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Water-soil-air-plant-human nexus: Modeling and observing complex land-surface systems at river basin scale

Key Points:
- The environmental factors interact, and they have complex influence on SOC
- The dominant factors for SOC are revealed, and revegetation advice is proposed
- Agricultural practices that promote the conservation of SOM should be recommended

Supporting Information:
- Supporting Information S1

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Vertical Distributions of Soil Organic Carbon and its Influencing Factors Under Different Land Use Types in the Desert Riparian Zone of Downstream Heihe River Basin, China

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Abstract The amount of soil organic carbon (SOC) reflects the ability of ecosystem to sequester carbon (C). In the desert riparian zone of Heihe River basin, northwest China, that has been the subject of an ecological water conveyance since 2000, studies on SOC under different land use types remain scarce. Yet analyzing soil organic carbon content (SOCC) and its spatial distribution in the area is a key component when studying C cycle in this desert ecosystem. We therefore investigated the vertical distribution of SOC and its influencing factors using field study, and we found significant differences among different land use types and soil depths. The average SOCC and soil organic carbon density in the 0–100 cm soil layers were 23.31 g kg^{-1} and 6.08 kg m^{-2}, respectively. SOCC and soil organic carbon density decreased in the following order: grassland (5.73 g kg^{-1}) > forestland (5.03 g kg^{-1}) > shrubland (4.79 g kg^{-1}) > cropland (4.28 g kg^{-1}) > Gobi desert (2.10 g kg^{-1}). We also found that vegetation and soil properties jointly affected SOCC in this riparian arid zone, in addition to human disturbance, as indicated by a low stratification ratio in the grassland (1.575) and cropland (1.366). When natural vegetation was transformed into cropland, SOCC decreased with the removal of plant biomass and the increase of wind erosion. Consequently, conservation agricultural practices that consider preservation of soil organic matter (e.g., no-tillage and intercropping with deep-rooted leguminous perennial plants) should be introduced in order to prevent further degradation.

1. Introduction

Soil is by far the largest carbon (C) pool in terrestrial ecosystem (Castellano et al., 2015; Luo et al., 2010). Globally, an estimate of 1,300–1,500 and 900 Gt of organic C stock is stored in the soil between 0 and 100 cm deep and between 100 and 200 cm deep, respectively (Kirschbaum, 2000; Schlesinger, 1990). While soil organic carbon (SOC) can be used as an important indicator of soil quality and soil fertility (Evans et al., 2006), in many regions, SOC is depleted by soil erosion and anthropogenic disturbance (Lal, 2003). As SOC accumulation and depletion processes influence global C cycle (Schrumpf et al., 2011), analyzing regional variation of SOC is important considering a highly spatial SOC distribution (Meersmans et al., 2009).

The arid area of China accounts for 25% of its total land area (Zhou et al., 2010) and has a significant C sequestration potential (Li, Wang, et al., 2015). It is also home to the desert riparian forests or "Tugai forests," which are mainly located in the floodplains of major central Asian rivers (Ding, Zhao, Daryanto, et al., 2017). Riparian zone is the linkage between terrestrial and aquatic ecosystems, and consequently, vegetation in the riparian zone is likely to be influenced by elevated water tables or extreme flooding and by the ability of soils to hold water. Desert riparian forests are the main communities in Heihe River basin, the second largest inland river in China (Zhao et al., 2016). Desert riparian forests are made up the core of the desert oasis which mainly comprised tree, shrub, and grass communities (Ding, Zhao, Daryanto, et al., 2017) and covered an area of 700 km^2. Before the implementation of ecological water conveyance project (EWCP or a diversion of water to downstream Heihe River since 2000), the low reaches (i.e., downstream) region experienced severe water shortages and environmental deterioration (Kharrazi et al., 2016). By delivering 300 billion m^3 of water every year, EWCP ensures a minimum amount of water to flow downstream and its implementation has significantly restored and supported a substantial vegetation regrowth (Trumbore, 2000; Yan et al., 2016).

With vegetation increase being considered one of the main reasons for increasing C sinks in terrestrial ecosystems including in the north and northwest China (Piao et al., 2009), desert riparian zone becomes a key area of ecological restoration (Liu et al., 2015). While there have been studies about SOC in the middle reaches of Heihe River basin (Li & Shao, 2014), there was no study of the SOC in the low reaches area after vegetation restoration. Since the middle and lower reaches of the Heihe river are very different in terms of vegetation composition and land use type (Li & Shao, 2014), research on SOC in the low reaches area has become critical.

Heihe River basin supports different land use types (e.g., forestland [FL], wetlands, grassland [GL], and cropland [CL]; Jiang et al., 2015), which has different potentials to sequester C. A large proportion of shrubs with rich herbaceous plants, for example, can sequester significant amount of C due to their dense rooting system (Li et al., 2016). In contrast, most C stock in the woodland consist of lignified litter that decomposes slowly, resulting in a low C turnover (Meersmans et al., 2009). Although it was not the intention of ecological water conveyance, there has been a large-scale expansion of CL with a guaranteed supply of water, which likely affects SOC accumulation. Currently, studies on SOC in downstream Heihe River basin only focused on the distribution and its variation in the riparian zone's topsoils (Li et al., 2016; Si et al., 2009). Yet deeper vertical distribution of SOC and possible mechanisms that lead to its variability remain unknown.

In this study, we measured SOC up to 100 cm deep in a desert riparian zone after 15 years of EWCP downstream Heihe River. The objectives of this work were (1) to quantify SOC under different land use types, including the vertical distribution of SOC content (SOCC) and SOC density (SOCD) concentrations, and (2) to analyze soil quality as influenced by selected biotic and abiotic factors, such as vegetation characteristics, soil physical, and chemical properties. This study will provide not only the basic data for subsequent studies but also the underlying mechanisms that lead to better understanding of C cycle in the region.

2. Materials and Methods

2.1. Study Area

The study area is located around Ejina Oasis, downstream Heihe River basin, northwestern China, where the Heihe alluvial plain lies (approximately 40°20′–42°30′N and 99°30′–101°45′E). The climate is a typical temperate continental climate with cold, long winter and hot, dry summers, and an average wind speed of 3.9 m s^{-1} (Ding, Zhao, Daryanto, et al., 2017). The average annual evaporation (>3,300 mm) is much larger than the average annual precipitation (<39 mm; Chen et al., 2014).

In this desert riparian zone, the trees are dominated by *Populus euphratica* Oliv., while the shrubs by *Tamarix ramosissima* Ledeb., followed by *Lycium ruthenicum* Murr., *Alhagi sparsifolia* Shap., and typical desert vegetation *Reaumuria songarica* (Pall.) Maxim. The herb species mainly consist of *Sophora alopecuroides* L., *Karelinia caspica* (Pall.) Less., and *Peganum harmala* L., while the CL is dominated by *Cucumis melo* L. plantation. The soils in the study area are mainly gypsum gray brown desert soils and gray brown desert soils, followed by brown desert soils, skeleton soils, and eolian sandy soils (Yu et al., 2013). Human population in Ejina is sparse (18,030 individuals in 2013; http://www.ejnq.gov.cn/Item/26075.aspx), and the local farmers are mainly engaged in cantaloupe farming and animal husbandry (Ding, Zhao, Daryanto, et al., 2017).

2.2. Sample Collection

In order to completely cover different land use types in the desert riparian forest of the study area, we established 69 sampling sites. All of those sites were located 1,000 m below sea level in the desert riparian zone, as part of Ejina Oasis, downstream Heihe River. Although previous studies indicated that the forests are distributed between 0 and 2,000 m from the river channel, corresponding to the influence range of ecological water conveyance our study extended beyond that range (i.e., up to 3,500 m from the river channel) to fully cover the distribution pattern of the desert riparian forests in downstream Heihe River. Between July and August 2015, 38 sampling sites were established, in addition to 31 sites between July to August 2016. The position of each sampling site (latitude, longitude, and elevation) was recorded using a Garmin GPS (version eTrex 30; Figure 1). The sites were selected based on five major land use types in this region; the number of CL, GL, FL, shrubland (SL), and Gobi desert (GD; Table 1). Different sampling number corresponded with the different coverage of each land use type, which have experienced rapid changes due to EWCP, for example, with the increase of CL by twofold since 2000 (Hu et al., 2015).

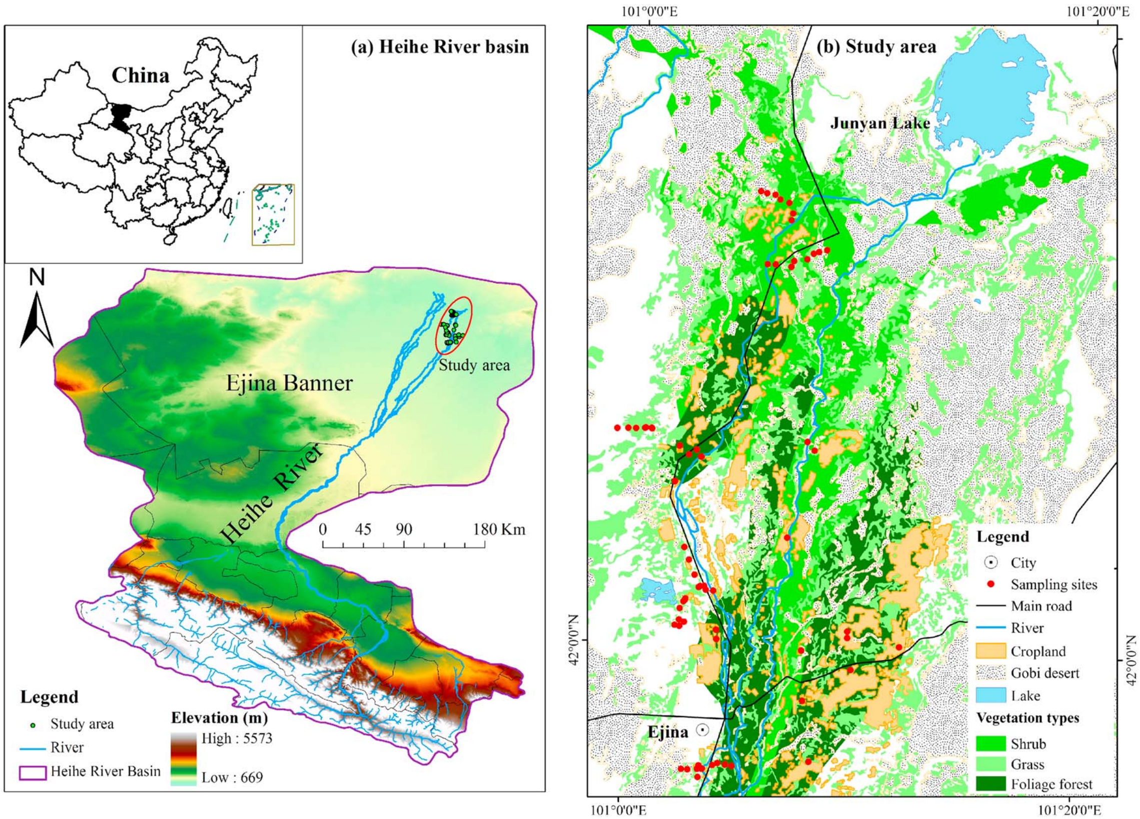

Figure 1. (a) The Heihe River basin in China and (b) the location of sampling sites in the study area.

2.2.1. Soil Sampling and Analysis

At each site, soil samples were randomly collected in three replicates using soil drilling (5 cm in diameter) at five soil layers (0–20, 20–40, 40–60, 60–80, and 80–100 cm). In sites where soil samples could not be collected using soil drilling (i.e., the soil was too loose), samples at four sampling points were collected by digging the soil profiles. After sampling, soils were weighed and dried in the oven at 105 °C for 48 hr to determine the soil moisture content (SMC). Soil bulk density (BD) of each soil layer was measured separately using cutting ring (100 cm^3). Ground temperature (GT) in each soil layer was recorded using geothermometer. Three additional replicate samples were collected from each layer, air-dried, sieved through a 2-mm sieve, and mixed in order to measure the following soil physical and chemical properties: soil particle size, SOCC, pH, electrical conductivity (EC), total nitrogen (TN), total potassium, total phosphorus (TP), and total salt content (TS). Soil particle size distributions (clay $<$ 0.002 mm, silt 0.002–0.05 mm, and sand 0.05–2 mm) were measured by using Malvern Mastersizer 2000. The SOCC was determined by the dichromate oxidation method (Kalembasa & Jenkinson, 1973). Soil pH was measured with a pH meter (PH-3CW) and soil EC with an EC mater (DDS-307W) using 1:5 soil: water suspension. Kjeldahl method was used to determine soil TN. TS was determined by oven method (Liu et al., 1996), and TP was determined using a UT-1810PC spectrophotometer (PERSEE, Beijing, China), after H_2SO_4-$HClO_4$ digestion.

Stratification ratio (SR), defined as the ratio of SOC at the surface layer to that at a deeper layer, was used to evaluate soil quality. High SR values ($>$2) usually indicate good soil quality (Corral-Fernández et al., 2013; Li et al., 2016). In this study, SR was the ratio between SOCC at 0–20 cm deep to that at 40–60 cm deep. Since the inherent soil differences can be indicated by an internal normalization procedure, SR allows a wide diversity of soil to be compared on the same assessment scale (i.e., same thickness of soil layer; Franzluebbers, 2002).

Table 1
Main Types of Plant on Different Types of Land Use

Land use types	Dominant plant species	Sampling number
Cropland (CL)	*Cucumis melo* L.	8
Grassland (GL)	*Sophora alopecuroides* L.; *Karelinia caspia* (Pall.) Less.	14
Forestland (FL)	*Populus euphratica* Oliv.	14
Shrubland (SL)	*Tamarix ramosissima* Ledeb.; *Lycium ruthenicum* Murr.	25
Gobi desert (GD)	*Reaumuria songarica* (Pall.) Maxim.	8

Soil organic carbon density was calculated using the following formula (Guo & Gifford, 2002):

$$\mathrm{SOCD} = \sum_{i=1}^{n} \mathrm{SOCD}_i = \sum_{i=1}^{n} \mathrm{SOC}_i B_i T_i (1 - G_i) \times 10^{-2} \quad (1)$$

where SOCD is the soil organic carbon density (kg m^{-2}); SOCD$_i$ is the SOCD of soil layer i (kg m^{-2}); B_i for the bulk density of soil layer i (g cm^{-3}); T_i is the thickness of soil layer i (cm); G_i is the gravel content (>2 mm) of soil layer i; and 10^{-2} is the unit conversion coefficient.

2.2.2. Vegetation Sampling and Analysis

In each site (except for CL sites), three 30 m × 30 m quadrats and three 10 × 10 m quadrats were selected randomly for tree and shrub investigation, respectively. The number of each species (tree and shrub), plant crown width (cm), plant height, coverage, and the diameter at breast height of the trees were recorded individually. In addition, four herb quadrats (2 m × 2 m) were established at each corner of the tree or shrub quadrat to collect data on the number of herb species, vegetation cover, height, aboveground biomass (g m^{-2}), and underground biomass (g m^{-2}), with the exception of GLs. In all GL plots, three herb quadrats (2 m × 2 m) were established randomly at each plot. Herb aboveground biomass was obtained by full cutting, and underground biomass was obtained by full excavation. Full excavation means that we dug up the underground biomass of herbaceous plants, up to 60 cm deep to obtain root biomass as accurately as possible according to the direction of the main root. The harvested biomasses were washed with water to remove any impurities and oven-dried at 65 °C to constant weight to determine the biomass. The diversity index of vegetation in the different ecosystems (GL, SL, FL, and GD) was calculated using the following four formulas (Li et al., 2016).

$$\text{Patrick richness index } (R) = S \quad (2)$$

$$\text{Simpson dominance index } (D) = \sum_{i=1}^{S} P_i^2 \quad (3)$$

$$\text{Shannon} - \text{Wiener diversity index } (H) = -\sum_{i=1}^{S} P_i \ln(P_i) \quad (4)$$

$$\text{Pielou evenness index } (E) = H/\ln(S) \quad (5)$$

where S is total number of plant species in each corresponding sample plot; $P_i = N_i/N$, N_i is number of individuals of one species, and N is total number of all individuals in the sample.

2.3. Statistical Analysis

The basic statistical parameters (mean, standard deviation, minimum, maximum, kurtosis, skewness, and coefficient of variation) were calculated and reported for each soil layer (Table S1 in the supporting information). The vertical distribution of SOCC and SOCD averaged across different land use type is also provided in Figure S1 in the supporting information. The Kolmogorov-Smirnov test was used to test the normality of variable distribution. Since all tested variables showed normal distribution, subsequent one-way analysis of variance was performed on SOCC and SOCD at each soil depth (layer) to understand the effects of vegetation types on the vertical distribution of SOC. In addition, one-way analysis of variance was used to test whether the SOCC and SOCD differed significantly between different soil layers in the same land use types (Table S2). If significant difference was detected at $P < 0.05$, post hoc differences in means were examined using least significant difference testing.

Pearson's correlation coefficient was used to analyze the correlation between SOCC and soil properties at each soil layer and between SOCC and vegetation properties. The environmental variables that had high weighted factor loadings were obtained by reducing the dimension of environmental variables by means of principal component analysis (PCA); the effect of a possible linear correlation between factors was also excluded (Webster, 2001). PCA analysis was performed only for variables that had a significant correlation with SOCC in the Pearson's correlation analysis. Therefore, due to constraint of variable availability that had significant correlations with SOCC, no PCA was performed of SL and CL.

It is worth noting that only principal components (PCs) having eigenvalues ≥1.0 and variables having highly weighted factor loading (i.e., those with absolute values for factor loading within 10% of the highest value)

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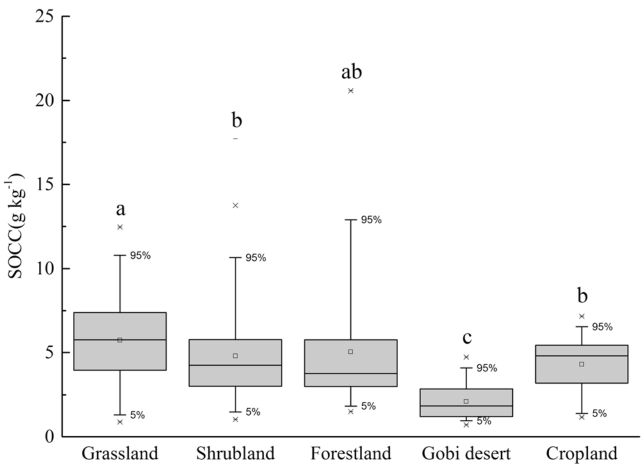

Figure 2. Soil organic carbon content for different land use types. Means with the same letter above the box are not significantly different at 0.05 significance level (least significant difference test).

were reserved for stepwise multiple linear regression (Andrews et al., 2002; Mandal et al., 2008). These regressions were performed using the filtered variables as inputs to explore the key factors that affect SOCC. Because CL was covered in mulch during the growth period, vegetation factor indicators were difficult to obtain and worked poorly in indicating the environment. Therefore, vegetation factors and some of the soil nutrient factors were removed from CL analysis since tillers added N, P, and K fertilizers to different degrees before sampling. In this study, both data processing and statistical analysis were conducted using SPSS (SPSS 20) and R 3.3.2, while plotting was conducted using Origin 9.2.

3. Results

3.1. Distribution of Soil Organic Carbon Under Different Land Use Types

The SOCC in 0–100 cm soil layer of the desert riparian zone in the downstream of Heihe River was between 5.72 and 43.57 g kg^{-1}, with the mean value of 23.31 g kg^{-1} across different land use types (Table S1). When differentiated according to different land uses, SOCC varied in the following order: GL (5.73 g kg^{-1}) $>$ FL (5.03 g kg^{-1}) $>$ SL (4.79 g kg^{-1}) $>$ CL (4.28 g kg^{-1}) $>$ GD (2.10 g kg^{-1}), although SOCC in FL, SL, and CL were not significantly different (Figure 2). Variation of SOCC was higher in FL, GL, and SL, followed by in CL and GD (Figure 2).

This study found different types of land use exerted different influence on SOCC and SOCD at different soil depths (Figure S2 and Table 2). In the surface layer (0–20 cm), GL and FL had significantly higher SOCC and SOCD compared to GD and CL, although the difference between GD and CL, as well as between FL, GL, and SL, was not significant. In the deepest layer (80–100 cm), SOCC in GD was significantly lower than other land types; SOCC and SOCD were different significantly between GL and SL ($P < 0.05$; Table 2). In addition, the proportion of SOCC in each soil layer relative to the overall SOCC in 0–100 cm soils tended to decline with depth (Table 2). There was also greater proportion of SOCC in the 0–40 cm soil layer for FL, SL, GL, and GD (i.e., 50%) compared to only 45% in CL (Table 2). Indeed, there was no difference between SOCC and SOCD in different soil depths at CL (Table S2).

The result of the SR for SOCC in the desert riparian zone in the downstream Heihe River indicated that FL performed best in retaining SOC. FL had an SR value of 2.39, in contrast to that of CL (i.e., 1.37), the lowest among all land use types. Although SR was not significantly different between SL, GL, and GD, in terms of absolute value, SL might still have better soil quality than GL and GD by having an SR value ≥2 (Figure 3).

3.2. Factors Influencing the Distribution of Soil Organic Carbon Content

3.2.1. Correlation Analysis Between Soil Organic Carbon and Environmental Factors

We found that SOCC in different land use types was explained by different explanatory variables. In FL, there were significant correlations between SOCC at different soil layers and soil properties (i.e., TN [0–60 cm], SMC [0–20 cm and 80–100 cm], BD [0–20 cm], and soil particle-size composition in the shallow layer [0–40 cm]) as well as grass height and herb belowground biomass (HBGB; Table 3). Fewer explanatory variables were found in SL, in which SOCC was positively correlated with TN (60–80 cm), TP (60–100 cm), shrub height (SH), and Patrick richness index (R; Table 3). In GD, SOCC was positively correlated with TN, TP, silt, clay, and SMC but negatively correlated with BD and sand. Vegetation factors including shrub crown width, SH, R, and Pielou evenness index (E) were also significantly correlated with SOCC in GD (Table 3). SOCC in GL showed significant correlations with TN (60–80 cm), TP (0–20 cm), pH (20–40 cm), and BD (80–100 cm), as well as with vegetation properties such as Simpson dominance index (D), Shannon-Wiener diversity index (H), and grass coverage (Table 3). In CL, the SOCC was positively correlated with EC and SMC but was negatively correlated with BD and GT (Table 3).

3.2.2. Principal Component Analysis

Our result showed that there were four PCs for FL, which explained 83% of the variance. Of the four PCs, the first three PCs contributed 73% explanation of the variance (Table 4). In PC1, variables with high factor loadings were soil pH and TN, followed by TS in PC2, SMC and HBGB in PC3, and grass height in PC4 (Table 4).

Table 2
Soil Organic Carbon Content (SOCC) and Soil Organic Carbon Density (SOCD) for Different Land Use Types

	Depth	GL		SL		FL		GD		CL	
	(cm)	Mean ± SD	Proportion	Mean ± SD	Proportion	Mean ± SD	Proportion	Mean ± SD	Proportion	Mean ± SD	Proportion
SOCC ($g\ kg^{-1}$)	0–20	7.99 ± 3.20a	0.28	7.28 ± 4.03ab	0.31	8.59 ± 5.61a	0.34	3.04 ± 1.22c	0.29	4.89 ± 1.29bc	0.23
	20–40	6.39 ± 2.36a	0.22	5.83 ± 2.10a	0.24	5.62 ± 2.90a	0.22	2.39 ± 0.90b	0.23	4.83 ± 1.25a	0.22
	40–60	5.47 ± 1.70a	0.19	4.22 ± 1.64b	0.18	4.18 ± 1.72b	0.17	1.85 ± 0.77c	0.18	3.85 ± 1.43b	0.18
	60–80	4.66 ± 2.15a	0.16	3.44 ± 1.54b	0.14	3.62 ± 1.38ab	0.14	1.81 ± 1.04c	0.17	3.89 ± 1.58ab	0.18
	80–100	4.14 ± 1.86a	0.15	3.17 ± 1.13b	0.13	3.16 ± 0.93ab	0.13	1.40 ± 0.55c	0.13	3.99 ± 2.30ab	0.19
SOCD ($kg\ m^{-2}$)	0–20	2.08 ± 0.82a	0.27	1.80 ± 1.16a	0.30	2.10 ± 1.16a	0.32	0.89 ± 0.39b	0.30	1.45 ± 0.35ab	0.23
	20–40	1.70 ± 0.66a	0.23	1.44 ± 0.51a	0.24	1.53 ± 0.76a	0.24	0.70 ± 0.30b	0.24	1.41 ± 0.30a	0.23
	40–60	1.49 ± 0.45a	0.19	1.06 ± 0.47b	0.18	1.04 ± 0.39b	0.16	0.45 ± 0.11c	0.15	1.10 ± 0.41b	0.18
	60–80	1.25 ± 0.58a	0.16	0.85 ± 0.42bc	0.14	0.96 ± 0.42ab	0.15	0.51 ± 0.32c	0.17	1.14 ± 0.48ab	0.18
	80–100	1.12 ± 0.47a	0.15	0.79 ± 0.31b	0.14	0.84 ± 0.28ab	0.13	0.40 ± 0.18c	0.14	1.12 ± 0.63a	0.18

Note. GL, SL, FL, GD, and CL refer to grassland, shrubland, forestland, Gobi desert, and cropland, respectively. The letters next to the mean ± SD indicate significant difference between land use types at 0.05 level of probability. Proportion represents each layer of SOCC (SOCD) accounts for the proportion of total (0–100 cm) SOCC (SOCD).

The two other land use types, GD and GL, each had three PCs. Three environmental variables with the highest factor loadings in the PC1 of GD are sand, silt, and clay content (Table 4), which represented soil particle-size composition. PC2 was correlated to SMC and E, while PC3 with TP (Table 4). Variables with high factor loadings in the PC1 of GL were GT, pH, and total potassium, while PC2 and PC3 were represented by soil nutrients (TN and TP) and vegetation diversity variables, respectively (Table 4). It should be noted that there was no PCA for SL and CL since only four variables in SL and CL had significant correlations with SOCC (Table 3).

3.2.3. Multiple Linear Regression Analysis

Different soil and vegetation properties explained SOCC variation in each land use type. TN, TS, and HBGB explained 44.7% of the variation in SOCC in FL, wherein the first two factors had a positive effect on the increase of SOCC (Table 5). For SL, TN and SH explained 30% of the variation in SOCC. TN and GT explained 73.5% of SOCC variability in GL. Meanwhile, E explained 33.8% of SOCC variation in GD, and GT explained 39.2% of SOCC variation in CL.

4. Discussion

4.1. Characteristics of Vertical Distribution and Variation of Soil Organic Carbon

We found that SOCC and SOCD in the arid riparian zone varied with different land use types. In general, they were highest on the surface layer and decreased with depth (Table 2 and Figure S1). These results were unsurprising, given most of organic matter in the soil was derived from plant litter. Consequently, the quantity of SOCC was greatly affected by the dominant plant species, consistent with many other studies in the dry areas (Daryanto et al., 2012; Li & Shao, 2014). Apart from litter, root biomass also contributes to the variability in SOC between different land use types, even to the deep soil layers (Imada et al., 2013; Trumbore, 2000). More than 60% of root biomass in GL of the Inner Mongolia is distributed in the 0–20 cm layer (Ma et al., 2008), and this skewed distribution of root biomass likely contributed to high SOCC on the top surface of the landscape. In contrast, the fine roots of trees are mainly distributed below 100 cm and they can be deeper as the frequency of drought increases (Xiao & Huang, 2016).

We also found greater variability of SOCC in the surface soil compared to the deeper soil layers, which partly led to differences in the SR (Figure 3). Apart from litter effect, numerous other factors such as wind, precipitation (Su et al., 2009), as well as land use change associated with human activities (Wang et al., 2012) increased SOCC variability in the surface. According to our field survey, low SOCC in the top 60 cm of CL corresponded to the tillage depth in the study area (i.e., 50–55 cm). In contrast, the absence of human disturbance in GD allowed the formation of biological soil crusts, which became a key factor in maintaining soil quality (Finstad et al., 2016). While GL had the highest SOCC and SOCD compared to other land use types (Table 2), its SR was lower than FL (Figure 3). Previous study showed that severe wind erosion and human disturbance could be the main reasons for the decrease of SR (Hernanz et al., 2009). Grazing and tourism are among common human disturbances found in GL (Ding, Zhao, Daryanto, et al., 2017), leading to the destruction of soil structure and exposure of SOC in the topsoil. Conversely, SR in FL

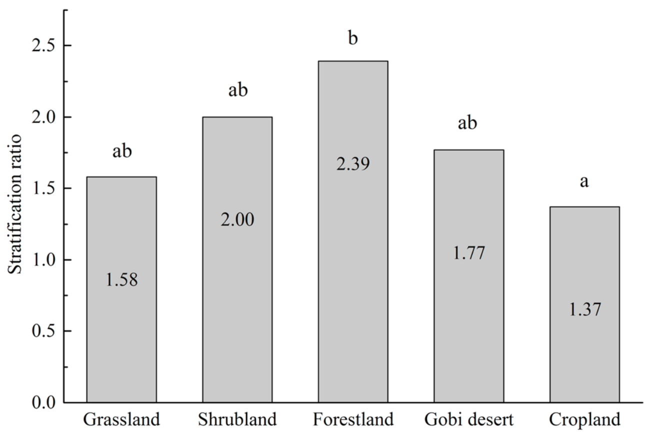

Figure 3. Stratification ratio of soil organic carbon content under different land use types. Means with different small letters are significantly different at 0.05 level.

were better due to the establishment of protected enclosures and local establishment of *P. euphratica* Oliv.

Compared to other land uses, we found no significant difference in SOCC and SOCD between different soil layers in CL (Table S2), in addition to a slight (but not significant) increase of SOCC and SOCD in the 60–100 cm soil layer compared to the 40–60 cm layer (Table 2). While one can easily envision that soil mixing during tillage process can reduce SOC difference between different soil depths (Liu et al., 2006), increasing SOC in the deep soil layers may be counterintuitive to explain. The mechanisms, however, could involve a combination of leaching or water transport (Li & Shao, 2014) and the legacy of the previous landscapes. Due to the common use of flood irrigation in the area, nutrients and fine particles may leach to deeper layers during the processes of infiltration (Li, Guo, et al., 2015). According to the monthly irrigation data sets (for both surface water and groundwater, 1981–2013) with 30-s spatial resolution over the Heihe River Basin (http://westdc.westgis.ac.cn/), the volume of irrigation from January to December 2013 was 0, 0, 0, 31,366.73, 179,164.46, 230,507.39, 458,933.73, 764,672.63, 524,745.35, 969,098.89, 1,296,214.49, and 0 m^3/month (Zeng et al., 2016) for an area of 638,341.43 m^2. This amount (6,979 mm) was much larger than the mean annual precipitation in the area (<39 mm). Since the conversion of natural landscape to agriculture only happened during the last 15 years (Hu et al., 2015), the lack of vertical soil mixing in the deep CL soil layers protected the remaining SOC from oxidation.

4.2. The Influencing Mechanisms on Soil Organic Carbon Distribution

Our Pearson correlation analysis showed that SOCC was strongly correlated with the amount TN in the soil of GL, SL, and FL (Table 3). In many ecosystems, C and N in the soil are two closely related biogeochemical processes (Hagedorn et al., 2003). As one of the most important nutrients for plant growth, N also regulates the ecosystem productivity in the arid areas, for example, by controlling the quality and quantity of litter and root exudates entering the soil (Imada et al., 2013). There are at least two species of leguminous shrubs (*Hedysarum scoparium* Fisch. et Mey. and *A. sparsifolia* Shap.) in our study sites (Li et al., 2016) that likely maintain the input of N in this desert riparian zone and indirectly increase SOCC. Partly due to their contribution, the increasing amount of TN likely influences the amount of SOCC (Bronson et al., 2004), including SOCC variation in FL, SL, and GL (Table 5).

In our study, soil texture could play a dominant role in determining the accumulation of SOC in Heihe riparian zone. There was a significant positive correlation between SOCC and clay/silt content, but a significant negative correlation with sand content (Table 3). In addition, silt content was the key factor affecting SOCC in FL (Table 5). These results were therefore consistent with studies showing that soil clay and silt content contribute to the formation and preservation of SOC (Corral-Fernández et al., 2013). Fine particles and microaggregates in the soil can protect soil organic matter (SOM) from decomposition (Zinn et al., 2005). Relatively small pores in soil can promote the aggregation of SOC and physically protect SOC against oxidation (Li et al., 2016).

In addition to soil texture, GT has been recognized as one of the important factors influencing SOC (Alvarez & Lavado, 1998). In this study, GT and TN explained 73.5% of the SOCC variation in GL (Table 5) and there was a significant negative correlation between GT and SOCC in GL (20–40 cm) and CL (80–100 cm; Table 3). These results showed that increases in GT had a generally negative effect on SOC accumulation in this riparian zone. Studies have found that a positive correlation between temperature and soil respiration; the latter is an important channel for organic C outputs from the soils (Davidson & Janssens, 2006). In the Indian Himalayan Region, for example, SOCC decreased by 0.3% from 1978 to 2004 due to temperature rise (Martin et al., 2010).

Meanwhile, the dynamic changes of SMC also affect the accumulation and decomposition of SOC. Water saturation or poor drainage in the soils will lead to the formation of anaerobic layers, reducing the oxidative decomposition of SOC (Meersmans et al., 2009). By stimulating vegetation growth, SMC also generates a

Table 3
Pearson Correlation Between SOCC and Selected Environmental Variables in Various Soil Layers of FL, SL, GD, GL, and CL

	GL					SL					FL				
	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
pH	0.63	**0.71**	0.57	−0.55	0.12	−0.11	0.08	0.12	0.53	−0.45	0.23	0.12	0.08	0.47	**0.79**
EC	−0.39	−0.70	−0.19	−0.04	−0.18	0.24	0.22	−0.24	−0.14	0.37	0.61	−0.07	−0.37	0.07	0.10
TN	**0.74**	**0.69**	0.52	**0.57**	**0.55**	0.33	0.11	0.15	**0.48**	0.40	**0.79**	**0.78**	**0.80**	0.55	0.41
TP	**0.74**	**0.73**	**0.75**	0.47	0.25	0.36	0.31	0.64	**0.66**	**0.72**	0.35	0.45	0.36	−0.14	−0.12
TS	0.09	−0.38	0.45	0.58	0.66	0.26	0.08	0.22	0.39	0.24	0.42	−0.04	−0.15	0.03	−0.34
TK	0.42	**0.84**	0.64	0.69	0.32	0.35	0.18	0.08	−0.03	−0.43	−0.70	−0.07	0.45	0.17	0.11
BD	−0.42	−0.08	−0.35	−0.23	**−0.62**	−0.12	−0.35	−0.12	−0.20	−0.17	**−0.73**	−0.38	−0.39	0.14	0.13
SMC	0.44	−0.42	0.17	0.03	0.05	−0.04	−0.17	−0.12	−0.05	0.22	**0.60**	0.46	0.22	0.41	**0.68**
GT	0.03	**−0.82**	−0.12	−0.39	−0.31	−0.28	−0.46	−0.55	−0.42	0.05	−0.38	−0.04	0.44	0.49	−0.02
Sand (%)	−0.18	−0.38	−0.02	−0.18	−0.24	0.20	0.40	0.04	0.13	0.09	**−0.88**	**−0.80**	−0.35	0.60	−0.22
Silt (%)	0.07	0.18	0.54	0.17	0.21	−0.26	−0.41	−0.04	−0.10	−0.14	**0.75**	**0.91**	0.46	−0.50	0.34
Clay (%)	0.38	0.08	−0.11	−0.05	0.17	0.15	−0.23	−0.03	−0.15	0.10	**0.98**	0.64	0.08	−0.67	−0.14
TCW											−0.32	−0.03	0.29	0.18	0.05
TH											−0.47	−0.25	0.32	−0.05	0.02
DBH											−0.19	−0.23	0.09	0.16	0.12
SCW						0.05	0.22	0.29	0.19	−0.14	−0.33	**−0.73**	−0.16	0.16	0.17
SH						0.18	**0.51**	**0.45**	**0.51**	0.09	−0.09	−0.41	−0.24	0.38	0.22
SBD						−0.06	0.26	0.26	0.20	0.03	−0.29	−0.07	0.04	−0.26	−0.20
GC	0.47	0.15	**0.60**	0.15	0.39	−0.17	−0.35	−0.16	−0.05	−0.15	0.46	0.53	0.41	0.02	0.22
GH	0.03	0.29	0.09	0.28	0.14	−0.03	−0.20	−0.14	−0.10	−0.37	0.30	**0.77**	0.51	−0.35	0.22
HAGB	−0.09	0.01	0.14	0.08	0.27	−0.03	−0.02	−0.33	0.10	−0.07	0.23	0.52	0.45	0.29	−0.10
HBGB	−0.27	0.53	0.13	−0.18	0.37	0.30	0.80	0.31	0.54	−0.65	−0.2	0.86	**0.96**	0.65	0.93
R	0.45	0.38	0.01	−0.18	−0.40	0.01	−0.15	**−0.40**	−0.09	0.01	0.22	−0.14	−0.04	−0.01	−0.03
D	−0.47	**−0.60**	−0.25	−0.01	0.04	0.01	0.22	0.15	−0.04	0.01	−0.48	0.05	0.38	0.15	−0.04
H	0.45	**0.58**	0.21	−0.02	−0.09	−0.10	−0.26	−0.21	−0.02	−0.13	0.49	0.00	−0.33	−0.06	0.04
E	0.31	0.45	0.11	−0.17	−0.16	−0.06	−0.25	−0.06	0.04	0.04	0.37	−0.13	−0.39	−0.23	0.08

Note. Significant correlations ($P < 0.05$) are shown in bold, and very significant correlations ($P < 0.01$) are shown in bold with underlines. EC, soil electrical conductivity; TN, total nitrogen; TP, total phosphorus; TS, total salt; TK, total potassium; BD, soil bulk density; SMC, soil moisture content; GT, ground temperature; TCW, tree Crown width; TH, tree height; SCW, shrub crown width; SH, shrub height; SBD, shrub basal diameter; GC, grass coverage; GH, grass height; HAGB, herb aboveground biomass; HBGB, herb belowground biomass; R, Patrick richness index; D, Simpson dominance index; H, Shannon-Wiener diversity index; E, Pielou evenness index. I-V: SOCC at different soil layer depth ranges, I: 0–20 cm, II: 20–40 cm, III: 40–60 cm, IV: 60–80 cm, V: 80–100 cm.

positive feedback on SOCC as vegetation increases the flux of C into the soil and protects the soil from erosion (Li et al., 2012). In this study, SMC had a positive effect on the accumulation of SOC in the desert riparian zone, indicated by their significant positive correlations in the FL, GD, and CL (Table 3). The relationship between soil moisture and SOC is different from existing studies which showed a negative effect due to microbial decomposition (Zhang & Shangguan, 2016).

Since vegetation is an important source of SOC, plant growth and subsequent decomposition determine the rate at which organic C enters the soil, including its quality (Fu et al., 2010). We consider higher SOCC in FL, SL, and GL to be related to the increase in above-ground biomass and root-system biomass. Among the most important contributors to this SOC increase is a continuous expansion of perennial trees (*P. euphratica* Oliv., *T. ramosissima* Ledeb., and *S. alopecuroides* L.) along Heihe riverbanks, which also provide numerous ecological services to the oasis (Ding, Zhao, Daryanto, et al., 2017). As vegetation canopy corresponds to the spatial variation of SOC in the arid ecosystem (Daryanto et al., 2013), one could expect greater C sequestration with increasing shrub crown width and SH. Carbon fixation via photosynthesis, and the subsequent transfer of C to the soil via leaf litter and root turnover, contributes to the accumulation of C in the soil (Cheng et al., 2015). Higher C input from surface litter, roots, root exudates, and root debris contribute to higher SOC stocks in the surface layer; some of these will be transferred to the deeper layer by soil fauna, in addition to input by roots and microbial activity (Paterson et al., 2009).

In addition, community diversity indices (D, H, and E) were the environment variables with high factor loadings, which could explain SOCC variability to certain extents (Table 4). Since grasses were the dominant vegetation in GL and herb species increased plant species richness and ecosystem productivity in FL (Ding, Zhao, Daryanto, et al., 2017), it was unsurprising if grass coverage and herb biomass were positively

Table 3
(continued)

	GD					CL				
	I	II	III	IV	V	I	II	III	IV	V
pH	0.66	−0.57	−0.37	0.21	0.04	0.23	0.32	−0.36	0.31	0.44
EC	0.59	−0.22	**0.71**	0.11	**0.74**	0.15	**0.73**	0.47	0.52	0.66
TN	0.15	**0.81**	**0.85**	0.70	−0.27					
TP	−0.42	0.60	**0.71**	0.18	0.07					
TS	−0.09	0.38	−0.02	−0.28	0.57					
TK	0.07	0.39	0.40	0.33	−0.06					
BD	−0.44	−0.29	−**0.91**	−0.10	−0.30	−0.60	−**0.88**	−0.14	−0.03	−0.49
SMC	0.53	0.46	**0.79**	0.20	0.58	0.40	0.47	0.40	**0.74**	0.60
GT	0.42	0.25	−0.13	0.53	−0.07	−0.15	−0.53	−0.70	−0.43	−**0.85**
Sand (%)	−0.58	−**0.87**	−**0.82**	0.51	−0.19					
Silt (%)	0.55	**0.89**	**0.82**	0.51	−0.13					
Clay (%)	0.62	0.68	**0.71**	0.47	0.36					
TCW										
TH										
DBH										
SCW	0.25	0.66	**0.71**	0.22	0.09					
SH	0.34	**0.71**	**0.81**	0.41	0.28					
SBD	0.32	0.19	0.17	−0.16	−0.09					
GC	0.24	**0.88**	**0.97**	0.34	0.49					
GH	−0.48	0.85	0.75	0.49	0.56					
HAGB	−0.11	0.17	0.32	0.38	−0.14					
HBGB										
R	0.38	**0.81**	0.86	0.12	0.05					
D	−0.39	−0.15	0.22	0.30	0.43					
H	0.54	0.20	−0.11	−0.21	−0.36					
E	−0.36	−0.50	−**0.77**	−0.65	−0.53					

correlated with SOCC in both landscapes. Correspondingly, SOCC in GD with sparse vegetation was sensitive to the effect of R (Table 3). Our results were therefore similar to a study showing that high R and increasing number of plants significantly improve organic C inputs (Sousa et al., 2012). Taken together, communities with high species diversity in arid areas tend to have more vegetation biomass (Tian et al., 2016). A large amount of litter on the soil surface and root biomass provide a suitable living environment for numerous soil bacteria, microbes, and enzymes, which in turn promotes the cycling of SOM (Paterson et al., 2009).

4.3. The Effect of Ecological Water Conveyance Project and Tillage on Soil Organic Carbon

Langxinshan hydrological station that recorded the total runoff into the downstream Heihe River indicated a significant increase in runoff after EWCP (Figure S3). Correspondingly, vegetation in the desert riparian zone of the downstream Heihe River has been significantly restored, shown by the increase in vegetation species diversity and NDVI (Ding, Zhao, Daryanto, et al., 2017; Ding, Zhao, Fu, et al., 2017). With the increase of vegetation, the input source of SOM also increased, improving soil structure and SOCC. Compared previous research in 2008 which showed that the average SOCC on the top 20 cm soil was only 2.89 g kg^{-1} (Si et al., 2009), our results showed a much higher amount (6.93 g kg^{-1}). This number was also higher compared to other arid areas (e.g., $<$6 g kg^{-1} in the oasis of south Tarim basin, Xinjiang; Huang et al., 2014). The SOCC in the downstream Heihe River was lower than that in the middle reaches, likely due to differences in long-term scarce precipitation and sparse vegetation. In the middle reaches of the Heihe River, SOCC on the top 40-cm soil in CL was higher than GL and FL, likely due to the application of farmyard manure in the CL (Li et al., 2016). This was quite different from our findings (Table 2).

While the influence of soil and vegetation dominated the SOC cycling processes in GL, FL, and SL, their effects were less apparent in CL due to the effect of human disturbance. SOCC was positively correlated with SMC but was negatively correlated with GT and BD in CL (Table 3). Continuous tillage has been associated with increasing BD (Dam et al., 2005) and exacerbates the effects of wind and water erosion on SOC (Quinton

Table 4
Principle Component Analysis (PCA) of Environmental Variables

	FL				GD			GL		
Principal component	PC 1	PC 2	PC 3	PC 4	PC 1	PC 2	PC 3	PC 1	PC 2	PC 3
Eigenvalue	3.7	2.2	1.4	1.0	7.2	1.5	1.1	4.3	1.9	1.1
Proportion %	37.0	22.0	14.0	10.0	56.0	11.0	9.0	48.0	21.0	12.0
Cumulative %	37.0	59.0	73.0	83.0	56.0	67.0	76.0	48.0	68.0	81.0
Factor loading										
GT								**0.96**	−0.13	0.18
EC					0.08	0.61	−0.03			
pH	−**0.95**	0.15	−0.02	−0.21				**0.96**	−0.16	0.14
TN	**0.92**	0.01	0.03	0.21	0.45	−0.04	0.73	−0.32	**0.85**	−0.01
TP					0.02	0.12	**0.90**	−0.13	**0.85**	−0.25
TK								**0.94**	0.02	0.21
BD	−0.37	−0.52	0.30	0.49	−0.59	−0.39	−0.06	−0.25	−0.61	0.35
SMC	0.07	0.52	**0.66**	−0.01	0.09	**0.79**	0.25			
Sand (%)	0.53	−0.62	0.32	0.33	−**0.92**	0.12	−0.28			
Silt (%)	0.53	**0.75**	−0.11	0.18	**0.90**	0.07	0.28			
Clay (%)	0.58	0.64	−0.27	0.08	**0.84**	0.26	0.14			
SCW	0.55	−0.44	0.54	−0.22	0.60	0.11	0.72			
SH					0.64	0.30	0.64			
GC					0.53	0.48	0.53	−0.03	−0.19	0.58
R					0.70	0.28	0.46			
E					−0.34	−**0.79**	−0.10			
D								0.37	−0.12	**0.87**
H								−0.42	0.15	−**0.84**
GH	−0.51	0.27	0.21	**0.67**						
HBGB	−0.61	0.25	**0.56**	0.10						

Note. PC refers to principal components. GT, ground temperature; EC, soil electrical conductivity; TN, total nitrogen; TP, total phosphorus; TS, total salt; TK, total potassium; BD, soil bulk density; SMC, soil moisture content; SCW, shrub Crown width; SH, shrub height; GC, grass coverage; R, Patrick richness index; D, Simpson dominance index; H, Shannon-Wiener diversity index; E, Pielou evenness index; GH, grass height; HBGB, herb belowground biomass. Highly weighted factor loadings are marked in bold.

Table 5
Result of Multiple Linear Regression Analysis for Soil Organic Carbon Content (SOCC) at Various Land Use Types

Land use types	Variables	Coefficients	Standard error	*t*-value	Significance level
FL	Constant	−16.478	10.611	−1.553	0.126
	TN	4.385	1.103	3.976	0.000
	Silt (%)	0.033	0.010	3.408	0.001
	HBGB	−0.175	0.055	−3.184	0.002
	R^2	0.447			
SL	Constant	−0.045	1.129	−0.039	0.169
	TN	4.263	1.059	4.026	0.000
	SH	0.008	0.003	2.521	0.014
	R^2	0.300			
GL	Constant	19.409	17.375	1.117	0.172
	TN	9.500	1.831	5.187	0.000
	GT	−0.451	0.130	−3.479	0.001
	R^2	0.735			
GD	Constant	4.526	1.133	3.995	0.000
	E	−3.352	1.624	−2.064	0.047
	R^2	0.338			
CL	Constant	14.685	4.562	3.219	0.003
	GT	−0.352	0.126	−2.798	0.008
	R^2	0.392			

Note. GL, SL, FL, GD, and CL refer to grassland, shrubland, forestland, Gobi desert, and cropland, respectively. TN, total nitrogen; GT, ground temperature; HBGB, herb belowground biomass; SH, shrub height; E, Pielou evenness index.

et al., 2010). In contrast, tillage reduction and/or no-tillage may reduce wind erosion and can be an effective method to improve C sequestration in CL (Li et al., 2016). Although tillage reduction and/or no-tillage may reduce wind erosion and can be an effective method to improve C sequestration in CL (Li et al., 2016), we do not know how these practices may affect crop yield. Therefore, future studies may be directed toward the application of conservation agriculture in Heihe River basin, including farmers' perception of the practice.

5. Conclusion

Our study indicated that different land use types led to different SOC accumulation in Heihe River Basin. The SOC in the study area has great potential to increase. Among the most important influencing factors that contributed to such variability were vegetation types and land management after EWCP. Vegetation is an important source of SOC; plant growth and subsequent decomposition determine the rate at which organic C enters the soil, including its quality. Soil texture (i.e., soil clay and silt content) played a key role in determining the accumulation and preservation of SOC in Heihe riparian zone.

Although the EWCP increases the downstream flow and brings a favorable opportunity for agricultural development (Hu et al., 2015), the impacts of human activities the study area (e.g., over-expansion of CL) should be

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controlled since human-associated disturbance (e.g., tillage and grazing) generated significant decline in the amount SOCC and SOCD. Agricultural practices that promote the conservation of SOM (e.g., no-tillage, mulching, or intercropping with perennial legumes) should therefore be recommended and become the basis of sustainable agricultural practices in the area.

Author contributions

Hao Fan performed the experimental work and prepared the manuscript. Wenwu Zhao and Stefani Daryanto designed the field experiment and reviewed the manuscript. Bojie Fu and Shuai Wang revised the manuscript. Hao Fan and Yaping Wang performed the experimental work and data collection.

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