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Reclamation promotes the succession of the soil and vegetation in opencast coal mine: A case study from *Robinia pseudoacacia* reclaimed forests, Pingshuo mine, China

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ABSTRACT

Robinia pseudoacacia is the dominant tree species in opencast coal mine reclamation in the Loess Plateau, China. Nevertheless, the long-term changes of reclaimed mine soils (RMSs) and vegetation in the reclaimed sites under *R. pseudoacacia* monoculture forest have not been sufficiently elucidated. In this study, the RMSs physicochemical properties were measured and vegetation (including tree, herb and reserved litter) indexes were surveyed in *R. pseudoacacia* monoculture forests at 7 reclamation ages (8-, 10-, 13-, 15-, 18-, 23- and 30-year) in the Pingshuo opencast coal mine, China. Adjacent, unreclaimed plot (hereafter called 0-year reclamation plot) was selected as the base line to detect the dynamics of RMSs properties and undisturbed site was chosen to compare with the reclaimed ones. The results showed that, pH (varied from 8.72 to 8.07) and soil bulk density (BD) (ranged from 1.62 to 1.36 $Mg\,m^{-3}$) decreased along reclamation chronosequence. In contrast, soil organic matter (SOM, differed from 3.97 to 35.17 $g\,kg^{-1}$), total nitrogen (TN, differed from 0.23 to 1.19 $g\,kg^{-1}$) and available potassium (AK, ranged from 62.87 to 233 $mg\,kg^{-1}$) were found to increase sharply ($P < 0.05$) in the initial phase of reclamation and tended to be stagnant in the subsequent stage. Moreover, available nitrogen (AN, varied from 7.07 $mg\,kg^{-1}$ to 82.20 $mg\,kg^{-1}$) was observed to follow a concave curve along reclamation chonosequence. Total phosphorus (TP, differed from 0.48 $g\,kg^{-1}$ to 0.60 $g\,kg^{-1}$), available phosphorus (AP, varied from 4.33 $mg\,kg^{-1}$ to 8.3 $mg\,kg^{-1}$) and total potassium (TK, varied from 14.23 $g\,kg^{-1}$ to 19.37 $g\,kg^{-1}$), however, fluctuated at steady conditions after reclamation and remained the undisturbed levels throughout the reclamation stages. The duration required to attain the nutrient level in undisturbed soils was speculated 10 years of reclamation in the Pingshuo mine. Tree indexes (i.e., diameter at breast height, height, canopy area, biomass and biomass density) increased with the duration of reclamation. Herb indexes (including height, coverage percentage and biomass density), however, followed inversed U functions. Conversely, reserved litter biomass decreased progressively over time. Vegetation indexes were found significantly correlated with SOM, TN, AN and AK ($P < 0.05$). Overall, *R. pseudoacacia* monoculture forests markedly ameliorated both soil and vegetation succession in the Pinshuo dumps.

1. Introduction

Surface mining, the most common technique used for coal mining, often causes intensive disturbance to terrestrial ecosystems (Ussiri and Lal, 2005). In the process, mining removes overburden by excavation, changes topography and geological structures permanently, and disrupts surface and subsurface hydrologic regime (Shrestha and Lal, 2011). In particular, fertile soil mixed with fragmented rocks is transported to form large-scale dumps (Zhao et al., 2013) and forest vegetation is removed with some forest biomass harvested and most bulldozed in piles and burned (Amichev et al., 2008). The natural succession process of both soil and vegetation in dumps requires a lot of time, during which, the dumps are exposed to wind and water erosion processes (Zhao et al., 2015). Thereby, restoration of soil and vegetation within a short-time period is a high priority for opencast coal mine reclamation. Meanwhile, the reclaimed mined ecosystem could be regarded as an "empty cup" with large potential to store tremendous amounts of soil nutrients and vegetation biomass (Amichev et al., 2008; Chatterjee et al., 2009), which provides a platform to observe the development of soil and vegetation from scratch.

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During reclamation, the new altered soils are called reclaimed mine soils (RMSs), which are characterized by high proportion of rock fragments, deprived of soil nutrients, high bulk density and low infiltration (Reynolds and Reddy, 2012; Shrestha and Lal, 2008). Compared to the undisturbed soils, as much as 80% soil organic carbon (SOC) and up to 50% of soil nitrogen (N) have been observed lost from scraped RMSs (Ahirwal and Maiti, 2016; Ghose, 2001). Fortunately, adverse properties (i.e., physical, chemical and biological properties) of RMSs could be restored with proper reclamation management practices (Shrestha and Lal, 2010). Researches showed that properties in RMSs followed polynomial functions with ages (Adeli et al., 2013; Shrestha and Lal, 2010; Zhao et al., 2013), despite the restoration rates were dictated by factors such as soil substrate, terrain, micro-climate, reclamation pattern, etc. (Józefowska et al., 2017; Yuan et al., 2016). Except for the amelioration of soil properties, the succession of reclamation ecosystem consists of the development of vegetation. Generally, vegetation community structure of reclaimed forest was observed more and more diverse and forest biomass increased over time (Frouz et al., 2008; Lei et al., 2016; Zhao et al., 2015).

The development of soil and vegetation in reclaimed ecosystem consists of complex interactions covering several trophic levels, including above- and under-ground vegetation, soil microbial (fungal and bacterial), soil macrofauna, etc. (Frouz et al., 2006). On the one hand, RMSs provide habitats for plants and affect successional changes of vegetation by effects on nutrient availability (Frouz et al., 2008; Scullion and Malinovszky, 1995). On the other hand, vegetation exerts both direct and indirect effects on RMSs succession. Direct effects result from root growth, production of litter and root exudates, which support the formation of soil pores and soil aggregates and improves RMSs structure and physicochemical properties (Angers and Caron, 1998). Indirect effects come from the effects that vegetation exerts on soil biota.

Robinia pseudoacacia, a kind of temperate deciduous tree species, is 10–25 m in height with pinnate fronds being 10–25 cm long at mature age. It is the dominant species in the Loess Plateau due to its capability of tolerating barren and dry environments and its nitrogen-fixing ability to cultivate the poor soils (Zhao et al., 2013). It is also identified as the pioneering tree species to restore the impaired RMSs in the Pingshuo opencast coal mine, being monoculture or inter-planted with other arbor species (e.g. *Ulmus pumila*, *Ailanthus altissima*, *Pinus tabuliformis* and *Populus simonii*). The dynamic of RMSs quality had been reported in Pingshuo opencast coal mine irrespective of forest types (Wang et al., 2013; Zhou et al., 2017), which resulted in some deviation in detecting the development of soil physicochemical properties accurately. In particular, the development of RMSs under the dominant tree species (*R. pseudoacacia*) was not elucidated along reclamation chronosequence. Moreover the dynamic of vegetation and the relationship between the development of soil and vegetation were rarely understood in *R. pseudoacacia* monoculture forest. In this study, we measured the soil properties and surveyed vegetation (including tree, herb and reserved litter) indexes from 7 reclamation ages (8-, 10-, 13-, 15-, 18-, 23- and 30-year) in *R. pseudoacacia* monoculture forests and the specific objects of our study were: (1) to detect the dynamics of RMSs properties and vegetation indexes over time; and (2) to reveal the relationship between soil and vegetation properties.

2. Materials and methods

2.1. Study area

Pingshuo opencast coal mine is the largest opencast coal mine in China. It is located in the north of Shanxi Province, east of the Loess Plateau with the coordinate of 112°10′–113°30′E, 39°23′–39°37′N (Fig. 1). It has an arid to semi-arid continental monsoon climate with fragile ecological environment. The total annual precipitation averages 450.0 mm and the average annual effective evaporation is 2160.0 mm. The annual mean temperature is 6.2 °C and the dominant vegetation is hay (Bai et al., 1999).

In coal mining process in Pingshuo opencast mine, the overburden, covered on the coal seams, is stripped, transported and piled to form large-scale dumps. Thus, the dump is predominately soils and rocks with large diameter and the slope phase distribution of a dump is of ladder terrain with relative height about 100–150 m and step height between 20 and 40 m (Zhao et al., 2015). The slope of a dump was 35°. In reclamation, the topsoil, characterized by sandy loam and consisted of illite, kaolinite and vermiculite, is applied on the top of dump and leveled subsequently. The reclamation of the dumps was initiated since 1987 and the reclaimed landscape was dominantly used for forest and agricultural purposes. The favorable tree species in reclamation were *U. pumila*, *Ailanthus altissima*, *P. tabuliformis* and *P. simonii*, above all, the *R. pseudoacacia*. The prevailing shrub species were *Hippophae rhamnoides* and *Caragana korshinskii* and the dominant herb was Asteraceae, Poaceae and Leguminosae (Zhang et al., 2005).

2.2. Sampling plots

Plots with 7 reclamation ages (8-, 10-, 13-, 15-, 18-, 23- and 30-year) were identified under *R. pseudoacacia* monoculture forests (Figs. 1–2). In addition, a plot without reclamation (thereafter called 0-year reclamation plot) was selected as the base line to detect the dynamics of RMSs properties. Considering the undisturbed *R. pseudoacacia* monoculture forest was unavailable around the Pingshuo mine, the undisturbed *Populus simonii* monoculture forest was chosen to compare with reclaimed sites. All the 9 plots, with an area of 1 ha (100 × 100 m) each, were located in the south and west dumps of the Pingshuo mine. In terms of the management practices, *R. pseudoacacia* in all plots was planted 1-m spacing and 1-m row spacing at the initial reclamation stage. In the first 3 years of reclamation, irrigation, fertilizer (~100 kg ha^{-1} NH_4NO_3; ~150 kg ha^{-1} P_2O_5; ~90 kg ha^{-1} K_2O) and precautions against pest (including *Ivela ochropoda*, *Drosicha contrahens*, *Cerambycidae*) were carried out every year. Other than this, there were no management practices (Zhao et al., 2015). The detailed information on sampling plots was showed in Table 1.

2.3. Soil sampling and analysis

Composite soil samples were collected from 0 to 20 cm depth using an auger for the determination of soil physicochemical properties during July 2016. Within each of the 9 plots, soil samples were collected randomly at 5 sampling locations after stripping the litter and fermentation on the horizon of topsoil. In each sampling location, 5 sub-samples were collected within a range of 10 × 10 m to make the composite samples and the sub-samples were sealed in plastic bags and transported to the laboratory. At the same time, soil samples for bulk density (BD) were obtained with stainless steel cylinders (5.0 cm diameter and 5.0 cm high) within each 10 × 10 m sub-plots. To determine soil properties, the composite soil samples were air-dried under shade and stones were removed.

BD and pH were determined according to the methods of the Institute of Soil Science, Chinese Academy of sciences (1978). Samples for BD were oven-dried at 105 °C for 48 h, after which the weight and volume of gravels (particles > 2 mm) were subtracted from the total soil weight and volume to calculate BD. pH was determined in H_2O suspensions (soil: water ratio of 1:2.5) with a pH Meter (FE20K, Mettler Toledo, Germany). To determine SOC content, Nelson and Sommers (1982) methods were employed: used using dry combustion with spectroscopic detection (NIR) to record released CO_2. Semi-micro Kjeldahl method (Kjeldahl, 1883) was used to determine total nitrogen (TN) concentration. Total phosphorus (TP) and total potassium (TK) concentrations were determined according to the methods of Liu (1996): the NaOH melting molybdenum antimony colorimetric method and the flame emission spectrometry method were used, respectively.