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REGULAR ARTICLE

Land use impacts on physical properties of 28 years old reclaimed mine soils in Ohio

Raj K. Shrestha · Rattan Lal

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Abstract Reclamation enhances soil quality by improving physical and chemical properties, which helps in restoration of mine soils. Evaluation of the effects of post-reclamation land uses on physical and chemical properties of mine soils helps to identify suitable land uses for mining companies. The objectives of this study were to evaluate the effects of post-reclamation land uses (e.g., forest, hay and pasture) on selected physical properties of soil in relation to undisturbed forest and agricultural land use. Soil samples were collected from the 0- to 5-, 5- to 15- and 15- to 30-cm depths in order to determine particle size distribution, bulk density, water-stable aggregates, mean-weight diameter and soil moisture retention. Cone index and infiltration rate were determined at soil surface. After 28 years of reclamation, bulk density in the surface layer of all land uses in the reclaimed mine soil (RMS) was similar to that of undisturbed forest (1.1 Mg m^{-3}) but lower than that of agricultural soils (1.3 Mg m^{-3}). However, soil bulk density at lower depths was not affected. The cone index was higher in the RMS-pasture (2.6 MPa) than the RMS-forest (1.4 MPa) and RMS-hay (1.5 MPa) due to the trampling effect of grazing animals. The water-stable aggregates (>2 mm), of 5–8 mm aggregates, were higher in RMS-forest by 24%, 90%, 66%, and under RMS-hay by 13%, 74%, 43% for the 0- to 5-, 5- to 15-, and 15- to 30-cm depths, respectively, than that under undisturbed forest. The mean-weight diameter (0- to 30-cm) of aggregates under RMS-forest and RMS-hay were higher than that under undisturbed forest by 41% and 27%, respectively. The initial infiltration rates at 5 min in RMS under forest, hay and pasture were less by 20%, 53% and 85%, respectively, than that under undisturbed forest (19.3 cm min^{-1}). The reclamation of mine soils with forest and hay improved surface soil bulk density and cone index, and enhanced water infiltration capacity and water-stable aggregates at the lower depths. Therefore, establishment of forest and hay should be encouraged in the RMS.

Keywords Reclaimed mine soil · Land use · Physical properties · Forest · Hay · Pasture

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R. K. Shrestha (✉) · R. Lal
School of Environment and Natural Resources,
The Ohio State University,
2021 Coffey Road,
Columbus, OH 43210, USA
e-mail: shrestha.10@osu.edu

Introduction

Land use, soil management, and vegetative cover play important roles in restoring quality of reclaimed mine soils (RMS) (Palumbo et al. 2004). The RMS are pedogenically young soils, developing on anthropogenically-altered landscapes (Sencindiver and Ammons 2000). These soils have higher bulk density (1.55 to 1.86 Mg m^{-3}), higher rock content (33–45%), poorer structure, lower porosity (26–

38%), lower water holding capacity, lower infiltration rates and slower hydraulic conductivity than undisturbed soils (Indorante et al. 1981; Thurman and Sencindiver 1986; Dunker and Barnhisel 2000; Shukla et al. 2004a). The higher bulk density of RMS is due to compaction by heavy equipments used during reclamation process. A low water-holding capacity is due to high rock/gravel fragments and low soil organic carbon (SOC) concentration in mine soils (Pedersen et al. 1980). These soils need be reclaimed with various land-use practices so that their properties would be similar to those of normal soils for revegetation.

Mining areas are located in southeastern Ohio. Ohio is the seventh largest state in coal mining, and coal generates nearly 90% of the electricity in the state (NMA 2004; OSM 2003). The federal Surface Mining Control and Reclamation Act (SMCRA) of 1977 followed the 1972 Ohio Surface Mine Law, which required grading of mine soil back to the approximate original contour, replacement of topsoil, and establishment of grass and/or legume cover before releasing reclamation bond (Barnhisel and Gray 2000). Reclamation is an integral part of coal mining. According to the reclamation law, mining companies are required to meet certain standards for plant growth and crop production to ensure successful restoration of RMS.

The effects of different post-reclamation land uses and degree of soil disturbances on soil properties are not adequately understood (Brye et al. 2002). In contrast to the vast literature on agricultural soils, few studies have assessed physical properties of RMS (Pedersen et al. 1980; Skousen et al. 1998; Shukla et al. 2004b) that compared the long-term effects of reclamation on physical soil quality of different post-reclamation land uses. Studies are needed to determine the appropriate land-use practices that can reclaim denuded land and improve physical properties as quickly as possible. Shrestha and Lal (2007) studied the effects of long-term reclamation practices on chemical properties of different land uses. This study provides a unique opportunity to evaluate the effect of long-term post-reclamation land uses on soil physical and hydrological properties of RMS compared with undisturbed forest and agricultural land as reference sites. These comparisons provide three contrasting scenarios: undisturbed (forest soil), moderately disturbed (agricultural soil) and severely disturbed RMS. The objective of the study was to evaluate the impacts of predominant post-reclamation land uses (e.g., forest, hay and pasture) on selected physical properties such as compaction (bulk density and cone index), pore-space, aggregate stability, and hydrological properties (water infiltration and soil water retention) of RMS in eastern Ohio.

Materials and methods

Study site description

The study sites are located in Morgan County, Ohio (39°59′21″ N and 81°79′44″ W). The elevation of the study sites ranges from 244 to 262 masl. The mean temperature is 22°C during the summer and −1°C during the winter. The 50-year average annual precipitation is 1,039 mm out of which 430 mm falls during the plant growing season between May and September.

The predominant post-reclamation land uses of Ohio (forest, pasture, and hay) were selected for this study. All of these three sites were approximately more than 10 ha, surface-mined for coal, and reclaimed in 1977 with 30-cm of topsoil (stripped during the coal mining operation), which provided an excellent opportunity to compare different post-reclamation land uses. These RMS sites have been studied to determine greenhouse gas emissions and carbon pool (Jacinthe and Lal 2006a, b; Ussiri et al. 2006a, b). This study is neither a replicated field plot experiment nor an established design. Therefore, due to lack of true replication, three sites with similar slope, elevation and soil type were selected for each land use as pseudo replications, giving a total of 15 sites. Three soil samples were randomly collected from each replication and composited by depth. The undisturbed forest sites selected adjacent to RMS were unmined and uncultivated. The agricultural sites, unmined but cultivated to hay and to corn (*Zea mays* L.), were also selected adjacent to RMS. Two years prior to this study, sludge was applied at the rate of 12–14 Mg ha^{-1} to enhance restoration of RMS. Similar type of mix grass species were grown in RMS-hay, RMS-pasture and agricultural land use (Table 1). The RMS-hay sites were never grazed, and were mowed once in June. The RMS-pasture sites were used for cattle grazing, with a stocking rate of 1.2 cattle ha^{-1}.

The soils in the study sites were mostly silty clay loam (USDA-NRCS 1998) (Table 2). The soil pH was

Table 1 Site history for different land uses in Morgan County, Ohio

Treatment	Vegetation	Site history
RMS-forest	White ash (*Fraxinus Americana* L.), tulip poplar (*Lirodendron tulipifera* L.), sycamore (*Platanus occidentalis* L.), autumn olive (*Eleaganus umbellate* L.), white pine (*Pinus strobes* L.)	Mined and reclaimed with grasses in mid 1970s. Originally forest plantation was established in 1977 and replanted in 1978
RMS-hay	Mostly Kentucky fescue (*Festuca megalura* L.) but mixed with birdsfoot trefoil (*Lotus corniculatus* L.), broom grass (*Bromus inermus* L.), clover (*Trifolium pretense* L.)	Mined and reclaimed with grasses in mid 1970s. Mowed for hay one to two times a year
RMS-pasture	Mostly clover (*Trifolium pratense* L.) but mixed with Kentucky fescue (*Festuca megalura* L.), birds foot tree foil (*Lotus corniculatus* L.), broom grass (*Bromus inermus* L.)	Mined and reclaimed with grasses in mid 1970s. Leased for cattle production to use as pasture since being reclaimed
Undisturbed forest	White pine (*Pinus strobes* L.), green ash (*Fraxinus pennsylvanica* L.), white ash (*Fraxinus americana* L.), Tulip poplar (*Lirodendron tulipifera* L.)	Undisturbed natural forest established in 1977 This was left undisturbed because of nearby cemetery
Agriculture	Clover (*Trifolium pratense* L.), Kentucky fescue (*Festuca megalura* L.), birdsfoot trefoil (*Lotus corniculatus* L.), broom grass (*Bromus inermus* L.), corn (*Zea mays* L.)	Two years rotation of corn and grasses. Corn was planted in 2004 and grasses were grown in 2005 for hay

neutral to alkaline (6.8 to 7.8) in RMS under forest and hay, and acidic (5.5 to 6.0) under RMS-pasture throughout the 0- to 30-cm depth (Shrestha and Lal 2007). However, pH for spoil material (30- to 50-cm depth) was alkaline (Ussiri et al. 2006a). In the 0- to 30-cm depth of RMS under forest, hay and pasture, C stocks were 36, 63, 61 Mg ha^{-1}, respectively. However, C stock in reference sites under undisturbed forest and agriculture were 38 and 43 Mg ha^{-1}, respectively (Shrestha and Lal 2007). The carbon stock in spoil material (30- to 50-cm depth) was 20 Mg ha^{-1} (Ussiri et al. 2006a).

Soil sampling and analysis

Soil samples were collected at the 0- to 30-cm depth, which was the average depth of topsoil application during reclamation in Ohio. Nine sampling locations were selected randomly for each treatment (three sites in each treatment × three locations in each site). Soil samples were collected for the 0- to 5-, 5- to 15-, and 15- to 30-cm depths, composited by depth, and transported to the laboratory. Soil samples were sealed in the plastic bags and transported to the laboratory in a cool box to avoid loss of soil moisture. The bulk soil samples were air-dried under shade, large clods gently crushed, stone removed, and then sieved through 5- and 8-mm sieves. Soil aggregates received between 5- and 8-mm sieves were used for aggregate analysis. The soil was also sieved using a 2-mm sieve for particle-size analysis.

The WSA was determined by the wet-sieving procedure (Nimno and Perkins 2002). Fifty grams of 5- to 8-mm aggregates were placed on the top containing a nest of the sieves of 4.75, 2, 1, 0.5, 0.25 mm sieves (Blanco-Canqui and Lal 2007; Shukla

Table 2 Site characteristics for different land uses in Morgan County, Ohio

Treatment/site	Slope (%)	Elevation in meter (masl)	Soil series	Soil classification
RMS-forest	6–10	256	Morristown silty clay loam	Loamy-skeletal, mixed, mesic Typic Udorthents
RMS-hay	2–6	244	Morristown silty clay loam	Loamy-skeletal, mixed, mesic Typic Udorthents
RMS-pasture	2–6	244	Morristown silty clay loam	Loamy-skeletal, mixed, mesic Typic Udorthents
Undisturbed forest	6–10	262	Elba silty clay loam	Fine, mixed, mesic Typic Hapludalfs
Agriculture	6–8	259	Westgate silt loam	Fine-silty, mixed, mesic Typic Hapludalfs

masl: mean above sea level, *RMS*: reclaimed mine soil et al. 2007). Aggregates were saturated with water due to capillary action for 30 min. The nested sieves were then mechanically oscillated in a water column at an amplitude of 30 cycles min^{-1} by moving the sieves up and down to a height of 5 cm for 30 min. Aggregates retained on each sieve were dried at 60°C for 72 h, weighed to compute the WSA and mean-weight diameter (MWD) (Nimno and Perkins 2002). Soil fraction <0.25 mm class size was obtained by collecting the sediment from container after decanting the water, and determining the oven-dry weight. The WSA between 4.75 to 8.0, 2.0 to 4.75, 1.0 to 2.0, 0.5 to 1.0, 0.25 to 0.5 and <0.25 mm for three depths in each land use were calculated and reported in g kg^{-1} soil. The MWD of the WSA was determined after correcting for the mass of skeletal fractions (>2 mm). The following equation was used to subtract weight of skeletal fractions from MWD (modified from Evrendilek et al. 2004 method for weight of skeletal fractions) (Eq. 1):

$$\begin{aligned}\text{MWD} = {} & [(M_{4.75\text{ to }8} - S)(4.75 + 8)/2] \\ & + [(M_{2\text{ to }4.75} - S)(2 + 4.75)/2] \\ & + [(M_{1\text{ to }2})(1 + 2)/2] + [(M_{0.5\text{ to }1})(0.5 + 1)/2] \\ & + [(M_{0.25\text{ to }0.5})(0.25 + 0.5)/2]\end{aligned} \tag{1}$$

where, "M" is the proportion of the soil weight in the aggregate class with a size given in the subscript and "S" is the weight of skeletal fractions >2 mm.

The bulk density was determined by collecting undisturbed intact soil cores from all three depths at the same location from where soil samples were collected (Grossman and Reinsch 2002). A core of 5.3-cm diameter and 3-cm deep was used for the 0- to 5-cm depth, and 5.3-cm diameter and 6-cm deep was used for the 5- to 15- and 15- to 30-cm depths. Core samples were collected from the middle of the soil depth to represent bulk density for the depth. The soil samples from the cores were washed after drying and weighing, and contents passed through a 2-mm sieve to determine the gravel content. The bulk densities were reported in Mg m^{-3} after making correction for gravel and rock fragments (Page-Dumroese et al. 1999). A 50 g soil sample sieved through a 2-mm sieve was used for particle-size analysis by the hydrometer method (Gee and Or 2002). The CI was measured using a hand-cone penetrometer (Eijkelkamp, Giesbeek, the Netherlands) (Bradford 1986). Fifteen measurements were made on the ground surface from each location for the determination of CI. The penetrometer was steadily pushed vertically downward at a rate of about 2 cm s^{-1}, applying equal pressure on both grips. The CI values were computed by dividing the manometer reading with the base area of the cone and expressed in MPa (Eq. 2).

$$\text{CI (Mpa)} = \frac{\text{Manometer reading (Newton)}}{\text{Base area of cone (cm}^2) \times 100} \tag{2}$$

Soil samples were also collected from the 0- to 5-cm depth simultaneously with CI for the determination of moisture, to see if there is any relationship with CI, and to make necessary adjustment to CI. However, the CI values did not vary with any small changes in the gravimetric soil moisture content ($P > 0.5$), and thus the CI values were not adjusted (Blanco-Canqui et al. 2005).

The soil moisture retention curves (SMRC) for all sites were determined using triplicate soil cores equilibrated successively at 0, 3, 6, 10, 100, and 300 kPa, and soil separates (<2 mm) equilibrated at 1,500 kPa. The SMRC for 0, 3, and 6 kPa suctions were measured using a tension table (Romano et al. 2002), and 10, 100, 300, and 1,500 kPa using pressure plate extractors (Dane and Hopmans 2002). Volumetric water content was determined by multiplying gravimetric moisture content with the soil bulk density.

Water infiltration rates were measured in the field using a double ring infiltrometer (outer diameter 27 cm and inner diameter 15 cm; Reynolds et al. 2002). Three infiltration tests using constant-head method were conducted for 2.5 h with measurements made at 1, 3, 5, 8, 11, 15, 20, 25, 35, 45, 60, 75, 90, 105, 120, 135, and 150 min for each sampling location. The infiltration rate and cumulative infiltration were calculated for each time. Soil moisture content was determined before and after the infiltration measurement using the time-domain reflectometry (TDR) technique (Kim et al. 2001).

Statistical analysis

The analysis of variance (ANOVA) was used to test the hypothesis that the differences in bulk density, CI, WSA, MWD, soil moisture retention and water infiltration among the land use in RMS were the same by depth. Analyses of the land use were done considering land use as fixed variable and soil depth as repeated measure using SAS (SAS 2001). The means were compared using the least significant difference (LSD) test at $P \leq 0.05$.

Results

Soil texture, bulk density, porosity, and cone index

The soil texture for the 0- to 15-cm depth under the RMS-forest and for the 0- to 30-cm depth under the undisturbed forest was clay (>448 g kg^{-1}) (Table 3). However, the 15- to 30-cm depth of RMS-forest had higher sand content (322 g kg^{-1}) than that under pasture and hay. Soil texture in the 0- to 30-cm soil depth of RMS was clay loam under hay and silty clay loam (>530 g silt kg^{-1}) under pasture. The proportion of the gravels in RMS increased with increase in depth. The gravel content in the study area was 4.37%, 4.45% and 6.99% of total soil weight at the 0- to 5-, 5- to 15-, and 15- to 30-cm depth, respectively. This increase in gravel content at lower depth of RMS is due to mixing of topsoil with the spoil during reclamation and grading.

Bulk density at the 0- to 5-cm depth was lower in the RMS-land use than in the agricultural land use (Table 4). At the 5- to 15- and 15- to 30-cm depth, bulk density was lower under the undisturbed forest than in the RMS-pasture. The bulk density of top soil ranged from 1.09 to 1.13 Mg m^{-3} in the 0- to 5-cm depth, and 1.50 to 1.51 in the 15- to 30-cm depth. However, bulk density of spoil material at the 30- to 50-cm depth ranged from 1.64 to 1.66 Mg ha^{-1} (Ussiri et al. 2006a). The bulk density of RMS at deeper depths was higher than that of the undisturbed soil and comparable to that of agricultural soil. In general, bulk density decreased with increased soil depth.

The CI was affected by post-reclamation land uses in RMS (Fig. 1). After 28 years of reclamation, CI was higher under the RMS-pasture than under other land uses in the RMS ($P<0.05$). The highest CI (2.56 MPa) was observed under RMS-pasture compared to that under RMS-forest (1.36 MPa) and RMS-hay (1.48 MPa). The CI values for RMS under forest and hay were similar to that of the undisturbed forest.

Aggregate stability

The WSA size fractions and MWD of RMS, measured from 5 to 8 mm aggregates, were affected by post-reclamation land uses (Table 5 and Fig. 2). The

Table 3 Particle size distribution in different land uses at Morgan County, Ohio

Soil depth (cm)	Land use	Proportion of soil minerals (g kg^{-1})		
		Sand	Clay	Silt
0 to 5	RMS-forest	176 (7)	468 (25)	356 (19)
	RMS-hay	262 (42)	364 (24)	374 (24)
	RMS-pasture	271 (26)	250 (10)	479 (26)
	Undisturbed forest	149 (7)	500 (10)	351 (6)
	Agriculture	96 (7)	377 (47)	527 (46)
	LSD (0.05)	74	97	93
5 to 15	RMS-forest	176 (37)	448 (26)	376 (23)
	RMS-hay	231 (33)	369 (17)	400 (46)
	RMS-pasture	98 (8)	321 (25)	581 (18)
	Undisturbed forest	136 (29)	513 (8)	351 (25)
	Agriculture	100 (25)	417 (48)	483 (58)
	LSD (0.05)	130	103	122
15 to 30	RMS-forest	322 (20)	358 (46)	320 (31)
	RMS-hay	281 (38)	363 (36)	356 (53)
	RMS-pasture	151 (30)	319 (29)	530 (82)
	Undisturbed forest	116 (33)	520 (18)	364 (15)
	Agriculture	106 (24)	393 (25)	501 (56)
	LSD (0.05)	201	115	171

Values in the parenthesis are standard error

Table 4 Effect of land uses on soil bulk density of reclaimed mine soils, Morgan County, Ohio

Treatments	Soil depth (cm)		
	0–5	5–15	15–30
Bulk density (Mg m^{-3})			
RMS-forest	1.11 (0.04)	1.29 (0.04)	1.50 (0.08)
RMS-hay	1.09 (0.01)	1.34 (0.10)	1.51 (0.03)
RMS-pasture	1.13 (0.02)	1.42 (0.04)	1.51 (0.10)
Undisturbed forest	1.05 (0.04)	1.17 (0.05)	1.24 (0.03)
Agriculture	1.27 (0.03)	1.29 (0.04)	1.47 (0.03)
LSD (0.05)	0.11	0.20	0.22

Values in the parenthesis are standard errors

dominant aggregate size fractions in the 0- to 5-cm depth were 4.75–8.0 mm (62%), and in the 15- to 30-cm depths were <4.75 mm (79%). At the 0- to 5-cm depth of RMS, micro-aggregates (<0.25 mm), measured from 5 to 8 mm aggregates, were higher under pasture (92%) and hay (67%) land uses than that under forest. Similarly, the meso-aggregates (0.25 to 2 mm) were also higher in soil under pasture and hay than that under forest by 105% and 49%, respectively. However, the macroaggregates (2 to 8 mm) were higher in the soil under RMS-forest than that under RMS-pasture by 20%. Irrespective of soil depth, the proportion of >2 mm aggregate fraction, obtained from 4.75–8 mm aggregate, in RMS increased with increase in clay content ($P<0.01$) (Fig. 3). In the 5- to 15-cm depth, the aggregates between 4.75 and 8 mm were dominant in RMS-forest (521 g kg^{-1}) and RMS-hay (458 g kg^{-1}). The WSA fractions of >2 mm decreased and <2 mm increased with increase in soil depth (Table 5). The relative amount of macro-aggregate fraction (>0.25 mm) was 920, 848, and 692 g kg^{-1} soil for the 0- to 5-, 5- to 15-, and 15- to 30-cm depths, respectively.

The MWD in RMS was also affected by the post-reclamation land uses especially for the 5- to 15-cm and 15- to 30-cm depths ($P<0.05$) (Fig. 2). The MWD was higher under RMS-forest (4.08 mm) and RMS-hay (3.74 mm) than those for RMS-pasture (2.62 mm) ($P<0.05$). The MWD in all RMS soils was lower than in agricultural soil (5.29 mm) ($P<0.05$).

Soil hydrologic properties

Infiltration rate

Both initial (infiltration measured at 5 min) and equilibrium (infiltration rates at steady state) infiltration rates were influenced by RMS-land uses ($P<0.05$) (Fig. 4). The RMS-hay and RMS-forest had higher initial and equilibrium infiltration rates than that under RMS-pasture. The initial infiltration rates in RMS soils

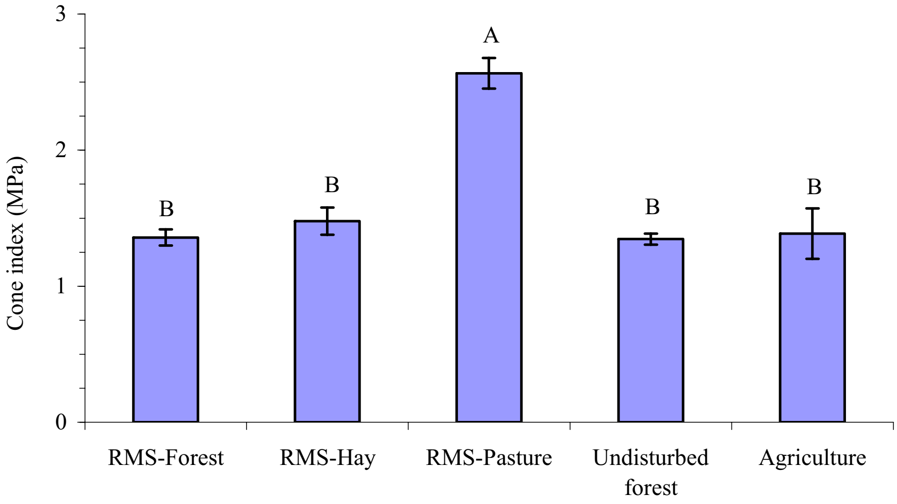


Fig. 1 Effect of post-reclamation land uses on cone index of reclaimed mine soil (RMS) in Morgan County, Ohio. The cone index for different land uses with the same capital alphabetical letters are not significantly different at $P=0.05$. *Bar* represents standard errors of the mean

Table 5 Effect of post-reclamation land uses on aggregates size distribution of 5–8 mm aggregates, Morgan County, Ohio

Soil depth (cm)	Aggregate size (mm)	Aggregates in different land uses (g aggregates kg^{-1} dry soil)					LSD (0.05)
		RMS-forest	RMS-hay	RMS-pasture	Undisturbed forest	Agricultural soil	
0 to 5	4.75 to 8	678 (21)	597 (28)	574(106)	434 (62)	653 (70)	224
	2 to 4.75	182 (13)	185 (17)	145(17)	259 (12)	119 (32)	69
	1 to 2	53 (4)	71 (6)	69 (18)	129 (14)	54 (24)	54
	0.5 to 1	24 (2)	42 (5)	67 (14)	64 (12)	49 (14)	38
	0.25 to 0.5	14 (1)	23 (3)	51 (18)	35 (10)	32 (8)	34
	<0.25	49 (3)	82 (3)	94 (19)	79 (9)	93 (7)	44
5 to 15	4.75 to 8	521 (45)	458 (78)	291 (24)	205 (35)	774 (59)	160
	2 to 4.75	171 (19)	176 (3)	130 (22)	159 (16)	80 (26)	69
	1 to 2	76 (7)	101 (4)	142 (68)	166 (8)	37 (7)	103
	0.5 to 1	55 (7)	76 (11)	101 (7)	155 (16)	31 (12)	32
	0.25 to 0.5	50 (17)	44 (12)	114 (4)	106 (11)	18 (7)	38
	<0.25	127 (18)	145 (5)	222 (20)	209 (17)	60 (5)	115
15 to 30	4.75 to 8	216 (53)	150 (46)	97 (36)	91 (32)	466 (134)	288
	2 to 4.75	145 (28)	162 (33)	81 (18)	127 (38)	116 (17)	98
	1 to 2	104 (6)	140 (30)	81 (12)	194 (40)	77 (29)	94
	0.5 to 1	115 (7)	143 (6)	140 (9)	170 (22)	93 (37)	56
	0.25 to 0.5	93 (7)	117 (15)	134 (12)	131 (17)	79 (31)	74
	<0.25	327 (14)	288 (38)	467 (52)	287 (39)	169 (20)	234

Values in the parenthesis are standard error

under forest (15 cm min^{-1}), hay (9 cm min^{-1}), and pasture (3 cm min^{-1}) were lower than the undisturbed forest (19 cm min^{-1}). The infiltration rate attained a steady state earlier in RMS-pasture (25 min) compared to those under RMS-hay (35 min) and RMS-forest (60 min). The equilibrium infiltration rates were 0.8 cm min^{-1} under RMS-pasture, 3.9 cm min^{-1} under RMS-hay, and 3 cm min^{-1} under RMS-forest ($P<0.05$).

The cumulative infiltration at 150 min was also affected by post-reclamation land uses in RMS ($P<0.05$) (Fig. 5). The cumulative infiltration at 150 min was higher under RMS-forest (531 cm) and RMS-hay (455 cm) than under RMS-pasture (118 cm). However, undisturbed forest which was not affected by restoration had the highest cumulative infiltration of 810 cm.

Soil water retention

The effect of post-reclamation land uses on soil water retention was evident in the surface layer (0- to 5-cm depth), but diminished with increase in soil depth (Fig. 6). The water retention was higher under undisturbed forest than that of RMS consistently for all soil water potentials at all the depths except for the RMS-pasture at the 0- to 5-cm depth. The soil water retention in RMS for the 0- to 5-cm depth decreased drastically from 300 kPa (0.45 cm^3 cm^{-3}) to 1,500 kPa potential (0.23 cm^3 cm^{-3}). Similar trends were also observed at the lower depths. However, the soil water content at the same potential decreased with increase in the depth.

Discussion

Prior studies have shown that soil compaction is a problem in RMS (Akala and Lal 2000). However, this study indicated that the level of soil compaction differs among post-reclamation land uses (e.g. forest, pasture, and hay). Excessive soil compaction in the RMS is a major constraint to returning land to pre-mining productivity soon after reclamation. After 28 years of reclamation, soil compaction, as indicated by CI and bulk density, for the surface layer (0- to 5-cm depth) of RMS especially for the forest and hay was similar to that under undisturbed forest. In contrast, Thurman and Sencindiver (1986) reported that bulk density, corrected for gravel, of the surface horizons in 25 years old RMS was higher than that of the native soils. High bulk density in the subsurface layer of RMS persisted even after 28 years of reclamation. The soil compac-

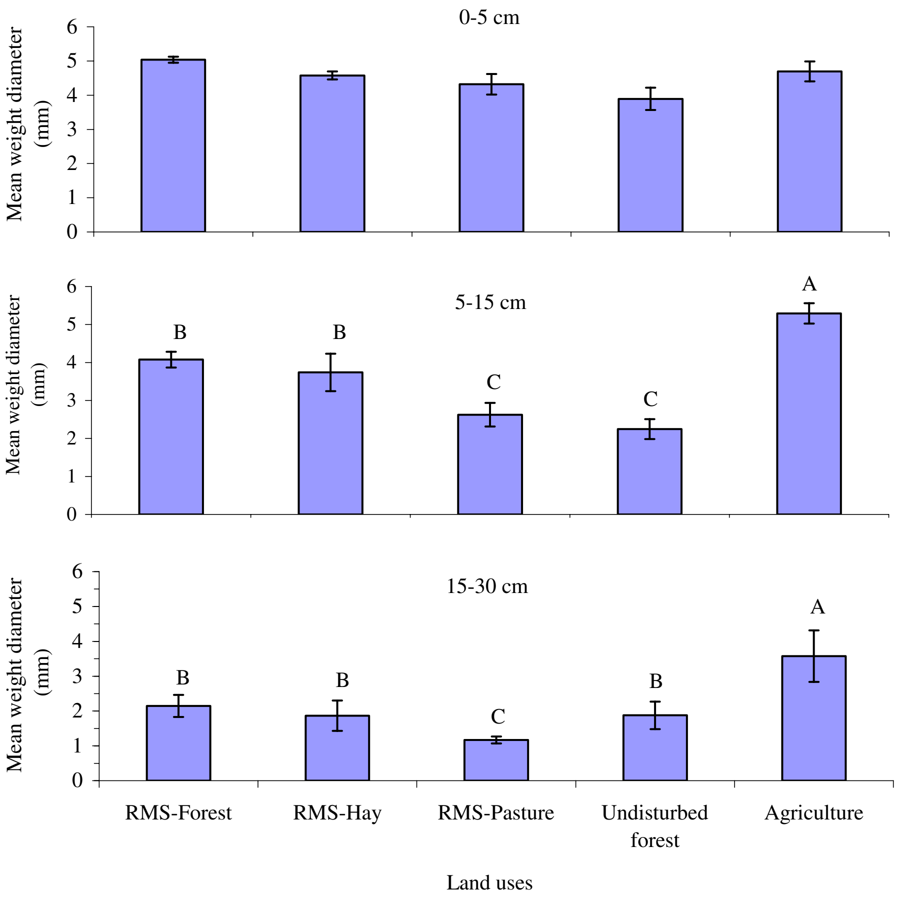


Fig. 2 Mean-weight diameter (MWD) of soil affected by post-reclamation land uses in reclaimed mine soil (RMS) in Morgan County, Ohio. The MWD for different land uses with the same capital alphabetical letters are not significantly different at $P<0.05$. *Bar* represents standard errors of the mean

tion of RMS is influenced by heavy equipment (used in the process of reclamation), gravel content, soil texture, aggregation, and amendments used (Barnhisel and Hower 1997). A trend of higher soil compaction observed in RMS-pasture is due to the trampling effects of grazing cattle as cattle were grazed at a stocking rate of 1.2 cattle ha^{-1}. Higher compaction observed in RMS-pasture reduced infiltration rate as observed in this study, and impeded root growth as reported earlier (Shrestha and Lal 2007). The lower bulk density observed at the surface layer of RMS-hay and -forest than those of agriculture may be due to increased biological activity (e.g., earthworms), increased soil organic carbon, and increased root growth. Similar decrease in soil compaction as indicated by the bulk density at the 0- to 5-cm depth had been also reported in mine soil added with (Ussiri et al. 2006a) or without topsoil application (Schafer et al. 1980; Varela

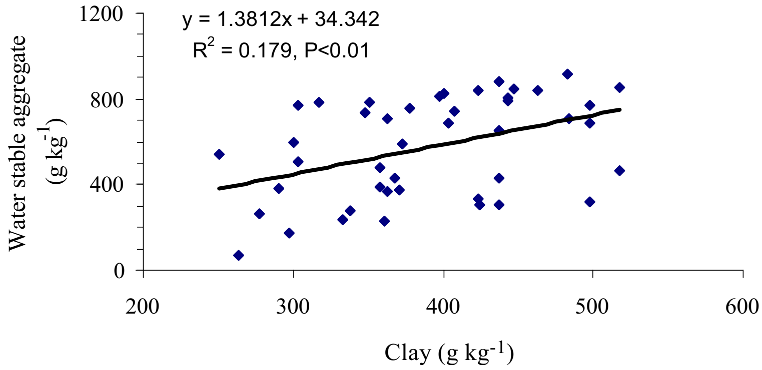


Fig. 3 The relation between large water-stable macro-aggregates (>2 mm) with clay contents

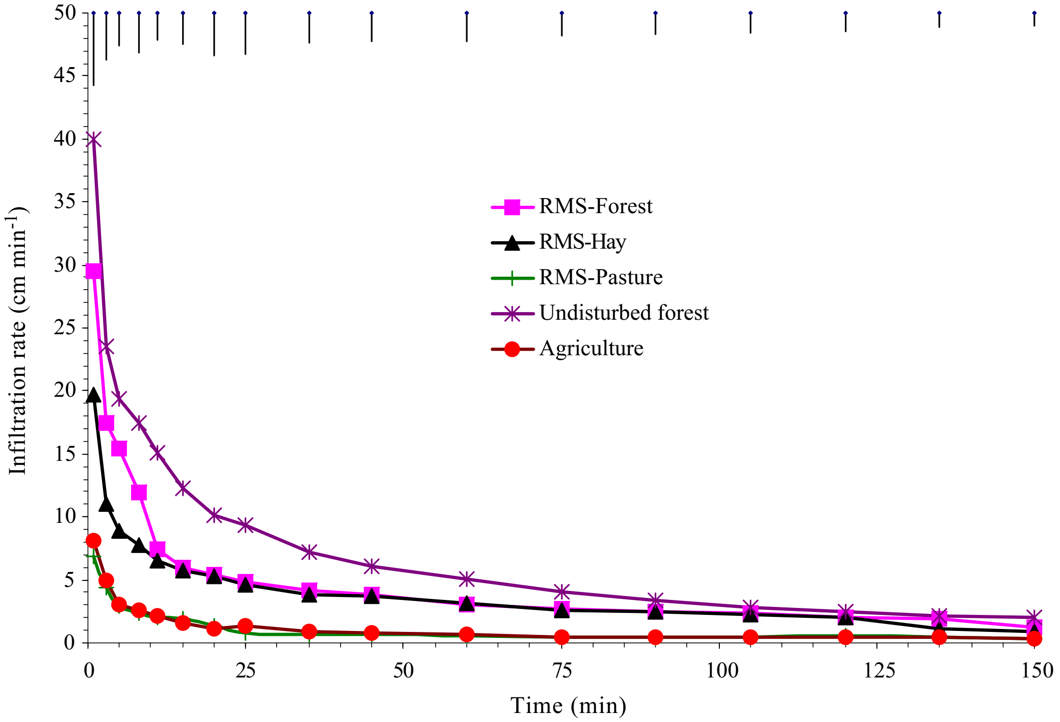
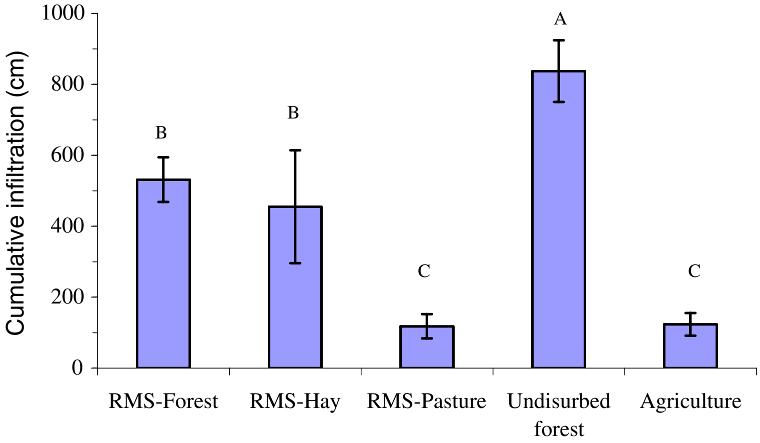


Fig. 4 The measured infiltration rate at 1, 3, 5, 8, 11, 15, 20, 25, 35, 45, 60, 75, 90, 105, 120, 135, and 150 min for different land uses in mine soil at Morgan County, Ohio. *Vertical bars* represent LSD value at P=0.05

et al. 1993). The bulk density in agricultural soils was significantly higher than that of RMS, which could be a result of using heavy agricultural equipments for plowing, planting, harvesting, and application of fertilizer, herbicides, and pesticides. Similarly, the CI was 88% and 73% higher in the soil under RMS-pasture than that under RMS-forest and -hay, respectively. The CI was not affected by the antecedent soil moisture content in this study, as was observed by Mosaddeghi et al. (2000), and therefore, was not correlated for differences in soil moisture content. The CI is easy to estimate and could be used to delineate regions of RMS, where adverse soil physical characteristics may negatively impact the biomass production.

Based on the proportion of 2–8 mm aggregates, aggregate stability of 5–8 mm aggregates was greater in soil under RMS-hay and RMS-forest than that under undisturbed forest. This indicates the positive effect of reclamation on aggregate stability. Better aggregation under hay may be due to high amount of

Fig. 5 Cumulative infiltration for post-reclamation land uses in reclaimed mine soil at Morgan County, Ohio. Land uses with same alphabetical letters are not different at P<0.05. *Bar* represents standard errors of the mean



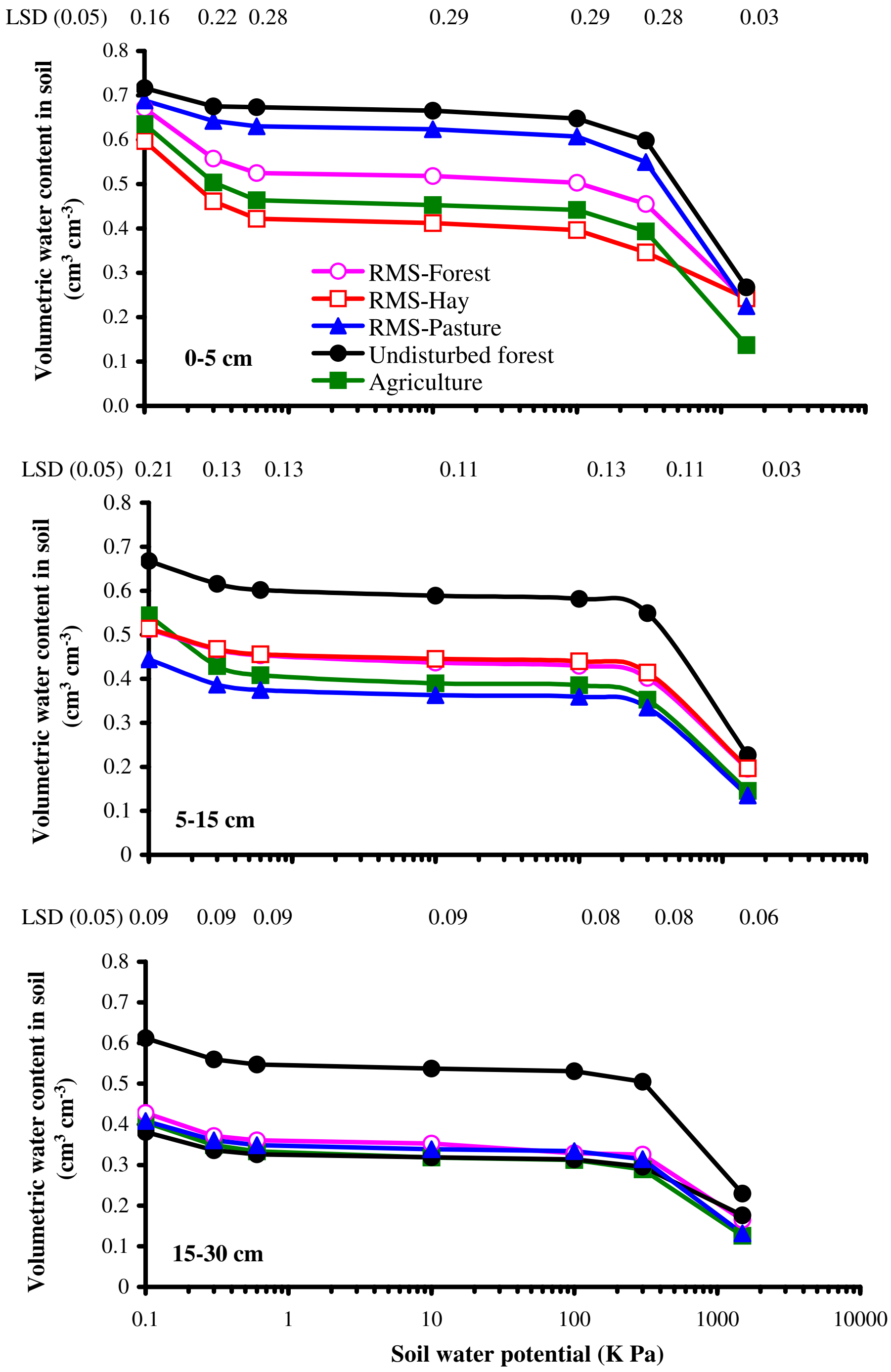


Fig. 6 Soil water retention curves affected by land use practices in mine soils in Morgan County, Ohio

C and a dense root system (Shrestha and Lal 2007). A dense root system in the 0- to 5-cm layer of RMS-hay after 28 years of reclamation enhanced formation of stable micro-aggregates (0.053 to 0.25 mm), which then coalesced to form macro-aggregates (>0.25 mm) and relatively stable soil structure. The presence of more root hair and fungal hyphae, which exude a range of organic substances like mucilaginous polysaccharides, may work as the binding agents and form a network there by enmeshing fine soil particles into aggregates (Haynes and Beare 1995). A high proportion of stable macro-aggregates present in soil under RMS-hay than that under RMS-pasture enhanced infiltration rate (Fig. 4), which may decrease surface runoff and improve soil water reserve (Shaver et al. 2002). The breakdown of macro-aggregates due to the trampling effect of cattle was indicated by the presence of lower MWD in the 5- to 30-cm depth of RMS-pasture than that of RMS-forest and -hay ($P < 0.05$). The higher MWD under RMS-forest and RMS-hay than those for RMS-pasture suggests that soil structure was improved by forest and hay land uses.

The decrease in infiltration rate and cumulative infiltration in RMS-pasture may be associated with the trampling effect of cattle, reduced aggregation, and high soil compaction as indicated by increase in CI (Holt et al. 1996). Differences in cumulative infiltration among land uses are indicative of differences in structural attributes or amount of aggregation, which influence water infiltrability (Lowery et al. 1996). High cumulative infiltration and water retention in soil under undisturbed forest compared to that of RMS may be attributed to the low bulk density, surface crusting, high porosity, and high organic carbon content (Shrestha and Lal 2007). Wuest (2001) also observed increase in earthworm activity and water infiltration in soil under undisturbed forest compared to agricultural soil. The soil water content at the same potential decreased with increase in the depth, which may be because of the decrease in pore space with increase in bulk density.

Conclusions

Post-reclamation land uses under forest and hay decreased soil compaction and increased aggregate stability of 5–8 mm aggregates, soil water infiltration, and water retention capacity at lower depth than those of pasture. Increased soil compaction in RMS-pasture was possibly a result of trampling effect of grazing animals. Despite harvest of aboveground biomass in RMS-hay, soil physical properties were similar to or better than that under agriculture land use. These results suggest that both hay and forest land uses can be recommended to reclaim mine soils as post-reclamation land use. Further studies are required to identify detailed site- and soil-related constraints of reclaimed mine ecosystems in Ohio, and to prepare digitized maps. These maps can be useful to identify appropriate soil management practices for the restoration of mined soil.

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