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Scale- and location-specific relationships between soil available micronutrients and environmental factors in the Fen River basin on the Chinese Loess Plateau

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ABSTRACT

Efficient scale- and location-specific soil micronutrients management is important for crop yield and environmental quality. This usually requires knowledge on scale- and location-specific control of soil micronutrients, which is not readily available from the traditional correlation analysis. The objective of this study was to analyze the scale- and location-specific relationships between surface (0–20 cm) soil available micronutrients (Cu, Fe, Mn, and Zn) and environmental factors by wavelet coherency analysis. For this purpose, soil available micronutrients, soil pH, soil organic matter (SOM), and topographic factors were obtained at 1 km interval along a 117 km-transect in the arable land of Fen River basin, China. The results showed that Cu, Mn, and Zn were positively correlated with SOM at scales 32–40 km at all locations, while Fe was positively correlated with SOM at scales 7–16 km at locations 75–117 km. Soil pH had negative influences on Cu and Zn at scales 25–40 km at all locations and on Fe at scales 12–21 km at locations 1–64 km. Both Cu and Zn had significantly negative relationships with aspect at scales 15–32 km at all locations, which cannot be detected at the sampling scale by the traditional correlation analysis. Wetness index had a significant impact on the distribution of Zn at scales 24–38 km at all locations and at scales 14–24 km at locations 1–60 km. Although elevation and slope showed significant correlations with Cu, Mn, and Zn at the sampling scale, wavelet coherence did not show any significant correlations in the scale-location domain. Therefore, the relationships of soil available micronutrients and influencing factors were scale- and location-dependent, which implies that different management practices are needed at different scales and locations to improve the global level of soil available micronutrients in the arable land of Fen River basin.

1. Introduction

Soil is the primary source of essential plant micronutrients, and the content of soil available micronutrients, including Cu, Fe, Mn, and Zn, can affect crop yield and quality. Imbalanced supply of soil micronutrient can negatively influence plant growth and even human health (Abrahams, 2002). Therefore, knowledge of the spatial distribution of these soil available micronutrients and their influencing factors is very important for effective management of soil and plant (Wani et al., 2013).

Scale-independent spatial patterns are usually assumed to examine the relationships between the influencing factors and soil available micronutrients at the sampling scale (Chukwuma et al., 2010; Škrbić and Onjia, 2007). Often than not, the spatial patterns of soil properties are scale-dependent in the natural world (Wiens, 1989). This means that the samples taken at a fine spatial scale may not be representative of the pattern of soil micronutrients at larger scales (Halvorson et al., 1997). In addition, the spatial variability of soil available micronutrients may represent interactions among soil physical, chemical, and biological processes that operate at different scales and locations (Si, 2008). Therefore, it is important to understand the scale- and location-specific relationships between soil available micronutrients and influencing factors.

Traditional statistical methods, such as Pearson or Spearman's rank correlation analysis, can explore relationships between variables only at the sampling scale (Gao et al., 2015; Wang et al., 2015). Furthermore, soil available micronutrients may be correlated with an environmental factor differently (positive or negative) over the scales and locations, which may further neutralize each other over the entire measurement region and mislead interpretation of the results (Biswas and Si, 2011b). This scale-dependent correlation requires other statistical methods.

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To determine the scale-dependent correlation between soil properties and their influencing factors, many methods including geostatistical method, multifractal analysis, empirical mode decomposition (EMD), and wavelet analysis have been proposed. For example, Lark and Papritz (2003) determined the relationships between trace metals based on geostatistical theory. Xu and Tao (2004) explored the correlations between soil heavy metals and environmental factors at different characteristic ranges (i.e., 200, 400, and over 1000 km). However, the geostatistical method is only a second-order statistical method (Kravchenko et al., 1999), and they cannot provide good characterization of the variability that takes place in the presence of intermittent low and high data values. The relationships between saturated hydraulic conductivity and soil physical properties at different scales were examined by multifractal analysis (Zeleke and Si, 2005), but location-specific relationships between variables are not available. In addition, the multifractal analysis assumes the system of interest is stationary, which is usually violated in geosciences. Recently, multivariate empirical mode decomposition (MEMD), which is suitable to deal with non-stationary and nonlinear system, was applied to identify the scale-dependent control of soil water and environmental factors (Hu and Si, 2013; She et al., 2014). However, location information was not identified in their studies.

Precision soil management requires location information. Wavelet analysis can partition a spatial variable into specific scales and locations, making it possible to reveal the scale- and location-dependent spatial variability. Wavelet coherency is used to examine the correlation between spatial variables at different scales and locations. It has been widely used to identify the scale- and location-specific relationships between soil properties (Biswas and Si, 2011a; Shu et al., 2008; Si and Zeleke, 2005; Tang and Piechota, 2009; Wu et al., 2002; Yates et al., 2007).

Fen River basin, located in the eastern Loess Plateau of China, is characterized by serious soil erosion in the world. The arable land (i.e., 11,591 km^2), suffering from the effects of long-term tillage, accounts for one third of the total area in this basin. This area is the main crops and vegetation production in Shanxi Province. Investigation on the spatial patterns of soil available micronutrients in arable land is needed for proper agricultural management in the Fen River basin and similar regions in the world. Therefore, the objective of this study was to explore the scale- and location-specific relationships between surface (0–20 cm) soil available micronutrients (Cu, Fe, Mn, and Zn) and environmental factors in the arable land of Fen River basin, China.

2. Materials and methods

2.1. Site description

This study was conducted at the Fen River basin (35°20′ to 39°00′ N latitude, 110°30′ to 113°32′ E longitude, an area of 39,721 km^2), located in the Loess Plateau, North China (Fig. 1). Fen River is one of the largest tributaries of the Yellow River in its middle reach, which joins the Yellow River in Hejing County. The Fen River basin is bounded by the Taihang Mountain to the east, and the Lvliang Mountain to the west, which is also the boundary between the Yellow River and the Fen River. The lowest elevation of the area is 240 m in the south and the highest is 2786 m in the north in the Fen River basin. Corn, wheat, and millet are the main crops in the arable land of this basin. Located in the eastern Loess Plateau of China, the Fen River basin is temperate and sub-humid with mean annual temperature of 10 °C and mean annual precipitation of 450 mm, and the temperature and precipitation decreased gradually from the south to the north (Editorial Board of China's Physical Geography, 1985; Hu et al., 2005). In this area, the landforms are usually capped by a thick layer of loess because of the dust deposition during the Quaternary (Hu et al., 2005). According to the FAO-90 soil classification system (Nachtergaele et al., 2008), the major soil type is Calcaric Cambisols under alkaline conditions.

2.2. Data acquisition

A total of 88,960 points of surface soil samples (0–20 cm) were gathered from 2006 to 2009 (Fig. 1c). For each soil sample, soil available Cu, Fe, Mn, and Zn were measured by atomic adsorption spectrometry, soil pH via combination electrode, and SOM by the wet oxidation method (Page et al., 1982). A sampling transect of 117 km (117 points at 1 km interval) of soil samples was established in a South–North direction in the area with dense sampling points (Fig. 1d). Because the established points in the transect were not always located at the measured points, the nearest measured points, which were within the grid of 1 km, were used to represent the established points. Considering that the average distance between the established and measured points was 430 m, we assume that the properties of measured soil samples could represent the corresponding established points considering the relatively large scale of the study.

The digital elevation model (DEM) of Fen River with 30 m resolution was downloaded from http://gdem.ersdac.jspacesystems.or.jp/, and then used to derive the topographic indices, including slope gradients, aspect, and wetness index in ArcGIS 10.1 (ESRI Inc.). Elevation was considered because its great variability (ranging from 434 to 1090 m) is supposed to affect microclimate and thus soil forming processes (Charan et al., 2013). Slope is related to soil erosion and deposition processes and has an effect on distribution of soil horizons, whereas aspect is related to the amount of solar energy received by the slope and affects plant growth and soil water content which in turn influence soil properties (Beguería et al., 2013). A multiple flow direction algorithm was employed to obtain the catchment area (Freeman, 1991). The topographic wetness index was derived from the slope and catchment area parameters (Moore et al., 1991), which is related to the soil moisture redistribution in the landscape or soil erosion and accumulation (Chi et al., 2009).

2.3. Wavelet coherency

Wavelet coherency is obtained by wavelet auto spectra and wavelet cross spectra calculated from the wavelet coefficients after wavelet transform. The wavelet coherence of two spatial series (*X* and *Y*) is defined as (Grinsted et al., 2004; Torrence and Webster, 1999)

$$R_i{}^2(s) = \frac{\overleftrightarrow{W_i}^{XY}(s)\,\overline{\overleftrightarrow{W_i}^{XY}(s)}}{\overleftrightarrow{W_i}^{XX}(s)\overleftrightarrow{W_i}^{YY}(s)} \tag{1}$$

where, *s* is the scale, *i* is the spatial location, $W_i{}^{XX}$ and $W_i{}^{YY}$ are the auto-wavelet power spectra of the spatial series *X* and *Y*, respectively, $W_i{}^{XY}$ is the cross wavelet power spectrum between *X* and *Y*, and $\overleftrightarrow{(\cdot)}$ is the smoothing operator. The wavelet phase between *X* and *Y* is

$$\varphi_i(s) = \tan^{-1}\left(\mathrm{Im}\left(W_i^{XY}(s)\right)/\mathrm{Re}\left(W_i^{XY}(s)\right)\right) \tag{2}$$

where Im and Re denote the imaginary and real part of $W_i^{XY}(s)$ respectively. A more detailed description of the wavelet coefficients, the cross wavelet power spectrum, the smoothing operator, and the wavelet phase can be found in other publications (Biswas and Si, 2011a; Grinsted et al., 2004; Si and Zeleke, 2005).

2.4. Data analysis

The descriptive data analysis and Pearson correlation analysis were implemented by IBM SPSS 19.0 (SPSS Inc.). The wavelet spectra of soil available micronutrients and wavelet coherency between soil available micronutrients and environmental factors were calculated by the MATLAB code written by Grinsted et al. (2004).