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ORIGINAL ARTICLE

# Soil organic carbon stock and carbon efflux in deep soils of desert and oasis

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**Abstract** An experiment was carried out in two soils of oasis farmland and the surrounding desert at the southern periphery of the Gurbantonggut Desert, in central Asia, to test the effects of land use on soil organic carbon (SOC) stock and carbon efflux in deep soil. The result showed that although SOC content in the topsoil (0–0.2 m) decreased by 27% after desert soil was cultivated, total carbon stock within the soil profile (0–2.5 m) increased by 57% due to the significant increase in carbon stock at 0.2- to 2.5-m depth, and carbon efflux also markedly increased at 0- to 0.6-m depth. In the topsoil, the carbon process of the oasis was mainly dominated by consumption; in the subsoil (0.2–0.6 m) it was likely to be co-dominated by storage and consumption, and the greatest difference in SOC stock between the two soils also lay in this layer; while in the deep layer (0.6–2.5 m) of the oasis, with a more stable carbon stock, there was carbon storage dominated. Moreover, carbon stocks in the deep layer of the two soils contributed about 65% of the total carbon stocks, and correspondingly, microbial activities contributed 71% to the total microbial activity in the entire soil profile, confirming the importance of carbon cycling in the deep layer. Desert cultivation in this area may produce unexpectedly high carbon stocks from the whole profile despite carbon loss in the topsoil.

**Keywords** Land-use · Soil organic carbon · Soil respiration · Microbial activity · Arid area

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## Introduction

The cultivation or tillage of land is one of the strongest human activities (Janzen et al. 1998). It has been reported extensively that cultivation of a virgin soil causes a drop in soil organic carbon (SOC) content (Jaiyeoba 2003; Gruenzweig et al. 2004), and SOC could decline with increased cultivation time (Dalal and Mayer 1986; Balesdent et al.1998). Burke et al. (1989) and Brown and Lugo (1990) reported average C losses ranging from 10 to 55% of the native C in the American grassland and the tropical forest zone. However, most studies on the effects of land-use change on SOC have focused on the topsoil or the top meter of the soil at most. This is understandable, given that the strongest effects of land-use change, the highest carbon concentration (Veldkamp et al. 2003), and the greatest microbial activity (Luizao et al. 1992) have been found in the topsoil. Meanwhile, SOC in deep soil is traditionally considered to be stable, relatively inert humus that is not likely to be affected by a change in land use (Sombroek et al. 1993). However, although SOC contents are low in the deep soil, the volume of these deep soil layers is very large. As a result, deeper soil horizons could contain large quantities of sequestered organic C (Jobbagy and Jackson 2002).

Arid areas account for nearly 30% of global terrestrial surface and are one of the ecology systems closely coupled with global change (Stanley et al. 2000). Virgin desert has

been cultivated into oasis farms, forming two land uses with the strongest divergence. Correspondingly, the soil property (Xu et al. 2006), the vegetation and root biomass (Tan et al. 2004), and the microbial composition and activity (Li et al. 2007) have also changed dramatically. Thus changes in the magnitude of soil $CO_2$ efflux and its driving forces could also occur and ultimately influence the input and output of the soil carbon pool and even affect the soil carbon balance in arid areas. However, little work related to this has been done in arid or semi-arid areas, probably because of the sparse desert plants and low biomass, soil organic matter, and nutrients in arid or semi-arid areas (West et al. 1994; Maestre and Cortina 2003). In the southern periphery of the Gurbantonggut Desert in central Asia, a typical temperate arid zone, our preceding studies have indicated that, after native desert soil cultivatation, SOC in the topsoil (0–0.2 m) decreased markedly (Li et al. 2007); however, the effect of cultivation on the SOC in deep soil layers in the region was unclear. In order to assess the characteristics of carbon stock and microbial activity in different soil layers after desert cultivation, we selected the soils in Fukang oasis, which had been cultivated for 16–17 years, and the surrounding desert located in the southern periphery of the Gurbantonggut desert for study. SOC, microbial biomass carbon, soil respiration, and soil basal respiration were measured at 0- to 2.5-m depth in the two soils, in order to understand the following questions:

(1) Is the effect of cultivation on carbon in deep soils similar to that in topsoil? Furthermore, what is the effect of land-use change on carbon sequestration for the soil profile?
(2) Is there measurable microbial activity in deep soil? What is the relative importance of soil carbon and microbial activity in deep soil?

## Materials and methods

### Study site

The experiments were conducted in the vicinity of the Fukang Station of Desert Ecology, Chinese Academy of Sciences, which is located in the hinterland of the Eurasia continent (44°17′N, 87°56′E). The location of the station is shown in Fig. 1. The station is 8 km from the south edge of the Gurbantonggut Desert and 72 km north of the highest peak of the eastern Tianshan Mountains. The plains area of this region is typical temperate desert with varying soil salinity and is influenced by a continental arid temperate climate, with dry hot summers and cold winters. The annual mean temperature is 6.9°C. The annual mean precipitation is 164 mm and pan-evaporation is 2,000 mm. The haloeremion in this region is either bare soil or covered with halophyte vegetation that is dominated by *Tamarix elongate*, *Tamarix ramosissima*, *Salsola collina*, and *Kalidium foliatum*. The soil is heavily textured saline-alkali gault of moderate salinity with plate structure and low organic matter (Xu and Li 2006). The new oasis, which has been cultivated since 1990, is the prevailing land-use cover in this region. Due to the limited water sources, cultivation is only conducted in part of the area, thus oasis farms are usually surrounded by native desert.

### Soil sampling

In 2007, three pairs of oasis sites and adjacent desert sites were selected, with uniform and flat topography, and the distance between the pairs was about 3 km. To avoid differences caused by crop species and cultivation time, cotton farms that had been cultivated for 16–17 years under integrated and conventional management were selected as oasis sites. The plant community in the native saline desert is composed of shrub and grass, and mainly dominated by *Tamaricaceae* and *Chenopodiacea*. The plant distributions are very uneven, with remarkable soil irregularity (Zhu et al. 2008). Thus, bare soil, soil with shrub vegetation, and soil with grass vegetation were set as the three sample types in the saline desert. Three sample points were placed in each of these three desert sample types and one oasis sample type. Thus there were 36 sample points for the three pairs of oasis and desert sites.

Soil samples for chemical and microbiological analysis were taken vertically by auger in July and August 2007 at the following depth intervals (m): 0–0.1, 0.1–0.2, 0.2–0.4, 0.4–0.6, 0.6–1.0, 1.0–1.5, 1.5–2.0, 2.0–2.5. Sampling was repeated three times per depth interval. Plant residues and visible soil organisms were removed, and then the soil sample was sieved with a 2-mm sieve. Some samples were stored in polyethylene bags at 4°C to maintain their moisture until the microbial measurements were carried out within 2 days; the rest of the samples were air-dried for the measurement of soil properties (Zhu et al. 2008). The soil pH was determined with a potentiometer in a 1:5 (v/v) soil-water suspension. The electrical conductivity (EC) was measured with a conductivity meter in a 1:5 (v/v) soil–water suspension. The soil particle sizes were determined by Mastersizer2000 (Malvern Instruments, Malvern, UK) and classified by the Udden-Wentworth scale standard. The total nitrogen (N) content was determined by Kjeltec system 1026 (Distilling Unit). Meanwhile, 100-$cm^3$ undisturbed soil samples were taken by soil sampler at the following depths (m): 0.05, 0.10, 0.30, 0.50, 0.80, 1.25, 1.75, and 2.25, for bulk density measurements. Sampling and measurement were repeated three times at each depth.

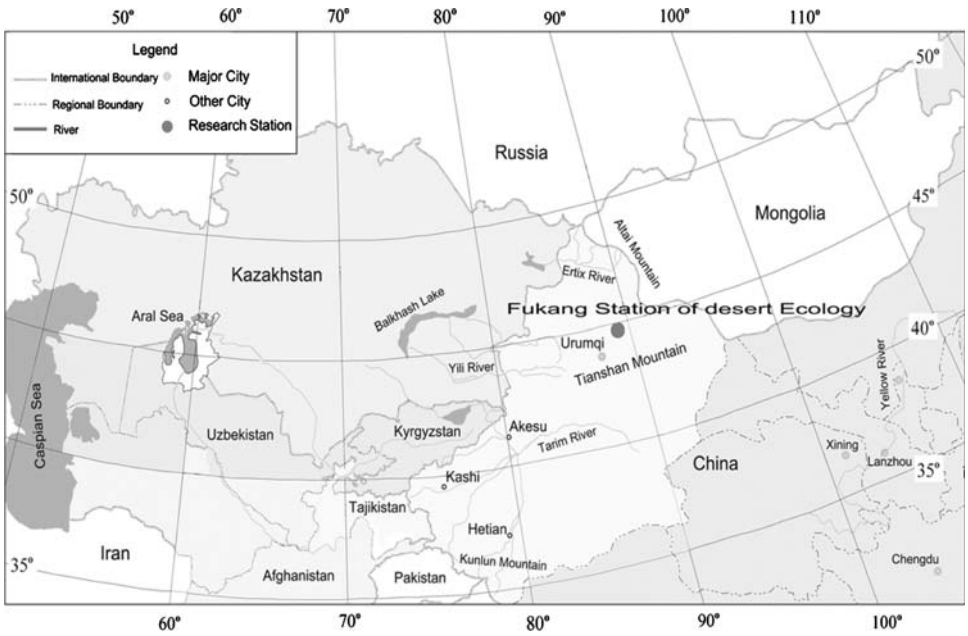


**Fig. 1** The location of the study site

## Quadrat investigation of plant biomass

In September 2007, 18 large quadrats of 10 × 10 m were placed in the desert and oasis sites (3 per site), and 4 small quadrats of 1 × 1 m in every big quadrat were selected randomly to survey vegetation cover. The aboveground parts of plants were collected with scissors. The intact roots were excavated and the soil surrounding the roots was removed. The roots were then dried at 80°C until they reached a constant weight. Dried plant samples were weighed to get aboveground and underground biomass (Fig. 2). Because the shrub root system in the saline desert was too large for a 1 × 1 m quadrat, the intact root of a single shrub plant was excavated (Xu and Li 2006), and then converted into the biomass per unit area according to shrub cover.

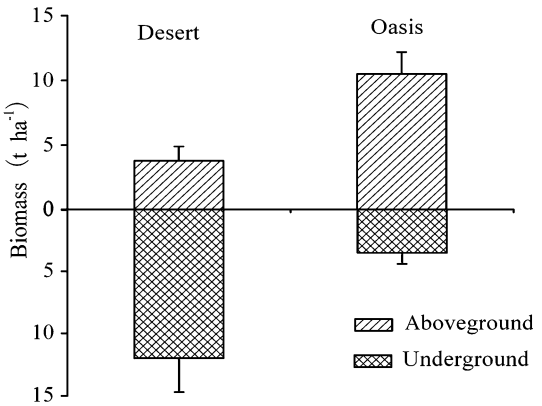


**Fig. 2** The aboveground and underground biomass (dry weight) in saline desert and oasis farm. *Bars* show the standard errors of means

## Soil organic carbon

The soil samples were sieved at 0.15 mm, then soil organic carbon was measured using an automated C analyzer (TOC-VCPH-SSM, Japan), and carbon stock (kg $ha^{-1)}$ was calculated using the following equation (Veldkamp 1994): $SOC = 10^4 \times C_s \times h \times \rho$, where $C_s$ is soil organic carbon content (%), $h$ is the thickness of soil layer (m), and $\rho$ is soil bulk density (g $cm^{-3}$). Microbial biomass carbon was determined by using the fumigation-extraction method combined with ultraviolet absorbance (Nunan et al. 1998).

## Soil respiration

Soil respiration in the field, as a major index of total metabolic activity, represents the sum of all soil metabolic processes in which $CO_2$ is produced (Joshi et al. 1991). Soil respiration from the desert and the oasis was measured using a Li 8100 Automated Soil $CO_2$ Flux System (LI-COR, Lincoln, NE, USA) equipped with a long-term monitoring chamber (LI-8100L). In July 2007, the diurnal pattern of soil respiration was measured at the following depths (m): 0, 0.1, 0.2, 0.4, and 0.6, by excavating layer by layer. Each measurement started at 14:00 and ended at 14:00 (local time) the next day, and was repeated three times.

## Soil basal respiration

Soil basal respiration represents soil microbial activity and the intensity of substance metabolism (Menyailo et al. 2003). The moisture content of soil samples was adjusted to 40% water-holding capacity (WHC), and the samples were

**Table 1** Soil texture in two soil types below saline desert and oasis farm

| Depth (m) | Saline desert (%) | | | Oasis farm (%) | | |
|---|---|---|---|---|---|---|
| | Clay | Silt | Sand | Clay | Silt | Sand |
| 0.0–0.1 | 7.3 (2.4) | 68.4 (4.6) | 24.3 (2.9) | 6.0 (2.3) | 79.4 (6.9) | 14.6 (1.9) |
| 0.2–0.4 | 6.3 (1.5) | 66.8 (7.9) | 26.9 (3.1) | 6.6 (3.1) | 71.1 (8.3) | 22.3 (2.3) |
| 0.6–1.0 | 6.1 (2.1) | 67.2 (5.2) | 26.7 (4.3) | 6.9 (3.6) | 63.8 (8.9) | 29.3 (5.1) |
| 1.0–2.0 | 7.6 (2.1) | 61.6 (8.4) | 30.8 (4.3) | 9.7 (4.0) | 74.6 (8.7) | 15.7 (2.6) |
| 2.0–2.5 | 8.1 (2.1) | 60.7 (7.0) | 31.2 (5.9) | 11.0 (4.2) | 78.0 (10.1) | 11.0 (3.3) |

Values are means with standard errors of means *in parentheses*

conditioned at 25°C in a thermostated container for 4 days, which contained deionized water to maintain high humidity and a beaker of 1 M NaOH to trap released $CO_2$. Subsequently, soil portions, each containing 25 g dry matter were continuously incubated at 25°C for 24 h. Each soil portion was spread on a plate with a diameter of 120 mm and placed in a 2-l stoppered glass bottle with deionized water and a beaker containing 10 ml 0.15 M NaOH (the concentration was determined by previous experiments). Total $CO_2$ in the NaOH solution was determined by back-titration using standardized 0.15 M HCl (Jenkinson and Powlson 1976; Wu and Brookes 2005), and then the $CO_2$-C efflux rate ($\mu g\ g^{-1}$dry soil $h^{-1}$) was calculated.

### Data analysis

According to the quadrat investigation and preceding research (Jiang and Li 1990), the weight of the soil under plant canopies and in bare land in native desert was assessed; the area of the soil under shrub and grass canopies and the area of bare soil accounted for 15, 30, and 55% respectively). Based on the above calculation, the weighted averages of relevant soil parameters were determined. Soil basal respiration is commonly expressed on a mass basis. In order to take the large volume of the deep soil into account, bulk density and volume of the sampled soil layer were used to calculate the soil basal respiration (Veldkamp et al. 2003). Data analysis used Origin 7.0 (OriginLab, Northampton, MA, USA.). The least significant difference test was used to analyze the significance in variance.

## Results

### Soil properties

Both soils are silty loam (Table 1). Silt content was 60–75% in the desert soil and 63–84% in the oasis soil throughout the soil profile. In both soils, pH increased significantly with soil depth ($P < 0.05$, Fig. 3a), and in the oasis soil there was a prompt increase at 0.6–2.5 m. Meanwhile, the soil electrical conductivity (EC) in both soils decreased significantly with soil depth (Fig. 3b). The highest EC value in the desert was found in the surface soil, but decreased promptly below the surface. And in the oasis soil there was a slight and mild decrease throughout the soil profile: the EC value at each depth was negatively correlated with the depth itself ($P < 0.05$). The soil pH and EC values at the 0- to 2.0-m depth in the oasis soil were significantly lower than those of the desert. Land use had strong effects on soil pH and salt content at the 0- to 2.0-m depth in the native desert. In addition, soil bulk density in both soils increased with soil depth ($P < 0.05$, Fig. 3c). At 0–0.6 m, soil bulk density was markedly higher in the oasis than in the desert, however, below 0.6 m, there was no significant difference in soil bulk density between the two soils (Fig. 3c), which showed that increase in bulk density after cultivation due to compaction occurred at 0- to 0.6-m. For the convenience of comparison, the total profile was divided into three soil layers: the topsoil (0–0.2 m), the subsoil (0.2–0.6 m), and the deep layer (0.6–2.5 m).

In the topsoil (0–0.2 m), there was no significant difference in total N content between the oasis and desert soils (Fig. 4). However, in the subsoil and deep layer of the oasis, the N content was significantly higher than that in the desert soil ($P < 0.05$), with particularly significant N accumulation in the subsoil (0.2–0.6 m).

### Soil organic carbon

Data on soil carbon content in 1987 were obtained from the background and land-use records of Fukang Station (Jiang and Li 1990) (Fig. 5). Both content and stock of SOC in saline desert soil showed no statistical difference between 1987 and 2007 (Fig. 5), which showed that the SOC in the saline desert has not changed significantly since 1987.

Between the desert and its adjacent oasis (cultivated in 1990–1991 from the same saline desert), however, there were significant differences in carbon content and carbon distribution in the soil profile. SOC content in the topsoil (0–0.2 m) of the oasis was markedly lower than that of the desert ($P < 0.05$, Fig. 6a), but SOC stock had no

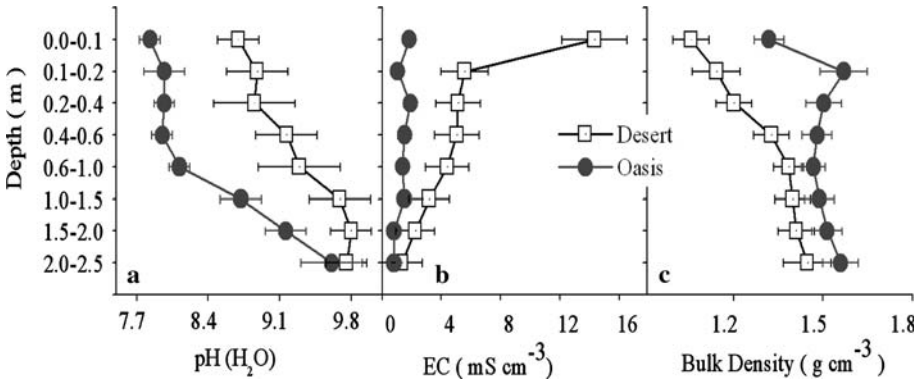


**Fig. 3** Soil pH (**a**), electrical conductivity (EC) (**b**), and bulk density (**c**) at different depths below the saline desert and oasis farm. *Bars* show the standard errors of means

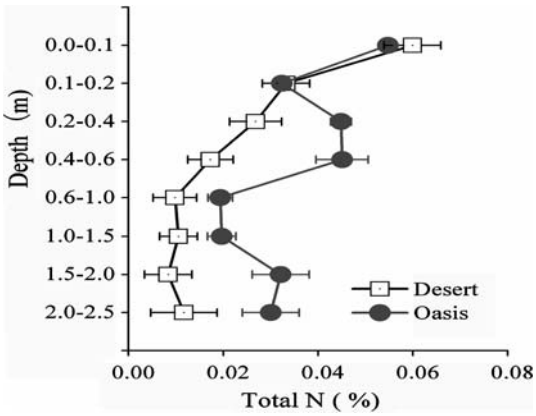


**Fig. 4** Total N content at different soil depths below the saline desert and oasis farm. *Bars* show the standard errors of means

significant difference between the two soils due to the increase in bulk density after cultivation ($P > 0.05$, Fig. 7a). Meanwhile, in the subsoil and deep layer (0.2–2.5 m) of the oasis there were significantly higher SOC content and stock than in the desert ($P < 0.05$, Figs. 6, 7a). Thus, the total carbon stock for the whole profile (0–2.5 m) increased by 57% after cultivation (112 kg C $ha^{-1}$ in the oasis and 71 kg C $ha^{-1}$ in the desert) (Fig. 7b). The subsoil (0.2–0.6 m) of the oasis also showed obvious C accumulation (Fig. 6a) and the biggest differences in SOC content and stock from those of the desert. Soil carbon stock in the subsoil of the oasis contributed 25% of the total carbon stock in the soil profile, while the same soil layer of the desert contributed 19%. Soil carbon stock in the deep layer contributed 65% (oasis) or 67% (desert) to the total soil carbon. Meanwhile, the microbial biomass C throughout the soil profile of the oasis was significantly higher compared with the desert ($P < 0.05$), especially at 0- to 0.6-m depth (Fig. 6b).

### Soil carbon efflux

In the field, soil respiration rates in the oasis at 0, 0.1, 0.2, 0.4, and 0.6 m were significantly higher than the desert ($P < 0.05$). The biggest difference in soil respiration between the desert and the oasis lay at 0 m (Fig. 8a), and the difference decreased with soil depth. At 0.6 m, the respiration rates in the two soils approached similar values (Fig. 8b).

Meanwhile, soil basal respirations could be detected throughout both soil profiles (0–2.5 m). As expected, basal respiration in both soils calculated on a mass basis was highest at the surface and decreased with depth (Fig. 9a), however, the decrease was very slow at 0.1–1.5 m. In the desert in particular there was no significant decrease in basal respiration with depth. Analysis of variance revealed that soil basal respiration at 0–0.6 m was higher in the oasis than in the desert ($P < 0.05$), which was similar to the results of field soil respirations. The basal respiration was also expressed on a volume basis using the bulk density data. Although the laboratory data on basal respiration cannot be assumed to parallel respiration levels in the field closely, the volume-based values are heuristically useful in demonstrating that a relatively low basal respiration multiplied over a large volume of soil can result in large values of total respiration (Veldkamp et al. 2003). For both soils, such volume-based values for basal respiration were higher in the soil layers below 0.2 m than in the top 0.2 m (Fig. 9b). The carbon efflux in the deep layer (0.6–2.5 m) contributed 75% (desert) and 68% (oasis) of the total carbon efflux throughout the soil profile. Above all, in the deep layer, no land-use effect on microbial activity was detected (Fig. 9a, b), and the respiration rates were 2.99 g $CO_2$–C $m^{-2}$ $h^{-1}$ in the oasis soil and 2.53 g $CO_2$–C $m^{-2}$ $h^{-1}$ in the desert soil.

## Discussion and conclusion

Soil salinity is a major restrictive factor for microbial activity and thus strongly alters organic carbon turnover processes (Wichern et al. 2006). The SOC in the topsoil (0–0.2 m) of the saline desert was of lower availability for

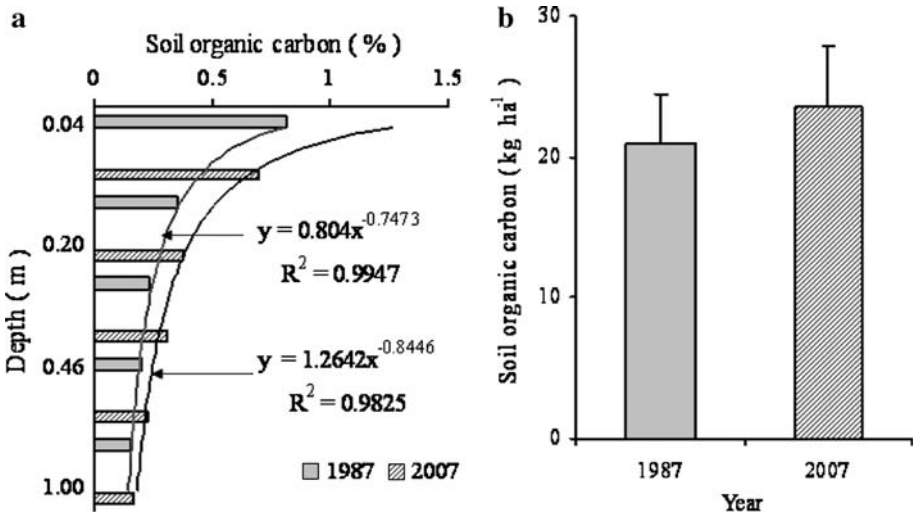


**Fig. 5** Soil organic carbon contents at different depths (**a**) and total organic carbon stocks at 0- to 0.6-m depth (**b**) below undisturbed saline desert in 1987 and in 2007. **a** is based on the calculation of trendline equations ,and the *arrows* indicate different years; *bars* show the standard errors of means

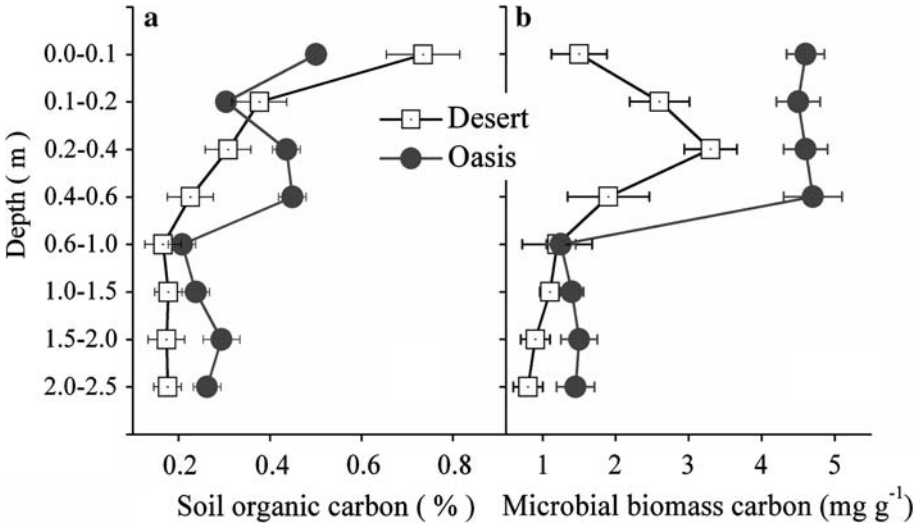


**Fig. 6** Contents of soil organic carbon (**a**) and microbial biomass carbon (**b**) at different depths below the saline desert and oasis farm. *Bars* show the standard errors of means

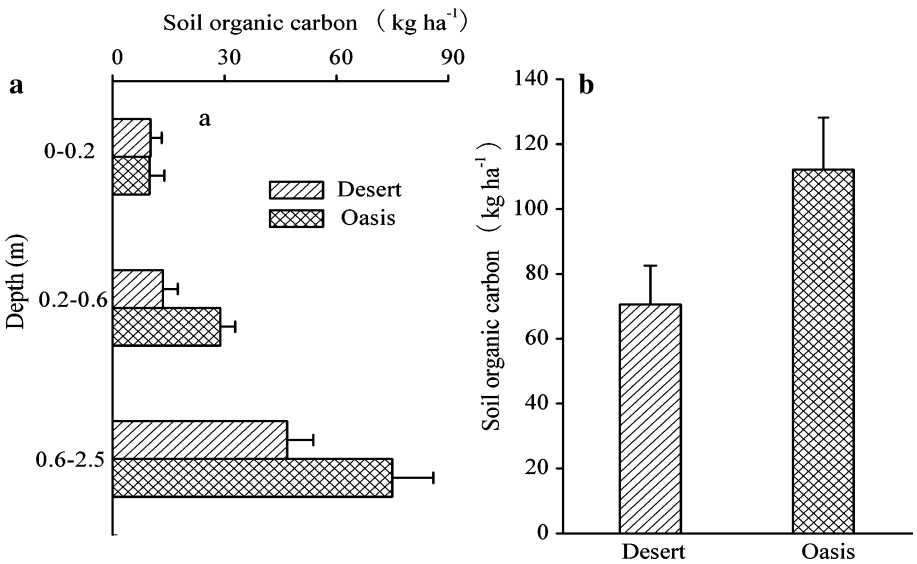


**Fig. 7** Soil organic carbon stocks at different depths (**a**) and total organic carbon stocks throughout the soil profile (0–2.5 m) (**b**) below the saline desert and oasis farm. *Bars* show the standard errors of means

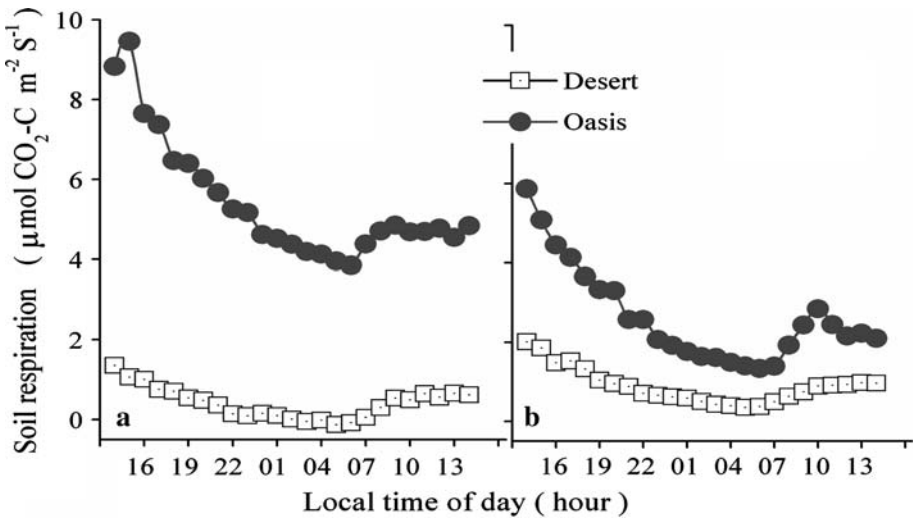


**Fig. 8** Daily variations in soil respiration at depths of 0 m (**a**) and 0.6 m (**b**) below the saline desert and oasis farm

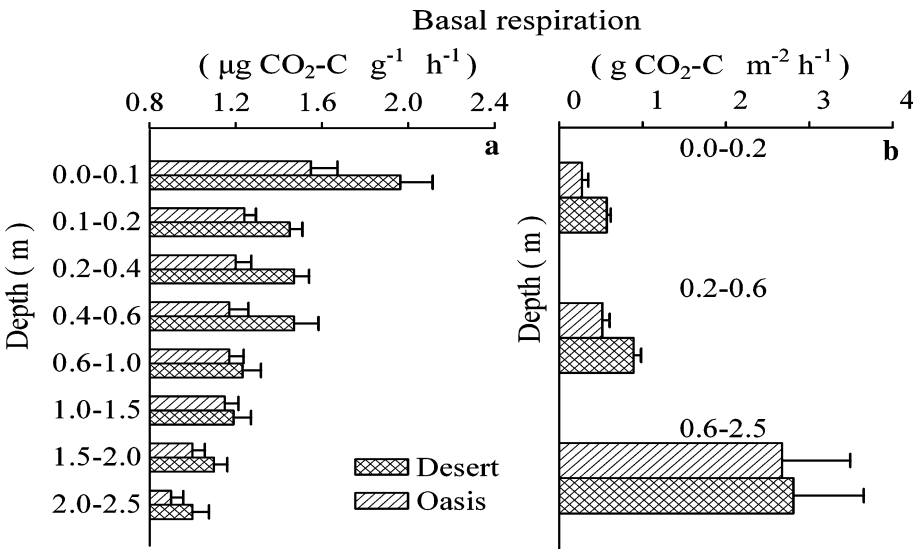


**Fig. 9** Soil mass-based (**a**) and soil volume-based (**b**) basal respirations at different depths below the saline desert and oasis farm. *Bars* show the standard errors of means

microorganisms due to the high salinity (Fig. 3b) and drought (Li et al. 2007). Herein, "availability of SOC" was defined as the degree to which the soil organic C was resistant to microbial mineralization (Fierer et al. 2003). After the desert land was cultivated and became oasis, soil properties in the topsoil in particular have significantly changed from the native desert: the soil pH and salt content decreased significantly (Fig. 3a, b) and soil moisture content increased significantly in the oasis due to periodic irrigation (Li et al. 2007), offering a favorable soil environment for microorganisms. Accordingly, the availability of SOC for microorganisms in the oasis increased compared with the desert. These changes resulted in significant differences in microbial composition and activity before and after cultivation because the community composition of soil microorganisms is usually controlled by the available quantity of soil organic carbon (Griffiths and Ebblewhite 2000). Previous studies (Li et al. 2007) showed fungal and bacterial codominance in heterotrophic respiration of the desert soil and increased bacterial dominance in the oasis soil. This was probably an important reason that in the topsoil the SOC content decreased and microbial activity markedly increased after cultivation (Figs. 6, 9) (Balser et al. 2002; Veldkamp et al. 2003).

However, in the subsoil (0.2–0.6 m), the SOC and microbial biomass C were significantly higher in the oasis than in the desert, and this depth showed the biggest difference in SOC content and stock between the two soils (Figs. 6, 7). The dense roots with high turnover rate in the subsoil (0.2–0.6 m) of the oasis were possibly the major reason for the higher SOC than that of the desert. In the desert, although the underground biomass was high (Fig. 2), it was distributed at much greater depths (Xu and Li 2006), and its turnover rate was low due to high salinity.

The distribution of plant roots could directly affect vertical distribution of SOC (Jobbagy and Jackson 2002), due to the large quantity of root excretion and dead roots, which could supply abundant carbon to the soil by microbial conversion. Previous studies also showed 30–40% of the total input of SOC was from root excretion and dead roots (Lee and Pankhurst 1992; Qian et al. 1997). Furthermore, soil cultivation changed the magnitude of soil carbon efflux (Fig. 8). In the subsoil, both soil respiration and microbial activity in the oasis were significantly higher than in the desert (Figs. 8, 9). Obviously, both carbon storage and carbon consumption processes were very active in the subsoil.

The soil at the site had low clay content and higher sand content (Table 1), thus, after cultivation, some dissolved nutrients in fertilizer were easily leached to deep soil by irrigation water. N leaching and accumulation may affect soil organic carbon in deep soil of the oasis. N fertilization and N deposition can increase the SOC pool in multiple ways (Hagedorn et al. 2003; Knorr et al. 2005; Jandl et al. 2007; Hyvonen et al. 2008). Modelling of bomb $^{14}C$ data from a field experiment indicated that repeated addition of 30 kg N $ha^{-1}$ $year^{-1}$ for 100 years may result in double (1.3 kg C $m^{-2}$) the amount of C stored in the mor layer (Franklin et al. 2003). In our studies, the total N throughout the soil profile of the oasis was highly correlated with the SOC ($r = 0.82$), and they showed similar changes: their contents in the oasis soil, with significant accumulation in the subsoil, were higher than in the desert soil at 0.2–2.5 m (Figs. 4, 6). Thus, soil texture, application of fertilizer, and irrigation may be another reason that in the subsoil the SOC increased and accumulated after cultivation and also likely reasons that SOC and microbial biomass C increased in the deep layer of the oasis (0.6–2.5 m) (Figs. 6, 7). The desert soil lacked such a condition (irrigation) for leaching, and as a result, leaching was not likely to occur, although the desert had higher sand content than the oasis in some soil layers (Table 1). Furthermore, soil microbial activity between the two soils showed no significant difference in the deep layer (Fig. 9), and the nutrients at that depth of the oasis were not likely to be absorbed by crops due to the sparseness of roots, which indicated the more stable carbon stock and the increased carbon storage dominance in the deep layer of the oasis. Meanwhile, microbial activity could be detected throughout all soil profiles in our study, and the importance of microbial activities in the deep layer became apparent when this index was assessed on a volume basis (Fig. 9b).

Land cultivation generally decreases SOC (Veldkamp et al. 2003; Jaiyeoba 2003; Gruenzweig et al. 2004); however, our results were significantly different. After 16–17 years of cultivation, although SOC content in the topsoil (0–0.2 m) decreased, the soil carbon in deep soil increased and accumulated in the oasis. However, it cannot be estimated whether such C sequestration has already reached the maximum level or whether it is stable and continual. To address these critical questions, there is a clear need to carry out long-term studies on the effects of land-use change on carbon storage in arid areas. It is noteworthy that the topsoil contributed 8.6–14% to the total amount of SOC, while soil carbon stocks in the deep layer contributed more than 65%, although SOC contents were lower in the deep layer for the same layer thickness. Moreover, about 71% of soil microbial activity was also found in the deep layer (Fig. 9b), which clearly indicates the importance of the deep soil in the overall carbon cycling in the soil profile. Thus, if study on the effects of land–use change on the global C cycle is limited to the topsoil, incomplete and even false conclusions could be drawn. Hence, relevant studies or models should clearly take the carbon contribution of deep soil into consideration.

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