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Reprint of “Effects of vegetation and physicochemical properties on solute transport in reclaimed soil at an opencast coal mine site on the Loess Plateau, China”☆

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ABSTRACT

Mine soils are often polluted and degraded. The objectives of this study were to assess the effects of soil properties and vegetation on soil solute transport in reclaimed soil at an opencast coal mine site on the Loess Plateau. Four reclaimed areas with different vegetation types were selected for the analysis of physical and chemical properties. The miscible displacement technique was used to obtain the breakthrough curves (BTCs) of NO_3^- ion transport in undisturbed soil columns, which were taken from the soil profiles of the different sites. The chemical properties, such as total N, P, K and SOM, exhibited low contents, and the soil physicochemical properties showed high heterogeneity between different depths and different reclaimed areas. The structural stability index was less than 5%. The initial and entire penetration times were longer in the deeper layers than in the top layer. The BTCs of NO_3^- were fitted well by the deterministic equilibrium convection dispersion equation (CDE) model. Preferential flow and transport were found in the soil columns. The reclaimed soil had poor structure, and planting vegetation improved the physiochemical properties of the soil. The soil solute transport parameters exhibited high heterogeneity between different samples and were significantly correlated with soil bulk density and soil texture, which were highly influenced by vegetation and human activities. In the process of land reclamation, increasing the bulk density and selecting fine-textured soils could reduce the average soil pore water velocity and the dispersivity coefficient, thereby extending the solute penetration time.

1. Introduction

Coal plays a leading role in the energy structure of China and contributes greatly to China's economic development (Wang et al., 2006). However, coal mining activities, especially opencast mining, have caused serious damage to the environment, including the elimination of vegetation, permanent topographic changes, dramatic changes in the soil and subsurface geological structure and disruption of the surface and subsurface hydrologic regimes (Keskin and Makineci, 2009). Coal mining produces a large amount of stripped soils, coal gangue, tailings and other solid wastes, which are buried or deposited in piles, replacing a large area of arable land with bare ground. Mine soils are usually degraded and are characterized by poor soil structure, high bulk density, low pH, low nutrient availability, low water holding capacity, low structural stability and low biomass productivity (Asensio et al., 2013; Palumbo et al., 2004; Shrestha and Lal, 2006). Reclamation of these bare ground soils is necessary to minimize the risk of land degradation (Pedrol et al., 2010).

Chemical, physical and biological properties are always selected as the main soil quality indicators and are monitored over time to determine changes in soil quality, i.e., improving, degrading, or stable (Carter et al., 1997; Shukla et al., 2004a). Several authors have studied the degradation and reclamation of mined soils and suggest that the establishment of vegetative cover should be encouraged. The selection of appropriate vegetation and soil amendments is essential to stabilizing a bare area and remediating adverse physical and chemical properties (Asensio et al., 2013; Keskin and Makineci, 2009; Wong, 2003; Zhao et al., 2013). Shukla et al. (2004a) found that bulk density was the most discriminating factor and that water-stable aggregation was the most commonly measured soil attribute and the most dynamic soil quality indicator for reclaimed mine soils in southeastern Ohio. The

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authors also found that there were no significant differences in several soil properties, such as bulk density and SOC content, between undisturbed (unmined) soil and reclaimed mine soil and that fertilizer treatments improved the soil quality of reclaimed mine soils (Shukla et al., 2004b). According to these studies, using several different treatments simultaneously may be better than using only one to improve the physical and chemical properties of mine soils.

In comparison with native soils, many mine soils have a higher proportion of rock fragments and possess poorer structure and coarser texture (Bussler et al., 1984). Soil texture and structure have a significant impact on water flow and contaminant transport in soils (Kodešová et al., 2009). The physical quality of coarse-textured soils (sandy, loamy sand and sandy loam) is often poor due to a high percentage of macropores, which results in losses of water and nutrients from the root zone via deep percolation and preferential flow (Asghari et al., 2011). Preferential flow may lead to rapid downward solute transport, which may cause nutrient loss and deep contamination, especially in coal mine soils, which commonly suffer from heavy metal pollution (Jiao et al., 2011; Li, 2006). Many contaminant transport solutes, including pesticides, virus, nutrition such as nitrogen and phosphorus, have been reported to bypass the soil matrix (Akhtar et al., 2011). Some researchers have studied transportation of heavy metals such as cadmium, copper, zinc, and lead in mine soils (Basta and McGowen, 2004; Runkel and Kimball, 2002). Hangen et al. (2005) assessed preferential flow processes in a forested-reclaimed lignitic mine soil by multicell sampling of drainage water and three tracers. Some non-reactive solutes, such as Br^-, Cl^- and NO_3^-, have been used as transport tracers to study solute transport processes. Valuable solute transport information can be deduced from breakthrough curves (BTCs) (Hillel, 1998), which utilize the convection dispersion equation (CDE) model.

Previous studies mostly focused on the effects of vegetation and various soil amendments on soil chemical, physical and biological properties to evaluate soil quality, in such a way, limiting factors were found in the process of vegetation restoration. A majority of studies focused on surface layers, with only a few studying deep layers. Studies on solute transport in reclaimed mine soil have not been well documented.

In this study, we focused on the physicochemical properties of soils on reclaimed waste dumps at the Heidaigou opencast coal mine, which is located on the Loess Plateau. By analyzing soil samples and conducting vertical soil column solute transport experiments, our objectives were to study the physicochemical properties and solute transport characteristics within the soil profile, to test whether the CDE model could effectively fit the solute transport parameters and to investigate the relationship between the physicochemical properties and solute transport characteristics.

2. Materials and methods

2.1. Site description

The study area is located at the Heidaigou opencast coal mine (110°13′–110°20′E, 39°43′–39°49′N), one of the largest opencast coal mines in China. The mine is located in Jungar Banner, Inner Mongolia Autonomous Region, northwest China. The area has a semi-arid, temperate continental climate, with a mean annual precipitation of 404 mm, of which approximately 64% falls between June and August (Sun et al., 2012). The average annual evaporation is approximately 2082 mm, 5 times more than the rainfall, and the mean daily temperature is 7.2 °C (Sun et al., 2012).

The Heidaigou opencast coal mine contains six waste dumps. The work of recovering the spoil banks began in 1992. The two largest waste dumps, i.e. the north waste dump, which began recovery in 1992, and the east waste dump, which began recovery in 1997. These two dumps were selected as the study area. Trees and grasses were planted to improve the soil conditions of the waste dumps, and there were no obvious dynamics in the reclaimed process. The typical vegetation types of the east waste dump were black locust (*Robinia pseudoacacia* L.) and lucerne (*Medicago sativa* L.), and those on the north waste dump were old world bluestem (*Bothriochloa ischaemum* (L.) Keng) and simon poplar (*Populus simonii Carr*). In August 2012, two plots with the corresponding typical vegetation type were selected on each of the two reclaimed waste dumps. The four sample plots were named M1, M2, M3 and M4. M1 and M2 were on the east waste dump and were dominated by black locust (*R. pseudoacacia* L.) and lucerne (*M. sativa* L.), respectively. Plots M3 and M4 were on the north waste dump and were dominated by old world bluestem (*B. ischaemum* (L.) Keng) and simon poplar (*P. simonii Carr*), respectively.

2.2. Soil sampling and analysis

The waste dumps were covered with loess soil, which was approximately 1.60–2.00 m deep. Soil samples were taken from soil profiles with a 160-cm-deep AC horizon to analyses the physical, chemical and solute transport properties (August 2012). Soil samples were collected at 20-cm intervals, and eight samples were obtained in each plot. Organic glass tubes 7.0 cm in diameter and 24 cm in height were used to collect undisturbed soil columns. The inner walls of the tubes were rubbed before the experiment to minimize the impact of the inner wall. Simultaneously, physicochemical test soil samples were obtained at 20-cm intervals and then stored in polythene bags. Once in the laboratory, the mixed samples were air-dried, screened through 2 mm, 1 mm and 0.25 mm meshes and then prepared for testing. Analyses were performed three times for each sample. The undisturbed soil columns were prepared for the solute transport experiments.

The bulk density of the soil samples was measured with stainless Kopecky cylinders. Soil cores were used to obtain the samples, and the samples were oven-dried at 105 °C for 48 h. The bulk density was calculated as the weight to volume ratio of the soil. The soil porosity was calculated with the following formula: porosity (%) = (1 − Bulk density / Particle density) × 100%.

Generally, the particle density of most soils is between 2.6 g cm^{-3} and 2.7 g cm^{-3} and is usually accepted to be 2.65 g cm^{-3}. Therefore, we used 2.65 g cm^{-3} in our calculations (Zhao et al., 2013). The distribution of soil particles was analyzed with a laser particle size analyzer (MS-2000, Malvern, Britain).

The soil pH was measured in water with a ratio of 1:2.5 using an Ion meter (Lei-ci PXSJ-216F, Shanghai REX Instrument Factory, China). Soil total nitrogen (N) was determined using an automatic Kjeldahl apparatus (2300, FOSSTECATOR, Sweden). Soil total phosphorus (P) was determined via the NaOH melting molybdenum antimony colorimetric method. Soil organic carbon (SOC) was determined using the dichromate oxidation method of Walkley–Black (Page et al., 1982). Nitrate nitrogen (NO_3^--N) and ammonium nitrogen (NH_4^+-N) were analyzed with an element flow analyzer (AutAnalyel, Bran + Luebbe GmbH, German). The cation exchange capacity (CEC) was determined after leaching 1 mm of air-dried soil with 1 M NH_4OAc at a pH of 7.0. The exchangeable cations (K^+ and Na^+) were analyzed by flame spectrophotometry (Blakemore, 1987).

A vertical soil column solute transport experiment was carried out at steady state conditions using 0.1 M NH_4NO_3 solution with specific microbial biocide as a tracer. Initially, undisturbed soil columns were placed in deionized water until the soil was completely saturated. Flow experiments were carried out by rapidly establishing and then maintaining a constant 2.0-cm head of 0.1 M NH_4NO_3 solution on the surface of the soil using a Mariotte bottle. The effluent was collected continuously in 30 ml volumetric flasks over timed intervals. The effluent samples were then analyzed using an element flow analyzer to determine the NO_3^--N and NH_4^+-N concentrations until they attained a stable level close to 0.1 M. The experiments were performed in a laboratory where the average temperature was 20 ± 3 °C. The relative humidity was not controlled but remained stable at 40 ± 10%.