Catena 167 (2018) 250–256

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Soil and vegetation development along a 10-year restoration chronosequence in tailing dams in the Xiaoqinling gold region of Central China

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ARTICLE INFO

Keywords:
Heavy metal pollution
Newly created habitat
Plant diversity
Soil microbial activity
Soil-plant feedback

ABSTRACT

Gold mining has increased sharply in response to global demand. Gold extraction usually causes the formation of tailing dams, in which organic matter and microbial activity decrease, and this consequently constrains plant growth. However, a full understanding of plant-soil interaction and plant community development in terms of natural restoration of gold mine tailing dam has not yet been developed. Three tailing dams, which had been naturally restored for 2 (R2), 5 (R5), and 10 (R10) years in the Xiaoqinlin gold region of Central China, were chosen to explore soil and plant community development in August, 2015. This study showed that soil bulk density and pH value were the lowest, whereas soil organic carbon, total nitrogen, microbial biomass carbon and nitrogen were the highest in the R10 tailing dam across two soil depths (0–10 cm and 10–20 cm). Soil organic carbon, total nitrogen, microbial biomass carbon and nitrogen decreased with soil depth across the restoration periods. The highest ratio of soil organic carbon to total nitrogen in the R10 tailing dam suggests that the rate of soil organic carbon accumulation may be restricted by the total nitrogen content in the long-term. Restoration stimulated plant community diversity and productivity, due to increment in soil nutrient content and microbial biomass carbon and nitrogen. The various ratios of root biomass to aboveground plant biomass among three tailing dams were caused by the shifting of the plant community composition from annual to perennial varietals. The mechanism by which plant-soil interaction and plant community composition change over time can be used to guide restoration programs in tailing dams in Central China.

1. Introduction

Gold mining has been expanding in recent years in response to increasing gold prices and worldwide demand (Alvarezberríos and Aide, 2015; Chainani, 2016). Gold ore is changed from a stone-like consistency into a slurry with the addition of vast amounts water using a ball mill instrument, or it is disaggregated under high pressure by water. Then, gold-bearing slurry is divided into gold particles and mine tailings in a sluice box (Román-Dañobeytia et al., 2015). Gold mining often renders land incapable of certain ecological functions, such as having enough nutrient supply for plant growth, and leaves a tailing dam with poor soil-forming materials and no vegetation (Herath et al., 2009; Keskin and Makineci, 2009; Alday et al., 2012; Albert, 2015; Kumar et al., 2015). Ecological restoration of degraded, bare tailing dams has become a major environmental issue, as mining and environmental enterprises seek to reduce the impact of mining on the degradation of soil and on biodiversity loss (Šourková et al., 2005a; Ilunga et al., 2015).

Gold mining affects soil quality, including the soil's physical structure (bulk density, particle size distribution), nutrient availability (soil organic carbon, total nitrogen), microbial activity (soil microbial biomass), and pH (Albert, 2015; Masto et al., 2015). After mining, the organic carbon pool in the soil can decrease by 70–81% due to increased sand proportion and deficiency in cation exchange capacity (Akala and Lal, 2001; Román-Dañobeytia et al., 2015). A larger proportion of sand in tailing soils may intensify water erosion during a rainy season, and strengthen wind erosion during a dry season (Ilunga et al., 2015; Pourret et al., 2015). The disproportionate sandiness of the soil texture causes low soil fertility, which is rendered insufficient to support normal plant growth. In addition, soil microbial biomass was

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https://doi.org/10.1016/j.catena.2018.05.007
Received 10 July 2017; Received in revised form 17 April 2018; Accepted 7 May 2018
0341-8162/

found to decrease in tailing dams in Peru (Román-Dañobeytia et al., 2015) and French Guiana (Schimann et al., 2012) due to lower soil nutrient conditions and lower plant productivity. Therefore, understanding how soil's physical, chemical, and microbial properties change during restoration is critical for guiding the restoration of mined land (Abreu et al., 2009; Ronan et al., 2010; Alday et al., 2012).

Plant primary succession is a significant source of ideas for planning restoration programs, and identifying appropriate species suitable for revegetating tailing dams is a main goal of restoration management (Porqueddu et al., 2016). Natural recovery provides valuable lessons for understanding the temporal dynamics of soil and plants through long-term observation of severely disturbed habitats (Walker and del Moral, 2009). Soil quality and vegetation compositional changes depend on restoration duration time, and the response of vegetation can induce soil development. Increasing plant community diversity in mined areas has been found to be beneficial to restoring soil (Isermann, 2005; Alday et al., 2012). However, other study shows that plant diversity has no relationship with soil properties in a sequence of restoration projects along embankments (Li et al., 2016). More attention should be paid to the process of plant and soil development over the course of the restoration of bare soils to identify plant-soil interactions (Kardol and Wardle, 2010; Ilunga et al., 2015). The significant relationship between soil properties and plant functional traits suggests that overall plant-–soil feedback effects should be studied to determine their suitability for enhancing ecological restoration (De Deyn et al., 2008; Putten et al., 2013; Ilunga et al., 2015). Natural restorations have been studied in clay wastes (Roberts et al., 1980), abandoned fields (Knops and Tilman, 2000), coal wastes (Alday et al., 2012; Kumar et al., 2015), forests (Matlack, 2009), inland drift sand dumps (De Kovel et al., 2000), and urban sites (Schadek et al., 2009). However, few attempts have been made to study the primary succession of natural restorations in gold mined tailing dams.

China has been the largest gold producing country since 2007, accounting for about 15% of global gold production (Chainani, 2016). The Xiaoqinling region, as the second largest gold mining area in China, has experienced a rapid expansion and an increased number of tailing dams since the early 1990s (Zhang et al., 2014). The 'space-for-time' method often offers valuable insights into soil and vegetation changes during restoration (Brantley, 2008; Chaudhuri et al., 2013; Kumar et al., 2015). The aims of this research were to examine the changes in the soil's physical, chemical, and microbial properties, and in the plant community structure in three gold mine tailing dams with an age sequence of 2-(*R*2), 5-(*R*5), and 10-(*R*10)-year primary succession, and discussed potential relationships between soil and plant properties.

2. Materials and methods

2.1. Study region

The field study was conducted in the Xiaoqinling region (34°29.39′-34°29.67′N, 110°21.20′-110°22.55′E, 530–560 m) in Central China, which has a continental climate (Zhang et al., 2014). According to data from the National Meteorological Information Center of China for the period from 1981 to 2010, the mean annual air temperature was 12.9 °C, ranging from −0.9 °C in January to 25.6 °C in July. The mean annual precipitation was 608.0 mm, with 82% occurring from May to October. The soil prior to the mining activity was derived from loessic parent materials and is classified as an Earth-cumuli-Orthic Anthrosol (Li et al., 2016).

2.2. Experimental design and sampling

Based on the chronosequence of the plant primary succession process in the study region, we selected three abandoned tailing dams, which were created by the gold extraction process and had terrain slopes of generally < 0.9% (Fig. S1). The three tailing dams, all located in the gully, had been naturally restored for 2, 5, and 10 years (R2, R5, and R10); therefore, they provided a good sample for us to study three different restoration treatments. The restoration ages were determined through interviews with local gold producers. The heavy metal content (Cu, Zn, Pb, Cd, Cr) and particle size distribution of the dams are shown in Table 1. One 20 m × 20 m plot was chosen in the center of each tailing dam in late August of 2015, when the highest biomass was attained. Then, five 1 m × 1 m quadrats were randomly set in each plot.

Table 1
Heavy metal content and particle size analysis in the three tailing dams with an age sequence of 2-(*R*2), 5-(*R*5), 10-(*R*10)-year natural restoration.

Sites	Heavy metal content (mg kg^{-1})					Particle size content (%)		
	Cu	Zn	Pb	Cd	Cr	Clay	Silt	Sand
R2	540.22	188.78	54.74	1.26	67.96	4.53	69.06	26.40
R5	501.35	183.24	54.85	1.23	81.47	6.42	69.70	23.88
R10	437.15	171.53	55.61	1.31	82.87	8.24	67.08	24.67

2.3. Soil sampling

Soil samples were analyzed for bulk density (BD), soil water content (SWC), pH, soil organic carbon content (SOC), total nitrogen content (TN), microbial biomass carbon (MBC), and microbial biomass nitrogen (MBN). One soil sample was taken at each of five points from each quadrat (four corners and the center of the quadrat) by drilling a 4 cm diameter soil sample at depths of 0–10 cm and 10–20 cm. One part of the soil sample was air-dried and then passed through a 0.25 mm sieve for SOC and TN analyses. Soil BD and SWC of the different soil layers were measured using soil cores (volume, 100 cm^3) and volumetric ring method (Li et al., 2016). Soil pH was determined at a soil-water ratio of 1:5. The dichromate oxidation method was used to measure SOC (Nelson and Sommers, 1982). The modified Kjeldahl method was used to measure TN (Bremner, 1996). The other part of the soil samples was sieved (< 2 mm) and stored at 4 °C prior to measuring MBC and MBN. The MBC and MBN were estimated by the fumigation-extraction method using 0.5 M K_2SO_4 as the extractant (Brookes et al., 1985). Each analysis was performed in duplicate.

2.4. Plant sampling

Aboveground biomass (AGB), root biomass (RB), plant community height, cover, species richness (S, total number of species in the each quadrat), and density (D) were measured. In each quadrat, all of the aboveground plant parts for each species were harvested, placed into envelopes and tagged. In order to measure RB, soil sampling was performed five times at depths of 0–10 cm and 10–20 cm in each quadrat using a 7-cm diameter root auger. Roots were separated by washing and sieving using a 0.5-mm sieve (Wang et al., 2015). Aboveground plant materials and root tissue were dried at 65 °C for 48 h and weighed to determine AGB and RB. The ratio of RB:AGB (R:S) was calculated using RB and AGB per square meter. A metal frame of 1 × 1 m with 100 equally distributed grids (10 cm × 10 cm) was constructed above the canopy in each quadrat during cover measurement. Canopy height in each quadrat was the average value of the height of five random individual plant. The number of ramets in the sampled quadrats represented the density of the plant community. The Shannon-Wiener diversity index (*H*) and Pielou evenness index (*E*) of the plant communities were calculated as (Wang et al., 2014).

2.5. Statistical analyses

All data are expressed as mean values ± standard error (SE) for the five quadrats. All variables were transformed to satisfy the normality criteria and the test of the homogeneity of variances, but the results and