Chin. Geogra. Sci. 2017 Vol. 27 No. 4 pp. 529–538
doi: 10.1007/s11769-017-0885-7

Springer Science Press
www.springerlink.com/content/1002-0063

Spatial Variability of Soil Carbon to Nitrogen Ratio and Its Driving Factors in Ili River Valley, Xinjiang, Northwest China

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Abstract: Soil carbon to nitrogen (C/N) ratio is one of the most important variables reflecting soil quality and ecological function, and an indicator for assessing carbon and nitrogen nutrition balance of soils. Its variation reflects the carbon and nitrogen cycling of soils. In order to explore the spatial variability of soil C/N ratio and its controlling factors of the Ili River valley in Xinjiang Uygur Autonomous Region, Northwest China, the traditional statistical methods, including correlation analysis, geostatistic alanalys and multiple regression analysis were used. The statistical results showed that the soil C/N ratio varied from 7.00 to 23.11, with a mean value of 10.92, and the coefficient of variation was 31.3%. Correlation analysis showed that longitude, altitude, precipitation, soil water, organic carbon, and total nitrogen were positively correlated with the soil C/N ratio (P < 0.01), whereas negative correlations were found between the soil C/N ratio and latitude, temperature, soil bulk density and soil pH. Ordinary Cokriging interpolation showed that r and ME were 0.73 and 0.57, respectively, indicating that the prediction accuracy was high. The spatial autocorrelation of the soil C/N ratio was 6.4 km, and the nugget effect of the soil C/N ratio was 10% with a patchy distribution, in which the area with high value (12.00–20.41) accounted for 22.6% of the total area. Land uses changed the soil C/N ratio with the order of cultivated land > grass land > forest land > garden. Multiple regression analysis showed that geographical and climatic factors, and soil physical and chemical properties could independently explain 26.8%and 55.4% of the spatial features of soil C/N ratio, while human activities could independently explain 5.4% of the spatial features only. The spatial distribution of soil C/N ratio in the study has important reference value for managing soil carbon and nitrogen, and for improving ecological function to similar regions.

Keywords: soil C/N ratio; spatial variability; geostatistical analysis; Cokriging interpolation; multiple regression analysis; Ili River valley

Citation: Sun Guojun, Li Weihong, Zhu Chenggang, Chen Yaning, 2017. Spatial variability of soil carbon to nitrogen ratio and its driving factors in Ili River valley, Xinjiang, Northwest China. *Chinese Geographical Science*, 27(4): 529–538. doi: 10.1007/s11769-017-0885-7

1 Introduction

Soil organic carbon (SOC) and total nitrogen (TN) are the essential nutrient elements for plant growth, and the important parts of soil carbon and nitrogen pool as well. The changes of their quantity and quality affect soil physical, chemical and biological features, and thus the maintenance and improvement of soil fertility (Zhang *et al*., 2013; Brevik *et al*., 2015; Zhang *et al*., 2015). The increase of SOC is important to improve soil structure, to provide carbon source for plant growth, and consequently to sequestrate the greenhouse gases in soil (Wang *et al*., 2011; Liu *et al*., 2016). In contrast, the increase of soil available nitrogen is good to meet the needs of crop nitrogen, to decrease the loss of nutrients, and to reduce the pollution of ecological environment

Received date: 2016-11-06; accepted date: 2017-01-12
Foundation item: Under the auspices of National Science and Technology Support Program of China (No. 2014BAC15B03), the West Light Funds of Chinese Academy of Sciences (No. YB201302)
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(Mallory and Griffin, 2007). As a result, the changes of SOC and TN well reflected the features of soil nutrients. Especially, soil carbon to nitrogen (C/N) ratio, as an indication of the relationship between SOC and TN, represents the characteristics of soil quality changes more comprehensively (Luo *et al*., 2015; Zhang *et al*., 2015). Generally, soil C/N ratio in natural ecological system could be relatively stable, however, it is easily affected by soil management measures (Luo *et al*., 2013; Zhou *et al*., 2014). It is well known that soil C/N ratio influences soil microbe activity and mineralization rate, and then regulates soil quality and the cycle of SOC and nitrogen (Bengtsson *et al*., 2003; Wan *et al*., 2014).

Soil C/N ratio could be influenced by variables including climate (such as temperature, precipitation) (Gao *et al*., 2011; Chang *et al*., 2014), soil conditions (such as soil water, soil bulk, soil pH) (Wang *et al*., 2014; Feng *et al*., 2016), and land use types (Zhang *et al*., 2015). Precipitation and temperature are known to influence vegetative cover, plant litter quality and soil biota, physical and chemical properties of soil, which in turn influence soil C/N ratio (Qin *et al*., 2016). Cools *et al*. (2014) found that soil C/N ratio had a negative relationship with temperature, but a positive relationship with precipitation. Wang *et al*. (2014) put forward that climate factors were the main environmental factors affecting soil C/N ratio. Feng *et al*. (2016) proposed that climatic and soil pH generally had a major contribution to the variations in soil C/N ratio. To be specific, climate data (precipitation, temperature) explained 34.2% of the variation in soil C/N ratio, and soil pH accounted for 15%–64% of the variation in soil C/N ratio. Land use altered soil C/N ratio by changing soil carbon and nutrient contents, soil bulk density (SBD), and soil pH. Luo *et al*. (2015) found that land use types could explain 24.1% of the spatial variability of soil C/N ratio and was the main factor controlling the changes of soil C/N ratio. Qi *et al*. (2008) proposed that excessive application of nitrogen fertilizer was the main reason for the decline in soil C/N ratio in the typical farmland of the Yangtze River Delta. Though the effect of SOC and nitrogen has been reported by many researches, very few investigated the spatial variation of soil carbon and nitrogen, especially the ratio between them (Bai *et al*., 2013; Shi *et al*., 2013; Dong *et al*., 2014; Zeng *et al*., 2014; Liu *et al*., 2016). It is therefore important to understand the spatial distribution of soil C/N ratio.

Typical methods of measuring soil C/N ratio require data collection of SOC and TN, which can be considered a time-consuming and labor-intensive work that is not cost effective (Yang *et al*., 2016). Cokriging interpolation has been gradually applied to aspects of soil property prediction because it provides a higher accuracy of estimation, especially in the case of low sampling density, than the other method (Yao *et al*., 2014). In China, it seems that concern about soil C/N ratio was mainly on monsoon and plateau regions, but few studies were given attention to spatial distribution characteristics and influencing factors of soil C/N ratio in northwest arid area, especially the Ili River valley, the most potential agricultural reclamation area and the key control region of water erosion in the northwest of Xinjiang Uygur Autonomous Region, China.

The objectives of this study were to: 1) investigate the possibility of using predicted environment variable data as auxiliary variables to estimate C/N ratio and analyze the spatial distribution of soil C/N ratio in the Ili River valley; 2) clarify the controlling factors of soil C/N ratio, including geographical and climatic factors, soil physical and chemical properties and land use types; and 3) determine the relative contribution of these factors to the change of soil C/N ratio. The outcome will have important ecological significance for the optimization of regional soil resources and ecological environment protection to similar regions of the world.

2 Materials and Methods

2.1 Study area

The Ili River valley (42º14' N–44º50' N, 80º09' E–84º56' E) is located on the western slope of the Tianshan Mountains and southwest of Junggar Basin in Xinjiang, Northwest China (Fig. 1). The Ili River, with a drainage area of 5.53×10^4 km^2, is mainly recharged by the three headwaters, i.e., the Kunes River, the Turks River and the Kaxgar River (Yang *et al*., 2010; Sun *et al*., 2012). The region has a temperate semiarid continental climate, and is dominated by westwinds throughout the year. The winter climate is mainly controlled by the intensity and position of the Siberia high pressure cell, the summer climate is partly affected by the Indian low pressure cell (Shi *et al*., 2013).

2.2 Data collection

We conducted two field campaigns in the Ili River valley

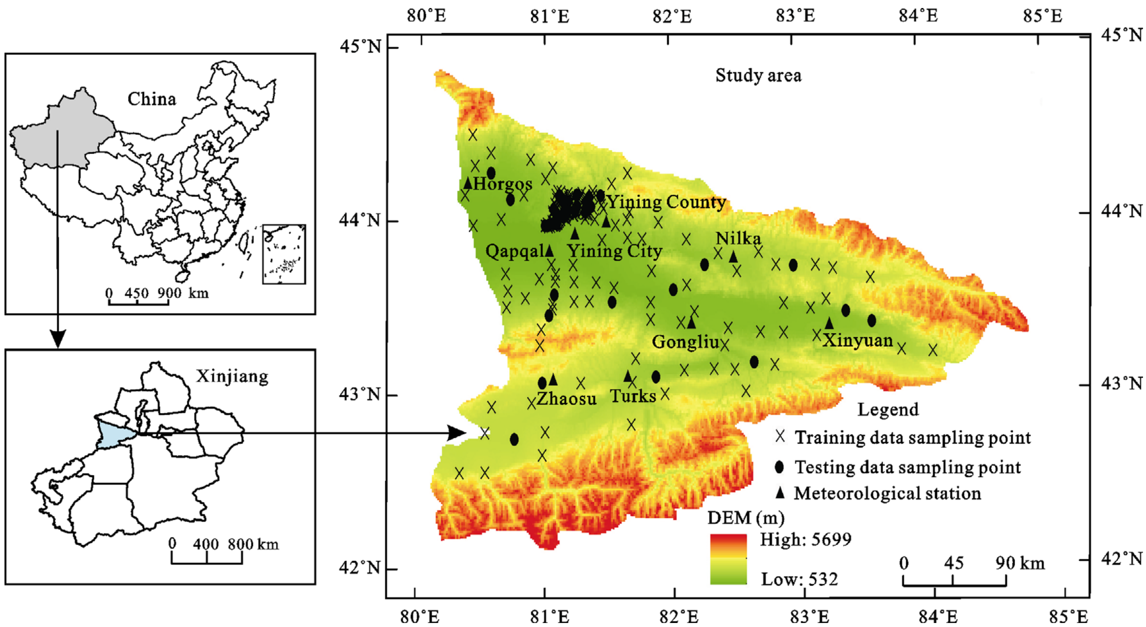

Fig. 1 Map of study area with distribution of sampling points in Ili River valley of Xinjiang, Northwest China

in May and August, 2015, respectively, associated with the records of natural conditions, such as regional landform, climate, soil, and vegetation. When an area has low altitude, terrain complexity and frequent disturbance of human activities, the sampling density is large, and vice versa. The sample density is following the distribution proportion of grassland, cultivated land, forest land, and garden land, which is 9∶2∶1∶1. The self-made sampler (10 cm diameter and 50 cm height) was used to collect topsoil samples (0–20 cm). Each sampling point was positioned by GPS in which latitude, longitude and elevation were recorded. In total, 223 topsoil samples were collected (Fig. 1), including 32 cultivated land samples, 21 garden samples, 17 forest land samples, and 153 grassland samples. For pretreatment, the soil samples were air dried, grinded and screened through a 2 mm sieve. SOC content was determined using the $K_2Cr_2O_7$-external heating method (Shi *et al*., 2013). Soil nitrogen content was determined using the perchloric acid-sulphuric acid digestion method (Wang *et al*., 2014). Soil pH was determined using the electric potential method (Feng *et al*., 2016). SBD was determined using the ring shear testing method (Yang *et al*., 2016). Soil water content (SWC) was determined using the drying methods (Wiesmeier *et al*., 2011; Shi *et al*., 2013; Li *et al*., 2014). In addition, to extrapolate the climatic information, the data from nine meteorological stations (Yining City, Yining County, Nilka, Xinyuan, Zhaosu, Qapqal, Gongliu, Turks, and Horgos) in the Ili River valley were collected from the China Meteorological Administration (http://cdc.cma.gov.cn) covering the period from 1961 to 2015 (Fig. 1). The ordinary Kriging method was used to derive annual mean temperature and precipitation data for each sampled location.

2.3 Statistical analysis methods

2.3.1 Correlation analysis

Measured variables in the data set were first analyzed using descriptive statistical method by SPSS 19.0. Correlations among different analyzed parameters were tested using Pearson's correlation coefficient by origin 8.0. The coefficient of variation (CV), Kurtosisand Skewness are defined as:

$$CV = \frac{SD}{\bar{x}} \times 100\% \tag{1}$$

$$Kurtosis = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^4}{(n-1)SD^4} - 3 \tag{2}$$

$$Skewness = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^3}{(n-1)SD^3} \tag{3}$$

where x_i is datum i in the data set; n is the number of data points; $\bar{x}$ is the mean; SD is the standard deviation. According to the standard of CV, CV less than 10% indicates weak variability, ranging from 10% to 100% indicates moderate variability, and *CV* higher than 100% indicates strong variability (Li *et al*., 2010; Zhao *et al*., 2011; Luo *et al*., 2015).

2.3.2 Geostatistical analysis

Semivariograms were used to determine the degree of spatial variability. The semi-variance function has a unique advantage in describing the structural and random factors of spatial variables. C_0 is the nugget value and indicates variation caused by random factors, such as measurement error. Sill is the base value and is the total variability caused by random and structural factors. The ratio of C_0 to Sill (C_0/Sill) is the nugget effect. Range (A_0) is the functioning range of the spatial correlation at a certain observation scale (Zhao *et al*., 2011). Furthermore, ArcGIS 10.0 was used to interpolate the spatial pattern of soil C/N ratio.

2.3.3 Evaluation of prediction performance

To evaluate the performance of the spatial interpolation method, the soil sample data were divided into testing data and training data (Fig. 1). Training data (191 soil samples) were used for prediction, and testing data (32 soil samples) were used to evaluate the accuracy of Cokriging interpolation. The accuracy of estimates was assessed by *r*, mean error (ME) and root mean squared error (RMSE) (Yang *et al*., 2014).

2.3.4 Multiple Regression analysis

The general purpose of multiple regression analysis is to characterize the relationship between several independent or predictor variables and a dependent or criterion variable (Wu *et al*., 2009). So, we used multiple regression analysis to analyze the influencing degree of environmental factors (geographical and climatic factors, and soil physical and chemical characteristics) and human factors (land use types) to soil C/N ratio. In this study, land use types were qualitative classification variables, we chose dummy variables to the assignment of land use (Luo *et al*., 2015).

3 Results

3.1 Statistical characteristics of soil C/N ratio

Table 1 shows that soil C/N ratio ranged from 7.00 to 23.11 in the study area. The average value of soil C/N ratio is 10.92, which was between the national averages of 10–12 (Wang and Yu, 2008). The *CV* of the soil C/N ratio in the study area was 31.3%, indicating a moderate variability.

3.2 Correlation analysis between soil C/N ratio and environmental variables

A correlation analysis was performed for soil C/N ratio and environmental variables as shown in Fig. 2 and Fig. 3. The results indicated that there were significant positive correlations between soil C/N ratio and longitude, altitude, precipitation, SWC, SOC and TN, and significant negative correlations between soil C/N ratio and latitude, temperature, SBD and soil pH. The best selection principle of auxiliary variable is that the correlation between the auxiliary variable and the main variable is high, and the auxiliary variable is easily obtained (Wang *et al*., 2013). Among the environmental variables, altitude showed high correlation (r = 0.301) with soil C/N ratio, and was easily obtained. Therefore, altitude can be used as auxiliary variable for soil C/N ratio prediction.

3.3 Spatial prediction of soil C/N ratio using ordinary Cokriging interpolation with altitude

The aforementioned 191 prediction samples were used for spatial prediction of soil C/N ratio by ordinary Cokriging interpolation with altitude data as an auxiliary variable (Fig. 1), the results are shown in Table 2.

The data can be well fitted by spherical model to describe the spatial structures of soil C/N ratio (Table 2, Fig. 4). The C_0/Sill of the soil C/N ratio was10%, less than 25%, which showed a strong spatial correlation, indicating that the spatial variation was influenced by structural factors (Zhao *et al*., 2007).

3.4 Accuracy validation of ordinary Cokriging interpolation

The aforementioned 32 validation samples were used to assess performance of ordinary Cokriging interpolation using altitude as auxiliary data (Fig. 1). Table 3 shows the comparison results. The maximum (–) error and

Table 1 Statistical characteristics of soil C/N ratio in Ili River valley

Item	Mean	Max	Min	*SD*	*CV*	Skewness	Kurtosis	Distribution type
Soil C/N ratio	10.92	23.11	7.00	3.41	31.3	0.57	–0.54	LND

Notes: *SD*, standard deviation; *CV*, coefficient of variation (%); LND, log normal distribution

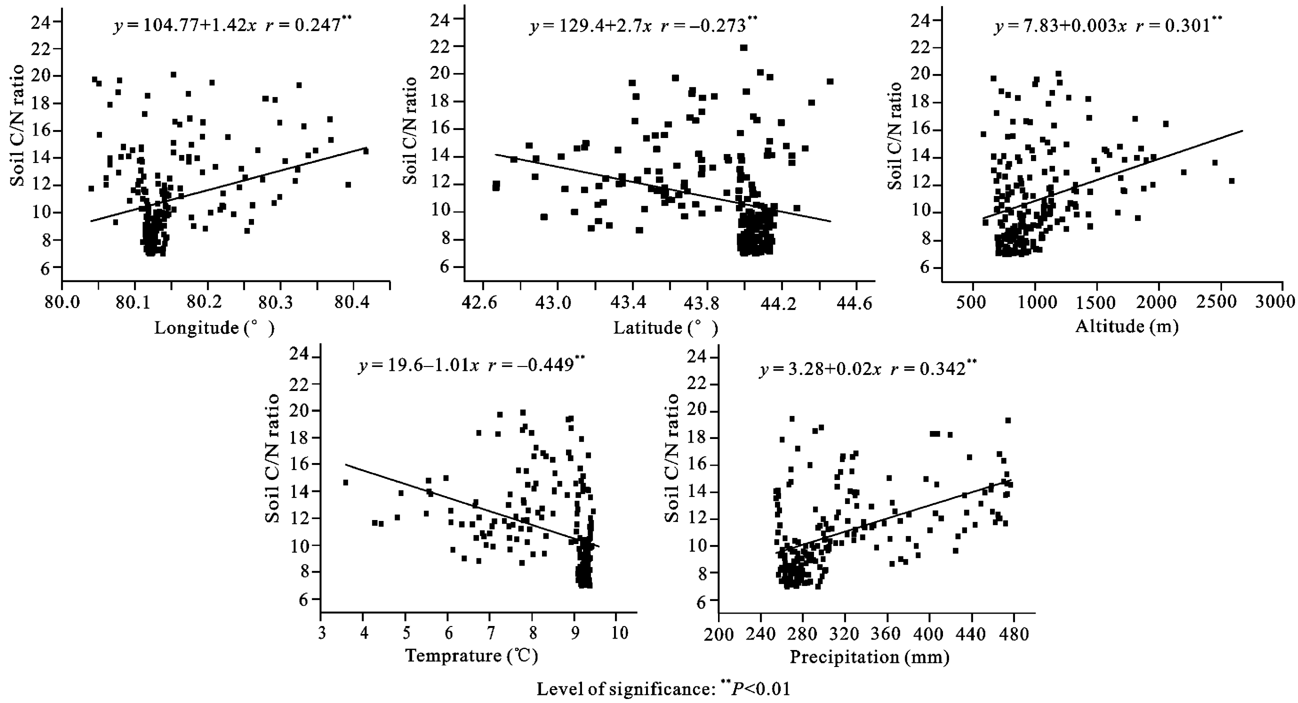

Fig. 2 Effects of geographical and climatic factors on soil C/N ratio in Ili River valley

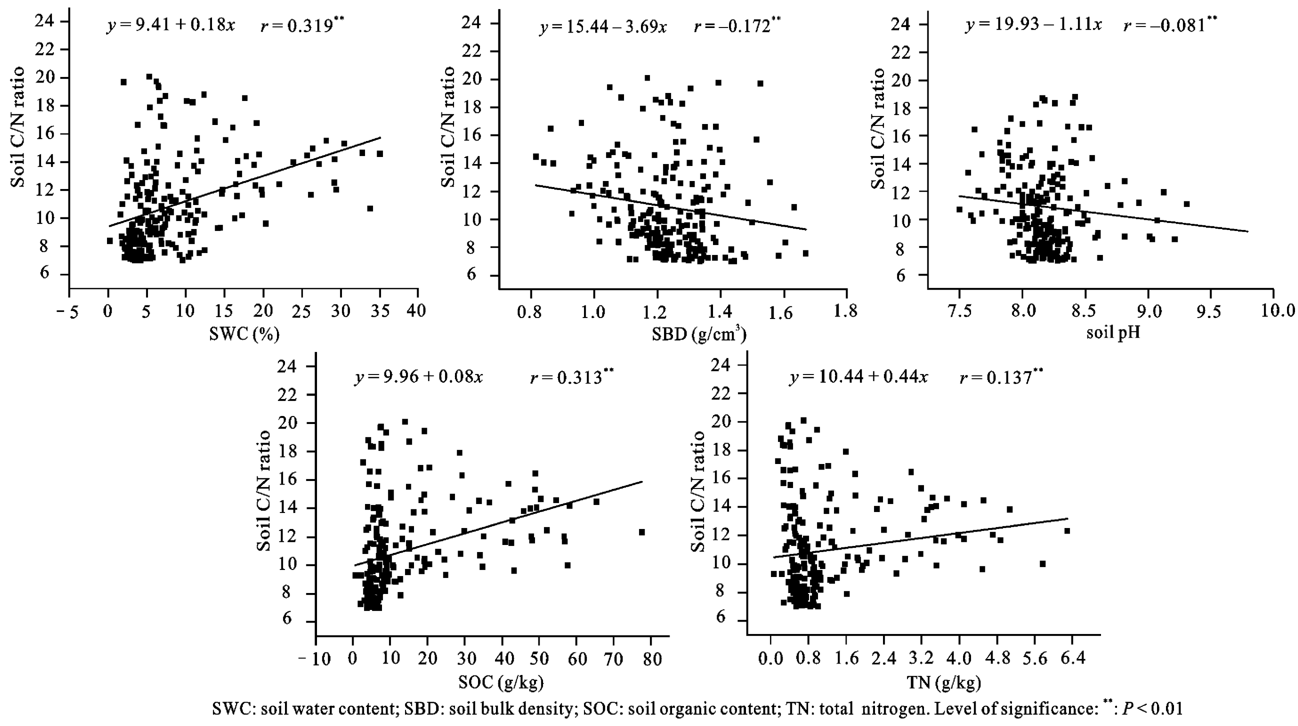

Fig. 3 Effects of soil physical and chemical properties on soil C/N ratio in Ili River valley

Table 2 Semivariationof soil C/N ratio in Ili River valley

Item	Nugget (C_0)	Sill	Range (km)	C_0/Sill (%)	Model	R^2	RSS
SoilC/Nratio	0.002	0.02	6.4	10	Spherical	0.87	1.35×10^{-5}

Notes: R^2, determination coefficient; RSS, reduced sum of squares

maxmum (+) error are –2.18 and 4.87, respectively. *r* was 0.73, which was more than 0.6, indicating that the prediction accuracy was high (Yang *et al.*, 2016). ME was 0.57, which was more than 0.5, indicating that the prediction accuracy was also high (Yang *et al.*, 2014).

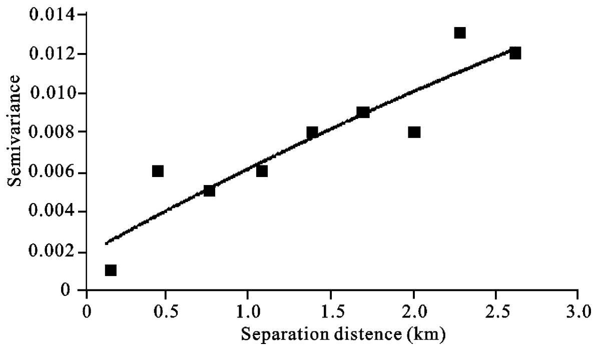

Fig. 4 Semivariogram of soil C/N ratio in Ili River valley

Table 3 Validationfor predicting soil C/N ratio using altitude as auxiliary data

	Minimum (–) error	Maximum (+) error	ME	RMSE	*r*
Cokriging	–2.18	4.87	0.57	1.94	0.73

3.5 Spatial and temporal distribution characteristics of soil C/N ratio

Figure 5a shows the distribution of soil C/N ratio in the study area. The high value area of soil C/N ratio (12.00–20.41) accounted for 22.6% of the total area, which was mainly distributed in the northern and the central parts of the study area, such as Huocheng County, Yining County, Nilka County, Xinyuan County and Qapqal County. The median value area of the soil C/N ratio (10.00–12.00) accounted for 74.4% of the total area, which was mainly distributed in the southern and eastern parts of the study area, such as Turks County, Zhaosu County, the east of Xinyuan County and the east of Nilka County. The low value area of the soil C/N ratio (7.58–10.00) accounted for 3.0% of the total area, which was fragmentarily distributed in the northwestern and the central parts of the study area, such as the southwest of Yining County, the south of Huocheng County, and the junction of Nilka County, Xinyuan County and Gongliu County.

3.6 Changes of soil C/N ratio under different land use types

Figure 5b shows the distribution of land use types in the study area. The soil C/N ratios were 12.89, 10.74, 10.49 and 9.59 for cultivated land, grassland, forest land and garden land, respectively, which showed that the soil C/N ratio in grassland is higher than forest land and garden land, on the contrary, the soil C/N ratio of cultivated land is larger than grassland. The transformation of grassland into cultivated land, garden land and forest land, decreased SOC, TN, soil organic matter (SOM), but increased SBD and soil pH (Table 4).

3.7 Regression analysis of soil C/N ratio with different factors

Regression analysis of soil C/N ratio showed that soil physical and chemical features could independently explain 55.4% of the spatial distribution characteristics of soil C/N ratio, followed by geographical and climatic factors with 26.8% contribution, whereas land use types could independently explain 5.4% of the spatial distribution characteristics of soil C/N ratio (Table 5).

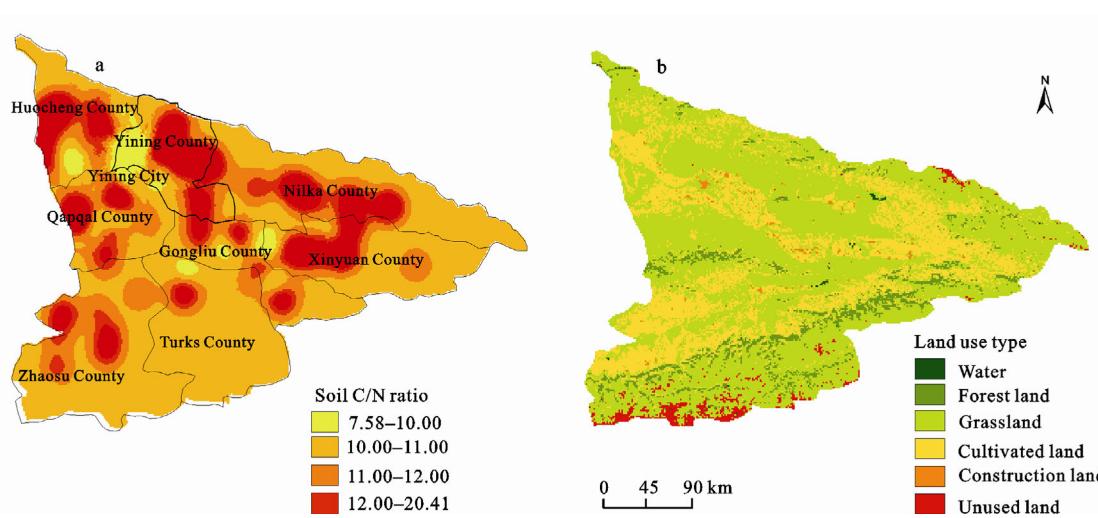

Fig. 5 Spatial distribution of soil C/N ratio (a) and land use types (b) in Ili Rive valley

Table 4 Soil physical and chemical properties and soil C/N ratio in different land use types

Land use type	Number of sample points	Soil C/N ratio	SBD (g/cm^3)	SOM (g/kg)	SOC (g/kg)	TN (g/kg)	Soil pH
Cultivated land	32	12.89	1.26	15.69	9.10	0.71	8.17
Grassland	153	10.74	1.21	26.03	15.09	1.33	8.14
Forest land	17	10.49	1.27	9.74	5.65	0.57	8.30
Garden land	21	9.59	1.27	10.35	6.01	0.61	8.18

Notes: SBD, soil bulk density; SOM, soil organic matter; SOC, soil organic carbon; TN, total nitrogen

Table 5 Regression analysis of soil C/N ratio with different factors

Factor	F	R^2	Adjusted R^2	P
Geographical and climate factors	15.7	0.268	0.25	< 0.01
Soil physical and chemical properties	53.4	0.554	0.54	< 0.01
Land use types	4.1	0.054	0.04	< 0.01

4 Discussion

4.1 Relationships between soil C/N ratio and geographical and climatic factors

Soil C/N ratio was influenced by geographical factors under natural conditions (Wang *et al*., 2014). Our investigation found that there was a significant positive correlation between the soil C/N ratio and longitude ($P < 0.01$) and a significant negative correlation between the soil C/N ratio and latitude ($P < 0.01$) (Fig. 2). This might be related to regional factors like temperature, precipitation and altitude since all those variables could affect the type of vegetation, yield, and the decomposition of plant residues, and thus directly or indirectly influenced the content of SOC and TN by affecting the amount of organic matter entering the soil (Wang *et al*., 2002; Miao *et al*., 2010).

Soil C/N ratio was also influenced by climatic factors under natural conditions (Wang *et al*., 2014). Wang *et al.* (2002) argued that there was a significant positive correlation between SOC and precipitation, the same as TN and precipitation ($P < 0.01$), while the relationship between temperature and SOC was complex. However, Miao *et al*. (2010) found that there was a significant negative correlation between temperature and SOC. We found that there was a significant negative correlation between the soil C/N ratio and temperature ($P < 0.01$), and a significant positive correlation between the soil C/N ratio and precipitation ($P < 0.01$) (Fig. 2). As a whole, with an increase in altitude, an increase of precipitation and a decrease of temperature, the soil C/N ratios increased.

4.2 Relationships between soil C/N ratio and soil physical and chemical properties

Many studies have shown that SWC, SBD, soil pH, SOM, SOC and TN regulated the change of soil C/N ratio (Wang and Yu, 2008; Wang *et al*., 2014; Luo *et al*., 2015). There was a significant positive correlation between the soil C/N ratio and SWC ($P < 0.01$), indicating the soil wetness increased the soil C/N ratio. By contrast, SWC stress decreased the growth in plant roots, stems and leaves and therefore reduced the soil C/N ratio (Mi *et al*., 2004). SBD was found to be a comprehensive reflection of soil porosity, soil texture and other physical properties, and its magnitude had a profound impact on the cycle of SOC and TN (Chai and He, 2016). There was a significant negative correlation between the soil C/N ratio and SBD ($P < 0.01$) (Fig. 3). This result was consistent with studies by Wang *et al.* (2014). There was a significant negative correlation between the soil C/N ratio and soil pH (Fig. 3). Soil pH can control microbial activity and then influence microbial decomposition of carbon and nitrogen (Bai *et al*., 2003). Our results showed that the soil pH was high in the study area, which maybe inhibit the decomposition of TN (Hu *et al*., 2016). In natural ecological systems, SOC is derived from organic matter mineralization and humus, while soil nitrogen is derived from nitrogen that has entered the soil by rainfall and biological nitrogen fixation (Wang *et al*., 2002). There was a significant positive correlation between the soil C/N ratio and SOC ($P < 0.01$) (Fig. 3), which was consistent with work by Geng *et al*. (2001). Ma *et al*. (2009) suggested that organic nitrogen could promote soil carbon mineralization rate and directly increase the SOC, so as to improve soil C/N ratio. This is consistent with the result obtained in the present study that, there is a positive correlation between soil C/N ratio and TN ($P < 0.01$).

4.3 Relationships between soil C/N ratio and land use types

The change of soil C/N ratio was influenced by the content of SOC and TN. The changes of land use caused by human activities will certainly affect the original C and N balance in terrestrial ecosystems (Wang *et al*., 2007). Compared to grassland, the value of SOC, TN, and SOM for garden land, cultivated land and forest land were lower (Table 4). After the grassland was reclaimed, the vegetation cover on the ground was reduced and further intensified the evaporation, which brought salinity into the surface layer, and then increased soil pH. This change also led to the increase of SBD, and affected soil permeability, water retention, and solute transport. Excessive SBD often inhibited plant leaf growth and reduced plant photosynthetic rate or aboveground productivity (Chai and He, 2016). These factors eventually led to the reduction of aboveground and underground biomass, and the decrease of SOC and TN (Guo *et al*., 2001). Our investigation found that soil C/N ratio of grassland was higher than forest land and garden land. This is because that the loss of SOC was much greater than TN in forest land and garden land. Soil C/N ratio of grassland was lower than cultivated land. This is because that the loss of TN was much greater than SOC in cultivated land. Therefore, we should pay more attention to C and N balance in the land development and utilization in the future.

4.4 Regression analysis of soil C/N ratio with different factors

Regression analysis of soil C/N ratio showed that soil physical and chemical features were the dominant factors controlling the spatial variability of soil C/N (Table 5). In hilly area of middle Sichuan Basin, Luo *et al*. (2015) found that land use types were main factor controlling the changes of soil C/N ratio, which could explain 23.9% of the spatial variability. This showed that human activities were the main factors to change the soil C and N. Geographical and climatic factors independently explained 26.8% of the spatial distribution characteristics of soil C/N ratio, which was similar as work by Wang *et al*. (2014) who found the climate is the important environmental influence factor on the soil C/N ratio in alpine steppe of the Qinghai-Tibet Plateau. Land use types explained the spatial distribution characteristics of soil C/N ratio less, this may be related to few sampling of cultivated land (the sampling points in cultivated land accounted for 14.3% of the total sampling points).

5 Conclusions

The soil C/N ratio was significantly positively correlated with longitude, altitude and precipitation, SWC, SOC and TN, and was significantly negatively correlated with latitude, temperature, SBD and soil pH. Prediction accuracy of soil C/N ratio by Cokriging with the altitude data as an auxiliary variable was high, showing that the Cokriging interpolation method was very promising for estimating the soil C/N ratio variables. The soil C/N ratio had a strong spatial correlation degree of spatial correlation, which was affected by structural factors. The soil C/N ratio values for the four land use types were in the order of cultivated land > grassland > forest land > garden. Land use types, soil physical and chemical properties and geographical and climatic factors could independently explain 5.4%, 55.4% and 26.8% of the spatial distribution characteristics of soil C/N ratio, respectively.

Acknowledgments

We would also like to thank Dr. Zhao Ying for valuable comments and the English language revision, which greatly improved the original manuscript.

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