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The impact of land use change on soil organic carbon and labile organic carbon stocks in the Longzhong region of Loess Plateau

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Abstract: Land use change (LUC) is widely recognized as one of the most important driving forces of global carbon cycles. The soil organic carbon (SOC) and labile organic carbon (LOC) stores were investigated at arable land (AL), artificial grassland (AG), artificial woodland (AW), abandoned arable land (AAL) and desert steppe (DS) in the Longzhong region of the Loess Plateau in Northwest China. The results showed that conversions from DS to AL, AL to AG and AL to AAL led to an increase in SOC content, while the conversion from DS to AW led to a decline. The differences in SOC content were significant between DS and AW at the 20–40 cm depth and between AL and AG at the 0–10 cm depth. The SOC stock in DS at the 0–100 cm depth was 39.4 t/hm², increased by 28.48% after cultivation and decreased by 19.12% after conversion to AW. The SOC stocks increased by 2.11% from AL to AG and 5.10% from AL to AAL. The LOC stocks changed by a larger magnitude than the SOC stocks, which suggests that it is a more sensitive index of carbon dynamics under a short-term LUC. The LOC stocks increased at 0–20 cm and 0–100 cm depths from DS to AW, which is opposite to that observed for SOC. The proportion of LOC to SOC ranged from 0.14 to 0.20 at the 0–20 cm depth for all the five land use types, indicating low SOC dynamics. The allocation proportion of LOC increased for four types of LUC conversion, and the change in magnitude was largest for DS to AW (40.91%). The afforestation, abandonment and forage planting on arable land led to sequestration of SOC; the carbon was lost initially after afforestation. However, the carbon sink effect after abandonment may not be sustainable in the study area.

Keywords: carbon sequestration; labile organic carbon; land use; cultivation; abandonment; Loess Plateau

The carbon pool in soils is approximately twice as much as that in the atmosphere (IPCC, 2007). The atmospheric CO₂ concentration is influenced by the balance between soil organic carbon (SOC) inputs and outputs (Lützow *et al.*, 2006). Land use change (LUC), one of the dominant components of global change, is estimated to be the second largest source of human-induced greenhouse gas emissions (1.5 Pg C/a) after fossil fuel combustion (5.3 Pg C/a) (IPCC, 2007). Changes in SOC upon LUC may occur due to changes in the rates of accumulation, turnover and decomposition of SOC (Li *et al.*, 2010; Poeplau *et al.*, 2011). Thus, improved understanding for land use impacts on

the terrestrial carbon balance is a necessary part of global efforts to mitigate climate change.

The SOC fractions differ in their response and sensitivity to LUC. Active soil organic carbon is easily and directly used by organisms. It is active and most sensitive to physical and chemical disturbances (Purakayastha *et al.*, 2007). These SOC fractions are also important for nutrient cycle. Labile organic carbon (LOC), a fraction of active soil organic carbon, can be measured easily using KMnO₄ oxidation and can serve as a sensitive indicator for the dynamic of SOC due to

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land use and management change (Wu *et al.*, 2004; Su *et al.*, 2009).

The Loess Plateau covers an area of some 640,000 km² in the upper and middle reaches of the Yellow River. Loess is a highly erosion-prone soil; in fact, the soil in this region has been called “the most highly erodible soil on earth” (Yang and Shao, 2000). The Loess Plateau and its dusty soil cover almost all of Shanxi and Shaanxi provinces, as well as parts of Gansu province, the Ningxia Hui autonomous region, and the Inner Mongolia autonomous region.

Since the 1950s, substantial efforts have been made to control soil erosion and restore vegetation in the hilly areas of the Loess Plateau by the Chinese government, including extensive tree planting, integrated soil erosion controls and the “Grain-for-Green” project. There is a diversity of land use types. The effects of land use on soil carbon storage have become the focus of research (Wu *et al.*, 2004; Chen *et al.*, 2007; Liu *et al.*, 2010). Longzhong is located in the middle of Gansu province and the west of the Loess Plateau, where the natural environment is harshest, the economy most undeveloped and vegetation restoration most difficult (Zhang and Huang, 2002). Reports on

soil carbon sequestration related to land use are, however, seldom available.

In this study, SOC and LOC storage were determined for each land use type: arable land (AL), artificial grassland (AG), abandoned arable land (AAL), artificial woodland (AW) and desert steppe (DS). The effects of land use on the SOC pool were analyzed to provide a theoretical basis to rational land use and conservation in the region.

1 Materials and methods

1.1 Study area

The experimental site is at the Gaolan Experiment Station for Ecology and Agriculture Research, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences (Fig. 1). The station is located in the northwest of the Loess Plateau (Gaolan county, Lanzhou, Gansu province; 36°13'N, 103°47'E) at an altitude of approximately 1,780 m. The climate is semi-arid and drought-prone: the mean annual precipitation is about 263 mm, with nearly 70% falling between May and September; the mean annual temperature is 8.4°C, with a maximum

Fig. 1 Location of the study area and sample scheme of different land uses

monthly mean value of 20.7°C (July) and a minimum monthly mean value of -9.1°C (January); the average annual pan evaporation is 1,786 mm. The vegetation is desert steppe. The soil is a silt loam of loess origin, which belongs to the Sierozem soil classifications according to Chinese Soil Taxonomy.

The AL in this study has a cultivation history of over 50 years and was planted with maize (*Zea mays* L.) continuously from 2004 to the present, and with wheat and vegetable previous to 2004. The fields were plowed before sowing in spring, and after harvest the maize residue was left in field. Experimental fields were irrigated three times per year following fertilizer application of di-ammonium phosphate (200 kg/hm²) and urea (100 kg/hm²). Organic manure was applied every 6 years at approximately 8,000 kg/hm². The AG had been under continuous alfalfa production since 2001, being irrigated once or twice per year. The alfalfa was harvested (cut near the soil surface) one or two times per year. Crops such as wheat and potato were grown previous to the alfalfa. Vegetation of the AW was oriental arborvitae (*Platycladus orientalis* L.), which was planted in 2003, following pear trees, which had been planted in 1992. The oriental arborvitae was 1.5 m apart within rows and 2 m apart between rows and trees were irrigated at their bases three to four times per year. The AAL was left abandoned for six years and had been planted with maize and vegetable previously. The species were *Artemisia frigida* L., *Artemisia sacrorum* L. and *Chenopodium album* L. The coverage was about 30%. Approximately 25% of the surface area of the DS was covered by *Reaumuria soongorica* L. and *Stipa breviflora* L., which were dominant, and other less prevalent species, such as *Peganum harmala* L., *Astragalus capillipes* L., *Cleistogenes mitica* L. and *Setaria viridis* L.

1.2 Soil sampling and analysis

In May 2010, we took soil samples from three sites of each land use type by collecting five cores (5 cm in diameter) from six depths (0–10, 10–20, 20–40, 40–60, 60–80 and 80–100 cm) in a zigzag sampling pattern. The five cores at each depth were mixed to form a composite sample. Soil cores were measured for soil

bulk density in a stainless steel cylinder of 100 cm³. In the laboratory, the bulked samples were air-dried and passed through a 2-mm sieve to remove coarse roots and easily-detected plant litter.

Soil particle size distribution was determined using the laser detection technique on a Malvern Mastersizer 2000 (Malvern Instruments Ltd., Malvern, UK). The particle size was classified by the American Soil Texture Taxonomy, and sand was in the range of 50–1,000 µm, silt 2–50 µm and clay <2 µm. Soil organic carbon (SOC) was measured by the K₂Cr₂O₇–H₂SO₄ oxidation method of Walkey and Black (Nelson and Sommers, 1982). Total nitrogen (total N) was measured by the micro-Kjeldahl procedure (ISSCAS, 1978). Labile organic carbon (LOC) was measured by the KMnO₄ (0.333 mol/L) oxidation method (Su *et al.*, 2009). For an individual profile with *k* layers, the following equation was used to calculate the storage of organic carbon at each layer of the soil profile:

$$SOC = h \times \rho \times C.$$

Where, *SOC* is the soil organic carbon storage (t/hm²), *h* the thickness of this layer (cm), *ρ* the bulk density (g/cm³), and *C* the proportion of organic carbon (%).

Labile organic carbon in soil was calculated using an equation similar to the above.

1.3 Statistical analyses

All data were analyzed using SPSS software. Multiple comparisons and analyses of variance (ANOVA) were used to determine the significance of differences in SOC and LOC at each depth among land use types.

2 Results

2.1 Effects of LUC on SOC content

Conversion from DS to AL led to a slight increase in SOC content at the 0–100 cm depth (Table 1). The SOC content decreased as land use changed from DS to AW, except at the 80–100 cm depth where it increased, and was significantly different at the 20–40 cm depth between the two land use types. Conversion from AL to AG led to an increase in SOC content at 0–10 and 60–100 cm depths, with a small decline at the middle of the profile. A trend to increased SOC content was observed in the transition of AL to AAL, but it was not statistically significant.

Table 1 SOC content for various land use types

Depth (cm)	Land use type				
	DS (g/kg)	AL (g/kg)	AG (g/kg)	AAL (g/kg)	AW (g/kg)
0–10	5.7±0.6 ^{ACa}	6.1±0.2 ^{ADa}	8.0±0.3 ^{Ba}	7.3±0.5 ^{BDa}	4.4±0.5 ^{Ca}
10–20	4.8±0.8 ^{ABab}	5.6±0.1 ^{Aa}	5.6±0.4 ^{Ab}	6.1±0.2 ^{Ab}	3.5±0.6 ^{Bac}
20–40	4.2±0.5 ^{ABd}	4.6±0.3 ^{Ab}	4.0±0.5 ^{Abc}	5.0±0.5 ^{Ac}	2.4±0.6 ^{Bbc}
40–60	2.9±0.2 ^{Ac}	3.9±0.4 ^{Abd}	3.8±0.8 ^{Abc}	4.0±0.3 ^{Ac}	2.4±0.6 ^{Abc}
60–80	2.6±0.2 ^{Ac}	3.1±0.3 ^{Ac}	3.6±1.2 ^{Abc}	3.2±0.3 ^{Ac}	2.1±0.6 ^{Abc}
80–100	2.1±0.1 ^{Ac}	2.8±0.3 ^{Ac}	3.0±1.1 ^{Ac}	2.9±0.2 ^{Ad}	2.2±0.4 ^{Abc}
Mean	3.7±0.3 ^{AB}	4.3±0.2 ^A	4.7±0.6 ^A	4.7±0.3 ^A	2.8±0.5 ^B

Note: Different capital letters in the same row and different small letters in the same column indicate significant difference at $P<0.05$. Means $\pm$ standard errors were calculated from three sites of the same land use type. DS, desert steppe; AL, arable land; AG, artificial grassland; AAL, abandoned arable land; AW, artificial woodland.

On average, over the 0–100 cm soil profile, the SOC content was in the order: AAL > AG > AL > DS > AW (Table 1). The SOC content was significantly higher in AL, AG and AAL than in AW ($P<0.05$) at the 0–40 cm depth, and was not significantly different among land use types ($P>0.05$) at the 40–100 cm depth. The SOC content decreased with increasing soil depth in the 0–100 cm soil profile for all the land use types, with a small amplitude at the 40–100 cm depth. The SOC content in the upper depths (0–10 and 10–20 cm) differed from that in the subsoil depths in all five land use types (Table 1).

Soil C/N ratio ranged from 6.4 to 8.6 (Fig. 2), and although not significant, the trend was to higher ratios in AAL, AL and AG than in DS and AW. The largest C/N ratio was with the topsoil layer. Total N was significantly and positively correlated with SOC content for all land use types ($P<0.001$).

Fig. 2 Soil C/N ratio for each land use type

2.2 Effects of LUC on SOC storage

At the 0–100 cm depth, the SOC storage in DS was

39.4 t/hm², increased to 50.6 t/hm² after cultivation by an amplitude of 28.5% and decreased to 31.9 t/hm² after conversion to AW by an amplitude of 19.1% (Fig. 3). The SOC storage reached 51.7 t/hm², with an increase of 2.1% for the transition from AL to AG and 5.1% after abandonment of AL. When the AL was converted to AG and was abandoned, the SOC storage at the 0–20 cm depth increased by 22.6%. The SOC storage at the 0–20 cm depth decreased by 22.2% after conversion from DS to AW, and increased by 13.2% after cultivation.

Fig. 3 SOC storages for each land use type. Data are the means $\pm$ standard error of 3 observations ($n=3$).

The order of SOC storage magnitude was consistent with that of the SOC content over the 0–100 cm profile among all land use types. The SOC storage of AL was higher at the 20–40 cm depth, which might be related to increasing bulk density due to tillage. The deep, dense roots of alfalfa might have contributed to the high SOC storage at the 60–100 cm depth, which was greater than in any other land use type (Fig. 3).

The amplitude of SOC storage change was higher at the 0–20 and 20–40 cm depths than at deeper soil depths for four land use conversions (Fig. 4). But it was also high at the 40–100 cm depth after conversion from DS to AL. The largest change in SOC storage (3.4 t/hm^2) occurred at the 20–40 cm depth in the change from DS to AL, while there was little difference among other soil depths (approximately $1\text{--}2 \text{ t/hm}^2$).

Fig. 4 Amplitudes of SOC storage change for different modes of land use conversion. 1, conversion from DS to AL; 2, conversion from AL to AG; 3, conversion from DS to AW; 4, conversion from AL to AAL.

2.3 Effects of LUC on LOC

The LOC storage in the 0–100 cm soil profile was 5.2 t/hm^2 in DS, increased to 6.94 t/hm^2 by an amplitude of 34.5% after cultivation and by 2.7% in the transition to AW. The LOC storage in the 0–100 cm soil profile increased by 6.2%, reaching 7.4 t/hm^2 following the conversion of AL to AG, and increased by 11.9% after AL was abandoned. The order of LOC storage was $\text{AAL} > \text{AG} > \text{AL} > \text{AW} > \text{DS}$. LOC storage was larger in AW than in DS, while SOC storage was larger in DS than in AW (Fig. 5). LOC storage decreased with the increase of soil depth.

The amplitude of LOC storage change was higher than that of SOC storage (Figs. 4, 6), which might indicate that LOC was more sensitive than SOC in response to LUC. Particularly, the LOC storage increased by over 80% at the 80–100 cm depth, which differed from the 10.7% increase in SOC storage at the 80–100 cm depth following the conversion of DS to AW. The LOC storage increased by 55.4% at the

Fig. 5 LOC storage for each land use type. Data are the means $\pm$ standard error of 3 observations ($n=3$).

20–40 cm depth and 52.5% at the 40–60 cm depth, higher than the increase in SOC storage (35.9% and 34.0%, respectively) after DS was cultivated. Additionally, the LOC storage increased at the 60–100 cm depth in the conversion from AL to AG.

Fig. 6 Amplitudes of LOC storage change for different modes of land use conversion. 1, conversion from DS to AL; 2, conversion from AL to AG; 3, conversion from DS to AW; 4, conversion from AL to AAL.

The allocation proportion of LOC is the ratio of LOC content to SOC content. For the soil sample at the 0–20 cm depth, the allocation proportion of LOC in DS was 0.14, increased by 11.2% after cultivation and by the largest degree (40.9%) when converted to AW (Fig. 7). The allocation proportion of LOC increased by 14.2% and 6.8% from AL to AG and AG to AAL, respectively.

Fig. 7 Allocation proportion change of LOC after land use conversion

3 Discussion

3.1 Impacts of LUC on SOC content and storage

In the study area, except for significant differences in SOC content at the 0–10 cm depth in the conversion from AL to AG and at the 20–40 cm depth in the conversion from DS to AW, the SOC content did not change significantly following LUC. This was probably related to the short period of time since the LUC occurred, the similar soil physical and chemical properties and the litter trait, as well as management among the land use types. Soil pH was in the range of 8.9–9.2 and soil bulk density was from 1.15 to 1.24 for the five land use types.

In this study, the conversion of DS to AL led to increases in SOC content and storage. This result was not consistent with the study by Liu *et al.* (2010), who reported that the accumulation of SOC was greater in natural grassland than in arable land in the southern Loess Plateau. Wang *et al.* (2007) concluded that SOC content in woodland and grassland decreased after

cultivation in the central Loess Plateau. The area in this study is located in the northwest of the Loess Plateau, with a temperate, semi-arid and drought-prone climate and mean annual precipitation of 263 mm. The mean annual precipitation is 602 mm and 558 mm in the other two areas, respectively. The zonal vegetation is also different, desert steppe for our study and forests for the other two studies. At the south and centre of the Loess Plateau, there is more litter and root in forest and grassland soils than in arable land, and consequently SOC accumulates in forest and grassland soils more than in arable land. At the northwest of the Loess Plateau, vegetation coverage and vegetation biomass are low in desert steppe; dry branches and fallen leaves decompose slowly and accumulate at the soil surface, and carbon input into the soil is less than in forest and grassland. The SOC stock of the arable land might be higher than that of the desert steppe due to organic manure applications and the effect of crop residues. Luo *et al.* (2005) found that the nutrient status of soil was improved after conversion of desert

to arable land in an arid region. The influence of conversion from natural vegetation to arable land on SOC differed among regions. It was concluded that cultivation of wetland at the Sanjiang Plain (Wang *et al.*, 2009), reclamation of alpine meadow in Haibei (Li *et al.*, 2006) and reclamation of grassland in a northern agro-pastoral ecotone (Liu *et al.*, 2009) led to decreased SOC content as well as transition from native forest to arable land in mid-subtropical mountainous areas (Yang *et al.*, 2009). Whereas, the SOC content in arable land was higher than that in a saline meadow or grassland of medium coverage in the middle of Heihe River (Zhang *et al.*, 2009; Wang *et al.*, 2011). In addition to the differences in climate, vegetation and soil type, the SOC content of irrigated soils increased after cultivation according to Wu *et al.* (2003). The study of Chen *et al.* (2008), which concluded that the dry field will be a large carbon sink under good management due to the reduction of slow organic carbon pool and an increase in the passive organic carbon pool from forest to dry farmland, supports our research result on the effect of LUC on SOC. Thus, the response of the carbon pool to LUC and its regional difference need to be examined.

In this paper, SOC stock in arable land increased after abandonment, which agrees with the results observed in the studies on land left abandoned for 20 years (Li *et al.*, 2009; Wei *et al.*, 2011) and 75 years (Guo *et al.*, 2010) in the Loess Plateau, and for a century in southeastern Ontario, Canada (Foote and Grogan, 2010). Land abandonment for several decades also improved soil physical-chemical and microbiological properties in semi-arid regions (Guo *et al.*, 2010; Zhu *et al.*, 2010; Wang *et al.*, 2011; Raiesi, 2012a, b). Consequently, the C sink after abandonment is correlated with the nutrient status of the soils. Nevertheless, it has been found that the herbage develops toward shrub in the middle and late stages of succession in other regions of the Loess Plateau (Du *et al.*, 2007; Zhu *et al.*, 2010; Wang *et al.*, 2011), and the increasing root to shoot ratio of the community would influence biomass accumulation and decomposition of soil organic matter (Du *et al.*, 2007). Thus, in the desert steppe, the soil carbon sequestration potential may be restricted with soil degradation when vegetation regenerates to desert steppe after abandonment of ar-

able land. The dynamics of plant and soil nutrients and chronosequences of abandoned farmland need to be investigated in the study area.

Conversion from AL to AG led to a significant increase of SOC content in this study, which is in accordance with the results of several studies (Guo and Gifford, 2002; Chen *et al.*, 2007; Su *et al.*, 2009) and is probably related to the input of more plant relicts into soil and the reduction of tillage operations (Wu *et al.*, 2004). The higher SOC content at the 10–60 cm depth in AL compared with AG might be due to increasing carbon sequestration after long-term fertilizer application (Morari *et al.*, 2006). Alfalfa has a strong taproot system, and its root can reach seven to nine meters (Guo *et al.*, 2002), whereas annual crop roots are shallow. Thus, the SOC content at the 60–100 cm depth was higher in alfalfa grassland.

The SOC content and storage decreased in the transition from DS to AW, which agrees with the results of afforestation in meadow steppe (Liu *et al.*, 2009) and in degraded sandy grassland (Hu *et al.*, 2007). Paul *et al.* (2002) summarized the results of forty three studies conducted in different regions and concluded that SOC content was usually lower in artificial woodland converted within less than ten years than in former land with other types of vegetation, declined slowly with increasing tree age, and would be higher than the former land after thirty years or longer time. Moreover, the main factors contributing to restoration of SOC after afforestation include previous land use, species of trees planted, soil clay content, preplanting disturbance and climatic zone (Laganière *et al.*, 2010).

3.2 Impacts of LUC on LOC storage

The LOC in soil derived from litter decomposition, root secretion, hydrolysis of soil organic matter and soil microorganisms, as well as its metabolic production, plays an important role in maintaining soil fertility and indicating the change in SOC storage (Wu *et al.*, 2004). In our study, the trend for LOC storage change resembled that for the SOC storage after land use conversions, which suggested that the size of the LOC pool was mainly determined by the SOC pool (Rong *et al.*, 2011). Matched application of organic manure and fertilizer efficiently increased the LOC content in AL (Xu *et al.*, 2006). Additionally, en-

hanced soil water content due to irrigation had a positive influence on the formation of LOC. The difference in LOC between AG and AL resulted from much root secretion and litter owing to a larger biomass in grassland and less human disturbance. Jia *et al.* (2006) reported soil microbial carbon and LOC increased following abandonment, which was similar to the increase in LOC in AAL in our study. The higher LOC storage in AW than in DS resulted from higher litter quality and quantity (Wu *et al.*, 2004; Laik *et al.*, 2009). Furthermore, the larger change in the amplitude of LOC than in SOC might imply that the change in SOC mainly occurred in the active fraction during the short period after land use conversion.

The proportion of LOC to SOC content is used to reflect the stability of soil carbon, and a higher proportion means greater activity and lower stability of SOC (Zhu *et al.*, 2006). In this study, the conversions between several land use types caused the increase in this proportion. Meanwhile, the proportion of LOC to SOC content at the 0–20 cm soil depth was in the range of 0.14–0.20, lower than 0.28–0.44 for different land use types in a dry, hot valley (Tang *et al.*, 2010) and 0.45–0.52 in subtropical forests (Zhu *et al.*, 2006). Thus, the activity of SOC was low and stable carbon was the main fraction in the study area. It was probably related to the fine soil texture in the study area. Poeplau *et al.* (2011) reported that a higher proportion of mineral and aggregate-bound SOC contributed to slower SOC dynamics in fine textured

soils compared with sandy soils in which the particulate SOC is more abundant.

4 Conclusions

The conversion of DS to AL caused a soil carbon sink. The combined use of irrigation, fertilizers, manure and plant residues has obviously changed the carbon content at the 100-cm depth in the last five decades. The abandonment and planting of forage on arable land led to sequestration of SOC, particularly in the topsoil layer. The afforestation on arable land had a negative effect on the SOC content at an early stage. After abandonment, however, the carbon sink is probably restricted under desert steppe conditions. Soil might degrade as vegetation regenerates to desert steppe during the secondary succession after abandonment. The carbon sequestration will be influenced by the degraded nutrient status of the soils. Thus, the carbon sink effect after abandonment may not be sustainable and might become a carbon source over time in the study area; however how long it would take is unknown.

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