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Effects of vegetation on runoff and soil erosion on reclaimed land in an opencast coal-mine dump in a loess area

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ABSTRACT

Vegetation reconstruction on opencast coal-mine dumps is an effective way to reduce runoff and soil erosion and is a key to restoring ecosystems in ecologically sensitive regions. To investigate the effects of vegetation on runoff and erosion, a field experiment involving eight erosion plots was conducted on a dump at the Antaibao opencast coal mine in, Shanxi Province. The plots were divided into two location groups, platforms and slopes. Each plot was planted with a typical vegetation pattern. The volumes of runoff and soil erosion during each rainfall event were recorded during the rainy season. The results showed that plots on the platforms experienced a larger volume of runoff than plots on the slopes, while the slope plots generated a larger value of soil erosion than the platform plots. Vegetation restoration has different impacts on runoff and soil erosion. A plot covered with 1-year-old *Robinia pseudoacacia* and *Hippophae rhamnoides* was most effective in terms of soil conservation; the plots covered with 5-year-old mixed legume plants and 5-year-old mixed grass-shrub-arbor forest were most effective overall in preventing both runoff and soil erosion. Over the long term, vegetation can increase soil organic matter, improve soil physical properties and soil anti-erodibility, and reduce runoff and erosion to a safe level. This study provides a theoretical basis and technical support for land reclamation and soil and water conservation in vulnerable ecological mining regions of a loess plateau.

1. Introduction

As one of the most important mainstay industries in the energy source market, opencast coal mines are primarily located in the vulnerable environments of northwestern China, such as Shanxi Province, Inner Mongolia, Gansu Province, Ningxia Province and Shaanxi Province. As the climates of these regions become warmer and more dry, the regions suffer greater soil and water losses, thus threatening local terrestrial ecosystems (Sun et al., 2013; Wang et al., 2013b). With the incentive of rapid economic development, extensive areas of mining are emerging in these regions. Opencast mining is an efficient and cost-effective mode for the exploitation of mineral resources. However, this modern mining technology can have a large impact on the surrounding landscape by eliminating vegetation and permanently altering topography, soils and subsurface geological structures, resulting in accelerated runoff and soil erosion compared with the local mean for natural surfaces (Zhao et al., 2013; Wang et al., 2014b). Waste dumps constitute the land most damaged by opencast mining. Runoff causes soil erosion, a selective process that sweeps away fine materials, and nutrients, from sloped lands, strongly impacting on the long-term development of waste dumps (Polyakov and Lal, 2004). The magnitude of erosion is highly dependent on rainfall characteristics, surface properties and topographic features (Puigdefabregas et al., 1999). As a result, land used for waste dumps becomes less fertile and more depleted in nutrients over time. Runoff and soil erosion hinder vegetative restoration in dumps, further inducing runoff and soil erosion and leading to a more severe threat to the stability of local ecosystems and economic development (Evans et al., 2004; Biemelt et al., 2005). It therefore follows that vegetation restoration is necessary for waste dump reclamation, ecological restoration and the long-term stability of engineered post-mining landforms (Miao and Marrs, 2000; Sever and Makineci, 2009; Bao et al., 2012; Drazic et al., 2012).

Many researchers have analyzed the effects of various types of vegetation on soil and water conservation, and the different ways vegetation can constrain soil loss and improve environmental conditions (Bochet et al., 1999). It has been found that vegetation structure (canopy cover, sapling density, litter depth, and woody debris) may be a main factor influencing soil and water loss. Multiply stratified areas are more advantageous than mono-stratified areas in respect to soil and water conservation (Casermeiro et al., 2004), and natural forests are superior to plantations for their diversities in structure and species. Pure trees

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(e.g., *Pinus massoniana* Lamb, without any grass and shrub under the canopy) show a positive effect of trees on soil and water conservation, accounting for approximately 70% and 55% of the total effect (from 2007 to 2010), respectively, during rainfall events with relatively higher rainfall depths, stronger intensities and shorter durations, whereas negative effects occurred during rainfall events with lower rainfall depths, weaker intensities and longer durations (Cao et al., 2008; Gu et al., 2013). Vegetation fractional coverage (VFC) which means the percentage of vegetation vertical projection area covering a workshop area, is an important parameter for reflecting community structure and was typically reported to be negatively correlated with soil and water loss (Krummelbein et al., 2010; Zuo et al., 2010; Zhang et al., 2011). The type and significance of the relationships varied depending on the conditions in which soil and water loss occurred. The relationships may be obvious in surface areas that are homogenous in terms of their vegetative cover but not in larger and heterogeneous areas, where surface geology varies (Braud et al., 2001). There are complex interactions between plants and soil properties. Plants can improve soil properties, and soil properties will, in return, affect plants. Considered as one of the more important indicators of soil erosion, soil structure is closely related to the process of water and soil erosion through good physical properties (such as high water storage capacity, bulk density, and porosity) to increase water infiltration. In addition, organic carbon increases the formation of soil aggregates, which then reduce runoff and soil loss (Deuchars et al., 1999; Casermeiro et al., 2004). Soil with higher silt and soil organic matter content can increase soil infiltration and soil aggregates, resulting in good structural stability and leading to reduced runoff and erosion (Zheng et al., 2008; Wu et al., 2010). However, the soil organic matter content of loess on the study mining area is generally low and its texture alters slightly, so the variation of particle-size distribution among which silt and clay contents mainly determine the soil erodibility. Soil resistance to erosion gets enhanced with increasing clay content. With increasing silt content increasing, soils are more apt to undergo erosion (Zhang et al., 2001). According to the above authors, vegetation plays an important role in water and soil erosion control. Vegetation cover can reduce the kinetic energy of raindrops. Vegetation covered plots and the litter layer protect soil surfaces, increase soil surface roughness, impede overland flow and increase infiltrating time. Vegetation root development can improve soil physical properties (e.g., soil strength, shear strength, structural stability and aggregate stability), which are closely related to soil erodibility, resulting in a contribution to soil loss control (Gao et al., 2009). The majority of recent field experiments and rainfall simulations have mainly focused on natural landforms and disturbed farmlands (Calvo-Cases et al., 2003; Hartanto et al., 2003; Biemelt et al., 2005; Cao et al., 2008; Shi et al., 2010; El Kateb et al., 2013) and have revealed the mechanism of the influence of vegetation on runoff and soil erosion and provided methods for similar research on mining landscape remediation. While fewer studies have focused on mining reclamation land, Z. Miao outlined the principles and approaches to ecological restoration and land reclamation in open-cast mines on the Loess Plateau of China (Miao and Marrs, 2000). The most common, efficient and practical way to conserve water and soil is to use biological methods by creating a diverse vegetation as soon as possible (Miao and Marrs, 2000; Josa et al., 2012; Xu, 2012). As the only source of soil organic carbon in artificial reclaimed sites, restored plants affect soil-forming processes. Differences in plant type result in different organic matter and organic carbon content, which mainly trigger for the change in the physical structure, chemical properties and microbiological properties of soil. And long-term reclamation can bring direct positive effects upon soil conservation (Dragovich and Patterson, 1995; Fu et al., 2010; Williamson et al., 2011; Zhao et al., 2013). This study contributes to the understanding of runoff generation and soil loss from a dump in mining areas on the Loess Plateau of China. The specific objectives of this experiment were to compare the ratio of runoff and soil losses for different aspects (1) among different plant systems, (2) on different landforms between flat platforms and steep slopes, and (3) under various rainfall event types on the dump, and to explain the mechanism of the effects of vegetation on water and soil conservation as well as the long-term influence of vegetation on environmental conditions.

2. Materials and methods

2.1. Study area

The experimental plots are located at the South Dump of the Antaibao (ATB) opencast coal mine, with geographic coordinates of 112° 10′ 58″–113° 30′ E, 39° 37′ N (Fig. 1) in Pingshuo, Shanxi Province, which is the largest opencast coal mining area in China. This area has a typical temperate arid to semi-arid continental monsoon climate and a fragile ecological environment. The annual mean temperature range is 5.4 °C–13.8 °C, and the total annual precipitation averages 426.7 mm, with 75%–90% occurring during the rainy season (June–September). The average annual effective evaporation, however, is approximately 2160 mm, almost 5 times greater than the amount of precipitation (Li et al., 2013). The study area, located east of the Loess Plateau where there are the older landforms (Fig. 2a), was once primarily a landscape of forests and prairies, whereas now it is covered in loess soil. However, during the past 200 years, the primary vegetation has been damaged by long-term human disturbance and climate change, leading to chronic water and soil erosion.

The ATB opencast coal mine has an area of 376 km^2 and has been mined for over 30 years (1985–2007). The specific study area was located in the South Dump of the ATB mine. The South Dump was used from 1985 to 1989, and reclamation began here in 1992, making it one of the earliest reclamation areas of the ATB opencast coal mine. The dump has a stepped design with a maximum step height of 50 m, a main step gradient of 35%–40%, a platform width of 50 m and a final height of 100–140 m. Because it was formed by piling waste soil and rocks throughout the mining process, the dump is an artificial landform significantly different from the original topography (Fig. 2b, c, d). According to previous research and the long-term records of the Shanxi Province Hydrology Calculation Manual on sediment and discharge at Dongyulin and Luozhuang Hydrological Station during the rainy season, dumps without reclamation had soil erosion totaling 15,060 $t \cdot km^{-2} \cdot a^{-1}$, or a 33% greater erosion rate than the original Loess Plateau landform, which has a typical soil erosion rate of 10,120 $t \cdot km^{-2} \cdot a^{-1}$ (The Bureau of Shanxi Province, 2011). After approximately 10 years of re-vegetation measures, the soil erosion of a dump can be reduced to 3438 $t \cdot km^{-2} \cdot a^{-1}$, or 194% less than that of the original Loess Plateau landform (Lv et al., 2003).

2.2. Experiment design

With the acknowledgment of the significance of vegetation to water and soil conservation and ecological restoration in an opencast mine area of loess area, a field experiment was needed to evaluate and explain the effects of vegetation on water and soil conservation, following the dominant vegetation configuration patterns, slope gradients and soil bulk densities of the study area. In the process of piling waste soils and rocks, the platforms were rolled flat using large-scale machines, while the slopes were formed without rolling. Therefore, the platform is characterized by a high bulk density (the average value range is 1.5–1.9 $g \cdot cm^{-3}$, 0.2–0.84 $g \cdot cm^{-3}$ larger than the original landform) and a flat surface, and the slopes are composed of loose soils and rocks (bulk density range is 0.9–1.2 $g \cdot cm^{-3}$) with high gradients (Wei et al., 2001). Four plots were set up on the platform, and the additional four plots were located on the slopes. Soil on these plots is composed of loessial soil, and the soil is silt loam according to the FAO soil classification system (Wang et al., 2014a). The effects of vegetation on runoff and soil erosion were analyzed. The detailed conditions of the two groups of study plots are shown in Table 1. The vegetation configuration types