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Spatial variability of soil nitrogen, phosphorus and potassium contents in Moso bamboo forests in Yong'an City, China

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ABSTRACT

Bamboo is an important forest type in Southern China, covering an area of 6.16 million ha, >70% of which is Moso bamboo (*Phyllostachys heterocycla* (Carr.) Mitford *cv. Pubescens*) forest. Moso bamboo forests are characterized by fast growth and high nutrient dynamics due to the annual timber harvest, and thus a high nutrient input is required compared with other forest types. Soil nitrogen (N), phosphorus (P) and potassium (K) are important micronutrients for plant growth and productivity. Because of the high spatial and temporal variability of soil, information on the spatial distribution of N, P and K contents in Moso bamboo forests is very limited, although this information is important for improving soil nutrient management. Therefore, in this study, soil samples at 0–20, 20–40 and 40–60 cm were taken from 138 locations in Moso bamboo forests across the study area. The N, P and K contents of different soil layers ranged from 1.01 to 4.11 g kg^{-1}, from 0.025 to 0.131 g kg^{-1} and from 0.42 to 5.40 g kg^{-1}, respectively. The coefficient of variation of N, P and K contents ranged from 26% to 43%, suggesting a moderate variability. Ordinary kriging (OK) and inverse distance weighting (IDW) approaches were applied to analyse the spatial patterns of N, P and K contents. Geostatistical analysis showed a moderate spatial dependence of N, P and K contents, indicating that N, P and K contents were controlled by both intrinsic and extrinsic factors. Cross-validation illustrated that OK performed better than IDW. OK and IDW showed a similar spatial pattern of N, P and K contents over the whole study area, demonstrating the suitability of OK and IDW in spatial interpolation. However, OK produced a smaller range of predicted N, P and K contents than IDW, highlighting the necessity of using different approaches when studying the spatial distribution of soil properties.

1. Introduction

Site-specific nutrient management has received considerable attention for increasing nutrient input efficiency, improving plant productivity and reducing the environmental risks (Yasrebi et al., 2009). Soil nitrogen (N), phosphorus (P) and potassium (K) are important sources of micronutrients for plant growth and productivity, and they play an important role in terrestrial functions by influencing soil properties, plant growth and soil activities (Hati et al., 2008; Liu et al., 2010a; Quilchano et al., 2008). Soil N, P and K can individually or jointly affect terrestrial productivity (Li et al., 2016; Tripler et al., 2006). However, soils are characterized by high spatial and temporal variability due to climatic variables (Patil et al., 2010), parent materials (Lin et al., 2009), topography (Rezaei and Gilkes, 2005), vegetation types (Rodríguez et al., 2009), soil texture (Gami et al., 2009) and land use (Ross et al., 1999). Appropriate soil management requires a deep understanding of the spatiotemporal variability of soil properties and production of effective maps for their prediction. Areas of particular concern, e.g. nutrient deficient areas, can then be identified using these prediction maps. In addition, soil N, P and K levels are closely related to soil organic carbon cycling (Bronson et al., 2004), which may lead to dynamic effects on greenhouse gas emissions, potentially causing global climate change feedbacks. Therefore, a better understanding of the distributions of N, P and K is necessary when evaluating current or potential soil productivity and identifying potential environmental protection measures (Jennings et al., 2009).

The objective of geostatistical methods is to predict a soil variable at unknown locations using a property measured at a given place and time (Yasrebi et al., 2009). Based on this assumption, many techniques have been developed to predict the spatial variability of soil properties in the last several decades, such as ordinary kriging (OK), inverse distance weighting (IDW), artificial neural network and pedo-transfer functions (Gao et al., 2016; Li and Shao, 2014; Martín et al., 2016; Veronesi et al., 2014; Zhao et al., 2010). Of those approaches, OK has been most widely used. For example, Wang et al. (2009) predicted the spatial distribution on N and P contents of different land uses on the Loess Plateau using OK. In contrast, Uygur et al. (2010) mapped the total N, available P and exchangeable-K contents in Amik Plain, Turkey using the IDW approach. However, different approaches generate substantial differences in regional or landscape estimates of soil properties. Bradley et al. (2005)

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found that the topsoil C in England and Wales was 99.33 Tg C and 48.66 Tg C for subsoil using pedo-transfer functions, but the results were much lower than those from co-kriging approach (162.91 Tg C for topsoil and 66.71 Tg C for subsoil) (Veronesi et al., 2014). In addition, because of the highly heterogeneous soil characteristics, most previous studies obtained a relatively low correlation, commonly with a model efficiency of 0.2–0.6 between the measured and predicted values of soil properties (Veronesi et al., 2014). This could cause another important uncertainty in the prediction of the spatial variability of soil properties and complicate comparisons between different studies. However, these uncertainties highlight the importance of comparing different geostatistical approaches to improve the accuracy of predicting the spatial variability of soil properties.

Bamboo is an important forest type in Southern China, representing an area of 6.16 million ha, >70% of which are Moso bamboo (*Phyllostachys heterocycla* (Carr.) Mitford *cv. Pubescens*) forests. Bamboo forests are famous for their rapid growth and high timber output. In recent years, driven by good prices and sustainable forest development policies, Moso bamboo forests have expanded rapidly (Wang et al., 2008). Because natural forests are not allowed to be felled in China for ecological protection, the bamboo is a major substitute for wood (Song et al., 2011). To meet the increasing demand for timber and maximize economic benefits, intensive management with fertilization of Moso bamboo forests is increasingly practiced in Southern China. These practices are particularly popular in the main bamboo-producing provinces, such as Zhejiang and Fujian Province (Du et al., 2015; Liu et al., 2011; Zhou et al., 2006). However, these activities have significantly changed the nutrient levels by affecting the microbial processes, soil structures and chemical compositions (Li et al., 2013; Xu et al., 2008). Although many studies of the spatial distribution of N, P and K contents have been conducted in different ecosystems (Morales et al., 2014; Wang et al., 2009), to our knowledge, no such study has been conducted in Moso bamboo forests. High nutrient output from annual harvest of timber and bamboo shoots and low nutrient input from litterfall of Moso bamboo forests requires a greater nutrient input than other forest types. As a result, these human activities enhance the Moso bamboo forest nutrient dynamics relative to native forests. Thus, improving our knowledge of the spatial distribution of N, P and K is important for land management and maintaining or improving stand productivity of Moso bamboo forests.

Therefore, the objectives of this study were to: (1) characterize the spatial distribution of soil N, P and K contents at 0–20, 20–40 and 40–60 cm soil depth in Moso bamboo forests; (2) test whether different geostatistical approaches (OK and IDW) produce different spatial patterns; (3) analyse the spatial patterns generated by OK and IDW.

2. Materials and methods

2.1. Study area

The study area is located in the Yong'an City, Fujian Province, China (117°56′–117°47′E, 25°33′–26°12′N). It has an elevation of 580–1605 m above sea level (Liu et al., 2010b). The city is characterized by a subtropical southeast monsoon climate, with a mean annual temperature of 19.3 °C, ranging from a minimum temperature of −11 °C to a maximum temperature of 40 °C (He et al., 2016; Liu et al., 2010b). There are about 290 frost-free days with a mean annual precipitation of 1600 mm (He et al., 2016). The accumulated temperature of ≥10 °C, a useful parameter for predicting onset or termination (Bartholomew and Williams, 2005), is 4520–5800 °C, lasting for 225–250 days (Liu et al., 2010b). The monthly average relative humidity is around 80% (Liu et al., 2010b). It has a forest cover of 82.3% with an area of 5.85×10^4 ha of Moso bamboo forests (He et al., 2016). Moso bamboo forests are mainly distributed below 800 m, most of which are pure stands and sometimes mixed with some arbor species, including *Keteleeria cyclolepis*, *Cunninghamia lanceolata*, *Myrica rubra*, *Choerospondias axillaris*, *Liriodendron chinense*, and *Schima Superba*. The Moso bamboo forests in this study were fertilized with N, P and other organic fertilizers. Besides the annual timber harvest, bamboo shoots were also harvested in winter and spring every year.

2.2. Soil sampling

The soils were sampled in the sub-compartment of forest resource management of Fujian province, China. The sub-compartment was visually selected on the map of forest resource management (Fig. 1) and guided by GPS. In the targeted sub-compartment, a cluster of three circular plots with a size of 33.3 m^2 were established, and 138 plots were created in total. In each plot centre, a profile was established down to 60 cm by: 0–20, 20–40 and 40–60 cm. Because most of the bamboo roots were distributed above 40 cm, soil sampling down to 60 cm was appropriate for the research purpose of this study to examine the spatial distribution of N, P and K contents (Tang et al., 2012). In the field, the soil samples taken from the same layer of each of the three circular plots were bulked together. In the laboratory, mineral soil was air-dried at room temperature and sieved through 2-mm and 0.15-mm sieves prior to the total N, P and K concentration analysis. Identifiable plant residues and root materials were removed during sieving. The N, P and K concentrations were measured according to the standard protocol of State Forestry Adiministration (1999). More details can be found in Qi et al. (2012).

2.3. Extraction of topographic variables from a Digital Elevation Model (DEM)

A DEM with a resolution of 90 m was obtained from Geospatial Data Cloud (http://www.gscloud.cn/). Mean values of aspect, elevation and slope with 3 × 3 windows were extracted for each sample plot in ArcGIS 10.2 (http://www.esri.com/). Further details of the calculation of aspect, elevation and slope are described by Pierce et al. (2005).

2.4. Statistical and geostatistical analyses

Traditional statistical analyses, such as mean and standard deviation, were conducted in R to illustrate the trend of original data and are shown in Table 1 (R Core Team, 2014). The correlations between topographic variables (aspect, elevation and slope) and soil N, P and K contents were analysed for each soil layer using linear regression. The coefficient of variation (CV) was used to describe the degree of general variation. To meet the assumption of normality for geostatistical analysis, the raw data were log-transformed and transformed back by weighted mean using GS + 10.0 (He et al., 2016). In this study, two interpolation approaches, OK and IDW, were compared. The distribution maps of N, P and K contents were produced in ArcGIS 10.2 (Liu et al., 2013b).

2.5. Ordinary kriging

Semivariograms are used based on the theory of regionalized variables to characterize the spatial autocorrelation and provide parameters for optimal spatial interpolation (Krige, 1951). Well-known theoretical models, such as the spherical, exponential and Gaussian models, are commonly used to calculate experimental semivariograms using the observed data (Goovaerts, 1999). The semivariograms are expressed as a function of distance between sampled points and calculate the integrity of spatial continuity in one or multiple directions using the following expression (Schöning et al., 2006):

$$\gamma(h) = \frac{1}{2N(h)} \sum\nolimits_{i=1}^{N(h)} [Z(X_i) - Z(X_{i+h})]^2 \tag{1}$$

where i, $z(x_i)$ and $z(x_{i+h})$ are values of z at locations x_i and x_{i+h}, respectively; h is the lag and $N(h)$ is the number of pairs of sample points