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Changes in soil properties across a chronosequence of vegetation restoration on the Loess Plateau of China

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ABSTRACT

Soil fertility is important for vegetation growth and productivity. The relationship between vegetation and soil fertility is important for both scientific and practical reasons. However, the effects of soil fertility on vegetation development and succession are poorly documented on the Loess Plateau. In this study, we compared soil properties of the Yanhe Watershed in northern Shaanxi across five different land uses (shrubland, farmland, natural grassland, woodland and artificial grassland) and a chronosequence of soils undergoing restoration for 5, 10, 15, 20, 25, 30, 35, 40 and 45 years. We found that revegetation had a positive effect on soil bulk density decrease, total porosity and capillary porosity increase in the surface soil layers but not in the subsurface layer. Additionally, soil organic matter, total nitrogen, available nitrogen and available potassium were greater at shrubland and woodland sites compared with other land uses. Total phosphorus and available phosphorus were greater at farmland sites. Results of the study indicate that revegetation on eroded soil can produce important increases in soil fertility on older plantations and in areas with natural succession.

1. Introduction

Past erosion in the Loess Plateau of China has been severe. As a consequence, the plateau's soils are now thin and nutrient poor (Li and Shao, 2003a,b). Additionally, overexploitation of the remaining vegetation further exacerbates land degradation and reduces soil nutrients and the supply of fuel and fodder in this area (Zha and Tang, 2003). Generally, soil structure degradation results in a reduction of total porosity and pore continuity (Dias and Northcliff, 1985), thereby reducing both soil aeration and water transport capabilities (Berger and Hager, 2000). This process yields barren soils that inhibit further plant growth (Wang et al., 2002). Hence, understanding declines in soil fertility is important for vegetation restoration, especially when converting agricultural land to reforested plantations or grassland. Additionally, there is need to understand natural vegetation recovery and its importance in soil rehabilitation on the plateau because very little natural vegetation exists. Better understanding of these processes will help guide current restoration of vegetation in western China.

Soil recovery during secondary vegetation succession has been recently studied (Chang et al., 1999; Lovich and Bainbridge, 1999; Wang et al., 2002). This attention on recovery shifts the focus from the examination of the soil properties of reclaimed lands in the postdeforestation process (Zheng and Zhang, 2002) to the contribution of revegetation or natural vegetation recovery (Zhang et al., 2004). Different vegetation types can be found within a short distance from a disturbed area simply because of changes in soil fertility levels (Harrington, 1991). In many ecosystems, especially in semiarid climates, vegetation productivity may be limited by nutrient availability (Aaron et al., 2001; Aerts and Chapin, 2000). In general, biomass and soil nutrients change substantially with plant age, and nutrient limitation is common during plant growth (Anderson and Ingram, 1989; Shao et al., 1996).

Human activities have greatly influenced the ecosystems on the Loess Plateau. Over the past century, population growth has resulted in fragmentation and degradation of the environment (Fu et al., 2000). To withstand further deterioration of the natural ecosystems, the Chinese government has launched a series of nationwide conservation projects focusing on the recovery of damaged ecosystems. One of the most pressing tasks involves the recovery of the vegetation because of its crucial role in the development of sustainable agriculture.

Although the study of degradation usually focuses on anthropogenic influences, the study of recovery is more important because it provides recommendations for eco-environmental reconstruction or rehabilitation. Recent research has addressed the influence of vegetation recovery on soil properties (An et al., 2009; Fu et al., 2003; Stolte et al., 2003). However, changes in soil properties during long-term vegetation recovery on the Loess Plateau still require thorough study. Research investigating changes in soil properties is necessary to understand the ecological consequences of vegetation recovery (Paniagua et al., 1999). In the semiarid area of the plateau,

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vegetation recovery is consistently nutrient limited. Few studies have addressed this issue. Studies of long-term changes in soil properties under natural revegetation regimes on the plateau are particularly needed (Chang et al., 1999). To rehabilitate eroded lands and improve the regional environment, some successful measures have been implemented throughout the Loess Plateau. Large areas of natural grassland on degraded land were reestablished to help hold soil and water to ensure improvement in the local ecosystem by natural succession after the cessation of grazing. The objective of the present study is to identify changes in soil properties associated with five different land uses, namely, shrubland, natural grassland, artificial grassland, farmland and woodland, and changes in soil properties following different intervals of planting for restoration. We hypothesized that local soil properties are largely a consequence of plant growth during secondary succession. The vegetation chronosequence of the grassland was also investigated to examine how soil properties change over time during restoration.

2. Materials and methods

2.1. Description of the study area

The study area was located in Yanhe Watershed of the Loess Plateau (36°23′–37°17′ N, 108°45′–110°28′ E) in northern Shaanxi Province. The area is 287 km in length. Of the total area (7687 km^2), 90% is hilly, 3% consists of villages, rivers, and lakes, and only 7% is considered suitable for intensive agriculture. Climate in the study area is semi-subarid with heavy seasonal rainfall and periodic flooding followed by drought. Average annual rainfall at the study site is 497 mm (1970–2000, CV 22%) with distinct wet and dry seasons. The rainy season is July to October, with August rainfall amounting to 23% of the annual total. Annual reference evapotranspiration is approximately 1000 mm. Most of the area lies at 900–1500 m altitude. The area's topography is characterized by cliffs and very steep slopes (40%). The topography, soil type, soil and land use patterns of Yanhe Watershed are typical of the Loess Plateau. The study area is composed of forest-steppe and temperate grassland. Typical vegetation includes *Bothriochloa ischaemun, Stipa bungeana, Artemisia sacrorum, A. giraldii Pamp,* and *Lespedeza davurica* (Li and Shao, 2003a,b).

2.2. Study approach and sampling design

Geographic characteristics of the sites are described in Appendix A. Soil samples were collected in August 2006 at 3 different depths: 0–20, 20–40 and 40–60 cm. For each type of land use, an area of 10 m × 10 m was selected at each site. Three 10 m × 3 m subplots were divided into five replicates for sampling. We used a soil sampling auger with a diameter of about 3 cm. An S-shaped soil sampling pattern was used in each subplot. Several 3 cm core samples were taken from each plot and mixed to form a pooled sample of about 1 kg. They were then air-dried and passed through a 2 mm sieve for soil analysis.

International standard methods adopted and published by the Institute of Soil Science, Chinese Academy of Sciences (1978) were used to analyze soil samples. Soil organic matter (SOM) was determined by oxidation with potassium dichromate in a heated oil bath. Total nitrogen (N_t) was measured by the semimicro Kjeldahl method. Available nitrogen (N_{avi}) was measured using the alkali diffusion method. Total phosphorus (P_t) was digested with perchloric acid and sulfuric acid and then measured by colorimetry. Total potassium (K_t) was digested with hydrofluoric acid and perchloric acid. Available phosphorus (P_{avi}) was extracted with sodium bicarbonate and measured with colorimetry. Available potassium (K_{avi}) in soil was extracted with ammonium acetate.

In situ slope angle and direction were determined using a pocket compass (DQY-1, China). Altitude, longitude and latitude were determined using a portable GPS. After removal of the litter and the humus layer, bulk density was measured using three intact soil cores from the surface layer (0–20 cm) and the subsurface layers (20–40 cm and 40–60 cm). Bulk density was determined by oven-drying the cores at 105–110 °C. Total soil porosity was calculated using Eq. (1) based on measured bulk density and assuming a soil particle density of 2.65 g cm^{-3}. Soil capillary porosity was subsequently calculated with Eq. (2) using bulk density and soil capillary water capacity data (Huang, 2003).

$$P_t = (1 - B_d / d_s) \times 100 \quad (1)$$

Where P_t is the total soil porosity (%); B_d is the soil bulk density (g cm^{-3}); d_s is the soil density (g cm^{-3}).

$$P_c = W_c \times B_d / V \times 100 \quad (2)$$

Where P_c is the soil capillary porosity (%); W_c is the soil capillary water content (%); V is the volume of soil core (cm^3).

A common approach in soil rehabilitation studies investigating vegetative cover is to monitor plant and soil changes along a vegetative chronosequence developed on similar soils under similar climatic conditions (Bhojvaid and Timmer, 1998). This chronological approach has been used widely in applied ecosystem research (Fang and Peng, 1997) and is considered retrospective research because existing conditions are compared with known original conditions and treatments. We used this approach here because nearby vegetation communities were established 5, 10, 15, 20, 25, 30, 35, 40 and 45 years ago on eroded soils with similar properties. These vegetation communities provide a time gradient of grass occupancy on similar sites. Rates of change in soil properties can be estimated by comparing sites of different ages. Nine sites (5, 10, 15, 20, 25, 30, 35, 40 and 45 years of age) that have undergone light livestock grazing in recent years were found at adjacent locations in the study area. Five sites were sampled within each series. Five nearby, nonvegetated sites (farmland) were used as controls for the chronosequence. The geographic characteristics of the sites are described in Appendix B.

2.3. Data analysis

Soil samples were compared among successional stages using analysis of variance (ANOVA). Correlations among soil variables were tested using SPSS, version 11.0. The LSD test (at $p<0.05$) was used to compare means of soil variables when the results of ANOVA were significant at $p<0.05$.

3. Results

3.1. Bulk density and total porosity under different land uses

Only in the 0–20 cm layer was soil bulk density associated with the different land uses. Shrubland soils had greater bulk density (1.35 mg m^{-3}) compared with other soils. The artificial grassland had the lowest bulk density value (1.24 mg m^{-3}) at the 10–20 cm soil depth, whereas the cultivated land had greatest bulk density values at either depth (Table 1). Bulk density was similar in the pasture and forest soils for the topsoil at 0–10 cm but was different at a soil depth of 10–20 cm. Bulk density differed significantly across soil depths in the pasture.

Total porosity and capillary porosity, like soil bulk density, changed in the 0–20 cm layer but not in the 20–40 cm layer under different land uses. Total porosity in the surface layer was greatest (53%) for artificial grassland and lowest (49.2%) for shrubland