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Effects of soil erosion and land use on spatial distribution of soil total phosphorus in a small watershed on the Loess Plateau, China

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ABSTRACT

Soil total phosphorus (STP) is a major determinant and indicator of soil fertility and quality. Information on the spatial distribution of STP is important in assessing current or potential soil productivity and estimating environmental pollution. In this study, a total of 1015 soil samples, taken at 20 cm intervals up to a depth of 100 cm, were collected from 202 sites representing five land-use types using grid sampling, this was an unprecedented high sampling density and sampling depth study in a small watershed on the Loess Plateau, China. Spatial variation in soil total phosphorus (STP) was studied using classical statistics and geo-statistics. Soil total phosphorus showed moderate variability across the soil profile and a marked dependence on depth, as follows: 0–20 cm (surface layer), 0.86–6.06 g/kg; 20–40 cm, 0.12–5.32 g/kg; 40–60 cm, 0.50–5.78 g/kg; 60–80 cm, 2.10–5.24 g/kg; and 80–100 cm (deepest layer), 2.00–5.60 g/kg. Of the five land-use types, the highest STP was recorded in dam field, followed, in that order, by terraced land, grassland, forest land, and sloped cropland. Redundancy analysis (RDA) showed that sand and SOC were the significant variables affecting STP in study area, which was also affected to some extent by the intensity of soil erosion, decreasing initially and then increasing slightly with depth. The minimum value of STP was affected by erosion intensities between 1000 t/km^2 and 2500 t/km^2 annually. Across the entire soil profile up to the depth of 1 m, STP varied with land use, as follows: grassland, 5.07 kg/m^2; forest land, 4.83 kg/m^2; dam, 4.73 kg/m^2; terraced land, 4.70 kg/m^2; and sloped cropland, 4.67 kg/m^2. STP up to a depth of 1 m was 24,908 tonnes in the study area. Thus, converting farmland to forest land or grassland would increase the levels of STP.

1. Introduction

As a dynamic component of terrestrial ecosystems, phosphorus (P) is an essential nutrient for plant growth and plays important roles in agricultural ecosystems (Zhang and McGrath, 2004; Hati et al., 2008). Soil total phosphorus (STP) is a major determinant and indicator of soil fertility and quality, both of which are closely related to soil productivity (Søvik and Aagaard, 2003; Al-Kaisi et al., 2005). Chemical fertilizers have been widely applied to topsoil to improve P levels in agricultural ecosystems and thus to sustain high yields, and farmers have been applying P fertilizers intensively for decades to prevent P deficiencies in plants (Roger et al., 2014). However, P discharge from anthropogenic sources is a crucial factor in the eutrophication of many inland aquatic systems worldwide (Smith, 2003), and excessive discharge of P from agricultural production systems can contribute to the eutrophication of natural water bodies (Smith et al., 2005; Lake et al., 2007; Chen et al., 2008). Furthermore, nitrogen (N) and P levels in soil are closely correlated to the soil organic carbon (SOC) cycle (Bronson et al., 2004); the cycle affects the levels of greenhouse gas emissions, which, in turn, are linked to global climate change (Lal, 2004). The scholars have conducted massive research about the spatial distribution of STP and they have obtained the plentiful research results (Cambardella et al., 1994; Cheng et al., 2016), but the research about STP vertical distribution and its storage in a regional is few. Therefore, reveal the vertical distribution characteristic of STP and its storage in a regional would give the important reference for high efficiency sustainable utilization of soil nutrients and provide scientific basic for sustainable agriculture development, as well as for a better understanding of climate change and its feedbacks (Jennings et al., 2009).

The spatial heterogeneity of soil P is a result of various factors

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(Cheng et al., 2016), both natural and anthropogenic, such as climate, soil texture, topography, vegetation cover, land use, and human activity (Gao et al., 2016a). These factors, especially such anthropogenic activities in agricultural ecosystems as irrigation, application of fertilizers, and field management, influence the spatial distribution of STP to different degrees (Huang et al., 2013). In addition, land use plays a more dynamic role in regulating spatial patterns of STP (Wang et al., 2009) as changes in land use become more frequent owing to both climate change and anthropogenic activity, especially those changes resulting from large-scale policy interventions (Ostwald and Chen, 2006; Stutter et al., 2015). Therefore, information on spatial variation in STP and on the factors that influence it can help in optimizing land use and provide a scientific basis for making decisions related to land management and planning for sustainable land use. In recent years, traditional statistics and geo-statistics have been used widely in research in soil science (Guo et al., 2000; Jia et al., 2009; Li et al., 2015), and spatial variability of soil nutrients and their relationship with environmental factors, especially those associated with land use, have been studied extensively using statistical methods (Fu et al., 2010; Gao et al., 2013; Xu et al., 2013). The studies have focused primarily on soil total nitrogen (STN), STP, and SOC (Zhang et al., 2013; Hu et al., 2014; Xu et al., 2015). However, only a few studies have focused on spatial variability of STP and the effects of pertinent factors including land-use type and soil erosion on the scale of a watershed (Du et al., 2008; Gitte et al., 2013). Phosphorus migration and transformation are closely related to soil run-off by erosion, which is the main channel of phosphorus loss (Withers and Jarvie, 2008). Therefore, it is necessary to study the effects of soil erosion on the spatial distribution of STP.

The Loess Plateau is known for its deep loess, unique landscapes, and intense soil erosion (Fu, 1989; Jiao et al., 2007; Zhu, 2012). Intense soil erosion hampers socio-economic development of the region seriously and threatens the safety of downstream channels, which is why the problem has received widespread attention both nationally and internationally in recent years (Li et al., 2006; Ouyang et al., 2010; Liu, 2011; Liu et al., 2013a; Xue et al., 2013; Xiao et al., 2014). Large quantities of soil P flow into the Yellow River along with run-off and sediments, introducing or intensifying the risk of water pollution and eutrophication, which, in turn, are a threat to sustainable development, ecology, and the environment of the basin of the Yellow River (Qin et al., 2006). To control soil erosion and to improve the ecology and the environment, the Chinese government carried out a series of large-scale ecological construction projects in the Loess Plateau including the ‘Grain for green’ project, land terracing, and gully treatment (Peng et al., 2005; Yang et al., 2006; Ping et al., 2012). Large-scale ecological restoration and land development change the structure of land use considerably (Zhang and Zhang, 2010), with inevitable effects on STP and its spatial distribution (Fu et al., 2000). As so often, small watershed were the source of the rivers, runoff and soil losses from watershed were investigated as the major non-point sources of phosphorus (P) entering the rivers and lakes, causing water quality degradation and other issues. In addition, the agricultural planting in the Loess Plateau is mainly concentrated in small watersheds. Therefore, research on the spatial variability of STP and its relationship with land use and soil erosion on the scale of a watershed in the Loess Plateau is particularly important for coordinated socio-economic development of the region and its ecology and environment.

It is against this background that the present study sought to (1) investigate STP and its spatial heterogeneity, (2) analyze the relationships between STP and land use, environmental factors, and the intensity of soil erosion, and (3) assess the variability of STP with depth and the storage of STP in the Wangmaogou watershed in the Loess Plateau.

2. Materials and methods

2.1. Description of study area

The study was conducted in the Wangmaogou watershed (37°34′13″–37°36′03″ N, 110°20′26″–110°22′46″ E), which is part of the Wuding River basin, 5 km south-east of Suide county in Shaanxi province, China (Fig. 1a and b). The watershed is spread over 5.97 km^2, and the elevation ranges from 936 m to 1188 m. The main channel is 3.75 km long, and the average slope of the channel is 2.7%. Upland and gully land occupy 2.97 km^2, or 46.7% of the total area of the Wangmaogou watershed (Fig. 1c). The watershed is characterized by a semi-arid continental monsoon climate; the mean annual temperature is 10 °C and the mean annual precipitation is 513 mm, a large proportion (70%) of which is received in the flood season (July–September), resulting in severe soil erosion: the annual sediment yield can be as high as 7 413 t/(km^2.a) (Gao et al., 2016b).

As is typical of the watersheds of the Loess Plateau, erosion in the Wangmaogou watershed consists mainly of water erosion and gravity erosion, although many soil and water conservation projects have been implemented in the watershed since 1953. By the end of 1999, these measures had resulted in significant achievements, including levelled terraces over 112.47 hm^2; afforestation, 199.96 hm^2; grasslands, 27.25 hm^2; and dam field 25.16 hm^2 (Fig. 1d). The total area under soil and water conservation measures is 367.81 hm^2, 61.6% of which is accounted for by measures to control erosion.

2.2. Soil sampling and analysis

Choosing the sites after taking into account the topography and spatial pattern of land use, soil samples were collected in the summer of 2014. This study encompassed five types of land use, which were distributed among 202 sites as follows: terraced land (29), grassland (103), forest land (34), sloped cropland (20), and dam field (16). Soil samples were collected, using a hand auger (approximately 7 cm in diameter), from the soil surface to a depth of 100 cm at intervals of 20 cm. The five soil layers were labelled as follows: A1, 0–20 cm; A2, 20–40 cm; A3, 40–60 cm; A4, 60–80 cm; and A5, 80–100 cm. While collecting the soil samples, the land-use type, altitude, slope, aspect, and plant species were also recorded. The normalized difference vegetation index (NDVI) is a ratio of the difference between near-infrared and red reflectance to the sum of near-infrared and red reflectance. The data for calculating NDVI for the study area were generated from a Landsat™ image (30 m resolution, August 2014), and the NDVI was used for expressing the spatial pattern of vegetation cover in the Wangmaogou watershed. The values were used for identifying the correlations between environmental factors and spatial variations in STP, and STP, STN, and soil available P (SAP) were determined using an automatic discrete analyzer (CleverChem 200, DeChem-Tech.GmbH, Hamburg Germany); and SOC was determined using an organic carbon analyzer (multi N/C® 3100, Analytik Jena, Jena, Germany).

Additionally, we collected 15 soil profiles – three each from the five land-use types – up to a depth of 60 cm (layers A1, A2, and A3). The cores were weighed after collection and again after drying in an oven at 105 °C for 24 h to calculate bulk density. The composition of soil in terms of particle size was analyzed using a particle-size analyzer (Mastersizer 2000, Malvern Instruments, Malvern, England). The components were clay (< 0.002 mm), silt (0.002–0.05 mm), and sand (0.05–2 mm).

2.3. Data analysis

Spatial variations in STP were analyzed by applying a semi-variogram to quantify spatial patterns in regionalized variables. These values were subsequently used for deriving important input parameters for Kriging spatial interpolation (Krige, 1951; Matheron, 1963). Based on