Changes in soil properties in the soil profile after mining and reclamation in an opencast coal mine on the Loess Plateau, China

Xiaoyang Liu^a, Zhongke Bai^{a,b,*}, Wei Zhou^{a,b}, Yingui Cao^{a,b}, Gengjie Zhang^{a,c}

^a School of Land Science and Technology, China University of Geosciences (Beijing),
Beijing 100083, PR China

^b Key Laboratory of Land Consolidation and Rehabilitation, Ministry of Land and
Resources, Beijing 100035, PR China

^c Engineering Research Center of Science and Technology of Land and Resources,
Yunnan Agricultural University, Kunming 650201, PR China

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* Corresponding author. Tel.: +86 10 82322182; fax: +86 10 82321807.

E-mail addresses: liuxiaoyangsd@163.com (X.Y. Liu), Baizk@cugb.edu.cn (Z.K. Bai), zhouw@cugb.edu.cn (W. Zhou), caoyingui1982@126.com (Y.G. Cao), Zhanggengjie1983@163.com (G.J. Zhang).

Abstract: Surface mining involves drastic disturbances to regional ecosystem and soil properties. Recovery of soil physicochemical characteristics is essential for successful restoration of the landscape and the soil itself after mining. To identify the changes in the soil profile after mining and reclamation, we studied the soils of the largest opencast coal mine in China, Pingshuo, located in the Loess Plateau. Soil samples representing three different land use types and six different reclamation times were collected in the soil profiles (0–100 cm) in 2012 and were analyzed for field capacity, bulk density, pH, soil organic matter (SOM), N, P, K, available P, and available K. Results showed that most reclaimed mine soil properties (including bulk density, pH, P, K, available P and available K) increased in comparison with those of the natural soils, whereas SOM and N decreased after mining and reclamation, especially in the topsoil (0–40 cm). Trend lines of P and available K in the reclaimed mine soils and natural soils were similar tested by Anova. Trend lines of P in the natural soils, and pH, P and K in the reclaimed mine soils were relatively stable and showed no difference in the soil profile ($P < 0.05$). Soil properties and their trend lines in forest land were more similar to natural soils than were cultivated land and grass land in deeper (60–100 cm) soil layers. Reclamation time (time that has passed after reclamation was finished) was positively associated with SOM, N, P, and available P in cultivated land; pH decreased with the increase of reclamation time in forest land but N showed the opposite trend; pH and P were positively correlated with reclamation time but K and available K showed negative relationships with reclamation time in grassland. Bulk density vs. field capacity and

available K vs. pH showed significant correlations in the soil profile (0–100 cm) ($P < 0.05$). Significant correlations were also observed for available K vs. bulk density in the topsoil layer (0–30 cm) and bottom layer (below 60 cm) ($P < 0.05$). P and pH showed positively significant correlation in the subsoil layer (30–60 cm) and bottom layer (below 60 cm) ($P < 0.05$). Most of heavy metals (As, Cd, Cr, Cu, Pb and Hg) of cultivated land exceeded their corresponding background values in Shanxi province, where our sites were located. However, compared with Chinese soil guidelines (Grade II values) (GB15618-1995), heavy metals were all below the threshold values.

1. Introduction

In 2015, China produced 3750 million tons of coal, more than any other country in the world. Coal mining has made great contributions to Chinese economic developments. However, it inevitably brings serious environmental and land problems (Bai et al., 2006; Topp et al., 2010). For example, it eliminates plants, removes soil and overburden by excavation, reshapes landforms, and disrupts surface and subsurface hydrologic regimes (Herath et al., 2009; Shrestha and Lal, 2011), making coal mining one of the most notable forms of human-caused ecosystem degradation. Reclamation is an effective way to improve soil quality in mining areas (Tripathi et al., 2016). Successful reclamation can be evaluated in many ways, but soil quality is among the most important parts of restoring functional ecosystems after mining. Soil is the basis of vegetation restoration in post-mining lands, and determines the direction of land use after reclamation. Therefore, knowledge about soil dynamics during reclamation and

recovery is particularly significant to guide future ecological restoration (Dutta and Agrawal, 2003; Courtney et al., 2009).

Physicochemical characteristics are the main indicators of mine soil quality (Yao et al., 2013; Mukhopadhyay et al., 2014; Mastro et al., 2015; Mukhopadhyay et al., 2016). The influences of reclamation activities on mine soils have also been widely reported (Nyamadzawo et al., 2008; Juwarkar et al., 2010; Krümmelbein and Raab, 2012). However, few if any studies have monitored changes of reclaimed mine soil properties throughout the soil profile, particularly among different land use types and time since reclamation.

In this study, we focused on nine physicochemical properties of reclaimed mine soils in the soil profile (0–100 cm depth) at the Pingshuo opencast coal mine, located on the Loess Plateau of China. The main objectives of our study were to: (1) compare the differences in soil properties between reclaimed mine soils, natural soils, and unreclaimed mine soils in the soil profile (0–100 cm); (2) analyze the influences of time since land reclamation (reclamation time) and land use types on soil properties; and (3) identify the relationships between soil properties in various soil layers of the profile (0–100 cm).

2. Materials and methods

2.1 Study area

The research was conducted in the opencast coal mine of Loess Plateau–Pingshuo, which is located in Shuozhou, northern Shanxi province of China (Fig. 1). Owing to

lying in the border regions of Shanxi, Shaanxi and Inner Mongolia provinces in the eastern Loess Plateau, this district is also called the “black triangle”. This region has the typical temperate arid to semi-arid continental monsoon climate, with the average annual temperature of 4.8–7.8°C and average annual precipitation of 428.2–449.0 mm. The geomorphic type of the mining area is loess low hill area and the zonal vegetation is steppe. The zonal soil is chestnut soil and loessial soil, characterized by low content of organic matter. Ecosystem resistance ability here is poor and belongs to the typical fragile eco-environmental zone in the Loess Plateau. The Pingshuo mining area includes three large opencast mines (Anjialing, Antaibao, and Donglutian) and three underground coal mines (No.1, No.2, and No.3). The total area is approximately 160 km². The reclamation types mainly include cultivated land, forest land and grassland (Table 1). The cultivated land in the reclaimed area had been used for agricultural production before coal mining commenced in 1986; during mining operations the cultivated land was destroyed, then gradually reclaimed as cultivated land starting in 1990.

2.2 Soil sampling and analysis

We chose eight mine soil sample sites from the dumps of Antaibao in a chronosequence of 2 years, 12 years, 14 years, 15 years, 18 years, and 22 years post-reclamation. Eight sample sites from natural sites and one sample site from unreclaimed dumps in or near the mining area were also chosen as references for comparative study (Table 1). To reduce the effects of inherent variations in soil properties, criteria of similar topography and geologic strata were applied to choose the

sample sites. Considering the limited soil depth, 10 samples from ten depths per site (0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, 50–60 cm, 60–70 cm, 70–80 cm, 80–90 cm, and 90–100 cm) were collected both in the reclaimed mine soil and natural soil; 4 samples from four depths per site (0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm) were collected in unreclaimed mine soil using a shovel during July 2012 (Fig. 2). Since the unreclaimed mine soils were all loess parent material and were just dumped a few months ago, the spatial distributions of soil properties were relatively uniform. One soil profile in the typical region can represent the whole condition of unclaimed mine soil properties to a great extent.

Before physicochemical analyses, all samples were air-dried, crushed, and sieved through a 2-mm polyethylene sieve. All samples were analyzed for field capacity, bulk density, pH, soil organic matter (SOM), N, P, K, available P, and available K. Field capacity was analyzed using the Wilcox method (Salter and Williams, 1965). Bulk density was analyzed with the cutting ring method (Zeng et al., 2014). pH was measured using a pH meter at a ratio of soil/water of 1:2.5 (Mc Lean, 1982). SOM concentration was analyzed by potassium dichromate oxidation titration (Liu et al., 1996). N concentration was measured by the semi-micro Kjeldahl method (Fawcett, 1954). P concentration was measured by the NaOH melting molybdenum antimony colorimetric method (Zhen et al., 2015). K concentration was measured by the filtered solution via flame emission spectrometry (Schneider and Mollier, 2016). Available P was measured using the Olsen method (Olsen and Sommers, 1982). Available K was measured using

flame photometric (Motsara and Roy, 2008).

Table 1

Basic description of the sample sites.

	No.	Location	Land use types	Reclamation time (year)	Vegetation
Natural soils	O1	North expansion of ATB West Dump	Cultivated land	--	<i>Fagopyrum esculentum</i>
	O2	Shidong village of Shuozhou city		--	
	O3	Dayinzhuang village of Shuozhou city		--	<i>Maize</i>
	O4	Shiyu village of Shuozhou city		--	
	O5	Quanwuying village of Shuozhou city	Forest land	--	<i>Populus simonii</i>
	O6	Northeast expansion of ATB West Dump		--	
	O7	Sishengdian village of Shuozhou city	Grassland	--	<i>Alfalfa</i>
	O8	Shizhuang village of Shuozhou city		--	
Reclaimed mine soils	R1	West Dump of ATB	Cultivated land	18	<i>Ricinus communis</i>
	R2	Expansion of ATB West Dump		15	<i>Solanum tuberosum</i>
	R3			2	
	R4	South Dump of ATB	Forest land	22	<i>Populus simonii</i>
	R5	18			
	R6	West Dump of ATB	Grassland	12	<i>Alfalfa</i>
	R7	Expansion of ATB West Dump		18	
	R8	South Dump of ATB		14	
Unreclaimed mine soil	U1	Inner Dump of ATB	Wasteland	--	--

2.3 Statistical analysis

Means and standard errors were calculated for the soil characteristics for both reclaimed mine soils and natural soils. Trend lines generated by multiple linear regressions were used to simulate the general trend of soil properties changing in the profile. The general shapes of trend lines were compared by overlaying pictures. One-way ANOVA was also used to test the differences of trend lines and the means of soil characteristics. Therefore, to identify the relationships between soil properties in various soil layers of the profile (0–100 cm), we divided reclaimed mine soils into three layers: surface (0–30 cm), middle (30–60 cm), and bottom (60–100 cm). A Pearson's

correlation matrix among soil characteristics for the reclaimed mine soils in three soil layers was constructed. All statistical analyses were performed using SPSS 19.0 (SPSS Inc. Chicago, USA).

3. Results

3.1 Physicochemical properties of the natural soils in the soil profile.

The physicochemical characteristics of the natural soils and their changes with the increase of soil depth within the profile (0–100 cm), based on trend lines and analysis of variance, are given in Fig. 3.

Trend lines of field capacity and P in the natural soil profiles were similar, decreasing first and then increasing with soil depth. However, the differences in these physicochemical characteristics between different soil layers in the full profile depth of 0–100 cm were not significant ($P < 0.05$). Bulk density increased from 1.28 g cm^{-3} in 0–10 cm to 1.41 g cm^{-3} in 10–20 cm ($P < 0.05$) and kept relatively stable in the deeper depth (20–100 cm). pH was alkaline throughout and its value in 10–40 cm was significantly higher than that in 80–40 cm. Concentrations of SOM and N both decreased with the increase of soil depth (0–100 cm) and showed similar change patterns. The rates of decreases of SOM and N were pronounced in the topsoil (0–30 cm), as shown by the ANOVA and in Fig. 3. The trend line of available P was consistent with that of available K, both forming an "S" shape in the graph of the profile. Concentrations of available P and available K at the depth of 0–10 cm were 4.95 mg kg^{-1} and $104.34 \text{ mg kg}^{-1}$, respectively, both significantly higher than their values at the

other soil depths ($P < 0.05$). The change trend of K varied from those of the other soil characteristics. The range of K was 15.05–18.58 g kg⁻¹. K concentration in the soil layer of 90–100 cm was significantly higher than that in the soil layer of 0–10 cm. In the soil layer of 20–80 cm, its trend line was relatively straight, indicating K concentration was relatively stable in this soil layer.

3.2 Physicochemical properties of the reclaimed mine soils in the profile

After mining and reclamation, physicochemical characteristics of soils varied considerably from those of the natural soils. The concentrations and trend lines of the soil properties in the soil profile are given in Fig. 4.

The ranges of field capacity, bulk density, P, K, available P, and available K in the reclaimed mine soils were larger than those in the natural soils; that is, these characteristics were more variable in the reclaimed mine soils. Field capacity varied between 16.4–18.15% in natural soils and between 15.33–19.14% in reclaimed soils; bulk density increased significantly after reclamation ($P=0.001$) and varied between 1.28–1.41 g cm⁻³ in natural soils and between 1.29–1.55 g cm⁻³ in reclaimed soils. Concentrations of P and K (0.41–0.54 g kg⁻¹ and 15.79–19.67 g kg⁻¹) in reclaimed mine soils were significantly higher than those in natural soil ($P=0.02$, $P=2.15E-5$). Similarly, ranges of available P and available K expanded in reclaimed mine soils compared with natural soils. For available P and available K, the increase was especially pronounced: available P rose from 1.61–4.95 mg kg⁻¹ to 6.98–13.2 mg kg⁻¹ and available K rose from 56.4–104.34 mg kg⁻¹ to 68.71–127.46 mg kg⁻¹. These results indicate that activities of

coal mining and reclamation have a great effect these properties.

Some soil characteristics had stable or narrowed concentration range in the reclaimed soils compared with natural soils. Both pH and N had similar ranges whether in natural or reclaimed mine soils, but pH was more alkaline in reclaimed mine soils (8.18–8.31) compared with that in natural soils (8–8.21) ($P=6.85E-12$) and N concentration decreased from 0.3–0.56 g kg⁻¹ in natural soils to 0.21–0.5 g kg⁻¹ in the reclaimed mine soils ($P=1.66E-4$). SOM concentration of the reclaimed mine soils decreased significantly ($P=0.04$) in the topsoils (0–40 cm), and its range narrowed down by about half in from that of the natural soils, meaning that topsoil SOM concentration had not recovered to the natural level after reclamation.

Trend lines of most soil characteristics within the profile differed from those of the natural soils. The downward trend of SOM and N with the increase of soil depth in natural sites was disturbed after mining and reclamation. Trend lines of field capacity, P, and available P of the reclaimed soils changed in the shape and fluctuated more significantly than the natural soils. Changes of field capacity were not significant in the natural soils, but in reclaimed mine soils, field capacity in the soil layer of 0–10 cm was higher than that in 40–50 cm and 70–100 cm soil depth. P concentration of natural soils and reclaimed mine soils showed no difference in the whole soil profile (0–100 cm). Available P had a difference between 10–30 cm and 90–100 cm soil layers for the reclaimed mine soils and had a difference between 0–10 cm and 10–100 cm soil layers for the natural soils. There was less variation in pH in the reclaimed soils than in the

natural soils. These changes in trend lines for most soil characteristics were further evidence of the great effects exerted by mining and reclamation on soil properties.

3.3 Physicochemical properties of reclaimed mine soils with different reclamation times and different land use types

The properties of reclaimed mine soils with different reclamation times and different land use types were compared with those of the natural soils and unreclaimed mine soils (Fig. 5, Fig. 6, and Fig. 7).

In the cultivated post-reclamation soil (Fig. 5), field capacity and bulk density of 15- and 18-year reclaimed mine soils were close to the levels of the natural soils in the 0–10 cm and 50–80 cm soil layers. Similarly, soil became looser with the increase of soil depth within 0–40 cm, but the change trend in field capacity was just the opposite. Trend lines of pH varied considerably among different chronosequence sites. At 0–20 cm, pH of the natural soils was higher than that of the mine soils, and at deeper layers the 15-year reclaimed mine soils had a higher pH than the natural soils.

Similar to the cultivated land, field capacity in topsoil (0–10 cm) of grassland exceeded the natural level, but in deeper layers, the field capacities of the reclaimed mine soils were below that of the natural soil. pH was positively correlated with reclamation time and the 18-year reclaimed mine soil was more alkaline than the natural soil.

In the post-reclamation forest land, P was similar in the 12- and 18-year reclaimed soils, with both values higher than in the 22-year reclaimed soil. K also showed little

change between 12- and 18-year reclaimed soils, but rose in the 22-year reclaimed soil.

SOM in 0 – 10 cm soil depth and N in the overall soil profile increased with reclamation time, with values in the order: natural soil > 18-year reclaimed mine soil > 14-year reclaimed soil > unreclaimed mine soil. P showed a positive correlation with reclamation time. Mine soils at 14 years (throughout the profile) and 18 years (at 0 – 10 cm) post-reclamation had lower P concentration than the natural soil, but P concentration in 18-year reclaimed mine soil deeper than 10 cm exceeded the natural level. K, available P, and available K of the reclaimed mine soils were all higher than those of the natural soil overall, and K and available K decreased with the increase of reclamation time.

3.4 Physicochemical properties of unreclaimed mine soil profiles

The physicochemical characteristics of the unreclaimed mine soils in the soil profile (0–100 cm) are given in Fig. 8. Values of bulk density, available P, and available K in the unreclaimed soils were significantly higher than the natural soils ($P = 0.023$, 0.003 and 0.001 , respectively) and reclaimed soils ($P = 0.021$, 0.047 , and 0.012). Bulk density concentration range rose from $1.28\text{--}1.41\text{ g cm}^{-3}$ and $1.29\text{--}1.53\text{ g cm}^{-3}$ in the natural soils and reclaimed mine soils, respectively, to $1.69\text{--}1.83\text{ g cm}^{-3}$ in the unreclaimed mine soils ($P=8.71\text{E-}5$), meaning that reclamation can effectively loosen mine soils. The increase trend was more significant for available P and available K, with available P changing from $1.61\text{--}4.95\text{ mg kg}^{-1}$ and $6.89\text{--}9.3\text{ mg kg}^{-1}$ in the natural soils and reclaimed mine soils, respectively, to $10.81\text{--}13.56\text{ mg kg}^{-1}$ in unreclaimed mine

soils, and available K from 57.91–104.34 mg kg⁻¹ and 68.71–127.46 mg kg⁻¹ to 155.74–178.58 mg kg⁻¹.

On the contrary, SOM concentration and N concentration of unreclaimed mine soils were lower than in natural soils and reclaimed mine soils at the soil depth of 0–40 cm, indicating that SOM and N easily escaped unreclaimed mine soils, owing to the absence of vegetation coverage. The variation range at 0–40 cm was extended for field capacity and K in comparison with natural soils and reclaimed mine soils. Meanwhile, the 0–10 cm soil layer showed the maximum values for these properties, reaching 20.45% and 25.36 g kg⁻¹ for field capacity and K, respectively. Unreclaimed mine soils had consistently alkaline pH. Its variation range was 8.21–8.28, between that of the natural soils and the reclaimed mine soils.

3.5 Relationship among soil properties in different soil layer

Relationship among soil properties is shown in Table 2. In 0–30 cm layer, there were five significant correlations between pairs of soil properties. Bulk density was negatively correlated with both field capacity and available K. pH and available K were negatively correlated with one another. SOM had significant correlations with N ($R^2 = 0.629$) and available K ($R^2 = 0.383$). In the middle soil layer of 30 – 60 cm, more significant correlations were found among the soil properties. Bulk density showed significant correlations with field capacity, N, and K. Significant correlations were also observed for pH vs. P, pH vs. K, pH vs. available K, P vs. K, and K vs. available K. As with soils within 0–10 cm, bulk density also showed negative correlations with bulk

density and available K in the 60–100 cm soil depth. pH was significantly correlated with N and available K. P showed a negative correlation with available K.

Table 2

Relationship among soil properties for the reclaimed mine soils in three different soil layers: 0-30 cm, 30-60 cm and 60-100 cm.

Soil depth	Soil properties	FC	BD	pH	SOM	N	P	K	AP	AK
0-30 cm	FC	1								
	BD	-0.633**	1							
	pH	-0.102	0.374	1						
	SOM	0.082	-0.073	0.048	1					
	N	-0.040	-0.025	0.328	0.629**	1				
	P	0.031	0.32	-0.217	-0.066	0.004	1			
	K	-0.119	-0.316	-0.350	-0.091	-0.363	-0.039	1		
	AP	0.029	-0.019	-0.084	-0.027	0.100	0.197	0.196	1	
	AK	0.192	-0.519**	-0.459*	0.383**	0.163	-0.314	0.004	-0.126	1
30-60 cm	FC	1								
	BD	-0.433*	1							
	pH	-0.182	0.198	1						
	SOM	-0.027	0.099	0.046	1					
	N	-0.284	0.564**	0.374	-0.009	1				
	P	0.041	0.442*	0.439*	-0.067	0.287	1			
	K	0.136	-0.593**	-0.658**	-0.03	-0.341	-0.741**	1		
	AP	0.088	-0.041	0.064	-0.154	0	0.146	-0.119	1	
	AK	-0.338	0.068	-0.464*	-0.058	0.37	-0.298	0.496*	-0.215	1
60-100 cm	FC	1								
	BD	-0.534**	1							
	pH	-0.079	0.280	1						
	SOM	0.031	0.194	0.257	1					
	N	0.230	-0.083	0.299	0.266	1				
	P	0.205	0.317	0.483*	0.214	0.249	1			
	K	-0.146	-0.315	-0.129	-0.094	0.112	-0.128	1		
	AP	-0.172	0.116	0.110	0.079	-0.021	0.036	0.224	1	
	AK	-0.020	-0.506**	-0.420*	-0.327	-0.089	-0.703**	0.329	-0.013	1

** Correlation is significant at 0.01 level; * Correlation is significant at 0.05 level. FC means field capacity; BD means bulk density; AP means available P; AK means available K.

3.6 Heavy metal concentrations of reclaimed mine soils and natural soils for cultivated land

Heavy metal concentrations of reclaimed mine soils and natural soils for cultivated land are shown in Table 3. Most of the heavy metals exceed their corresponding background values in Shanxi province, where our sites were located. However, compared with Chinese soil guidelines (Grade II values) proposed by the State Environmental Protection Administration of China (GB15618-1995), which can be used as the threshold values for protecting human health and ensuring agricultural production, the levels all six heavy metals were below the threshold values.

Table 3

Heavy metal concentrations in reclaimed mine soils and natural soils of cultivated land. Soil samples (0-30 cm) were collected in the study area during August 2013.

	Number of sample	Concentrations of heavy metal elements/(mg·kg ⁻¹)					
		As	Cd	Cr	Cu	Pb	Hg
Reclaimed mine soils	5	9.19-12.04	0.12-0.14	64.10-76.00	21.52-24.72	20.27-22.06	0.02-0.03
Natural soils	19	8.62-13.07	0.10-0.16	58.70-88.70	16.27-25.07	17.79-25.09	0.02-0.51
Shanxi Background		7.80	0.112	53.00	22.50	13.80	0.017
Grade II values		20	0.20	90	35	35	0.15

4. Discussion

4.1 Reclamation effect on soil properties

In order to analyze reclamation effect on soil properties, we made comparisons with other literatures. The comparisons are shown in Table 4.

Table 4

Concentrations of the soil properties acquired in this study and comparisons with other selected sites.

Location	Soil properties	Concentration in this study	Concentration in the reference	Reference
Yang coal mine, China	Field capacity	18.86-30.82 % in reclaimed mine soils	15.33-19.14 % in reclaimed mine soils	Wang et al., 2011

Malanzhuang mine, China		18.86-30.82 % in reclaimed mine soils	10.50-16.34 % in reclaimed mine soils	Li et al., 2014
Kusunda opencast projects, India	Bulk density	1.29-1.55 g cm ⁻³ in reclaimed mine soils	1.47-1.67 g cm ⁻³ in reclaimed mine soils	Mukhopadhyay and Maiti, 2011
Manganese spoil dump, India	pH	8.18-8.31 in reclaimed mine soils and 8-8.21 in natural soils	7.5 in reclaimed mine soils and 6.9 in natural soils	Juwarkar et al., 2010
Global databases of soil profiles	SOM	SOM decreased from 10.69 g kg ⁻¹ to 2.61 g kg ⁻¹ in the profile (0-100 cm)	soil organic carbon decreased from 41(%) to 9 (%) in the profile (0-100 cm)	Jobbagy and Jackson, 2000
Naya Dara colliery coal mine, India	N	0.3-0.56 g kg ⁻¹ in natural soils, 0.22-0.5 g kg ⁻¹ in reclaimed mine soil and 0.19-0.2 g kg ⁻¹ in unreclaimed mine soils	954-1870 kg ha ⁻¹ in reclaimed mine soils and 810 kg ha ⁻¹ in unreclaimed mine soils	Singh et al., 2012
Eight counties of eastern Ohio, USA			1.1-2.96 g kg ⁻¹ in natural soils 0.54-1.1 g kg ⁻¹ in reclaimed mine soil	Shrestha and Lal, 2011
Naya Dara colliery coal mine, India	P	0.42-0.54 g kg ⁻¹ in reclaimed mine soils and 0.36-0.41 g kg ⁻¹ in natural soils	414-862 kg ha ⁻¹ in reclaimed mine soils and 604 kg ha ⁻¹ in natural soils	Singh et al., 2012
Vishwakarma opencast projects, India	Available P	6.98-13.2 mg kg ⁻¹ in reclaimed mine soils	4.8-10.8 mg kg ⁻¹ in reclaimed mine soils	Mukhopadhyay et al., 2013

Field capacity is an important parameter in soil water research, especially in the drought-prone Loess Plateau since soil water is the restrict factor for vegetation to grow normally there. The increase in field capacity after mining and reclamation was smaller in our study than has been previously reported (Wang et al., 2011). However, Li et al. (2014) found that field capacity varied between 10.50% and 16.34% in the soil depth of 0–60 cm after reclamation under three different vegetation types, higher than that found in the reclaimed mine soils of our study. The different results may be due to differences in the vegetation species planted or recruited after mining. Because of the frequent movement of heavy machinery excavating and replacing topsoil material in the

reclamation process, the reclaimed mine soils were highly compacted, leading to high bulk density (Shrestha and Lal, 2011). This is in agreement with the previous reports that bulk density of unreclaimed mine soils ($1.71\text{--}2.04\text{ g cm}^{-3}$) was significantly higher than reclaimed mine soils ($1.47\text{--}1.67\text{ g cm}^{-3}$) (Mukhopadhyay and Maiti, 2011) and increased with soil depth (Ahirwal and Maiti, 2016). pH plays an important role in ecological restoration owing to its function in moderating availability of plant nutrients. Severe soil disturbance inevitably causes changes in soil pH, usually resulting in increased pH (Ganjegunte et al., 2009). The type of bedrock and carbonate-rich overburden materials promote the increase in soil pH. Our finding that the pH of reclaimed mine soils was higher than that of natural soils was also reported by Juwarkar et al. (2010). Recovery of SOM in soils after reclamation is a slow process and usually takes decades to recover close to the natural level. According to Cui et al. (2012), soil organic carbon (SOC) concentration declines initially after reclamation and takes about 40 years to recover. At our site, SOM concentration in topsoil was significantly higher than in deeper layers in both the natural soils and the reclaimed mine soils, which may be attributed to the conversion from leaf litter fall to humus in the topsoil. A similar finding was also reported by Jobbagy and Jackson (2000). In general, inputs of N are minimal in natural ecosystems because N retention and efficient cycling are essential for the maintenance of ecosystem productivity (Mummey et al., 2002). Reclamation activities help to increase the proportion of soil aggregates and could reduce loss of soil nutrients (N and P) from tillage practices and irrigation (Bronick and Lal, 2005), and

this may be one reason why P and K increased throughout the soil profile after reclamation. The influence of mining activity on N concentration was also studied by Singh et al. (2012) and Shrestha and Lal (2011), who found similar results. Concentrations of available P and available K in the reclaimed mine soils were significantly higher than those in natural soils but lower than those in the unreclaimed mine soils. The lower concentrations of available P and available K in natural soils might be attributable to the increased uptake and assimilation by plant roots in the ecosystem reconstruction progress. Available P concentration in the reclaimed mine soils of our sites was higher than available P concentration of coal mine soils after reclamation founded by Mukhopadhyay et al. (2013).

4.2 Influence of reclamation age and land use type on soil characteristics

Restoration of soil properties depends on post-reclamation land use type. Reclamation age also exerts a significant influence on soil properties due to the vegetation functional and structural changes in the process of ecological restoration (Hodkinson et al., 2003; Kumar et al., 2015). In general, SOM and N were low in mine soils, which is unfavorable for vegetation establishment and sustainable productivity (Li, 2006; Zhao et al., 2013). Both could be replenished from roots, harvest residues, and organic fertilizers (Khan et al., 2016). In our study, SOM and N were connected and positively associated with reclamation time overall, except N of the 15-year reclaimed mine soils in 20 – 80 cm, in the order: natural soils > 18-year reclaimed soils > 15-year reclaimed soils > 2-year reclaimed soils > unreclaimed mine soils. A decrease of N in

mining-affected lands was also found by Ahirwal and Maiti (2016). Both P and available P improved significantly with reclamation and showed positive relationships with reclamation time. However, K and available K of 18-year reclaimed mine soils were lowest among the chronosequence, and were below that of the natural soils at 20–100 cm for K and the whole profile for available K. It was notable that available K of the unreclaimed mine soil was much higher than that of the natural soils and reclaimed mining soils. This may be caused by the more uptake of available K by plants and crops on the natural sites and reclaimed area.

In the post-reclamation forest land, field capacity of the three chronosequence sites exceeded the natural levels in most soil layers within 0–100 cm. This may be due to the increases in clay content, litter accumulation, and canopy cover (Maiti, 2013) and was in agreement with the earlier study (Venkatesh et al., 2011). Field capacity of the 22-year reclaimed mine soil decreased to 9.78% at 70 – 80 cm and remained below the natural level at deeper layers. Compared with reclaimed mine soils of cultivated land in the profile and natural soils in the 0 – 20 cm depth, bulk density was lower in the forest land. This may be attributed to root system development, addition of biomass, and the reduction of anthropogenic disturbance after reclamation (Thomas et al., 2000). The 22-year reclaimed and 18-year reclaimed mine soils were looser than the 12-year reclaimed mine soil at 0 – 30 cm depth, but at greater depths soils became compacted and bulk density exceeded that of the 12-year reclaimed mine soil. Overall, reclamation activity improved mine soil physical quality as reported in earlier studies (Asensio et al.,

2013; Srivastava et al., 2014). An increase in reclamation time also saw a decreased pH overall. This decrease in pH was probably due to the change in SOC and clay percentage after reclamation, which could extract base cations from and release protons into the soil (Van Breemen et al., 1984). The 22-year reclaimed mine soil had pH levels near and around the natural levels. The trend lines of SOM and N of this soil were similar to those of the natural soils, but unlike the earlier study (Banning et al., 2008), the post-reclamation accumulations of SOM and N were slow and their levels were lower than in the natural soils. Reclamation time was negatively correlated with N concentration. This might mainly attributed to the change of vegetation types along reclamation time. In the early years after reclamation, trees are sparse but shrub and annual grass grow well, and litter with rich organic nitrogen source returned to the soil and decomposed. But over reclamation time, trees dominate. Annual litter decreases whereas uptake of N by vegetation from soil increases, which leads to the decrease of N concentration in soil. It was notable that P, K, available P, and available K increased after mining and reclamation. This is evidence of the important roles played by litter accumulation and root development on mine soil quality changes after reclamation.

All post-reclamation mine soils were looser than natural soil at 0–40 cm depths and all depths of unreclaimed mine soil, a finding consistent with that reported by Wu et al. (2016), who suggested that the types of artificial grassland used in reclamation, and their resultant root biomasses, have significant influences on the physical properties of mine soils. Compared with soils of cultivated land and forest land, SOM and N of the

natural soil in the grass land were higher at 20 – 80 cm soil depth, which was probably owing to the important role of annual grasses in conservation and improvement of soil quality (Wang and Gong, 1998).

4.3 Relationship of soil properties for the reclaimed mine soils among various soil layers

Agricultural soil is usually divided into three layers: topsoil (0–30 cm), subsoil (30–60 cm), and bottom (below 60 cm) (Lin et al., 2002). Topsoil is affected mainly by human activities and has abundant roots from crops, grass, and trees; subsoil is less affected by the external environment; and the bottom layer is mainly affected by the deeper wastes, such as those associated with mining.

Many other studies have also found significant relationships among various characteristics of reclaimed mine soils (Shrestha and Lal, 2011; Zhen et al., 2015; Datta et al., 2015). The lower number of significant relationships found in the surface and bottom soil layers compared with the middle soil layer was probably caused by disturbances from both contact surfaces, above and below. Reclaimed mine soils are unique in their characteristics, simultaneously disturbed by human activities in the surface layer and influenced by wastes associated with mining in the bottom layer.

4.4 Heavy metal pollution of cultivated land

Pollution of soil by heavy metals is among the main environmental problems that endangers human health and ecosystems (Clemente et al., 2007), and it has attracted much attention from mine eco-environmental researchers in recent years (Gomez-Ros et al., 2013; Cai et al., 2015). Mining activities are often associated with heavy metal

pollution in cultivated land because the mining wastes are highly enriched in heavy metals. Phytotoxicity resulting from toxic metal contamination in cultivated land and crops affects the food chain and threatens human health. Therefore, it is essential to address heavy metal pollution for soils of cultivated land. Concentrations of heavy metals found at our sites were compared with those of other relevant studies. It was found that As concentration was higher than the finding in coal mine-affected agricultural soils in the northern part of Bangladesh (Bhuiyan et al., 2010), with the range of 5.66–8.25 mg/kg. Pb and Hg concentrations were much lower than those in soils from the Oltu coal mine district in Turkey (Tozsın, 2014).

5. Conclusions

Mining and land reclamation significantly altered the physicochemical characteristics in the soil profile. Our findings suggest most reclaimed mine soil properties (bulk density, pH, P, K, available P, and available K) increased after reclamation. However, SOM and N are not easy to recover in years, especially in the topsoil. Land use type also had significant influences on reclaimed mine soil. We found that soil properties and their trend lines in forest land were more similar to those of natural soils than to those of cultivated and grasslands in deeper soil layers (60–100 cm).

Our findings suggest that effects of reclamation time on soil properties differed in different land use types. Reclamation time showed positive associations with SOM, N, P and available P in cultivated land; pH decreased with an increase in reclamation time,

but N showed the opposite trend in forest land. In grassland, pH and P were positively correlated with reclamation time, but K and available K showed a negative relationship with reclamation time.

The significant correlated pairs of soil properties in the whole soil profile (0–100 cm) were field capacity vs. bulk density and available K vs. pH. Available K vs. bulk density both showed a significant correlation in the surface soil layer (0–30 cm) and the middle soil layers (30–60 cm). P vs. pH was significantly correlated in the middle soil layers (30–60 cm) and bottom soil layer (60–100 cm).

Most of the heavy metals exceeded their corresponding background values in Shanxi province. However, they were all below the threshold values (Grade II values) (GB15618-1995) for protecting human health and ensuring agricultural production.

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Figure Captions:

Fig. 1. Location of the study area and distribution of the soil samples.

Fig. 2. Soil profiles excavated in the field.

Fig. 3. Physicochemical properties of the natural soils in the soil profile. Letters show significant differences ($P < 0.05$) among different soil layers.

Fig. 4. Physicochemical properties of the reclaimed mine soils in the profile. Means were produced using the data of all the soil samples collected from the reclaimed areas. Letters show significant differences ($P < 0.05$) among different soil layers and whiskers indicate Standard Deviation.

Fig. 5. Mine soil characteristics in cultivated land.

Fig. 6. Mine soil characteristics in forest land.

Fig. 7. Mine soil characteristics in grass land.

Fig. 8. Physicochemical properties of the unreclaimed mine soils in the profile.