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Methods for modeling spatial variability of soil organic carbon under different land use in middle reaches of the Heihe river basin, northwestern China

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The aim of this paper is to identify the influence of land uses on soil organic carbon (SOC) distribution in the middle of Heihe, China. Geostatistical methods including ordinary kriging (OK), spline (SPLIN), inverse distance weight (IDW) and local polynomial interpolation (LP) were compared. It is noteworthy that OK engenders smaller prediction errors than SPLIN, IDW, and LP. We selected the OK method to estimate SOC distribution. Results show that spatial distribution of SOC has an obvious gradual decreasing trend from high to low sections at different layers in the depth of the 100 cm soil profile. Most notable is that SOC content of cultivated land is higher than that of desert, sandlot, saline-alkali and naked fields. From a spatial perspective, paddy fields with a long history of cultivation are distributed on the two sides of Heihe river, while land with a shorter history of cultivation is located at a greater distance from the river. Land use change will increase or decrease SOC content. The extension of cultivated land with desert, naked land, sandlot, saline-alkali fields and middle density grassland with low SOC content will enhance the content of SOC in soil profile by a carbon fixation process, although sandy desertification is a reverse process. The results show that cultivation is an important process of increasing SOC content.

Key words: Distribution, SOC storage, Land use, Cultivation, Heihe river basin

INTRODUCTION

Global warming and the climate change including warming temperature, changing precipitation and rising sea levels are some of the most serious environmental problems in the world confronting the international community [1]. The essential issue is the increasing level of CO_2 in the air because the rate of anthropogenic emissions exceeds the rate of absorption by natural carbon sinks (terrestrial biosphere and oceans). The Intergovernmental Panel on Climate Change reports that more than 95% in 2014 are being caused by anthropogenic activities. However, we still cannot balance the global C budget and predict its change because of a number of unknowns [2]. At present, SOC pool in soil is twice that of the atmosphere [3], with estimated value at about 1550 Pg in the world [4,5]. Change here may be the source or sink of carbon in CO_2 [6-10]. If more carbon is stored in the soil and transformed to soil organic carbon (SOC), it will reduce or decrease the amount present in the atmosphere, and help ease the problem of global warming and climate change. Therefore, it is very important to comprehend the dynamic change of SOC, as well as its role in bringing about food security [11] and cutting carbon emissions down to air from the terrestrial ecosystem [12].

Content and storage of SOC and its composition are the foundation of the mechanism of organic carbon changes in different regions [13-15]. Methods for modeling spatial distributions of SOC can be realized by using GIS (Geographic information systems) models integrated with image data using remote sensing methods in regional scale, to select the appropriate model to improve the simulation accuracy. Geostatistics provides a superior tool to quantify the spatial variations of SOC and to perform spatial interpolation. It can calculate and visualize the spatial differences between SOC distribution and its influencing factors.

Arid regions are one of the highest sensitivity zones for global changes. The oasis is one of main productive bases in arid regions. Although their area amounts to only 3.3% of the arid regions in China, they support over 90% of the population and create over 95% production values of industry and agriculture. The study area is situated in the middle of Heihe River Basin. Land use and farming have modified SOC content and the related properties. In this study, the objectives were to investigate (1) the spatial variation characteristics of SOC under different land uses, and (2) to evaluate the methods including OK, SPLIN, IDW, LP. and to search for the best one to simulate the spatial variability of soil organic carbon.

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EXPERIMENTAL

Study area

The study area is situated in the northwest of China between 37°45′-42°40′ N and 97°05′-102°00′ E (Figure 1). Because of the position in the inner Eurasia, it belongs to a kind of dry climate with high temperature and evaporation rates. Yearly rainfall average ranges between 110 mm and 130 mm, and annual evaporation average is 2341 mm. Evaporation surpasses precipitation, so irrigation is a typical means for increasing crop production. However, water resources including surface water and groundwater from the melting ice and snow from the Oilian Mountains are unevenly temporal-spatial distributed. It brings cropland to mostly occupy both sides of the Heihe River. From south to north of the study area. The soil is mainly formed under drought conditions, there are respectively the types of chesnut soil, sierozem, gray desert soil, gray-brown desert soil, aeolian sand soil and dry saline soil. Away from village or small town area to desert, the soils are respectively deep dark horsebean, irrigated aeolian sand soil and aeolian sand soil. Horsebean and fluvo-aquic soil are the two main agricultural soils occupying abundant area.

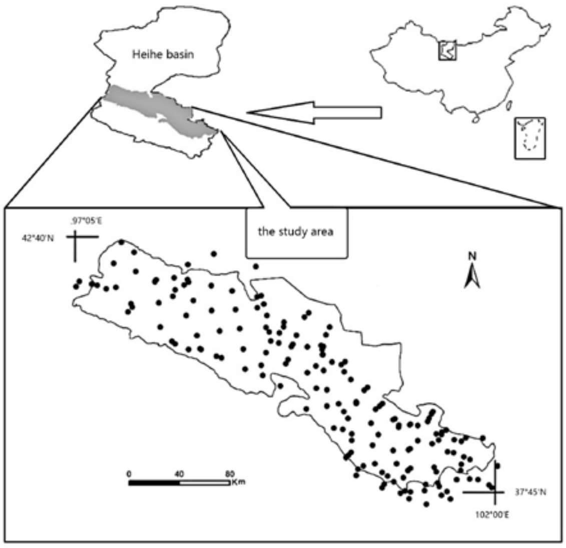

Fig. 1. Location of field sampling points

Data Collection

Field sampling was carried out using a grid with 12 km×12 km cells. 195 soil sampling points were chosen and the locations were measured with a GPS instrument (global positioning system) (Figure 1). It was divided into five layers in 100 cm depth of the soil profile, with an interval of 20 cm. The fresh soil was collected and then moved to the laboratory for further air-dried disposal process. After removal of visible roots, the soil sample was passed successively through 2 mm and 0.15 mm sieves. SOC content was measured by the method of acid dichromate digestion and $FeSO_4$ titration [16].

Introduction of application models

Previous studies have used geostatistical analysis methods for soil organic carbon content interpolation at spacial scale based points' data [17-19]. Four classical interpolation models, IDW, OK, SPLINE and LP were tested to estimate different layers distribution of SOC. IDW obtained the value at unsampled region using a weighted average from exsting adjacent points, and the weight designated to each adjacent point diminshed the adjacent point increase at the distance [20]. The IDW model can be given as Eq.1.

$$Z(i)=\frac{\sum_{j=1}^{n} z(j)/D_{ij}^{r}}{\sum_{j=1}^{n} 1/D_{ij}^{r}} \quad (1)$$

where $Z(i)$ is the value at location i， $Z(j)$ is the value at sampled location j， D_{ij} is the distance between i and j, n is the quantity of sampled points; and r is the power of inverse-distance weight.

OK is the most commonly and extensively used Kriging method. It supposes that the distance or direction between spatial points reflects a spatial correlation that can be used to interpret changes in the surface. OK model is given as Eq.2.

$$Z(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i) \quad (2)$$

where $Z(x_i)$ is the monitoring value at point x_i, $Z(x_0)$ is the predicted value at the unexpected point, λ_i is the kriging weight.

SPLINE estimates values using a mathematical function that minimizes over surface curvature. It forms a smooth surface relying on the input points or the given point. It is based on modeling the measurements $Z(S_i)$ where $S_i=(x_i,y_i)$ is a point of coordinates x_i, y_i (Eq.3).

$$Z(S_i) = f(S_i) + \varepsilon(S_i),\ i = 1,......,n \quad (3)$$

where n is the number of measurement points or controlling points; f is an unknown deterministic smooth function, and $\varepsilon(S_i)$ are random errors. The function can be estimated by minimizing:

$$\Sigma[Z(S_i) - f(S_i)]^2 + \lambda J_2(f) \quad (4)$$

where $J_2(f)$ is a measure of smoothness of f computed by the following double integral (Eq.5)

$$J_2(f)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left\{\left(\delta^2 f/\delta x^2\right)^2+2\left(\delta^2 f/\delta x\delta y\right)^2+\left(\delta^2 f/\delta y^2\right)^2\right\}dxdy \quad (5)$$

λ is the smoothing parameter which regulates the trade off between the closeness of the function to the data and the smoothness of the function.

LP method suits numerous polynomials to the whole surface, each within specified overlapping neighborhoods. It fits the specified order polynomial based known points only in the range of the defined neighborhood. The neighborhoods overlap, and the predicted value of each point is the value of the fitted polynomial at the center of the neighborhood.

Statistical parameters including ME (mean error) and RMSE (root mean square error) were used as evaluation criteria for IDW, OK, SPLINE and LP models (Eq. 6).

$$ME = \frac{1}{n}\sum_{i=1}^{n}(\hat{z}_i - z_i)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\hat{z}_i - z_i)^2}{n}} \qquad (6)$$

where z is the value at point i, $\hat{z}_i$ is the predicted value, and n is the number of data points.

RESULTS AND DISCUSSION

Model tests

In order to obtain the best simulation results, all data were divided into two parts: analog part set and validation part set. Simulations of the positions of the validation points and experimental value at spatial position were compared by ME and RMSE (Figure 2).

By comparing simulated results of the four models, it was found that ME error is relatively low for OK and SPLINE models, and is generally the lowest on for OK model in the soil profile. OK method gives the lowest RMSE, IDW gives poor performance in the whole profile. In addition, there is similar variation in error in the soil profile, the highest value is in 0-40 cm and the lowest in 80-100 cm, which probably reflects the greater regional SOC differences in the surface layer.

Prediction errors with the worst results were produced by LP and IDW. Spatial result of IDW method has a higher error and is prone to appear “buphthalmos” for uneven sampling points. LP method must be considered spatially trendy ignoring the local variations, as a result of which the simulation is not consistent with the actual situation. SPLINE needs data with little change without extreme values. OK method considers the points’ distance, azimuth and irregular changes of spatial continuity, it can give appropriate description using a random surface. It is proved that OK model does the best job and is the best choice to perform the trend prediction in the study.

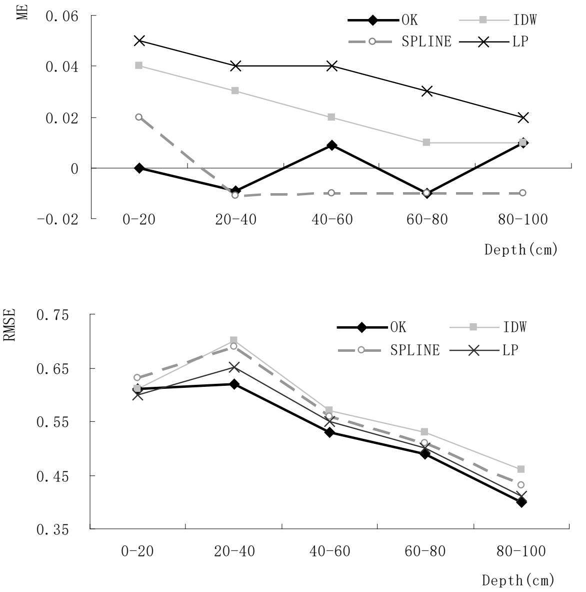

Fig. 2. Validation of ME and RMSE for the four interpolation methods in 0-100 cm depth

Spatial distribution of different land use

Land use map in the region was obtained from the website (http://heihe.westgis.ac.cn). Figure 3 shows the spatial distribution of the land use.

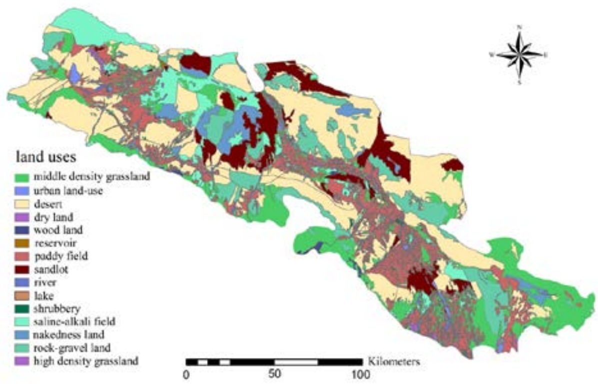

Fig. 3. Distribution of different land use in the area

There are 15 types of land use in middle Heihe river basin: desert, paddy field, middle-density grassland, rock-gravel land, saline-alkali field and sandlot. Each covers a relative large portion of the region, whereas, lake, reservoir, dry land, high-density grassland, shrub land, woodland, river, urban land-use, and bare land each cover a relatively small portion. The cultivated land including dry land and paddy field is about 17.09% of the total. From a spatial perspective, paddy field and urban land-use are mainly located along the two sides of the Heihe River, and the middle-density grassland is close to the paddy field and dry land. Desert, sandlot, saline-alkali field, bare land, and rock-gravel land are more distant from the river.

Spatial distribution of SOC in soil profile

Spatial distribution between SOC and land use displays a homologous trend in each layer of soil profile (Figure 4). There are two high-value areas, the one is situated in the southeast of the study area near to Qilian Mountain, affected by factors including climate, plants and soil animals. For the reason of high precipitation and low temperature, vegetation species and coverage are rich, litter and falling matter have adequate sources. This will enhance the SOC content in the surface layer (0-20 cm), and further increase the content in the deep layer (20-100 cm). The other high section is the paddy field near to the suburb of Jiuquan city. It is found that irrigation from domestic sewage is the main reason. From surface layer (0-20 cm) to deep layer (80-100 cm) in 0-100 cm, SOC content gradually decreased at the same land use, the reduced amplitude is smaller. From high to low section at different layers in the depth of 100 cm soil profile, it is an obvious gradually decreasing trend.

In the oasis region of the study area, the most notable character is that SOC content of cultivated plots is higher than those of the desert, sandlot, saline-alkali field, and naked land at each layer. This trend is most obvious in the surface 0-20 cm and 20-40 cm. From a spatial perspective, paddy fields with a long history of cultivation are located at both sides of the river, while land with a shorter history of cultivation is located at a greater distance from the river. This reflects the trend in cultivation to spread from the river border to the outer wilderness. Previous studies showed that the cultivation activites cause SOC content reduction and loss, such as plough, fertilization, etc. On the other hand, some measures can enhance SOC content under the effect of the straw organic matter returning, crop rotation and organic fertilizer increasing. At the study area, SOC content is low compared with the land use of desert, sandlot, saline-alkali field, naked land and rock-gravel. These lands distribute the oasis inward and show an inlaid distribution pattern with the cultivated plots. For the low vegetation coverage and few plant species, it will cause a little litter and falling matter and low organic matter return. Under the effect of high temperature and low precipitation conditions, the amount of SOC decomposition and transformation is less. So, if these land uses with low SOC are changed into cultivated plots, it will increase the content of SOC. Land uses such as rock-gravel land, high density grassland, woodland and shrub land are unsuitable for cultivation.

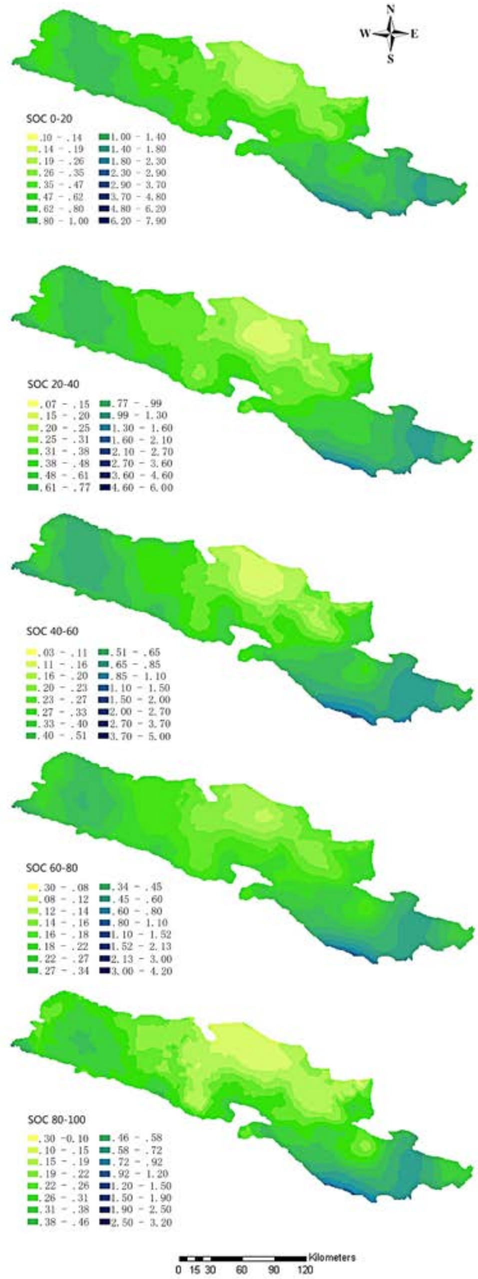

Fig. *4*. Spatial distribution of soil organic carbon in 0-100 cm (%)

Rock-gravel land is located at the foreland of the Heli-longshou Mountains which are far away from water sources and are not covered with any vegetation. High-density grassland and woodland occupy the transitional zone between the middle Heihe River Basin and the low-temperature section of the Qilian Mountains. Shrubbery land provides ecological protection but covers only small areas at scattered locations.

DISCUSSION

SOC is an important matter in soil, and also the basis of soil fertility. How to improve soil organic carbon content in the region has become the core issue of climate change and food production. Usually, the results of experiments are constrained to points or the region where the experiments are involved, the forecasts of soil organic carbon at regional scale are scarce for their spatial variability for lack of amounts of experimental data. Spatial variability based on GIS methods at spatial scale is more advantageous than the studies at points or regions where the experiments are carried out for resource utilization and rational allocation.

Comparing OK, SPLINE, IDW and LP models, the simulated results showed that OK model provides minimum error with higher spatial resolution. Spatial distribution between SOC and land use is a homologous trend in each layer of soil profile.

There are significant spatial differences of SOC content under different land use types in 0-100 cm. The transitions or conversions of different land uses drive the SOC content changes. Land use change will increase or decrease SOC content. Numerous studies have shown that the expansion of cultivated plots, sandy desertification and urban land-use are the primary factors driving land use change in oasis regions, resulting in the shrinkage of middle-density grassland and water area [21-27]. The extension of cultivated land, by which low SOC content uses such as desert, naked land, sandlot, saline-alkali field and middle-density grassland are changed to dry land and paddy field, will enhance the content of SOC in the soil profile, is a carbon fixation process, although sandy desertification is a reverse process. Many studies have also proven that cultivation and soil desertification have an important influence on SOC content and pools for oasis farmland, and that oasis soil can act as a carbon sink [28-32].

CONCLUSION

It is very important to build better models at a regional scale because it is the level at which management and decision making are carried out. By comparing four interpolation models (OK, IDW, SPLINE and LP), the prediction errors indicate that OK model does the best job and is the best choice to perform the trend prediction in the study.

Spatial distributions of SOC are an obvious gradually decreasing trend from high to low section at different layers of soil profile, the high sections located at the southeast of the study area near to Qilian Mountain and the paddy field near to the suburb of Jiuquan city.

In the oasis region of the study area, the most notable character is that SOC content of cultivated plots is higher than those of desert, sandlot, saline-alkali field and naked land. From a spatial perspective, paddy fields with a long history of cultivation are distributed on both sides of Heihe river, while land with a shorter history of cultivation is located at a greater distance from the river. The transitions of different land uses drive the SOC content changes, the extension of cultivated land, by which low SOC content such as desert, nakedness land, sandlot, saline-alkali field and middle density grassland are changed to dry land and paddy field will enhance the content of SOC in the soil profile. It is a carbon fixation process, although sandy desertification is a reverse process. These should attribute to deserts and desertification land uses initially having a low SOC content because of the effect of scarce water resources. Reasonable cultivation is an important process of increasing SOC content.

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