Before that, it was part of a natural desert shrubland, dominated by *Tamarix ramosissima* and *Haloxylon ammodendron* (Fig. 2). Over the past 50 years, the original desert landscape has been gradually replaced by the oasis landscape dominated by crops and selected tress. Currently, the vegetation of the oasis is in transition: annual crops such as wheat, maize and cotton are being replaced with perennials such as grape. The land management practices such as the regime of crop rotation, disposal of crop residue, and application of fertilizers has also changed. Thus, the dynamics of SOC have been influenced by a variety of management practices (Xu et al., 2006; Luo et al., 2010; Xie and Liu, 2010).

2.2. Field and laboratory methods

Data on soil of the Fubei Farm came from soil samples collected over a number of years. Soil organic matter was measured in 1982, 1999, 2003, and 2004. All the samples were collected from the top layer (0–20 cm) and always in May. In 1982, during the Second National Soil Survey, 472 soil samples were collected including 10 from the natural shrubland around the Fubei Farm, and 421, 332, and 35 samples were collected in 1999, 2003, and 2004, respectively. Soil organic matter content was determined by the $K_2Cr_2O_7$ titration method and the value multiplied by the unitless Bemmelen Index of 0.58 to determine the mean SOC content (Mann, 1986; Li et al., 2007).

2.3. Simulation modelling with CENTURY

The CENTURY model simulates long-term dynamics of C, N, P, and S for different plant-soil systems (Parton et al., 1988, 1995; Parton and Rasmussen, 1994). The model operates on a monthly time step and represents SOC in three conceptual pools, named active, slow, and passive, to represent fast, medium, and slow rates of turnover of carbon in the soil respectively. Version 4.0 of the CENTURY model can simulate the effect of complex agricultural management practices including crop rotation, tillage practices, fertilizer and irrigation regimes, and methods of harvest on the dynamics of carbon in the agro-ecosystem. The major input variables for the CENTURY model include (1) monthly average maximum and minimum air temperature, (2) monthly precipitation, (3) lignin content of plant material, (4) C:N ratio of plant tissue and initial levels of soil C and N, (5) soil texture, and (6) N added to soil through fertilizers and deposition of atmospheric N (Parton et al., 1988; Parton and Rasmussen, 1994).

Data on monthly precipitation and mean maximum and minimum temperatures from 1990 to 2007 were obtained from a station lying within the study area, namely the Fukang Experimentation Station of Desert Ecology of the Chinese Academy of Sciences (CAS) (Fig. 1). Data on climatic parameters for other simulation periods were stochastically generated based on the skewed distribution of climate data from 1990 to 2007. Site-specific parameters and data on initial state of the soil and vegetation, such as soil texture (proportions of sand, silt, and clay), bulk density, soil depth, pH, lignin content of plant material, C:N ratio, and total SOC and N content, were assigned values obtained from field experiments at the Fukang Experimentation Station of Desert Ecology of CAS (Table 1). The main input data, such as those related to crop rotation, yield, fertilizers, and irrigation, were provided by the production department of the Fubei Farm.

Table 1
Soil characteristics and climatic parameters used as inputs for the CENTURY model.

Parameter	Value
Soil characteristics	
Texture (sand, silt, clay)	44.1%; 43.2%; 12.7%
Bulk density (g/cm^3)	1.2
pH	8.7
Initial total SOC (g/m^2)	2152.67
Climatic parameters	
Minimum mean monthly temperature (°C)	−0.23
Maximum mean monthly temperature (°C)	11.20
Mean monthly precipitation (mm)	13.88

Table 2
Land management practices change during the different periods and blocks set up in the CENTURY model.

Blocks	Periods	Management practices	Repeating sequence (years)
B1	Up to 1958	Natural desert shrub, low-intensity grazing	1
B2	1959–1984	Wheat–corn rotation, ploughing, removing straw, applying organic manure	2
B3	1985–1992	Cotton, ploughing, removing straw, applying inorganic fertilizers	1
B4	1993–1998	Cotton, ploughing, crushing straw and returning it to soil, applying inorganic fertilizers	1
B5	1999–2008	Grape, no tillage, applying fertilizers scientifically and ensuring a balanced dose of fertilizers	10

Based on field investigation, history of crop rotations, and past farm practices in Fubei Farm, land management practices were divided into five categories, corresponding five periods, 0–1958, 1959–1984, 1985–1992, 1993–1998 and 1999–2008 (Table 2). Every period was called a block for CENTURY model, which is a series of events which will repeat themselves, in sequence, until the ending time of the block is reached. In Fubei farm, past farm practices may have included breaking of the natural desert shrub in 1959, a wheat–maize rotation with ploughing and removal of straw until 1984, cotton with removal of straw until 1992, cotton with crushing the straw and returning it to the soil until 1998, followed by grape cultivation with no tillage (Table 2).

3. Results

3.1. Simulation the SOC change under natural desert shrub

The CENTURY model simulated the dynamics of total SOC and active, slow, and passive carbon pools during the process of establishing equilibrium state (Fig. 3). The model was run to equilibrium for 1950 years assuming that the land was a natural desert shrub with low-intensity grazing. By comparing changes in the curves of carbon pools during the process of establishing equilibrium state (Fig. 3), we knew that active and slow carbon pools grew rapidly in the initial 30 years and 100 years respectively whereas the passive carbon pool was slow in building up during the whole equilibrium process. The accumulation rate of carbon was relative to the turnover rate of the active, slow, and passive carbon pools (Parton et al., 1988, 1995; Parton and Rasmussen, 1994). The active pool has a turnover time of a few months to a few years depending on the environment and sand content; the slow pool includes resistant plant material and therefore has a turnover time of 20–50 years; and the passive pool is very resistant to decomposition and has a turnover time of 400–2000 years.

In the equilibrium state, assumed that the period was from 1951 to 1958, the proportions of active, slow, and passive organic carbon pools in total SOC were 3.78%, 61.41%, and 34.81% respectively, indicating that total SOC in the study area was dominated by the slow carbon pools. The scatter plot in Fig. 3 shows that annual changes in total SOC and the slow carbon pool were marked, while those in the active and passive carbon pools were slight, probably due to the influence of environmental factors such as temperature and precipitation.

Because the Fubei Farm was originally a natural desert shrubland, soil samples in 1982 included 10 samples taken from natural desert shrubland around the Fubei farm. These 10 samples can be reasonably considered to represent the original levels of SOC in the shrubland. When the CENTURY model was run to equilibrium state, the simulated value of total SOC was 2152.7 g/m^2 in 1951–1958, which was fairly close to the actual value of 2173.7 g/m^2, the mean of the 10 soil samples. Therefore, the model was considered suitable for simulating the dynamics of SOC of the study area in its initial years.

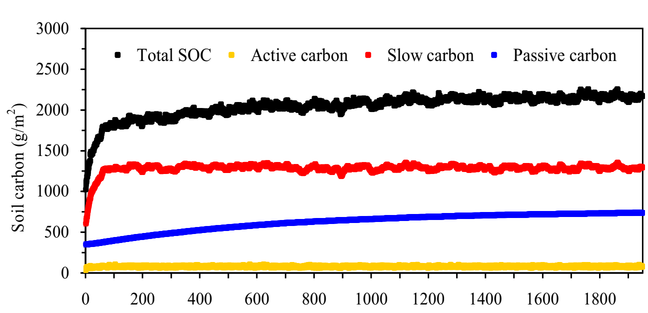

Fig. 3. The carbon pools change during the process of establishing equilibrium state using the CENTURY model.

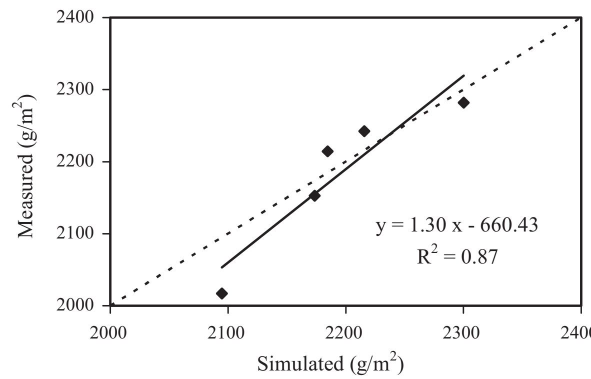

Fig. 4. Relationship between measured and simulated values of total SOC.

3.2. Comparison between measured and simulated SOC

The measured data on total SOC spans five periods, each represented by a different year in which the soil was sampled: the period before the land was reclaimed (represented by the 10 soil samples collected in 1982 mentioned above), followed by 1982, 1999, 2003, and 2004. A significant linear relationship ($R^2 = 0.87$) was found between measured and simulated total SOC (Fig. 4). *t*-Test was used to ascertain whether the difference between the measured and simulated values of total SOC was significant. The test consisted of 5 paired samples (4 degrees of freedom). The *t* value at $p < 0.01$ level was 0.63, showing that the difference was not significant and that the CENTURY model had been accurate in simulating the dynamics of SOC in Fubei farm.

3.3. Changes in SOC under the different land management practices

As land reclaimed, the conversion of natural vegetation to farmland changed the level of SOC in the study area. The CENTURY model simulated how total SOC and the three carbon pools (active, slow, and passive) changed before and after the land reclamation (Fig. 5). Block B1 represents the period before the land reclamation, when the site was a natural desert shrubland; Block B2 to B5, spans the four period, represents the period after the land reclamation from 1959 to 2008 (Table 2). Different land management practices in each period had a marked effect on the total SOC and the three carbon pools.

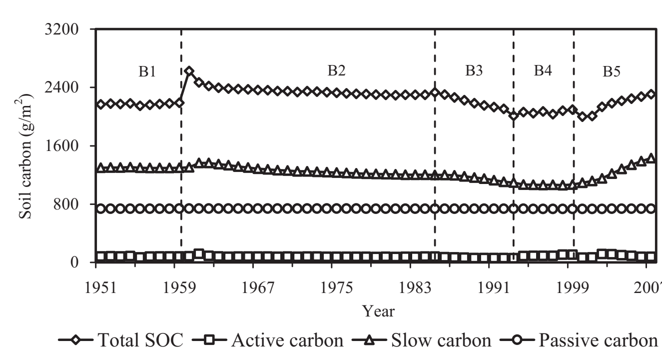

Fig. 5. Variation in total SOC and three organic carbon pools before and after land reclamation. B1 represents the equilibrium state before land reclamation under the natural desert shrub in 1951–1958; B2, B3, B4 and B5 represent the period after land reclamation in 1959–1984, 1985–1992, 1993–1998 and 1999–2008, respectively.

Table 3
Descriptive statistical of total SOC change under the different periods in study area.

Periods	B1	B2	B3	B4	B5
Mean (g/m^2)	2169.7	2355.9	2212.8	2050.7	2181.3
Standard deviation	10.83	76.71	82.27	26.40	120.52
Maximum (g/m^2)	2180.7	2625.6	2333.0	2081.6	2348.4
Minimum (g/m^2)	2147.1	2188.1	2107.8	2010.7	1999.3
Coefficient of variation (%)	0.50	3.26	3.72	1.29	5.53

B1 represents the equilibrium state before the land reclamation under natural desert shrub in 1951–1958; B2, B3, B4 and B5 represent the period after land reclamation in 1959–1984, 1985–1992, 1993–1998 and 1999–2008, respectively.

3.3.1. Carbon dynamics before the land reclamation

The state of equilibrium of total SOC and the active, slow, and passive carbon pools that existed before 1959 when the site was a natural desert shrubland was simulated by the CENTURY model (Fig. 3). The dynamics of SOC during the process of establishing equilibrium state was influenced by low-intensity grazing and environmental factors, particularly temperature and precipitation. The Standard Deviation and Coefficient of Variation of total SOC were minimum in this period (Table 3). However, the conversion to oasis agriculture disturbed the equilibrium state.

3.3.2. Carbon dynamics during the period 1959–1984

In 1959–1984, the land management practices at Fubei farm comprised a wheat–maize rotation, removal of straw, and application of organic manure (Table 2). The active and slow carbon pools and total SOC increased rapidly in the first 2 years after shrubland reclamation, then decreased, and trended to stabilize after 5 years (Fig. 6A, B, and D). The passive carbon pool changed only slightly, a small increase followed by a small decrease (Fig. 6C). Changes in SOC were primarily influenced by management practices such as application of fertilizers and ways of disposing of the crop residue. During the first 2 years after land reclamation, yields of the annual crops (wheat and maize) were small, and their above-ground biomass and surface litter much larger than those of the original desert shrub. Moreover, cultivation also involved applying organic manure. Therefore, the accumulation rate of total SOC was higher in the first 2 years. However, as grain yield increased and straw was removed in later 3–5 years, SOC began to decrease. For the whole period of 1959–1984, the mean of total SOC was higher than those during the equilibrium state under the natural desert shrub in 1951–1958 (Table 3).

3.3.3. Carbon dynamics during the period 1985–1992

In 1985–1992, as the economy developed, the wheat–maize rotation was gradually replaced with cotton. During the period B3, the active and slow pools and total SOC decreased rapidly (Fig. 6A, B and D) and the passive pool decreased slowly (Fig. 6C), probably because chemical fertilizers were applied only in small quantities, the residue left by cotton was removed, and the grain was also harvested. Compared with the period B2, the mean of total SOC during the period B3 in the surface layer (0–20 cm depth) decreased by 6.1% (Table 3). Therefore, land management practices in this period were not sustainable but exploitative, and resulted in rapid depletion of SOC.

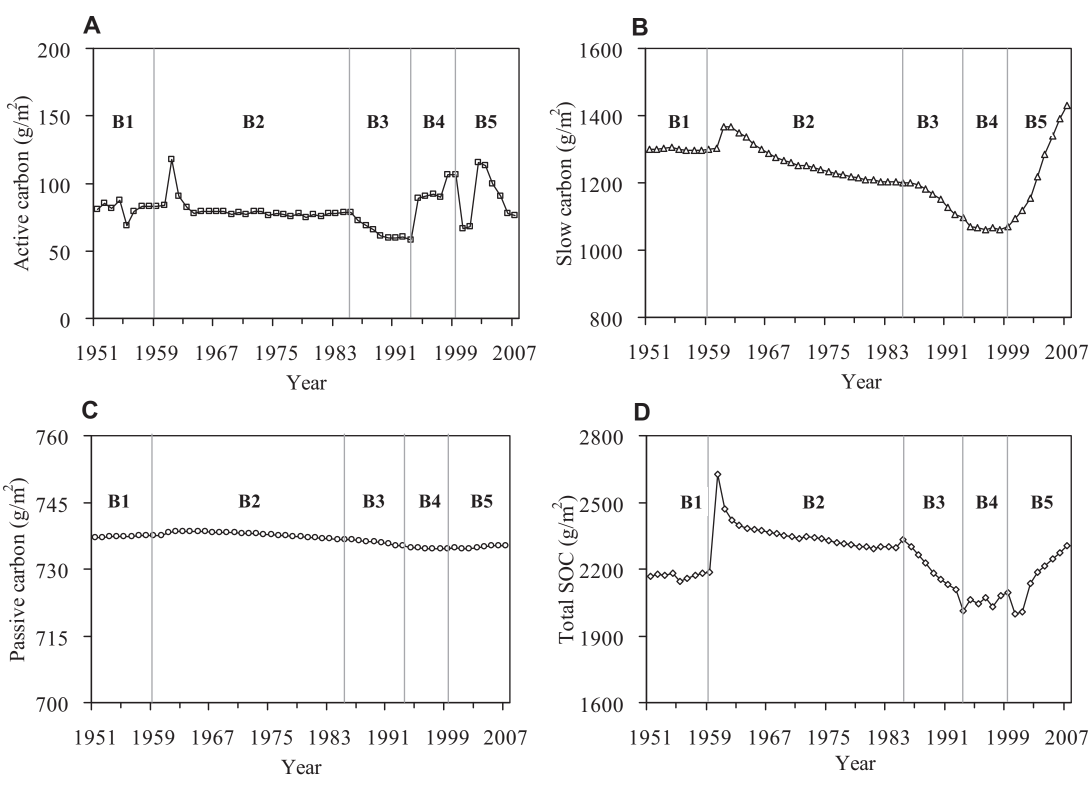

Fig. 6. Variation in active (A), slow (B), and passive (C) carbon pools and total SOC (D) under different simulation periods. B1 represents the equilibrium state before land reclamation under the natural desert shrub in 1951–1958; B2, B3, B4 and B5 represent the period after land reclamation in 1959–1984, 1985–1992, 1993–1998 and 1999–2008, respectively.

3.3.4. Carbon dynamics during the period 1993–1998

In 1993–1998, cotton continued to be the dominant crop. The active carbon pool and total SOC increased, especially the active pool (Fig. 6), probably due to the change of crop residue management from straw of cotton removal to crushing and returning to the soil, which increased the biomass of the surface litter, the humus from which served as a source of carbon for the active pool. However, the slow and passive pools did not change markedly during the period B4. Compared with the period B1 under the natural desert shrub, the mean of total SOC during the period B4 was decreased by 5.5% (Table 3).

3.3.5. Carbon dynamics during the period 1999–2008

During the period 1993–1998, cotton was gradually replaced by grapes in Fubei farm. Grape vines are perennial, and require no tillage. In this period, the active, slow, and passive carbon pools and total SOC changed in different ways (Fig. 6). The active pool decreased rapidly during the first 2 years, increased in the 3rd and the 4th year, and gradually decreased after the 5th year (Fig. 6A), mainly because of the influence of the growth characteristics of grape vines and fertilizer management. During the first 2 years, the vines were seedlings, and little inorganic fertilizer was applied: the above- and below-ground biomass was therefore low, which decreased the active carbon pool. In the 3rd year of period B5, the vines began yielding. Although the yield was small in the 3rd and the 4th year, enough inorganic fertilizer was applied scientifically base on the scientific fertilization technique, which the dose of fertilizer was decided base on soil analysis. As a result, the active carbon pool increased in the 3rd and the 4th year. After 4th year, the yield began to increase gradually, which decreased the biomass returned to the soil, and the active carbon pool decreased continually after the 4th year. On the other hand, the slow and passive carbon pools, especially the slow carbon pool, increased during the period B5, probably because no-tillage helped to increase the accumulation rate of the slow carbon pool (Hussaina et al., 2009; Moussa-Machraoui et al., 2009); given that it has the largest share in total SOC, total SOC also increased rapidly.

Overall, as a result of human activity over the past 50 years, total SOC exhibited complex ways. Total SOC increased rapidly in the first 2 years (1959–1960) after shrubland reclamation, and declined slowly during the period 1961–1984 and then decreased rapidly from 1985 to 1992. Between 1993 and 1998, it remained relatively stable, and climbed rapidly again during 1999–2008. However, the total SOC in 2008 exceeded the original level of SOC under the natural desert shrub (Table 3).

4. Discussion

4.1. Dynamics of total SOC over the past 50 years

The original desert landscape witnessed a number of changes and activities when its vegetation was supplanted with annual crops: irrigation and silting, desalination by drainage, planting trees to serve as shelter belts, and application of fertilizers. With changes in land use policy and prices of farm produce, some annual crops were gradually replaced with a perennial crop, namely grapes, because they fetched higher returns. The perennial crop differed from the annual crops in its season of growth, distribution of roots, biomass, and management practices including irrigation and application of fertilizers, which made the soil more fertile under the perennial crop than under the annual crop (Mannaa et al., 2005; Mantineo et al., 2009). Moreover, the practice of no tillage followed in grape reduces the intensity of cultivation and thus protects the aggregate structure of the soil and enhances its stability, ultimately favouring the accumulation of SOC (Birda et al., 2002; Johna et al., 2005; Wick et al., 2009). Therefore, the mean of total SOC increased during the period B5 due to the planting of the perennial crop (Fig. 7).

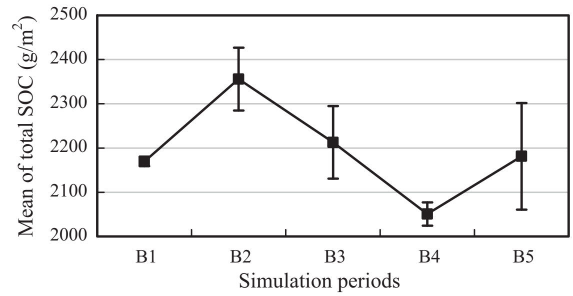

Fig. 7. Change in mean values of total SOC under different simulation periods. Error bars indicate standard deviation. B1 represents the equilibrium state before land reclamation under the natural desert shrub in 1951–1958; B2, B3, B4 and B5 represent the period after land reclamation in 1959–1984, 1985–1992, 1993–1998 and 1999–2008, respectively.

On the whole, the simulation results indicated that the trend in total SOC showed "N" shape, i.e., increase, decrease, then increase, but the mean of total SOC during the period B5 exceeded the original level of SOC under the natural desert shrub. Over the 50 years' cultivation (1959–2008), total SOC is greater (8.2%) in 2008 than the original level of SOC under the natural desert shrub, which suggests that soil serves as a carbon sink. This results contrary to the reduction in SOC and degradation of land seen elsewhere after mechanized farming was established in some tropical regions (Eswaran et al., 1993; Martinez and Zinck, 2004). Our results also challenge the belief that continued cultivation of the Nigerian semiarid Savannah and the semiarid grasslands of northern China would deplete the stocks of SOC (Jaiyeoba, 2003; Su et al., 2004; Prato, 2008)

4.2. Changes in SOC over the first few years after shrubland reclamation

After shrubland reclamation, total SOC increased rapidly in the first 2 years (Fig. 6D), a result different from the rapid decrease in SOC in the initial years due to conversion reported from the tropical forests in Brazil, semiarid grasslands of northern China, and the tree–grass system in the semiarid Savannah to farmland (Eswaran et al., 1993; Jaiyeoba, 2003; Martinez and Zinck, 2004; Su et al., 2004; Zinn et al., 2005). The increase of total SOC simulated by CENTURY model in Fubei farm was probably due to the influence of difference in biomass, recycling of soil nutrients, and fertilizer management between natural desert shrub and annual crop.

The original desert shrubland had sparse vegetation (the cover ranged from 8% to 25%), lower SOC, and higher salt content before shrubland reclamation (Zhao et al., 2004). Therefore, the decomposition and accumulation of SOC and recycling of nutrients under the annual crops followed obviously different patterns and scale from those under the natural desert shrub. The annual crops produced much greater biomass than the natural desert vegetation (Luo et al., 2008). In addition, organic manure applied during the period B2 served to enhance the content of SOC, especially the active carbon pool. Therefore, SOC increased rapidly in the first 2 years of oasis agriculture when the natural desert shrubland with its weak soil nutrient recycling was replaced by annual crops with better soil nutrient recycling.

4.3. Effect of land management practices on the dynamics of SOC

Over the 50 years' cultivation (1959–2008) after shrubland reclamation, the trend in total SOC showed "N" shape. The land management practices in Fubei farm played a decisive role in this process because it can influence the decomposition and accumulation of SOC (Montes and Joes, 2001; Zhou et al., 2006). The management practices can be divided into three categories, namely crop rotation, disposal of crop residue, and fertilizer management.

(1) When crop rotation was changed, the annual crops of wheat, maize and cotton, which required ploughing, gave way to the perennial crop of grape, which requires no tillage. Although it was not possible to ascertain whether each of the three annual crops affected the content of SOC differently, the overall change from ploughing to no-tillage favoured the accumulation of SOC (Follett, 2001; Leitea et al., 2004).
(2) Crop residue was disposed of differently during the different periods. While straw was removed (for use as fuel) in the early years, after 1993 it was crushed and returned to soil, where it underwent decomposition and thus contributed to the accumulation of SOC (Duiker and Lal, 1999; Bierke et al., 2008). This pattern of managing the crop residue was sustainable and beneficial to the soil.
(3) Fertilizer management changed from relying only on organic manure to using chemical fertilizers. The technique of applying chemical fertilizers also changed from conventional low-precision broadcast application to high-precision application (balanced fertilization techniques), based on soil analysis, which ensures that fertilizers are supplied in optimum quantities (Ge et al., 2009).

The improvements of land management practices such as no tillage, straw returning to soil, and the balanced fertilization techniques in Fubei farm, played a key role in the change in total SOC. Especially, soil carbon sequestration was obvious after protective management practices were implemented after 1993 (Fig. 6D). Extending such protective management practices over the entire oasis offers immense potential for carbon sequestration and is therefore of great significance to enhancing soil quality, increasing soil carbon storage, and reducing emissions of carbon dioxide.

5. Conclusions

The CENTURY model was applied successfully to simulate the SOC dynamics of oasis agriculture in the arid region of Northwestern China. Over the 50 years' cultivation (1959–2008) after shrubland reclamation, total SOC exhibited complex ways. Total SOC increased rapidly in the first 2 years (1959–1960) after shrubland reclamation, and declined slowly during the period 1961–1984 and then decreased rapidly from 1985 to 1992. Between 1993 and 1998, it remained relatively stable, and climbed rapidly again during 1999–2008. Finally, total SOC is greater (8.2%) in 2008 than the original level of SOC under the natural desert shrub, which suggests that soil serves as a carbon sink. Especially, soil carbon sequestration was obviously increased since protective management practices were implemented in 1993, such as no tillage, straw returning to soil, and the balanced fertilization techniques. The results were different from the conclusions that loss of soil organic carbon would happen due to reclamation and continuous farming in tropical forests, semiarid grasslands of northern China and Nigerian semiarid Savannah.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (project No. 40801113) and the West Light Foundation of the Chinese Academy of Sciences (XBBS200903).

References

Bierke, A., Kaiser, K., Guggenberger, G., 2008. Crop residue management effects on organic matter in paddy soils – the lignin component. Geoderma 146, 48–57.
Birda, S.B., Herricka, J.E., Wanderb, M.M., Wright, S.F., 2002. Spatial heterogeneity of aggregate stability and soil carbon in semi-arid rangeland. Environmental Pollution 116, 445–455.
Breuer, L., Huisman, J.A., Keller, T., Frede, H.G., 2006. Impact of a conversion from cropland to grassland on C and N storage and related soil properties: analysis of a 60-year chronosequence. Geoderma 133, 6–18.
Chen, X.Y., Lindsay, B., Eamus, H.D., 2005. Soil organic carbon content at a range of north Australian tropical savannas with contrasting site histories. Plant and Soil 268, 161–171.
Cole, C.V., Flack, K., Lee, J., Sauerbeck, D., Stewart, B., 1993. Agricultural sources and sinks of carbon. Water, Air and Soil Pollution 70, 111–122.
Duiker, S.W., Lal, R., 1999. Crop residue and tillage effects on carbon sequestration in a Luvisol in central Ohio. Soil and Tillage Research 52, 73–81.
Elberling, B., Touré, A., Rasmussen, K., 2003. Changes in soil organic matter following groundnut–millet cropping at three locations in semi-arid Senegal, West Africa. Agriculture, Ecosystems and Environment 96, 37–47.
Eswaran, H., Van, B.E., Reich, P., 1993. Organic carbon in soils of the world. Soil Science Society of America Journal 57, 192–194.
Foereid, B., Hogh, J.H., 2004. Carbon sequestration potential of organic agriculture in northern Europe: a modeling approach. Nutrient Cycling in Agroecosystems 68, 13–24.
Follett, R.F., 2001. Soil management concepts and carbon sequestration in cropland soils. Soil and Tillage Research 61 (1–2), 77–92.
Fu, B.J., Li, S.G., Yu, X.B., Yang, P., Yu, G.R., Feng, R.G., Zhuang, X.L., 2010. Chinese ecosystem research network: progress and perspectives. Ecological Complexity 7 (2), 225–233.
Ge, G.F., Li, Z.J., Zhang, J., Wang, L.G., Xu, M.G., Zhang, J.B., Wang, J.K., Xie, X.L., Liang, Y.C., 2009. Geographical and climatic differences in long-term effect of organic and inorganic amendments on soil enzymatic activities and respiration in field experimental stations of China. Ecological Complexity 6 (4), 421–431.
Grace, P.R., Post, W.M., Godwin, D.C., Bryceson, K.P., Truscott, M.A., Hennessy, K.J., 1998. Soil carbon dynamics in relation to soil surface management and cropping systems in Australia agroecosystems. In: Lal, R., Kimble, J.M., Follett, R.M., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, FL, pp. 175–193.
Hussaina, I., Olsonb, K.R., Ebelhar, S.A., 2009. Impacts of tillage and no-till on production of maize and soybean on an eroded Illinois silt loam soil. Soil and Tillage Research 52, 37–49.
IPCC, 2007. Climate Change 2007: Synthesis Report. Cambridge University Press, New York.
Jaiyeoba, I.A., 2003. Changes in soil properties due to continuous cultivation in Nigerian semiarid Savannah. Soil and Tillage Research 70, 91–98.
Johna, B., Yamashitac, T., Ludwigb, B., Flessa, H., 2005. Storage of organic carbon in aggregate and density fractions of silty soils under different types of land use. Geoderma 128, 63–79.
Kasel, S., Bennett, L.T., 2007. Land-use history, forest conversion, and soil organic carbon in pine plantations and native forests of south eastern Australia. Geoderma 137, 401–413.
Leitea, L.F.C., Mendonc, E.S., Machadoc, P.L.O.A., Filhob, E.I.F., Neves, J.C.L., 2004. Simulating trends in soil organic carbon of an Acrisol under no-tillage and disc-plow systems using the Century model. Geoderma 120, 283–295.
Li, Z.P., Han, F.X., Su, Y., Zhang, T.L., Sun, B., Monts, D.L., Plodinec, M.J., 2007. Assessment of soil organic and carbonate carbon storage in China. Geoderma 138, 119–126.
Luo, G.P., Yin, C.Y., Chen, X., Xu, W.Q., Lu, L., 2010. Combining system dynamic model and CLUE-S model to improve land use scenario analyses at regional scale: a case study of Sangong watershed in Xinjiang, China. Ecological Complexity 7 (2), 198–207.
Luo, G.P., Zhou, C.H., Chen, X., Li, Y., 2008. A methodology of characterizing status and trend of land changes in oases: a case study of Sangong River watershed, Xinjiang, China. Journal of Environmental Management 88, 775–783.
Mann, L.K., 1986. Changes in soil carbon storage after cultivation. Soil Science 142, 279–288.
Mannaa, M.C., Swarupb, A., Wanjari, R.H., 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 Research 93, 264–280.
Mantineo, M., Agosta, G.M., Copani, V., 2009. Biomass yield and energy balance of three perennial crops for energy use in the semi-arid Mediterranean environment. Field Crops Research 114, 204–213.
Martinez, L.J., Zinck, J.A., 2004. Temporal variation of soil compaction and deterioration of soil quality in pasture areas of Colombian Amazonia. Soil and Tillage Research 75, 3–17.
Montes, R.A., Joes, J.J., 2001. Management effects on carbon stocks and fluxes across the Orinoco savannas. Forest Ecology Management 150, 293–311.
Moussa-Machraoui, S.B., Errouissi, F., Ben-Hammouda, M., 2009. Comparative effects of conventional and no-tillage management on some soil properties under Mediterranean semi-arid conditions in northwestern Tunisia. Soil and Tillage Research 106, 247–253.
Parton, W.J., Rasmussen, P.E., 1994. Long-term effects of crop management in wheat– fallow: II. Century model simulations. Soil Science Society of America Journal 58, 530–536.

Parton, W.J., Scurlock, J.M., Ojima, D.S., Schimel, D.S., Hall, D.O., Scopegram Group Members, 1995. Impact of climate change on grassland production and soil carbon worldwide. Global Change Biology 1, 13–22.

Parton, W.J., Stewart, J.W.B., Cole, C.V., 1988. Dynamics of C, N, P e S in grassland soils: a model. Biogeochemistry 5, 109–131.

Prato, T., 2008. Conceptual framework for assessment and management of ecosystem impacts of climate change. Ecological Complexity 5 (4), 329–338.

Schlesinger, W.H., 2006. Global change science. Trends in Ecology and Evolution 21, 348–351.

Song, C.H., Woodcock, C.E., 2003. A regional forest ecosystem carbon budget model: impacts of forest age structure and landuse history. Ecological Modelling 164, 33–47.

Su, Y.Z., Zhao, H.L., Zhang, T.H., Zhao, X.Y., 2004. Soil properties following cultivation and non-grazing of a semi-arid sandy grassland northern China. Soil and Tillage Research 75, 27–36.

Thuille, A., Buchmann, N., Schulze, E.D., 2000. Carbon stocks and soil respiration rates during deforestation, grassland use and subsequent Norway spruce afforestation in the southern Alps, Italy. Tree Physiology 20, 849–857.

Tornquist, C.G., Mielniczuk, J., Cerri, C.E.P., 2009. Modeling soil organic carbon dynamics in Oxisols of Ibirubá (Brazil) with the Century Model. Soil and Tillage Research 105 (1), 33–43.

Wick, A.F., Ingramb, L.J., Stahl, P.D., 2009. Aggregate and organic matter dynamics in reclaimed soils as indicated by stable carbon isotopes. Soil Biology and Biochemistry 41, 201–209.

Xie, J.B., Liu, T., 2010. Characterization of spatial scaling relationships between vegetation pattern and topography at different directions in Gurbantunggut desert, China. Ecological Complexity 7 (2), 234–242.

Xu, W.Q., Luo, G.P., Chen, X., 2006. Response of soil nutrients to the change of crop systems in the Oasis of Arid land. Chinese Science Bulletin 51 (1), 167–172.

Zhao, C.Y., Song, Y.D., Wang, Y.C., Jiang, P.A., 2004. Analysis on the dynamics of desert-oasis vegetation in the Sangong river basin. Chinese Journal of Applied Ecology 15 (2), 249–254 (in Chinese with English abstract).

Zhou, G.M., Xu, J.M., Jiang, P.K., 2006. Effect of management practices on seasonal dynamics of organic carbon in soils under Bamboo plantations. Pedosphere 16 (4), 525–531.

Zinn, Y.L., Lal, R., Resck, D.V., 2005. Changes in soil organic carbon stocks under agriculture in Brazil. Soil and Tillage Research 84, 28–40.