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Evaluation of soil quality along two revegetation chronosequences on the Loess Hilly Region of China

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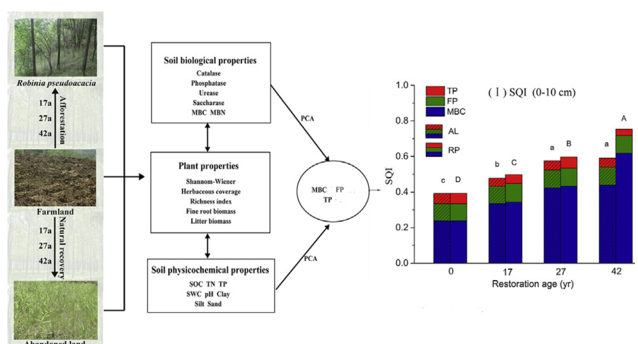
HIGHLIGHTS

- SQI was developed from physicochemical and biological properties.
- Key indicators are microbial biomass carbon, silt, clay, total phosphorus and pH.
- SQI values for *Robinia pseudoacacia* L. markedly increased with restoration age.
- SQI values for abandoned land reached a steady-state after 27 years of restoration.
- SQI values were higher in *Robinia pseudoacacia* L. than abandoned land.

GRAPHICAL ABSTRACT



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ABSTRACT

Vegetation restoration has been widely implemented to control soil degradation, reduce soil erosion, and improve soil quality. It is vital to understand the mechanisms affecting soil quality in soil restoration processes and to determine an appropriate recover pattern for soil restoration. Thus, a soil quality index was developed using integrated approach to assess soil quality after vegetation restoration in this study. Soil samples were collected from two restoration pathways (afforestation by *Robinia pseudoacacia* L. and natural recovery of abandoned farmland) with ages sequence of 0, 17,27 and 42 years old at two soil depths (0–10 and 10–20 cm) to measure soil physicochemical and biological properties on the Loess Hilly Region of China, China. The results showed that soil quality index (SQI) was developed based on microbial biomass carbon (MBC), fine particles (FP), and total phosphorus (TP). The MBC, which had the fastest increase rate than TP and FP, had the highest contribution to the final SQI and these contributions increased with recovery age. The MBC values were higher in *Robinia pseudoacacia* L. than in abandoned land sites at all recovery ages with greater increases along with restoration age. The SQI values significantly increased with increasing restoration age up to 27 years ($P < 0.05$). After 27 years, SQI values for the AL sites remained stable, while SQI values for RP sites continually improved with increasing restoration age. In addition, SQI values were higher for RP sites than for AL sites for all restoration ages.

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1. Introduction

Vegetation restoration by converting farmland into perennial vegetation occurs globally in various climatic conditions (arid, semi-arid, temperate, and tropical) and ecosystem types (cropland, grassland, and forestland) (Cao et al., 2008; Raiesi, 2011; Templer et al., 2005; Zhang et al., 2011). During vegetation restoration, changes in plant species composition and coverage can alter litter input, root architecture (Schedlbauer and Kavanagh, 2008), and physical (Zhao et al., 2017a), chemical (Lucas-Borja et al., 2012) and biological properties of the soil (Ren et al., 2016a). Changes in soil function and quality may occur as a consequence of these variations (Raiesi, 2017). However, large uncertainties remain concerning the effects of vegetation restoration on soil quality due to differences of revegetation type, restoration age, ecosystems and biomes (An et al., 2009; Zhang et al., 2011). For example, Zhang et al. (2011) found that improvements in soil quality for abandoned land were better than grassland and shrubland after eight years vegetation restoration on the Loess Hilly Region of China. Therefore, it is vital to assess the impacts of vegetation restoration on soil quality during soil restoration processes.

Soil quality, defined as the soil capacity to ensure the sustainability of the soil environment and biosphere, can be estimated using various soil quality indicators (Doran et al., 1996; Karlen et al., 2003; Raiesi, 2017). Several soil physical and chemical properties of the soil, such as soil texture, pH, soil water content (SWC), soil organic carbon (SOC) and total nitrogen (TN), reflect soil fertility and structure, and are widely used to indicate soil quality (Raiesi, 2017; Zhang et al., 2011). However, these properties usually change slowly and do not reflect soil quality changes over short time period. Whereas, soil biological properties, such as soil microbial biomass and enzyme activity, are sensitive to soil disturbance and are involved in nutrient cycling and organic matter dynamics (Bastida et al., 2008; Raiesi, 2011). Even though these individual soil properties can be considered as soil quality indicators, the impacts of vegetation restoration on soil quality cannot be assessed using individual soil parameters as they are interdependent and unlikely to thoroughly reflect these complex ecosystems (Raiesi and Kabiri, 2016; Yakovchenko et al., 1996). Therefore, developing a soil quality index based on several different soil characteristics can provide a more effective evaluation of soil quality after vegetation restoration. For example, Mukhopadhyay et al. (2016) developed an SQI evaluate reclaimed coal mine spoil, and recommended two native species for restoration. Using this approach, Zhang et al. (2011) developed an SQI to compare the impacts of different revegetation types on soil quality, and revealed that natural recovery is the best choice for soil restoration on the Loess Plateau. Although SQIs have been showed to be an effective method to reflect soil quality changes in a variety of ecosystems, there is little available information on soil quality evaluation along two chronosequences, especially on the Loess Hilly Region.

The Loess Hilly Region of China has a typical semiarid climate and is known for its considerable soil erosion (Li et al., 2016); soil erosion and desertification have resulted in severe land degradation (Bai and Dent, 2009; Li et al., 2016). To change these conditions and restore ecosystems, the Chinese government undertook vegetation restoration programs in the 1950s (Deng et al., 2013; Ren et al., 2016b); to data, >9.27 million ha of farmland have been converted into grassland and forest (Ren et al., 2016a). Vegetation reestablishment on farmland has greatly reduced soil erosion (Fu et al., 2010). The reclaimed land has been stabilized using different vegetation types at various points in time, which provides an opportunity to study the mechanisms affecting soil quality at different stages in the restoration process. Meanwhile, a comparison of the effects of different revegetation types (afforestation by *Robinia pseudoacacia*. L and natural recovery of abandoned farmland) on soil quality along two chronosequences is essential to select the appropriate vegetation type for restoration in fragile areas. In the present study, we hypothesized that vegetation restoration would improve soil quality, and the stage increase rate in soil quality would decrease in the later recovery age. We also hypothesized that higher soil quality and faster increase rate would be found in afforestation land. Thus, the objectives of this study were to (1) develop a comprehensive soil quality index, (2) evaluate the long-term impacts of vegetation restoration on soil quality, and (3) determine the most suitable revegetation type, which is most capable of restoring soil quality.

2. Materials and methods

2.1. Study sites

The study was carried out in the Wuliwan watershed in Ansai County, Shaanxi Province, northern Loess Plateau, China (36°51′41.23′′-36°52′50.87′′N, 109°19′49.20′′-109°21′46.46′′E). The region has hilly-gullied loessial landforms with a temperate semiarid climate. The area's mean annual temperature is 8.8 °C and mean annual precipitation is 505 mm (with 70% falling between July and September) (Zhao et al., 2017a). The soil is mainly composed of Calcaric Cambisol, originating from primitive or secondary loess parent materials, which is characterized by weak cohesion and is easily eroded (Fu et al., 2010). The study region has experienced severe soil erosion and degradation. Since the implementation of the vegetation restoration program, farmlands with slopes higher than 25° have gradually been abandoned for natural recovery and afforestation. *Robinia pseudoacacia* L. is the main species used for vegetation restoration. Our study area has been protected as an experimental site by the Institute of Soil and Water Conservation, Chinese Academy of Science (CAS) since 1973 (Ren et al., 2016b).

2.2. Experimental design, field investigation and sampling

In July 2016 (based on the space-for-time substitutions method), we selected sites representing two typical vegetation restoration types, at three recovery ages, with similar environmental conditions: land abandoned for natural recovery for 17 years (AL17), 27 years (AL27), and 42 years (AL42), and land planted with *Robinia pseudoacacia* L. for 17 years (RP17), 27 years (RP27) and 42 years (RP42). Millet (*Setaria italica* L.) farmland (FL) was chosen as a reference area (0 years recovery); millet was sown at a depth of 20 cm in May 2016 and the plants were harvested in August 2016. Prior to afforestation, there was little difference in farming practices between the sampling sites.

Within each sites, three independent replicate plots (30 × 30 m) were established for sampling. The distance between any two plots was <500 m to ensure that they had similar environmental conditions. Five subplots (1 × 1 m) were established within each plot, at the four corners and the center, to conduct the field investigations. Herb coverage and species presence were determined for all vegetation types (Table 1).

After removing the litter layer and debris, soil samples from the 0–10 cm and 10–20 cm soil layers were collected from 10 points in an "S" shape, using a soil auger (5 cm inner diameter). For each soil layer, these ten samples were homogenized to provide a composite sample for each replicate site. The final samples were sieved through a 2-mm screen to remove roots and other debris. Thereafter, these fresh samples were divided into three parts, one of which was used to measure the soil water content (SWC); the second part was air-dried at room temperature, and stored for analysis of the physical and chemical properties; the last part was stored at 4 °C to analyze its biological properties. Root samples were collected from each plot at 10 points in an "S" shape at a soil depth of 0–20 cm using a root auger (9 cm inner diameter). In each plot, five 1 × 1 m random quadrants were established, all the living biomass was removed, and the litter biomass was collected to provide a final litter sample. The soil bulk density (BD) of each soil layer was measured using a soil bulk sampler (5 cm diameter and 5 cm height) with three replicates and then dried in an oven at 105 °C for 48 h.