Catena 137 (2016) 328–339

Contents lists available at ScienceDirect

Catena

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

Multi-scale variability of soil carbon and nitrogen in the middle reaches of the Heihe River basin, northwestern China

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ARTICLE INFO

Article history:
Received 15 April 2015
Received in revised form 6 October 2015
Accepted 13 October 2015
Available online xxxx

Keywords:
Soil nutrients
Spatial distribution
Landscape heterogeneity
Arid region

ABSTRACT

Insight into the variability of soil carbon and nitrogen at multiple scales is essential for accurately recognizing their distribution and stocks in arid inland river basins where landscape patterns are complex. For this objective, soil sampling and vegetation survey were conducted in 2012 to estimate the regional distribution and analyze the differences of soil organic carbon (SOC), total carbon (TC, the summation of organic and inorganic carbon) and total nitrogen (TN) among landscapes (cropland, desert, woodland and grassland) and sub-regions in the middle reaches of the Heihe River basin, northwestern China. The effects of soil properties, vegetation conditions and management practices on soil C and TN were determined. The results showed that the average regional densities of SOC, TC and TN were 68.2, 216.9 and 6.90 Mg ha^{-1} in the 0–80 cm soil profile, respectively, and approximately 16% and 31% were stored in the 0–10 and 0–20 cm layers, respectively. Cropland stored the highest SOC and TN, whereas grassland stored the highest TC and woodland had the lowest SOC and TC. Variability in soil texture, frequency and amount of irrigation, fertilizer type and fertilization rate contributed to the differences in SOC and TN densities among croplands in the three sub-regions. Cropland and woodland far from the river bank (approximately 16–18 km away) accumulated more SOC, TC and TN than those near the river bank (approximately 4 km away). Soil texture was the predominant factor influencing SOC and TN in the surface soil of woodland. Aboveground biomass of shrubs and herbs, especially fresh weight, was regarded as a dominant factor affecting TC in desert soil and SOC, TC and TN in grassland soil. The results of this study are essential for accurately recognizing the status and variability of soil C and TN in complex landscape patterns in arid regions.

1. Introduction

Soil organic carbon (SOC) and total nitrogen (TN) play key roles in pedogenic processes and contribute to soil fertility (Jiménez et al., 2011). Soil inorganic carbon (SIC), primarily as carbonate carbon, is of particular relevance to dry land because the formation of secondary carbonates is a principle process in the soils of arid and semiarid regions (FAO, 2004). Soil C and TN are involved in various biogeochemical processes with a direct impact on soil–plant interactions (Chang et al., 2012; Fu et al., 2010). The levels of soil C and TN are good indicators of soil quality and productivity due to favorable effects on physical, chemical and biological properties of soil (Bauer and Black, 1994).

Soil C and TN are controlled by various natural factors such as climate change (He et al., 2014; Rustad and Fernandez, 1998), topographical factors (Fernández-Romero et al., 2014; Griffiths et al., 2009; Kunkel et al., 2011; Parras-Alcántara et al., 2015b), vegetation conditions (Fu et al., 2010; Kunkel et al., 2011) and soil properties (Côté et al., 2000; Su et al., 2007). Anthropogenic activities have been shown to have profound impacts on soil C and TN status in recent decades (Parras-Alcántara et al., 2013). As the repository for approximately 60% of the global terrestrial C pool, soil organic matter (SOM) is sensitive to agricultural management such as tillage (Dikgwatlhe et al., 2014; Urioste et al., 2006), fertilization (Su et al., 2006; Yang et al., 2007), land use change (Gami et al., 2009; Post and Kwon, 2000; Wei et al., 2014a, 2014b), grazing (Pringle et al., 2014; Silveira et al., 2013) and afforestation and deforestation (Li et al., 2013; Zeng et al., 2014). Contradictory results on the impacts of afforestation and land management change on soil C and TN sequestration have been reported (Li et al., 2013; Parras-Alcántara et al., 2014; Perez-Quezada et al., 2011; Zeng et al., 2014) due to the dependence on tree types, stand ages, soil properties and depth and previous land uses (Côté et al., 2000; Wei et al., 2012; Zeng et al., 2014). Changes in pedogenic and hydrological processes caused by natural factors and human activities both affect C and N cycles. Elucidating the variability of soil C and TN and the underlining factors governing their distribution have important implications for the sustainable management of land resources and provide a basis for predicting how terrestrial ecosystems respond to global climate change (Meersmans et al., 2008, 2012).

In the middle reaches of the Heihe River basin, the resources of surface water and groundwater support both the natural and

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http://dx.doi.org/10.1016/j.catena.2015.10.013
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agricultural ecosystems. Soils in this region are characterized by obvious heterogeneity in both the vertical and horizontal directions (Li and Shao, 2013). The distribution and properties of vegetation differ according to the ecological functioning and soil properties of the landscapes. Representative landscapes (cropland, desert, woodland, and grassland) are distributed patchily and are interspersed with each other. Previous studies on SOC and nutrients in this region were commonly conducted in irrigated cropland or in small areas. Su et al. (2006) found that long-term application of inorganic fertilizer combined with farmyard manure greatly improved the SOC and nutrient levels in cropland. Li and Shao (2014) estimated that SOC density was 59.4, 149.6 and 174.4 Mg ha^{-1} in the 0–3 m profiles of the desert, cropland and wetland in a 100 km^2 area, respectively. The effect of land use change on SOC and nutrients has also been extensively studied. Li et al. (2009) found that crop rotations increased SOC and TN densities by 30–65% and 61–64%, respectively, in the 0–30 cm soil during the 10 years of cultivation after the desert was transformed into irrigated cropland. The SOC and TN contents in the topsoil of sand-fixing shrubs, irrigated cropland and shelter forest increased with time after the reclamation of desert land (Su et al., 2007, 2010a, 2010b). Su et al. (2009) reported that SOC and TN accumulated at rates of 0.4 Mg C ha^{-1} year^{-1} and 0.04 Mg N ha^{-1} year^{-1}, respectively, after the conversion of cropland to alfalfa forage land in the marginal oasis. Lü et al. (2014) indicated that cropland expansion or continuous cultivation significantly reduced SOC content, whereas progressive succession of the natural ecosystem led to SOC sequestration from 1986 to 2007. The above studies have provided insight into the variability of soil C and TN in the middle reaches of the Heihe River basin. However, the spatial variability of soil C and TN has rarely been studied at multiple scales considering the complex landscape patterns in this region. Knowledge about the regional distribution, the variability and influencing factors of soil C and TN among landscapes and sub-regions is deficient.

Therefore, the detailed objectives of this study were: (1) to analyze the variability of soil C and TN at landscape, sub-regional and regional scales, and (2) to determine the predominant factors influencing soil C and TN concerning soil and vegetation properties and management practices in the middle reaches of the Heihe River basin.

2. Materials and methods

2.1. Study area

This study was conducted in Zhangye city of Gansu province, China (Fig. 1). This region is located in the central portion of the Hexi Corridor of northwestern China, and is characterized by a continental dry temperate climate. Mean annual air temperature is approximately 7.6 °C, with the lowest and highest air temperature of −27 °C in January and 39 °C in August, respectively. Mean annual precipitation is approximately 120 mm in Ganzhou and Linze (Lü et al., 2014) and 79 mm in Gaotai (Li et al., 2009). Precipitation is erratic and shows strong seasonal variation, with approximately 60% occurring from July to September and only 3% falling during winter (from December to February). The Heihe River flows through the region and supplies a large share of available water resources for both domestic and production use (Fig. 1A and B).

Maize (*Zea mays* L.) for seed production is the staple crop in this region and its growth mainly relies on irrigation by groundwater and the Heihe River water. Shrubs in the desert mainly consist of *Salsola passerina* Bunge, *Suaeda glauca* (Bunge) Bunge and *Alhagi sparsifolia* Shap. Herbs in the desert and grassland include *Sophora alopecuroides* L, Common Reed (*Phragmites australis* (Cav.) trin. ex Steud), Common Leymus (*Leymus secalinus* (Georgi) Tzvel), *Achnatherum splendens* (Trin.) Nevski and *Sonchus brachyotus* D C. To control desertification, sand breaks have been built on the edge of desert–oasis ecotones and shelterbelts have been planted around cropland in the oases since 1975 (Su et al., 2007). *Populus simonii* Carr and *Elaeagnus angustifolia* Linn are the main afforestation tree species. The zonal soils are gray brown desert soil, aeolian soil and irrigated desert soil according to Chinese Soil Taxonomy, which are equivalent to the Aridosols, Entisols and Inceptisols in terms of USDA Soil Taxonomy, respectively (Li et al., 2009; Su et al., 2009).

2.2. Experimental design and data collection

Soil sampling was conducted at 86 points from July to October in 2012 (Fig. 1C). Among these points, 47 points were for cropland, and

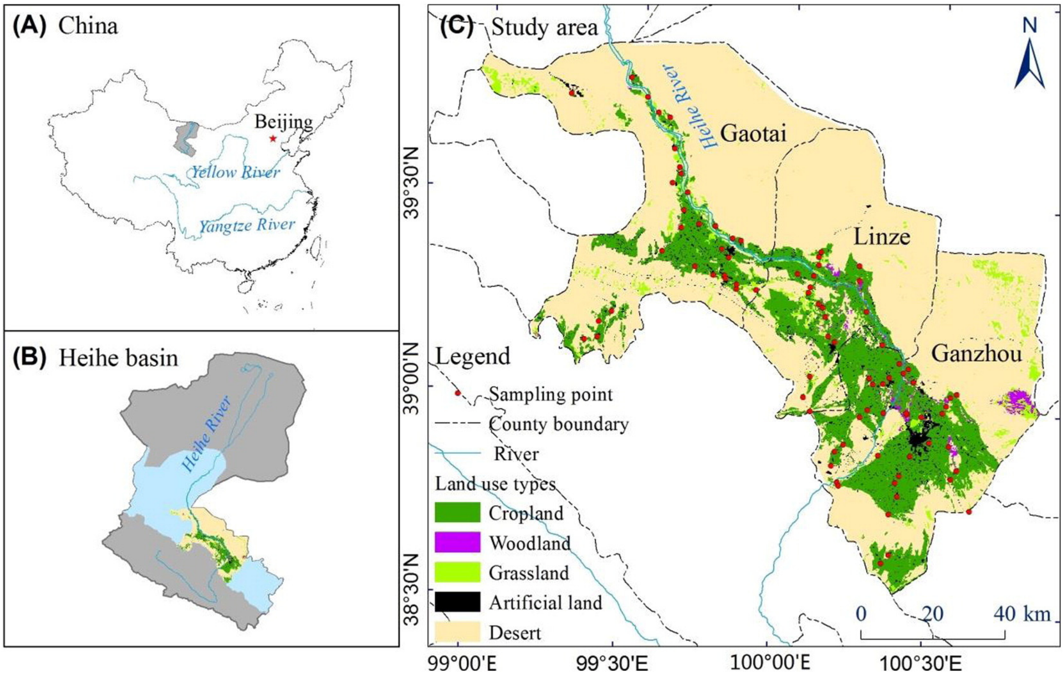

Fig. 1. The location of the sampling points in the study area (C) in the middle reaches of the Heihe River basin (B) of China (A).

11, 18 and 10 points were for desert, woodland and grassland, respectively. The position of each sampling point was recorded using a handheld differential GPS receiver with an accuracy of 3–5 m. At each point, disturbed soil samples were collected at five depth increments (0–10, 10–20, 20–40, 40–60 and 60–80 cm) at three random locations as replicates using a hand auger (5 cm in diameter) in a representative 400-m^2 plot. Three samples at each layer were mixed evenly to form one composite sample and sealed in air-tight bags and taken to the laboratory. In the laboratory, disturbed soil samples were air-dried at room temperature (20–25 °C) and sieved (2 mm) to discard coarse particles. Each sample was divided into two subsamples. One subsample was used to determine sand, silt and clay contents using laser diffraction with a Mastersizer 2000 (Malvern Instruments, Malvern, England). The other subsample was passed through the 0.25-mm sieve to measure the concentrations of SOC, total C (TC, both SOC and SIC) and TN and pH values. Soil organic carbon concentrations (SOCC) were determined by dichromate oxidation (Nelson and Sommers, 1982). Soil total carbon concentrations (TCC) and TN concentrations (TNC) were determined using the Kjeldahl digestion procedure (Bremner and Tabatabai, 1972). Soil pH values were measured for a soil–water mass ratio of 1:5 using a pH meter. A soil profile to a depth of 1 m was dug at each point, and the undisturbed soil cores were collected at the respective depth using a stainless-steel cutting ring (100 cm^3 in volume) for measuring soil bulk density and field capacity using the oven-drying method (Arshad et al., 1996) and Wilcox method (Hanks et al., 1954), respectively.

Except the cropland points, three quadrats at sizes of 20 × 20 m for trees, 10 × 10 m for shrubs and 1 × 1 m for herbs were designed to conduct a vegetation survey around each point. In each quadrat, plants were separated and counted. Properties including species, number, height (H_G, cm) and coverage (%) of shrubs and herbs were recorded. Aboveground biomass of shrubs and herbs was measured following identification and clipping. Fresh weight (Fw, $g\ m^{-2}$) was measured, and dry weight (Dw, $g\ m^{-2}$) was then determined by oven-drying at 65 °C for 72 h. Species, number, canopy (m^2), height (H_T, m) and diameter at breast height (DBH, cm) of trees were recorded in the woodland. The summary statistics of vegetation condition in desert, woodland and grassland are listed in Table 1.

2.3. Data processing and analysis

The stratification ratio (SR) is defined as a soil property on the surface soil divided by the same property at a lower depth (Franzluebbers, 2002). The SR value of SOM is used to assess stratification characteristics, serving as an indicator of soil quality or soil ecosystem functioning because that surface SOM is essential to erosion control, water infiltration and nutrients conservation (Corral-Fernández et al., 2013; Franzluebbers, 2002). The SR values for SOCC, TCC, TNC and C:N ratio in the 0–10 cm layer to the corresponding values in the 10–20, 20–40, 40–60 and 60–80 cm layers were calculated, respectively.

Table 2

Descriptive statistics of soil organic carbon concentration (SOCC), total carbon concentration (TCC), total nitrogen concentration (TNC), C:N ratio, soil organic carbon density (SOCD), total carbon density (TCD), and total nitrogen density (TND) in various soil layers of the study area.

Property	Layer (cm)	Statistics [a]				K-S test p value[b]
		Min	Max	Mean	CV (%)	
SOCC ($g\ kg^{-1}$)	0–10	2.73	19.27	8.68	37.4	0.43
	10–20	0.97	15.78	7.80	42.1	0.92
	20–40	1.30	11.96	5.85	46.2	0.64
	40–60	1.34	12.21	5.13	45.6	0.71
	60–80	0.53	11.85	4.89	45.8	0.58
TCC ($g\ kg^{-1}$)	0–10	8.75	40.99	21.42	27.5	0.16
	10–20	5.61	41.59	20.57	30.4	0.42
	20–40	8.40	40.62	19.11	32.1	0.22
	40–60	5.37	37.91	18.40	28.8	0.65
	60–80	5.55	43.91	18.02	32.1	0.21
TNC ($g\ kg^{-1}$)	0–10	0.24	1.92	0.91	41.9	0.97
	10–20	0.13	1.74	0.81	45.4	0.94
	20–40	0.16	1.34	0.60	46.3	0.79
	40–60	0.07	1.18	0.50	44.0	0.75
	60–80	0.07	1.13	0.47	46.1	0.77
C:N ratio	0–10	6.08	36.21	10.47	42.8	0.06
	10–20	5.27	31.48	10.47	40.7	0.05
	20–40	2.95	19.49	10.19	33.2	0.20
	40–60	4.03	79.27	11.55	76.0	0.09
	60–80	4.07	98.73	12.15	48.8	0.07
SOCD ($Mg\ ha^{-1}$)	0–10	3.91	23.02	11.84	34.4	0.43
	0–20	8.22	41.46	22.67	34.9	0.94
	0–80	21.94	139.48	68.25	36.2	0.97
TCD ($Mg\ ha^{-1}$)	0–10	12.87	54.40	29.35	25.6	0.89
	0–20	25.66	105.56	57.89	25.4	0.56
	0–80	100.26	389.42	216.90	24.7	0.91
TND ($Mg\ ha^{-1}$)	0–10	0.34	2.41	1.24	39.9	0.92
	0–20	0.63	4.76	2.36	41.0	0.94
	0–80	1.92	14.54	6.90	39.8	0.70

[a] Min, Max and CV refer to minimum, maximum and coefficient of variation, respectively.

[b] $p > 0.05$ indicates that data are normally distributed at the 95% confidence level.

Densities of SOC, TC and TN for a soil profile with n layers were calculated as follows (IPCC, 2003):

$$\begin{aligned} SOCD_h &= \sum_{i=1}^{n} \frac{SOCC_i \times Bd_i \times T_i \times (1-S_i)}{100} \\ TCD_h &= \sum_{i=1}^{n} \frac{TCC_i \times Bd_i \times T_i \times (1-S_i)}{100} \\ TND_h &= \sum_{i=1}^{n} \frac{TNC_i \times Bd_i \times T_i \times (1-S_i)}{100} \end{aligned} \tag{1}$$

where $SOCD_h$, TCD_h and TND_h are the stocks of SOC, TC and TN over depth h per unit area ($Mg\ ha^{-1}$), respectively; i is the ith layer and n is the total number of soil layers in a soil profile; $SOCC_i$, TCC_i and TNC_i are the SOCC, TCC and TNC ($g\ kg^{-1}$) of the ith layer, respectively; Bd_i and T_i are the bulk density ($g\ cm^{-3}$) and the thickness (cm) of the ith

Table 1

Summary statistics of shrubs, herbs and trees obtained from vegetation survey in the study area.

Landscape	Species number [a]	Index [b]										
		mean coverage (%)	H_G (cm)	Fw ($g\ m^{-2}$)	Dw ($g\ m^{-2}$)	R	H	D	J	Canopy (m^2)	H_T (m)	DBH (cm)
Desert	12	20.57	21.21	493.31	169.92	2.10	1.09	0.76	0.94	–[c]	–	–
Woodland	43	18.02	33.96	428.84	89.89	4.37	1.22	0.40	0.84	11.53	10.42	17.49
Grassland	15	17.63	14.34	122.53	30.84	4.44	1.09	0.43	0.78	–	–	–

[a] Total species numbers of shrubs and herbs in the quadrats of vegetation survey.

[b] H_G, Fw and Dw are the abbreviations of mean height, fresh weight and dry weight of shrubs and herbs, respectively. *R*, *H*, *D* and *J* refer to Patrick richness index, Shannon–Wiener diversity index, Simpson dominance index and Pielou evenness index, respectively. H_T and DBH are the abbreviations of mean height and mean diameter at breast height of trees, respectively.

[c] "–" indicates data do not exist.

soil layer, respectively; S_i is the proportion (%) of coarse (>2 mm) fragments in the ith layer, which is negligible due to the very low content (Zhang et al., 2012).

Species diversity indices of vegetation (shrubs and herbs) in the desert, grassland and woodland including the importance value (N_i), Patrick richness (R), Shannon–Wiener diversity (H), Simpson dominance (D), and Pielou evenness (J) indices were calculated using the following equations:

$$\begin{aligned} N_i &= \frac{(RC_i + RF_i + RA_i)}{3} \\ R &= m \\ H &= -\sum_{i=1}^{m} p_i \ln(p_i) \\ D &= \sum_{i=1}^{m} p_i^2 \\ J &= \frac{H}{\ln(m)} \end{aligned} \tag{2}$$

where N_i is the importance value (%) of the ith plant species; RC_i, RF_i and RA_i are the relative coverage (%), relative frequency (%) and relative abundance (%) of the ith plant species, respectively; m is the total plant species in the three quadrats around each point; p_i is the relative importance value of the ith plant species ($p_i = \frac{N_i}{N}$, N is the sum of the importance values for all plant species in a quadrat).

The Kolmogorov–Smirnov (K–S) test was used to test the normality of the distribution of various variables. The results showed that site variables (latitude, longitude and elevation), soil properties (clay, silt and sand contents, field capacity and bulk density) and vegetation indices (H_G, H_T, Fw, Dw, DBH, R, H, D and J) were all normally distributed. Pearson correlation analysis was used to determine the strength of possible relationships among SOCC, TCC and TNC and site variables, soil properties and vegetation indices. One-way analyses of variance (ANOVA) were performed on SOCD, TCD and TND among landscapes and subregions (Ganzhou, Linze and Gaotai). Stepwise multiple linear regressions were performed to explain the variations of SOCC, TCC and TNC using combinations of various variables. Statistical analyses were conducted using SPSS software (version 20.0. SPSS lnc.).

3. Results

3.1. Descriptive statistics of regional SOC, TC and TN

In the 0–80 cm soil profiles, SOCC, TCC and TNC generally decreased with increasing depth, and the percentage of SOCC to TCC declined from 40.6% in the 0–10 cm layer to 27.2% in the 60–80 cm layer (Table 2). The C:N ratio increased from 10.2 in the 20–40 cm to 12.2 in the 60–80 cm layer (Table 2). The SOCD, TCD and TND in the 0–80 cm soil profiles were 68.2, 216.9 and 6.90 Mg ha^{-1}, respectively, among which, approximately 16% were stored in the 0–10 cm soil layer and 31% were in the 0–20 cm soil layer (Table 2). Coefficients of variation indicated that

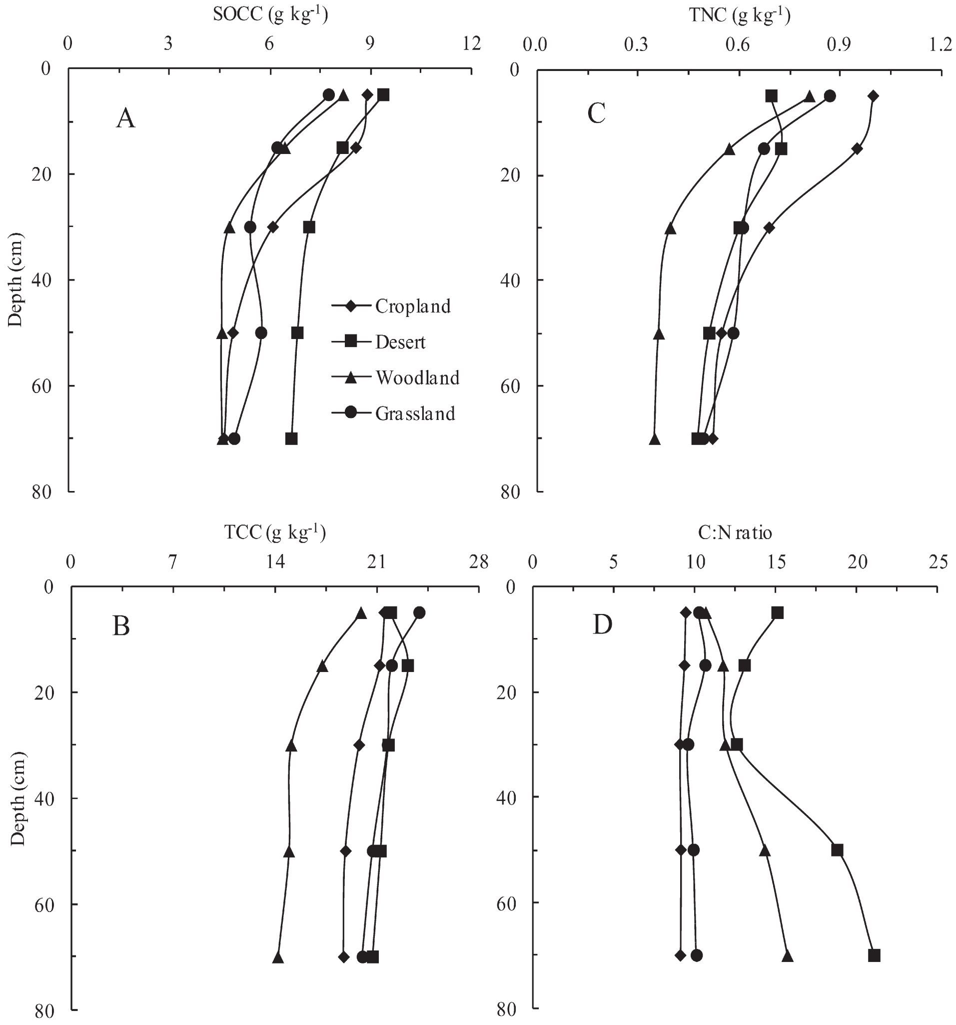

Fig. 2. Vertical distributions of (A) soil organic carbon concentration (SOCC), (B) total carbon concentration (TCC), (C) total nitrogen concentration (TNC) and (D) C:N ratio in different landscapes.

Table 3
The declining trend of soil organic carbon concentration (SOCC), total carbon concentration (TCC), and total nitrogen concentration (TNC) with depth fitted by the power function in different landscapes.

Property	Landscape	Equation [a]	R^2
SOCC (g kg^{-1})	Cropland	$SOCC = 15.21x^{-0.274}$	0.89
	Desert	$SOCC = 11.67x^{-0.136}$	0.99
	Woodland	$SOCC = 11.91x^{-0.240}$	0.94
	Grassland	$SOCC = 9.71x^{-0.155}$	0.90
TCC (g kg^{-1})	Cropland	$TCC = 24.05x^{-0.058}$	0.91
	Desert	$TCC = 23.60x^{-0.026}$	0.43
	Woodland	$TCC = 24.31x^{-0.129}$	0.98
	Grassland	$TCC = 26.46x^{-0.063}$	0.97
TNC (g kg^{-1})	Cropland	$TNC = 1.69x^{-0.272}$	0.89
	Desert	$TNC = 0.97x^{-0.155}$	0.78
	Woodland	$TNC = 1.37x^{-0.338}$	0.97
	Grassland	$TNC = 1.18x^{-0.195}$	0.96

[a] x in the equation refers to depth (cm).

SOCC, TCC, TNC, C:N ratio, SOCD, TCD and TND all exhibited moderate spatial variability (Table 2). The spatial variability of SOCC, TCC and TNC increased with depth in the 0–40 cm soil. The K–S test showed that these seven properties were all normally distributed ($p > 0.05$, Table 2).

3.2. Vertical distributions and stratification of SOCC, TCC, TNC and C:N ratio

Vertical distributions of SOCC, TCC, TNC and the C:N ratio are shown in Fig. 2. In the 0–10 cm layer, desert had the highest SOCC (9.38 g kg^{-1}), followed by cropland (8.91 g kg^{-1}), while grassland had the lowest SOCC (7.75 g kg^{-1}) (Fig. 2A). The TCC in the 0–10 cm layer of cropland, desert, woodland and grassland were 21.51, 21.97, 19.91 and 23.92 g kg^{-1}, respectively (Fig. 2B). As for TNC, cropland had the highest value of 1.00 g kg^{-1}, followed by grassland of 0.87 g kg^{-1}, and desert had the lowest value of 0.70 g kg^{-1} in the 0–10 cm layer (Fig. 2C). Woodland had the overall lowest SOCC, TCC and TNC, whereas desert had the highest SOCC and TCC in the 20–80 cm soil profiles (Fig. 2A–C). The decreasing trend of SOCC, TCC and TNC with increasing depth in the four landscapes could be well fitted by power functions with coefficients of determination (R^2) for SOCC and TNC larger than 0.89 and 0.78, respectively. As for TCC, the R^2 values of the power function were larger than 0.91 for cropland, woodland and grassland (Table 3). The percentage of SOCC to TCC also decreased with increasing depth, with means of 32.7%, 35.0%, 34.6% and 27.6% in the 0–80 cm soil profiles of cropland, desert, woodland and grassland, respectively. Cropland had the lowest and most homogeneous C:N ratio, followed by grassland, ranging from 9.58 in the 20–40 cm to 10.6 in the 10–20 cm layer (Fig. 2D). The C:N ratio of woodland increased with depth, whereas that of desert decreased from 15.1 in the topsoil to 12.6 in the 30 cm soil and increased again. (Fig. 2D).

The SRs for SOCC, TCC and TNC were greater than one and increased with depth in the four landscapes, whereas the values in woodland were generally higher than those in cropland, desert and grassland (Fig. 3). The increase in SRs for SOCC, TCC and TNC corresponded to the decrease in the absolute quantities of SOCC, TCC and TNC with depth in the 0–80 cm soil profiles (Fig. 2A-C). As for SOCC, SRs in cropland and woodland varied from 1.08 to 2.07 and from 1.30 to 2.17, respectively, and the SRs in desert and grassland both ranged from about 1.20 to 1.50 (Fig. 3A). The SRs for TCC in cropland and desert were nearly identical, ranging from 1.00 to 1.20. The SR of TCC for the 0–10 cm layer to 10–20 and 60–80 cm layers in grassland increased merely from 1.15 to 1.24, while that of woodland increased from 1.22 to 1.46 (Fig. 3B). The SRs for TNC showed similar values as those for SOCC in the four landscapes (Fig. 3C). All SRs for C:N ratio were near to one, however, no uniformly explicit trend was observed with regard to SRs for C:N ratio with increasing depth in the four landscapes (Fig. 3D).

3.3. Variability of SOCD, TCD and TND among landscapes

Cropland was characterized by the highest SOCD and TND and grassland had the highest TCD, whereas woodland had the lowest SOCD and TCD in the 0–10, 0–20 and 0–80 cm layers (Fig. 4). No significant

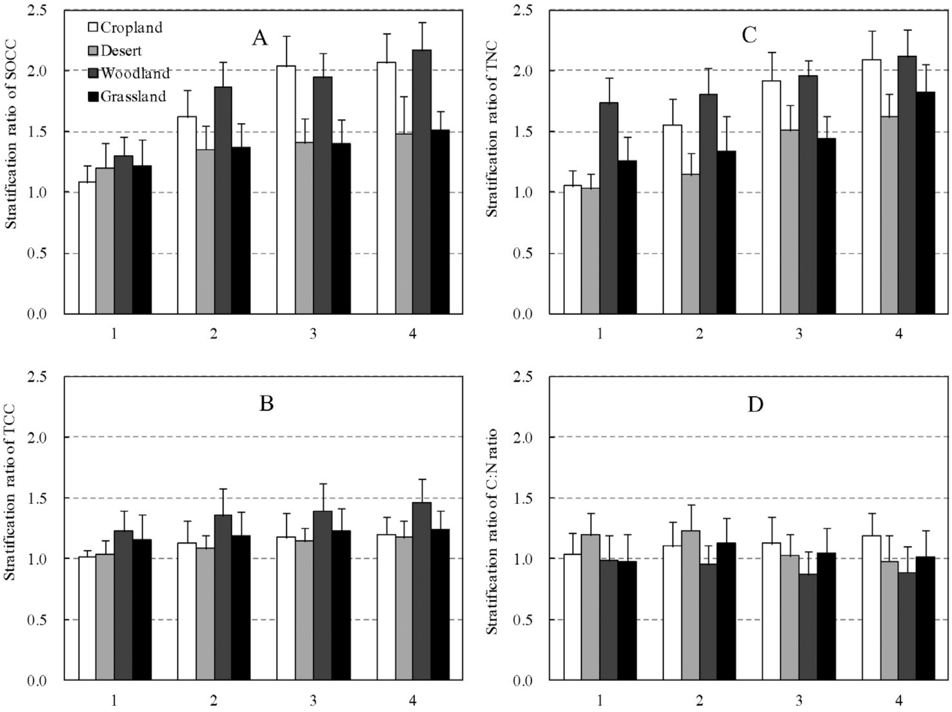

Fig. 3. The stratification ratios for (A) soil organic carbon concentration (SOCC), (B) total carbon concentration (TCC), (C) total nitrogen concentration (TNC) and (D) C:N ratio in different landscapes. Numbers of 1, 2, 3 and 4 refer to the stratification ratios for each of the three soil properties at the 0–10 cm layer to 10–20, 20–40, 40–60 and 60–80 cm layers, respectively.

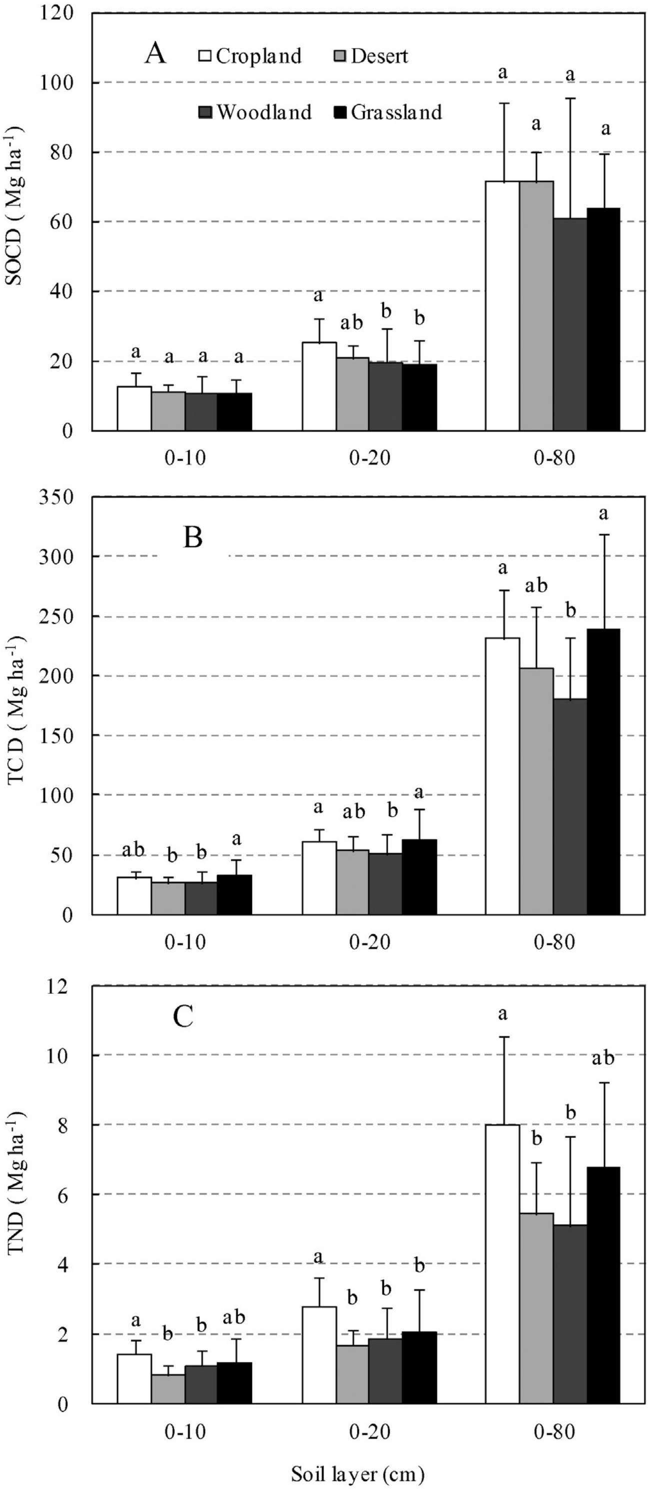

Fig. 4. Comparison of (A) soil organic carbon density (SOCD), (B) total carbon density (TCD) and (C) total nitrogen density (TND) among different landscapes in the study area. Different lowercase letters above the bars indicate the significant difference at the 0.05 level.

difference in SOCD was observed among cropland, desert, woodland and grassland in the 0–10 and 0–80 cm layers ($p > 0.05$, Fig. 4A). In the 0–20 cm layer, cropland stored significantly more SOC (25.0 Mg ha^{-1}) than woodland (19.6 Mg ha^{-1}) and grassland (18.9 Mg ha^{-1}) ($p < 0.05$, Fig. 4A). The TCD in soils of grassland and cropland were generally 1.26 and 1.22 times that in woodland (Fig. 4B), respectively, and the difference in TCD between cropland and grassland was not significant in the three soil layers ($p > 0.05$, Fig. 4B). Cropland stored significantly more TN (1.41, 2.78 and 8.00 Mg ha^{-1}) than desert (0.81, 1.65 and 5.45 Mg ha^{-1}) and woodland (1.06, 1.85 and 5.09 Mg ha^{-1}) in the 0–10, 0–20 and 0–80 cm layers ($p < 0.05$, Fig. 4C), whereas no significant difference was observed among grassland, woodland and desert ($p > 0.05$, Fig. 4C).

3.4. Variability of SOCD, TCD and TND among sub-regions

Croplands in Ganzhou, Linze and Gaotai displayed obvious differences in SOCD, TCD and TND (Fig. 5). The SOCD in cropland of Ganzhou were 14.1, 27.4 and 79.0 Mg ha^{-1} in the 0–10, 0–20 and 0–80 cm layers, respectively, which were 1.41, 1.40 and 1.31 times those of cropland in Linze, and 1.13, 1.09 and 1.14 times those of cropland in Gaotai at the corresponding soil layers, respectively (Fig. 5A). Croplands in Ganzhou (31.1 and 62.0 Mg ha^{-1}) and Gaotai (32.1 and 63.8 Mg ha^{-1}) had significantly more TC than in Linze (26.8 and 54.6 Mg ha^{-1}) in the 0–10 and 0–20 cm layers ($p < 0.05$, Fig. 5B). No significant difference in TCD at the 0–80 cm layer was observed among croplands in Ganzhou (222.3 Mg ha^{-1}), Linze (223.4 Mg ha^{-1}) and Gaotai (243.5 Mg ha^{-1}) ($p > 0.05$, Fig. 5B). Cropland in Ganzhou had significantly higher TND than Linze and Gaotai ($p < 0.01$, Fig. 5C), whereas the difference between croplands in Linze and Gaotai was not significant in the three soil layers ($p > 0.05$, Fig. 5C).

For cropland and woodland at different distances from the Heihe River bank in Ganzhou, SOCD, TCD and TND differed both in each landscape and between landscapes (Fig. 6). The SOCD, TCD and TND in the 0–80 cm soil profiles of cropland far from the river bank (10 points with an average distance of 15.7 km) were 1.15, 1.14 and 1.02 times those of cropland profiles near the river bank (11 points with an average distance of 4.0 km), respectively. Differences in SOCD, TCD and TND between croplands far from and near the river bank, however, were not significant in the 0–10, 0–20 and 0–80 cm layers ($p > 0.05$, Fig. 6A–C). The SOCD, TCD and TND in the 0–80 cm soil profiles of woodland far from the river bank (5 points with an average distance of 18.0 km) were 1.83, 1.08 and 1.00 times those of woodland profiles near the river bank (6 points with an average distance of 4.4 km), respectively (Fig. 6A–C). Differences in SOCD at the 0–10, 0–20 and 0–80 cm layers and in TCD at the 0–10 and 0–20 cm layers were significant between woodlands far from and near the river bank ($p < 0.05$, Fig. 6A and B).

In the sub-region far from the river bank, SOCD, TCD and TND in the 0–80 cm soil profiles of cropland were approximately 0.95, 1.41 and 1.65 times those of woodland profiles, respectively. Differences between cropland and woodland were not significant for SOCD in the three soil layers and for TCD and TND in the 0–10 cm layer ($p > 0.05$, Fig. 6A–C). In the sub-region near the river bank, SOCD, TCD and TND in the 0–80 cm soil profiles of cropland were generally 1.51, 1.34 and 1.62 times those of woodland profiles, respectively. Differences in TCD and TND between cropland and woodland near the river bank were significant in the three soil layers ($p < 0.05$, Fig. 6B and C).

4. Discussion

Various studies have showed the influences of abiotic and biotic factors on the nature and dynamics of soil C and N. For example, the tillage depth and drainage was found significantly affecting the evolution of SOC distribution with depth in cropland and grassland of north Belgium (Meersmans et al., 2009). It is necessary to recognize the influences of various factors on soil C and TN levels at different scales. Except soil properties (Table 4), vegetation indices have varying degrees of association with SOCC, TCC and TNC in the present study (Tables 5 and 6).

4.1. Influences of site variables and soil properties

The Pearson correlation indicated that latitude (elevation) was negatively (positively) correlated with SOCC, TCC and TNC and longitude

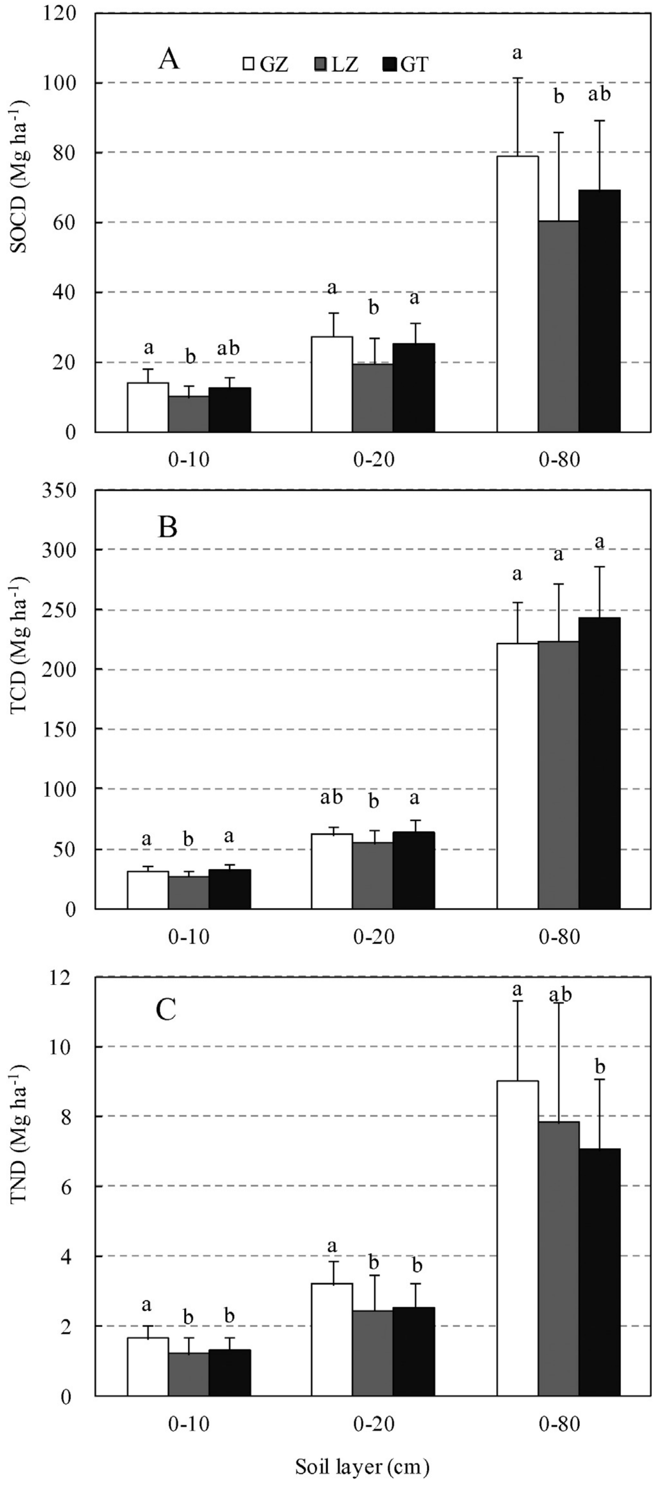

Fig. 5. Comparison of (A) soil organic carbon density (SOCD), (B) total carbon density (TCD) and (C) total nitrogen density (TND) among croplands in Ganzhou (GZ), Linze (LZ) and Gaotai (GT) in the study area. Different lowercase letters above the bars indicate the significant difference at the 0.05 level.

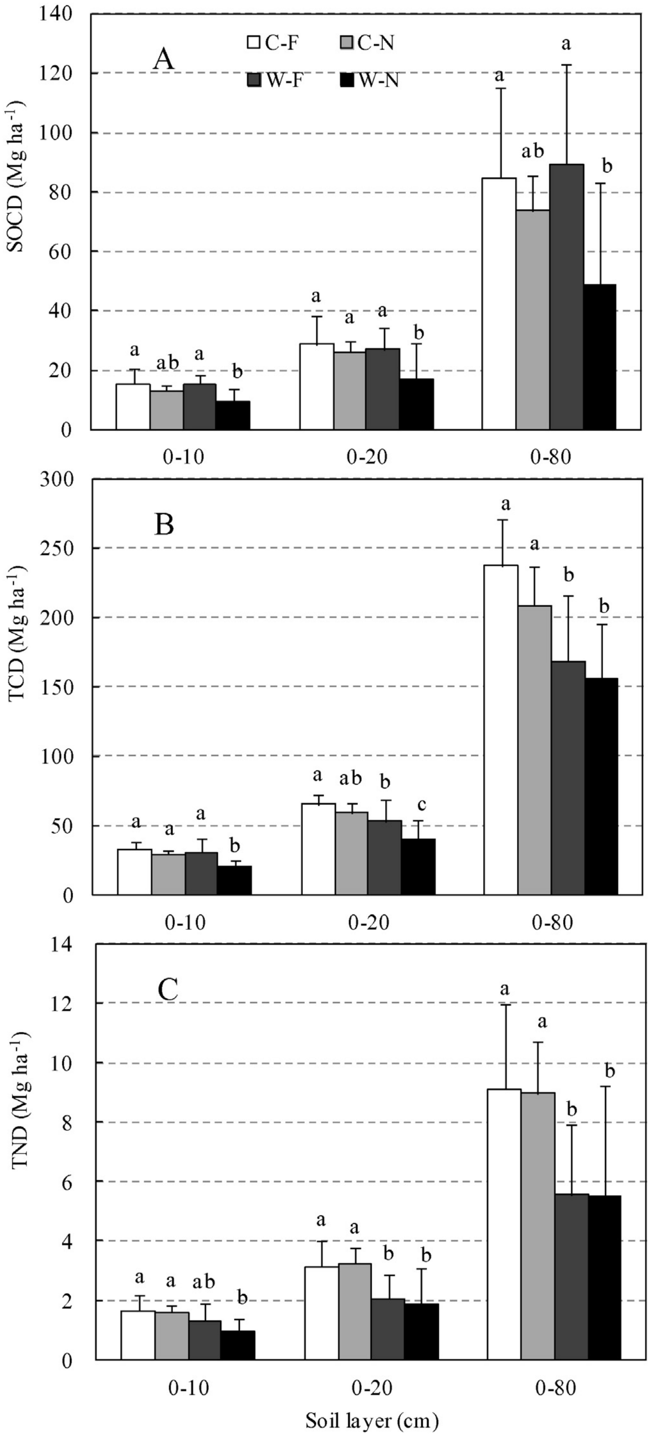

Fig. 6. Comparison of (A) soil organic carbon density (SOCD), (B) total carbon density (TCD) and (C) total nitrogen density (TND) in croplands and woodlands at different distances from the Heihe River bank in Ganzhou (C-F: cropland far from the river bank; C-N: cropland near the river bank; W-F: woodland far from the river bank; W-N: woodland near the river bank). Different lowercase letters above the bars indicate the significant difference at the 0.05 level.

showed no relationship (Table 4). Many studies focused on the influence of elevation on the SOM accumulation in different regions worldwide (Kunkel et al., 2011; Leifeld et al., 2005; Wiesmeier et al., 2013). Site variables, however, failed to explain the variations of SOCC, TCC and TNC in soils of the four landscapes due to their narrow ranges in this study.

Fine-textured soils tend to store more C and TN. Higher SOC content in clayey soils may be due to more decomposed organic matter and the stabilization of clay particles in soil (Leifeld et al., 2005; Puget and Lal, 2005). The protection of SOC by clay particles from decomposition was hypothesized to occur through at least two separate mechanisms (McLauchlan, 2006). First, SOC is chemically stabilized and absorbed onto negatively charged clay minerals with large surface areas when SOC becomes humified. Second, SOC is physically protected from microbial mineralization by forming soil aggregates. Changes in TNC in soil

Table 4

Pearson correlation between soil organic carbon concentration (SOCC), total carbon concentration (TCC), total nitrogen concentration (TNC) and soil properties and site variables in various soil layers of the study area.

Property	Layer (cm)	Lat. (°)[a]	Lon. (°)	E (m)	Clay (%)	Silt (%)	Sand (%)	Fc (%)	Bd (g cm^{-3})	pH
SOCC (g kg^{-1})	0–10	−0.29*[b]	0.12	0.29*	−0.06	0.29	−0.27	0.37**	−0.44**	−0.19
	10–20	−0.19	−0.05	0.40**	0.01	0.39*	−0.37*	0.48**	−0.32*	0.05
	20–40	−0.27*	0.11	0.39**	−0.32	0.16	−0.14	0.28*	−0.21	−0.18
	40–60	−0.20	0.16	0.19	−0.12	0.03	−0.02	0.20	−0.01	0.08
	60–80	−0.18	0.11	0.22	−0.22	0.07	−0.08	0.18	−0.14	−0.20
TCC (g kg^{-1})	0–10	−0.16	−0.11	0.43**	0.02	0.47**	−0.46**	0.46**	−0.51**	0.10
	10–20	−0.17	−0.12	0.46**	0.12	0.59**	−0.57**	0.47**	−0.44**	0.01
	20–40	0.06	−0.22	0.24	−0.13	0.29	−0.27	0.41**	−0.28*	−0.19
	40–60	0.22	−0.40**	0.18	0.10	0.29	−0.28	0.32*	−0.56**	−0.17
	60–80	0.22	−0.36**	0.17	−0.03	0.12	−0.11	0.42**	−0.38**	−0.06
TNC (g kg^{-1})	0–10	−0.41**	0.26	0.37**	−0.06	0.31	−0.30	0.36**	−0.54**	−0.07
	10–20	−0.39**	0.27	0.29*	0.05	0.44**	−0.43**	0.25	−0.35*	−0.17
	20–40	−0.34*	0.22	0.39**	−0.20	0.21	−0.19	0.20	−0.07	−0.10
	40–60	−0.28*	0.23	0.26	−0.07	0.09	−0.08	0.26	−0.17	−0.07
	60–80	−0.38**	0.29*	0.41**	−0.16	0.01	−0.01	0.18	−0.16	−0.10

[a] Lat., Lon., and E are the abbreviations of latitude, longitude and elevation, respectively. Fc, Bd and pH refer to field capacity, bulk density and pH value, respectively.
[b] "**" and "*" indicate significance levels of 0.01 and 0.05, respectively.

Table 5

Pearson correlation between soil organic carbon concentration (SOCC), total carbon concentration (TCC), total nitrogen concentration (TNC) and vegetation (shrubs and herbs) indices in various soil layers of desert and grassland.

	Index [a]	SOCC (g kg^{-1})					TCC (g kg^{-1})					TNC (g kg^{-1})				
		0–10	10–20	20–40	40–60	60–80	0–10	10–20	20–40	40–60	60–80	0–10	10–20	20–40	40–60	60–80
Desert	$H_{G\ (cm)}$	−0.48	−0.67* b	−0.73*	−0.44	−0.17	−0.69*	−0.74*	−0.70*	−0.84**	−0.80**	−0.71*	−0.79**	−0.69*	−0.89**	−0.76*
	Fw (g m^{-2})	0.76*	0.60	0.58	0.04	0.37	0.47	0.60	0.62	0.52	0.60	0.69*	0.84**	0.77**	0.69*	0.47
	Dw (g m^{-2})	0.77**	0.61	0.61	0.08	0.37	0.53	0.64*	0.65*	0.57	0.65*	0.73*	0.86**	0.78**	0.72*	0.50
	R	−0.39	−0.65*	−0.62	−0.30	−0.41	−0.36	−0.50	−0.41	−0.58	−0.53	−0.50	−0.74*	−0.58	−0.77**	−0.57
	H	−0.40	−0.61	−0.50	−0.19	−0.53	−0.20	−0.38	−0.27	−0.42	−0.36	−0.39	−0.71*	−0.52	−0.67*	−0.41
	D	0.38	0.53	0.36	0.07	0.62	0.05	0.27	0.14	0.25	0.18	0.29	0.64*	0.43	0.53	0.24
	J	−0.77	−0.99**	−0.83	−0.91	−0.62	−0.07	−0.32	−0.35	−0.51	−0.49	−0.20	−0.76	−0.74	−0.82	−0.78
Grassland	$H_{G\ (cm)}$	0.43	0.58	0.80**	0.38	0.06	0.43	0.51	0.47	0.32	0.08	0.59	0.69*	0.63	0.51	0.10
	Fw (g m^{-2})	0.81**	0.86**	0.83**	0.35	0.24	0.88**	0.88**	0.74*	0.71*	0.52	0.94**	0.89**	0.78*	0.64	0.37
	Dw (g m^{-2})	0.76*	0.80*	0.80**	0.33	0.19	0.82**	0.82**	0.71*	0.65	0.43	0.89**	0.85**	0.76*	0.60	0.29
	R	−0.36	−0.09	−0.34	−0.29	−0.43	−0.36	−0.30	−0.35	−0.21	−0.18	−0.35	−0.23	−0.34	−0.14	−0.36
	H	−0.63	−0.42	−0.61	−0.01	−0.34	−0.65	−0.61	−0.50	−0.47	−0.35	−0.66	−0.56	−0.52	−0.22	−0.19
	D	0.74*	0.60	0.74*	0.19	0.20	0.79*	0.75*	0.58	0.62	0.46	0.81**	0.72*	0.61	0.46	0.01
	J	−0.72*	−0.65	−0.51	−0.73*	−0.34	−0.59	−0.66	−0.23	−0.55	−0.47	−0.68*	−0.65	−0.25	−0.77*	−0.45

[a] H_G, Fw and Dw are the abbreviations of mean height, fresh weight and dry weight of shrubs and herbs, respectively. *R*, *H*, *D* and *J* refer to Patrick richness index, Shannon–Wiener diversity index, Simpson dominance index and Pielou evenness index, respectively.
[b] "**" and "*" indicate significance levels of 0.01 and 0.05, respectively.

followed changes in SOCC. It has been shown that N mineralization decreases when clay content increases in soil (Côté et al., 2000; Corral-Fernández et al., 2013; Parras-Alcántara et al., 2013). In the 0–80 cm soil profiles, the average silt and sand contents were 56.0% and 41.1%, respectively. Low clay fraction might be responsible for the lack of its association with SOCC, TCC and TNC. Clay content, however,

Table 6

Pearson correlation between soil organic carbon concentration (SOCC), total carbon concentration (TCC), total nitrogen concentration (TNC) and vegetation (trees, shrubs and herbs) indices in various soil layers of woodland.

Vegetation	Index [a]	SOCC (g kg^{-1})					TCC (g kg^{-1})					TNC (g kg^{-1})				
		0–10	10–20	20–40	40–60	60–80	0–10	10–20	20–40	40–60	60–80	0–10	10–20	20–40	40–60	60–80
Tree	Number	−0.24	−0.30	−0.05	−0.27	−0.21	−0.33	−0.24	−0.17	−0.32	−0.17	−0.39	−0.27	−0.03	−0.27	−0.13
	Canopy (m^2)	−0.01	−0.02	−0.15	−0.37	−0.31	0.25	0.24	0.39	0.34	0.39	0.33	0.04	0.01	−0.21	−0.26
	H_T (m)	0.27	0.09	−0.01	0.12	0.07	−0.18	−0.12	−0.39	−0.38	−0.35	0.06	0.13	−0.12	0.06	0.03
	DBH (cm)	−0.09	−0.10	−0.32	−0.41	−0.30	−0.25	−0.21	−0.12	−0.15	−0.05	−0.17	−0.14	−0.28	−0.34	−0.34
Shrub + herb	H_G (cm)	0.56*[b]	0.52*	0.33	0.17	0.29	0.33	0.41	0.07	0.01	0.01	0.37	0.36	0.10	0.05	0.13
	Fw (g m^{-2})	0.56*	0.46	0.47*	0.17	0.35	0.38	0.34	0.21	0.05	0.06	0.31	0.13	0.21	0.05	0.08
	Dw (g m^{-2})	0.54*	0.45	0.46*	0.16	0.34	0.38	0.35	0.21	0.05	0.06	0.31	0.13	0.20	0.06	0.07
	R	−0.24	−0.14	−0.22	−0.06	−0.15	−0.26	−0.10	−0.24	−0.02	−0.06	−0.18	−0.10	−0.05	−0.12	−0.03
	H	−0.25	−0.10	−0.12	−0.07	−0.03	−0.33	−0.20	−0.28	−0.15	−0.15	−0.21	−0.05	−0.02	−0.10	−0.01
	D	0.28	0.09	0.08	0.13	0.03	0.36	0.25	0.27	0.19	0.17	0.21	0.03	0.01	0.12	0.04
	J	0.31	0.46	0.52*	0.43	0.53*	0.08	0.03	0.02	0.16	0.11	0.17	0.12	0.27	0.04	0.10

[a] H_T and DBH are the abbreviations of mean height and mean diameter at breast height of trees, respectively. H_G, Fw and Dw are the abbreviations of mean height, fresh weight and dry weight of shrubs and herbs, respectively. *R*, *H*, *D* and *J* refer to Patrick richness index, Shannon–Wiener diversity index, Simpson dominance index and Pielou evenness index, respectively.
[b] "*" indicates significance level of 0.05.

Table 7
Stepwise multiple linear regression of soil organic carbon concentration (SOCC), total carbon concentration (TCC), total nitrogen concentration (TNC) with soil properties, site variables and vegetation indices in various soil layers of the study area.

Layer (cm)	Variable	Cropland			Desert			Woodland			Grassland		
		Predictor [a]	Adjusted R^2	p [b]	Predictor	Adjusted R^2	p	Predictor	Adjusted R^2	p	Predictor	Adjusted R^2	p
0–10	SOCC	Lat., Bd	0.42	<0.001	–	–	–	–	–	–	Fw	0.61	<0.01
	TCC	Lat., Bd	0.44	<0.001	Dw	0.92	<0.05	Lon., H_G, pH	1.00	<0.001	Fw, Bd, *D*	0.94	<0.001
	TNC	Lat., Bd	0.35	<0.001	E	0.99	<0.01	Silt	0.63	<0.05	Fw, *J*, Lat.	0.98	<0.001
10–20	SOCC	Lat.	0.35	<0.001	*J*	0.99	<0.01	Silt	0.97	<0.001	Fw	0.69	<0.01
	TCC	Fc, Silt, Clay	0.60	<0.001	Fw, Dw, E	1.00	<0.001	–	–	–	Fw	0.75	<0.01
	TNC	Lat.	0.18	<0.01	Bd, Clay, Lon.	1.00	<0.001	Sand, *J*	0.95	<0.01	Fw	0.76	<0.001
20–40	SOCC	E, pH	0.27	<0.01	–	–	–	–	–	–	Fw	0.65	<0.01
	TCC	E	0.14	<0.05	Fw, Fc, E	1.00	<0.001	Fc	0.64	<0.05	Fw, Lat.	0.80	<0.01
	TNC	E	0.16	<0.01	*R*	0.96	<0.05	–	–	–	Fw	0.55	<0.05
40–60	SOCC	Lat.	0.24	<0.001	–	–	–	Silt, H_G, Fc	1.00	<0.001	*J*	0.46	<0.05
	TCC	pH	0.09	<0.05	Clay	0.97	<0.01	–	–	–	Fw	0.43	<0.05
	TNC	–	–	–	*R*	0.98	<0.01	Bd	0.58	<0.05	*J*, pH	0.74	<0.01
60–80	SOCC	Lat.	0.25	<0.001	–	–	–	Sand, Fw, pH	0.99	<0.01	–	–	–
	TCC	E	0.11	<0.05	Clay	0.99	<0.01	–	–	–	–	–	–
	TNC	E	0.25	<0.001	*R*	0.98	<0.01	–	–	–	–	–	–

[a] Lat., Lon. and E are the abbreviations of latitude (°), longitude (°) and elevation (m) of the sampling points, respectively. Bd, Fc, pH, Clay, Silt and Sand are the bulk density (g cm^{-3}), field capacity (%), pH value, clay content (%), silt content (%) and sand content (%) of the soil, respectively. Fw, Dw and H_G are the abbreviations of fresh weight (g m^{-2}), dry weight (g m^{-2}) and mean height (cm) of shrubs and herbs, respectively. *J*, *R* and *D* refer to Pielou evenness index, Patrick richness index and Simpson dominance index, respectively.

[b] $p < 0.05$, 0.01 and 0.001 indicate that the regression equations are significant at the 0.05, 0.01 and 0.001 levels, respectively. "–" indicates that data do not exist.

explained 97% and 99% of TCC variations in the 40–60 and 60–80 cm layers of desert soil, respectively (Table 7).

In this study, silt particles, especially fine silt particles (with diameter ranging from 0.002 to 0.02 cm), might play a similar role on the accumulation of SOC as clay particles. Fine silt contents were generally equal to clay contents with depth for the four landscapes. Mean fine silt contents were 23.1% and 27.7% in the 0–80 cm soil profiles of cropland and grassland, respectively, occupying 57.9% and 56.9% of the respective silt contents of the two landscapes in the study area. In this study, silt content (sand content) was positively (negatively) correlated with SOCC, TCC and TNC in the 0–80 cm soil profiles (Table 4). Silt and clay contents were able to explain 15% of the TCC variation in the 10–20 cm cropland soil (Table 7). In arid sandy land, fine wind-blown particles will deposit when the wind speed decreases or large turbulent eddies are disrupted by the tree canopy of shelterbelts or windbreak. The accumulation of SIC will occur once cations are supplied by inputs of rain and dust (Monger and Martinez-Rios, 2001). This might be able to account for the association between fine (clay plus silt) particles and TCC in desert and cropland soils. This result coincides with the report that fine particles input by dust deposition and irrigation using silt-laden Heihe River water has positive effect on soil fertility improvement (Su et al., 2007).

Soil texture plays predominant roles on the accumulation of SOC and TN in the surface soil of woodland. Silt content explained 97% and 87% of the SOCC variation in the 10–20 and 40–60 cm layers, respectively (Table 7). As for the variation of TNC, silt content accounted for 63% in the 0–10 cm layer and sand content explained 59% in the 10–20 cm layer of woodland (Table 7). In Ganzhou, the average silt contents in the 0–10, 0–20 and 0–80 cm layers of woodland far from the river bank were 64.8%, 64.6% and 59.5%, respectively, which were higher than that of woodland near the river bank (62.2%, 62.0% and 55.9% in the corresponding layers) (Fig. 7A). Sand contents in the corresponding layers of woodland far from the river bank were 32.4%, 32.6% and 37.8%, which were lower than the values of woodland near the river bank (35.9%, 35.9% and 42.1%, respectively) (Fig. 7B). On the other hand, soil in woodland far from the river bank was relatively deficient in water, and soil–water stress might decrease SOM decomposition (Norton et al., 2008). This result is indicative of the higher SOCD and TND in various layers of woodland far from the river bank compared with that near the river bank (Fig. 6).

4.2. Influence of vegetation

Vegetation types and properties affect the input of plant biomass into soil, thus indirectly affecting SOM levels. The accumulation of organic carbon in soils and the proportion allocated to soil C pools with different turnover rates tend to vary with vegetation types (Fu et al., 2010). Vegetation cover is a good indicator of the spatial variation of soil C and N (Kunkel et al., 2011). Desert in the study area consisted of

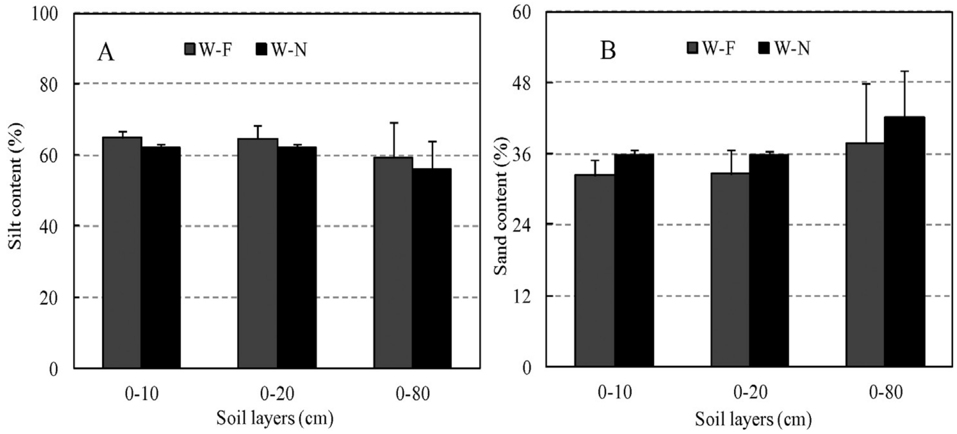

Fig. 7. Comparison of (A) silt content and (B) sand content between woodland far from the river bank (W-F) and woodland near the river bank (W-N).

12 species of shrubs and herbs, dominated by *S. passerina* Bunge and *A. sparsifolia* Shap (Table 1). Herbs and shrubs in the woodland summed up to 43 species, dominated by *L. secalinus* (Georgi) Tzvel and *S. alopecuroides* L (Table 1). Shrubs have more tap roots and less fibrous roots, whereas herbs have more shallow fibrous roots. The SOM in woodland is mostly derived from lignified material, which is of low litter quality and has a high C:N ratio (Gami et al., 2009). Lignified litter is incorporated into the soil more slowly than herbaceous litter in the desert and woodland (Post and Kwon, 2000). The dense and homogeneous root system of herbaceous plants provides more SOC in the subsoil via the fast root turnover in the grassland (Meersmans et al., 2009). The transfer of large amounts of C into the soil by roots is slow, however, its contribution to the underground C content increase accumulates over time (Parras-Alcántara et al., 2013).

Although certain associations were observed (Tables 4 and 5), species diversity indices of shrubs and herbs had a limited ability to explain the variations of SOCC, TCC and TNC in different landscapes. Negatively correlated with TNC, the Patrick richness index explained 96%, 98% and 98% of the TNC variation in the 20–40, 40–60 and 60–80 cm layers of the desert, respectively (Table 7). There was no N input by direct fertilization, the addition of N in terms of airborne deposition was negligible due to the small amount of rainfall, and N might be the limiting nutrient in the desert. The high C:N ratio indicated the scarcity of N and the higher concentration of less decomposed SOM in the desert (Batjes and Dijkshoorn, 1999; Lou et al., 2012; Puget and Lal, 2005). There were two types of leguminous shrubs (*Hedysarum scoparium* and *A. sparsifolia* Shap) among the plants in the desert. The capacity of N fixation by the leguminous plants was low and contributed little to the TN accumulation in the desert soil. In the present study, tree species were unitary. Shelterbelts of *P. simonii* Carr were mainly planted in 3 to 5 rows around cropland. The windbreak of *P. simonii* Carr or *E. angustifolia* Linn was mainly distributed on the edge of the desert. Agroforestry has been demonstrated as an important strategy for soil C accumulation (Oelbermann and Voroney, 2007; Watson et al., 2000). The sampling strategy focusing merely on windbreak might explain to some extent the lower SOCD, TCD and TND in the woodland than in the cropland (Fig. 4).

Aboveground biomass of plants and the degrees of its impact on soil C and TN differed among landscapes. A large proportion of shrubs in the desert led to higher aboveground biomass than the woodland and grassland. The mean fresh weight of plants in the desert (493.3 g m^{-2}) was generally 1.2 and 4.0 times those in the woodland and grassland, respectively. The dry weight in the desert (169.9 g m^{-2}) was 1.9 and 5.5 times those in the woodland and grassland, respectively (Table 1). Plant production and decomposition determine C input to soil, as indicated by the positive correlations between aboveground biomass and SOCC and TCC (Tables 4 and 5). The dry weight of shrubs and herbs explained 92% of the TCC variation in the 0–10 cm soil, whereas fresh weight explained 99% of the TCC variation in the 10–20 and 20–40 cm layers of the desert (Table 7). There were two approaches to elucidate the role of plant biomass on TCC in desert soil. On the one hand, SIC (primarily as carbonate C) is of particular relevance to dry land because the formation of secondary carbonates is a principle process in the soils of arid regions (FAO, 2004). The increase in biomass and consequent litter input can enhance the activity of soil fauna and increase the formation of secondary carbonates through litter decomposition in the desert (Lal, 2008). On the other hand, root exudates may lead to relatively high carbonate concentrations in the vicinity of plant roots (Lal, 2004).

In the grassland, the fresh weight of shrubs and herbs accounted for 61%, 69% and 65% of the SOCC variation in the 0–10, 10–20 and 20–40 cm layers, respectively (Table 7). Variations of TCC accounted for by the fresh weight of shrubs and herbs were 75% in both the 0–10 and 10–20 cm layers and 48% in the 20–40 cm layer (Table 7). As for TNC, the fresh weight of shrubs and herbs explained 88%, 76% and 55% of the variations in the 0–10, 10–20 and 20–40 cm layers, respectively (Table 7). Nitrogen in grassland soil might derive from lateral seepage of irrigation water with dissolved fertilizer of nearby cropland. Eutrophication might improve grass productivity and in turn increase the plant litter, which could accelerate N turnover. Aboveground biomass of shrubs and herbs, especially the fresh weight, was therefore considered as a dominant predictor of TCC in the desert and of SOCC, TCC and TNC in the grassland in the 0–40 cm soil. This is consistent with previous finding that aboveground plant biomass acts as a key factor driving the changes of SOC and TN along the aridity gradient from southeast to northwest in China (Yang et al., 2011). In addition, the capillary rise of Ca^{2+} from shallow groundwater and its re-precipitation in the surface soil may also contribute to the formation of secondary carbonates and thus the accumulation of SIC and TC in grassland soil (Lal, 2008).

4.3. Influence of agricultural management practices

Agricultural strategies have profound impacts on soil C and TN levels. In the study area, conventional tillage using mechanical equipment is commonly adopted by farmers. Perturbation of soil by plowing leads to aeration, incorporation of aboveground C and subsequent drying/rewetting of topsoil (Balesdent et al., 2000). Macro-aggregates are destroyed and the formation of micro-aggregates is deteriorated. Some SOM physically protected in micro-aggregates is exposed to biodegradation, and soil microbial activity is promoted by the increase in soil temperature (Alvarez et al., 2001; Balesdent et al., 2000; Meersmans et al., 2009). The homogeneous distribution of the C:N ratio in the soil profile of cropland is related to soil structural distortion and higher SOM decomposition due to tillage. After harvest of maize, stalks are collected as livestock feed, and residues and roots are gathered and removed from cropland. The soil surface remains bare during winter and early spring when strong sand-drifting occurs and fine particles are blown and carried away. Management strategies, such as conservation tillage, crop rotation, residue return and elimination of bare fallow may be efficient to accumulate soil C and TN (Dikgwatlhe et al., 2014; Lou et al., 2012; Lozano-García and Parras-Alcántara, 2013). It has been reported that SR for SOCC was greater under non-tillage or organic farming compared to conventional tillage (Corral-Fernández et al., 2013; Franzluebbers, 2002).

Agriculture relies on flood irrigation sourced from the Heihe River water and groundwater in the study area (Ji et al., 2007). Irrigation is applied 7 times, summing up to 9660 m^3 ha^{-1} in Linze and Ganzhou (Lü et al., 2014). In Gaotai, maize is irrigated 4–5 times, totaling 11,250 m^3 ha^{-1} throughout the growing season (Li et al., 2009). Relatively more irrigation water might percolate, subsequently nutrients and fine particles might leach to deeper layers during the processes of infiltration, redistribution and percolation in the Gaotai cropland. Furthermore, changes in soil water content during the periodical irrigation affect the microbial activity and thus SOM decomposition. The wetting of soil by irrigation following periods of drought can create large flushes of nutrients and SOC by releasing, through diffusion, drought accumulated SOM, inorganic N and microbial necromass (Schimel et al., 2007). Large pulses of microbial respiration may follow the flush of fresh substrate (Butterly et al., 2009). During two irrigation events, microorganisms in soils undergoing water stress may devote more carbon resources and more nitrogen-rich organic substrates to survival mechanisms such as mucilage production, membrane transport proteins and protective osmolyte production, and the respiration costs associated with these functions (Schimel et al., 2007; Tiemann and Billings, 2011).

The fertilizer type and fertilization rate also contribute considerably to soil C and TN levels in cropland. According to the conventional cultivation custom, approximately 516 kg N ha^{-1} and 86 kg P_2O_5 ha^{-1} are applied during the maize growing season, including one base fertilization of urea and di-ammonium phosphate and three topdressings of urea later in Gaotai (Li et al., 2009). The rate of fertilizer application for maize is approximately 300–450 kg N ha^{-1}, 90–150 kg P_2O_5 ha^{-1}, 60–90 kg K_2O ha^{-1} and 3–6 t ha^{-1} farmyard manure in cropland of Linze each year (Su et al., 2010b). In the Ganzhou cropland, approximately 120–150 kg N ha^{-1}, 60–75 kg P_2O_5 ha^{-1}, 60–75 kg K_2O ha^{-1} and 30–45 t ha^{-1} of farmyard manure composed of 190 g OC kg^{-1} and 21 g N kg^{-1} are applied each year (Su et al., 2006). Application of organic manure combined with mineral fertilizers has been shown to be effective in increasing both TN and the labile and recalcitrant pools of topsoil OC under conventional management (Su et al., 2006; Yang et al., 2007; Zhou et al., 2013). The combined effects of the aforementioned factors contributed to the higher SOCD and TND in soil profiles of cropland in Ganzhou than Gaotai and Linze.

4.4. Influence of sampling strategy

In addition to various factors discussed above, sampling strategy may be another reason for the stratification characteristics and stocks of SOC, TC and TN. Franzluebbers (2002) considered that high stratification of SOC and N pools would reflect relatively undisturbed soil with high-quality topsoil leading to (1) improved water infiltration, (2) better macro-pore development, (3) more stable aggregates, (4) an ample supply of organically bound slow-release nutrients and (5) a diverse food supply for beneficial soil organism activities. Almost all SRs for SOCC, TCC and TNC were <2 in this study. Except relatively low SOM levels, this might be associated with the sampling method using soil control section with different depth increments (0–10, 10–20, 20–40, 40–60 and 60–80 cm). Such a sampling method mixed the pedogenetic horizons in a soil profile. Furthermore, the calculation of SOCD, TCD and TND might be indirectly affected due to the direct influences on bulk density, SOCC, TCC, TNC, gravel content and thickness of soil layers (Parras-Alcántara et al., 2015a). Nowadays there are different opinions on whether SOC stock should be inventoried by genetic horizons in entire soil profiles or using depth increments within a soil control section. Parras-Alcántara et al. (2015a) compared these two sampling methods and found that soil control section method would overestimate total SOC stock. In this study area, landscapes are heterogeneous and soils are layering structured. It is necessary to resample by genetic horizons using entire soil profile to determine the most appropriate sampling depths for accurately estimating the stocks of SOC and TN in future study.

5. Conclusions

In the middle reaches of the Heihe River basin, the concentrations and densities of SOC, TC and TN differed among landscapes, subregions, and among soil layers at regional scale. Factors involving soil properties, vegetation condition and agricultural management practices exerted varying degrees in explaining the variations of SOCC, TCC and TNC at different scales.

At landscape scale, conventional tillage may be inappropriate for nutrients improvement indicated by the low SRs of SOCC, TCC and TNC in cropland soil. Reduced tillage, organic manure application, crop rotation and residue return should be introduced and popularized in current management mode for promoting soil quality. The dominant role of silt particles on the SOCC, TCC and TNC in woodland indicate the importance of shelterbelts or windbreak to alleviate wind erosion, deposit fine particles and improve soil nutrient levels. Aboveground biomass of shrubs and herbs, especially fresh weight, was regarded as a dominant indicator of TCC in the desert and of SOCC, TCC and TNC in the grassland. This emphasized the importance of vegetation recovery on controlling desertification and soil degradation. In regard to sub-regional scale, longer-term cultivation and application of mineral fertilizer combined with farmyard manure led to relatively higher SOCD and TND in cropland of Ganzhou. Fine-textured soil and water deficiency contributed to the higher SOCD and TND in soils of woodland far from the river bank than woodland near the river bank in Ganzhou.

This study provided detailed knowledge about the status and variability of soil C and TN at multiple scales, which is fundamental for up-scaling and down-scaling studies on soil nutrients in arid regions. However, the ecological impacts of current land management concerning the coexistence of different landscapes should be further investigated for its contribution to ecological functioning and ecosystem sustainability.

Acknowledgments

This study was financially supported by the National Natural Science Foundation of China (91425301, 91025002 and 91025018), and the 12th Five Year Science and Technology Development Program (2012BAC08B01). Sincere thanks go to Mr. Zhimin Ma for collecting field data. We thank the anonymous reviewers for their constructive comments which improved the overall quality of the manuscript.

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