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Land Management Effects on Carbon Sequestration and Soil Properties in Reclaimed Farmland of Eastern Ohio, USA

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ABSTRACT

Reclaimed mined soils (RMSs) could restore soil quality and ecosystem productivity while sequestering C and off-setting some of C emissions associated with coal utilization. The study was conducted to evaluate the effects of tillage and pasture management on soil physical properties, soil organic carbon (SOC) and microbial biomass carbon (MBC) in RMSs managed for agricultural use in eastern Ohio. Soil bulk density (ρ_b) of the top 50 cm ranged from 1.11 to 1.93 $Mg \cdot m^{-3}$. The ρ_b of the RMSs was significantly more than that of the undisturbed soils. Water stable aggregates (WSA) and mean weight diameter (MWD) of the 0 - 10 cm soil layer were significantly lower under reclaimed conventional tillage (RCT) than reclaimed no tillage (RNT) and reclaimed pasture (RP), probably due to tillage-induced disturbance. The SOC pool of the top 50 cm layer was 64.2, 66.5, 75.4, 86.1 and 101.1 $Mg \cdot C \cdot ha^{-1}$ for undisturbed pasture (Und P), RNT, RCT, RP and undisturbed hardwood forest (Und HWF), respectively (LSD = 7.7 $Mg \cdot ha^{-1}$). The RMSs under pasture accumulated SOC at higher rates than RMSs under cropland. Reclaimed pasture land use increased SOC pool by 14% or 0.5 $Mg \cdot ha^{-1} \cdot yr^{-1}$ and 30% or 0.9 $Mg \cdot ha^{-1} \cdot yr^{-1}$ relative to RNT and RCT land uses, respectively. Our data indicated that RMSs under forest and pastures had higher SOC sequestration rates than RMSs under arable land use, probably due to disturbances associated with farm operations. The MBC of the RMSs were generally lower than those of the undisturbed sites. The disturbances associated with mining and reclamation reduced the MBC by 39%, 53% and 21% under RCT, RNT and RP compared to the undisturbed forest and pasture sites. However, the amount of mineralizable C was not significantly different among land disturbances or land uses.

Keywords: Carbon Sequestration, Surface Mining, Soil Organic Carbon, Microbial Biomass Carbon, Reclaimed Minesoils

1. Introduction

Surface mining for coal results in drastic landscape disturbance and soil degradation. It strongly changes the antecedent soil profile, along with alterations in physical, chemical and biological properties and processes of soils [1]. Mining and related activities also lead to severe loss of soil organic carbon (SOC) because of topsoil loss, mechanical mixing of soil horizons during removal and storage of topsoil, increased mineralization, soil erosion and leaching from exposed topsoil. Reclamation is the process of restoring the mined land to a useful state [2,3]. Reclamation can improve soil quality, enhance mined soil productivity and increase SOC concentration [4]. Adverse physical (high bulk density, poor soil structure, poor aggregation and low water infiltration rate), chemical (salinity/acidity, low SOC content, low soil fertility, and elemental imbalances) and biological conditions (reduced microorganisms and soil biotic activity) often limit vegetation establishment and restoration of reclaimed minesoils (RMSs) [1,5-8].

The US Surface Mining Control and Reclamation Act of 1977 (SMCRA) mandates that surface mined areas be restored to level similar to that of the pre-mining state. This entails the restoration of landscape topography and the application of topsoil to create a soil environment capable of supporting plant growth. The top 1.5 m of the RMSs should be constructed from medium-textured materials (silt loams, loams or light silt clay loams) for generating high water storage capacity for crops [9]. For the surface mined cropland, the SMCRA requires the reclaimed land to meet or exceed crop yield it had prior to mining and that the yields are comparable to unmined

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farmland in the surrounding area under equivalent level of management. Unlike reclaimed grassland or forest land where management interventions are minimal, reclaimed cropland soils are intensively managed, with periodic tillage or major seedbed preparation for the purpose of establishing annual, biennial or short-lived perennial herbaceous plants. In cropland, annual plants are established for the exclusive purpose of direct harvest as a cash crop or livestock feed [10]. Tillage has been identified as a major land management factor impacting SOC dynamics and C cycling in agricultural soils [11,12]. Soils under continuous tillage (CT) have lower SOC pools than those under no-tillage (NT) mainly due to mechanical breakdown of soil aggregates and loss of aggregate-protected SOC [13,14]. However, the impacts of management interventions on agricultural land on C sequestration and ecological recovery of the RMSs under cropland are not fully understood.

Several studies have assessed the potential of RMSs for SOC sequestration, and have documented that RMSs could be an important sink for atmospheric CO_2 and thus offset some of the CO_2 emitted as a result of mining and utilization of coal for power generation [8,15-21]. These assessments have documented rapid SOC accumulation with sequestration rates generally higher than in agricultural lands [15,17,20,22,23]. For example, Akala and Lal [15] reported C sequestration rates of 2 to 3 $Mg \cdot ha^{-1} \cdot yr^{-1}$ in the first 20 yrs after reclamation, decreasing to 0.4 to 0.7 $Mg \cdot ha^{-1} \cdot yr^{-1}$ by 20 to 30 yrs after reclamation. Shukla *et al.* [8] reported an average C sequestration rate of 0.75 $Mg \cdot C \cdot ha^{-1} \cdot yr^{-1}$ for the fertilized hay fields in Ohio during the first 20 years after reclamation. Other studies (*i.e.*, [19,20,24] reported sequestration rates as high as 3 to 4 $Mg \cdot C \cdot ha^{-1} \cdot yr^{-1}$ in reclaimed grass and forest land uses. The restoration of RMSs to grasslands for pastures and hay is the most widespread land use in Eastern United States due to current reclamation regulations which require grading the land to approximate original contour, overall creating lands with gentle slopes that are more readily traversed and amenable to management and high potential for economic returns [2, 10].Very few studies have been conducted to evaluate SOC sequestration on intensively managed RMSs under agriculture land use. Given different land management practices and plant biomass inputs in agricultural land use, it is unclear whether RMSs under arable land use can sustain similar SOC sequestration rates as those under pastoral and silvicultural land uses.

Soil microbiota are the basis of all terrestrial ecosystems recovery from major disturbances, playing significant role in soil formation, soil organic matter (SOM) transformation, nutrients cycling, N fixation and soil quality improvement. Significant degradation of the microbial community can occur after drastic soil disturbance associated with mining and reclamation, both in total microbial biomass and species composition. Studies of RMSs ecosystems indicate that microbial communities may take up to 20 years or more to recover in terms of biomass and diversity similar to that under an undisturbed soil [23,25-27]. While gross measures of microbial biomass C (MBC) reveals little information about functional groups and roles that specific microbes play in soil processes, it is reasonable to assume that MBC comparable to that observed in the undisturbed native soils nearby is a good indicator of a restorative soil system. Understanding the effects of post-reclamation land use, management and its influence on SOC storage and MBC is important to assessing the ecosystem function and the level of reclamation. Therefore, the objectives of this study were to: 1) assess the effects of tillage on soil physical properties and C sequestration in RMSs under arable land use, 2) to evaluate the impact of tillage on microbial biomass in RMSs under arable land use.

2. Materials and Methods

2.1. Site Description and Soil Sampling

The experimental site is located in Tuscarawas County near Ragersville, (40˚27'47"N, 81˚38'13"W) Eastern Ohio. Soils of the experimental site belong to Coshocton-Bethesda-Guernsey soil association, well to moderately well drained soils formed from siltstone, shale, and sandstone [28]. The region has temperate continental climate, with average annual temperature of 9.7˚C and precipitation of 983.2 mm, of which 55% is received between April and September. The predominant land use of the region is crop and pasture production.

Prior to mining the study site was under pasture and corn (*Zea mays* L.) production for gentler slope (2% - 4% slope) and forest for steeper slopes (>5% slope). The site used for this study was mined and reclaimed under SMCRA cropland guidelines in 1984. Mining process involved clearing secondary forest portion, followed by scraping and storing topsoil and subsoil from forest and agricultural sites, and removing overburden to access coal seams. After extracting coal, the site was reclaimed back to original topography by grading the mine spoil, application of stored subsoil and topsoil over the graded overburden to create suitable cropland. The site was then seeded with mixtures of grass species. In 1995, the reclaimed sites were returned to the land owner (farmer). The farmer maintained one portion of the reclaimed site (10 ha) for intensively managed hay production for dairy cows since 1995; reclaimed pasture (RP), while the remaining reclaimed site was converted to cropland in 1995. Part of the cropland have been under conventional tillage and corn (RCT; about 8 ha) while no-till (RNT;

about 10 ha) and corn was practiced on the other part of the field for the past 10 yrs. Both RCT and RNT were under continuous corn for the past 10 yrs and received 5 $Mg \cdot ha^{-1}$ of manure every 3 yrs. In addition, corn received 112 $kg \cdot ha^{-1}$ N, 25 $kg \cdot ha^{-1}$ P and 46 $kg \cdot ha^{-1}$ K as NPK fertilizer applied at planting. Nearby remnant unmined and unmanaged pastures (Und P) and hardwood forest (>70 yrs old; Und HWF) soils were sampled as control.

2.2. Soil Sampling and Analysis

The Soil samples were collected between June and July 2007 within each land use from summit, shoulder, and foot-slope landscape positions. Bulk and undisturbed soil core samples were collected from the 0 - 10, 10 - 20, 20 - 30 and 30 - 50 cm depths at each landscape position. Undisturbed core samples were collected using 6 cm diameter and 6 cm long soil cores and used for bulk density determination. Soil bulk density (ρ_b) was computed as the weight to volume ratio of oven-dried (105˚C) soil corrected for roots and gravel [29].

Bulk soil samples were air dried and 50 g of aggregates between 5 and 8 mm size were sieved from a part of sample for aggregate analysis. Aggregates were separated using wet-sieving apparatus [30] as described by Nimmo and Perkins [31]. The aggregate analysis was conducted by using a nest of five sieves (5, 2, 1, 0.5 and 0.25 mm) oscillated in water for 30 min. following gentle wetting. Water stable aggregates (WSA) retained on each sieve were backwashed from the sieve with deionized water, oven dried at 60˚C for 72 h and weighed. The mean weight diameter (MWD) was computed as the sum of the weighted average diameter of all size classes, where weighting factors were the proportions of the oven-dry (60˚C) mass of each size class to the total sample weight [31]. A 2 g subsample of each aggregate-size fraction was finely ground to pass through a 0.25-mm sieve for total organic carbon (TOC) and total nitrogen (TN) determinations.

The remainder of the bulk soil was ground and sieved through a 2-mm sieve. A sub sample (10 g) of each sample was finely ground with a ball mill and passed through a 0.25-mm sieve for total organic carbon (TOC) and total nitrogen (TN) determinations. Concentrations of C and N in composite samples and aggregate fractions were determined by the dry combustion (900˚C) method using elemental CN analyzer (VarioMax, Elementar GmbH, Hanau, Germany).

The SOC pool for a specific depth range was calculated using equation:

$$\mathrm{SOC}\left(\mathrm{Mg} \cdot \mathrm{ha}^{-1}\right) = \frac{\mathrm{SOC}(\%)}{100} \times \rho_b \times d \times \frac{10^4 \mathrm{m}^z}{\mathrm{ha}}$$

where ρ_b is bulk density ($Mg \cdot m^{-3}$), of the soil layer, SOC is SOC concentration, and d is soil depth in m.

2.3. Microbial Biomass and Mineralizable Carbon Determination

Fresh soil samples from the top 0 - 10 and 10 - 20 cm depths for each land use were used for this assay. Freshly sampled soils were stored in a cooler, transported to the laboratory, and sieved through a 2-mm sieve. Sieved samples were stored in cold room (4˚C) and the microbial biomass carbon (MBC) and mineralizable C (MIN-C) assay were conducted within 1 week of soil sampling. The MBC was quantified by the chloroform fumigation incubation method [32,33] and CO_2 evolved was quantified by gas chromatography (GC). Briefly, duplicate 50 g (oven dry equivalent) of sieved soil samples were placed in glass jars (500 mL), wetted to 50% of soil saturation moisture content (SMC) and incubated for 72 hr at 25˚C in the dark. After 72 hr, one set was transferred into 100 mL beakers, placed in the desiccator lined with moist paper towels to prevent desiccation of soil samples during fumigation. A beaker containing 50 mL of ethanol-free chloroform and anti-bumping granules was placed together with soil samples in the desiccator. The desiccator was evacuated until chloroform bubbled vigorously. Air was let back into desiccator to allow the distribution of chloroform throughout the soil. This was repeated four times, and then the desiccator was evacuated until the chloroform bubbled vigorously for 2 min. The desiccator valve was closed, and placed in the dark for 24 hr. The unfumigated set (control) was kept at 25˚C in the dark during this process.

After 24 hr fumigation, chloroform beaker and paper towels were removed under fume hood, desiccator evacuated several times, each time allowing air to pass into desiccator until soil samples were free of chloroform. After removal of chloroform, soils samples were transferred to mason jars, and inoculated with 1 g of unfumigated soil and mixed thoroughly with spatula.

Both fumigated-inoculated and unfumigated (control) samples were adjusted to 50% of water holding capacity and incubated in closed air tight mason jars in the incubator at 25˚C in the dark for 10 days. Head space air was sampled and analyzed for CO_2 concentration at 1, 2, 4, 7, and 10 d intervals by 5 mL syringe. The concentration of CO_2 evolved in each jar was quantified using GC (Shimadzu, GC 14A, Kyoto, Japan) equipped with thermal conductivity detector (TCD).

After each sampling, samples were aerated for 30 minutes in the lab and soil moisture content was adjusted to 50% SMC. The MBC was calculated as the C concentration difference between fumigated-inoculated and control using a correction factor of $K_c = 0.41$ [33]. After

10 days the CO_2 production monitoring from chloroform-fumigated samples was terminated, but the monitoring from the unfumigated samples continued for the extra period of 90 days for the determination of potentially mineralizable C. Head space air samples were collected at 7 d interval and analyzed for CO_2 concentration using GC. Cumulative CO_2 produced was converted to C based on mass balance and gas laws.

2.4. Statistical Analyses

Analysis of variance was conducted using proc GLM available in SAS (SAS Institute Inc., Cary, NC, 2001). Soil properties were analyzed separately for each depth interval and the entire soil profile (0 - 50 cm depth) to compare differences among land use treatments. When statistically significant effect was detected, Fisher's protected LSD test was performed for mean separations. Statistical significance was determined at the $p < 0.05$.

3. Results and Discussion

3.1. Soil Bulk Density and Aggregate Stability

Soil ρ_b of the RMS ranged from 1.26 to 1.93 $Mg \cdot m^{-3}$, and it increased with increase in soil depth for all management practices (**Figure 1**). Similar results have been reported in other studies conducted on RMSs [8,17,22,34,35]. The lower ρ_b of the 0 - 10 cm soil layer is consistent with the high biological activity, more root development, greater SOC concentration which enhances soil aggregation and biological activity and freeze/thaw cycles occurring on or near the soil surface. Mining and reclamation increased ρ_b of the soils significantly at all depths compared to the undisturbed land uses ($p < 0.05$; **Figure 1**). Such a trend may be attributed to mixing of soil layers during scraping and storage of topsoil, and soil compaction caused by heavy equipment involved in mining and reclamation processes. Among the reclaimed sites, ρ_b of the top 50 cm was in the order: RP (1.63 $Mg \cdot m^3$) < RCT (1.69 $Mg \cdot m^3$) < RNT (1.73 $Mg \cdot m^3$) (LSD = 0. 20 $Mg \cdot m^3$; $p < 0.05$). Increase in ρ_b under RNT than RCT is consistent with data from agricultural soils which have shown that in the first decade of cultivation NT soils have higher ρ_b than CT soils [36,37], suggesting that under RMSs, tillage management may have impact similar to that observed on unmined agricultural soils during the first 10 yrs.

The percentage of water-stable aggregates (WSA) > 0.25 mm ranged from 30% to 95%, and decreased with increase in soil depth (**Figure 2**). The MWD ranged from 0.27 to 4.77 mm (**Figure 3**). For all sites, MWD was the greatest in the 0 - 10 cm soil layer and decreased with increase in soil depth (**Figure 3**). The larger WSA and associated MWD in the surface soils may be due to accumulation of fresh and active organic matter (OM) relatively rich in monosaccharides and polysaccharides which enhance aggregate formation and its stability [38,39]. Mean WSA of the top 50 cm soil layer was 53, 65, 65, 67 and 69% in the RCT, RNT RP Und HWF and Und P, respectively (LSD = 10%). On average, the MWD of the top 50 cm was 1.49 ± 0.35, 1.75 ± 0.32, 2.07 ± 0.42, 2.14 ± 0.23, 2.15 ± 0.29 mm for RCT, RNT, Und HWF, RP and Und P, respectively (LSD = 0.45 mm).

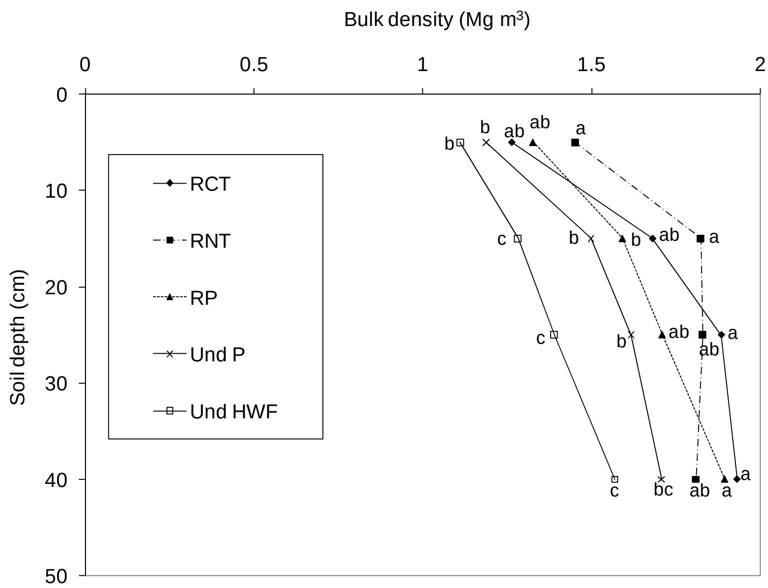

Figure 1. Land use effects on soil bulk density of the reclaimed cropland in Eastern Ohio. For each depth, same lower case numbers (or none) within the same column and sand same depth interval are not statistically significant at p = 0.05 level according to least significant difference (LSD).

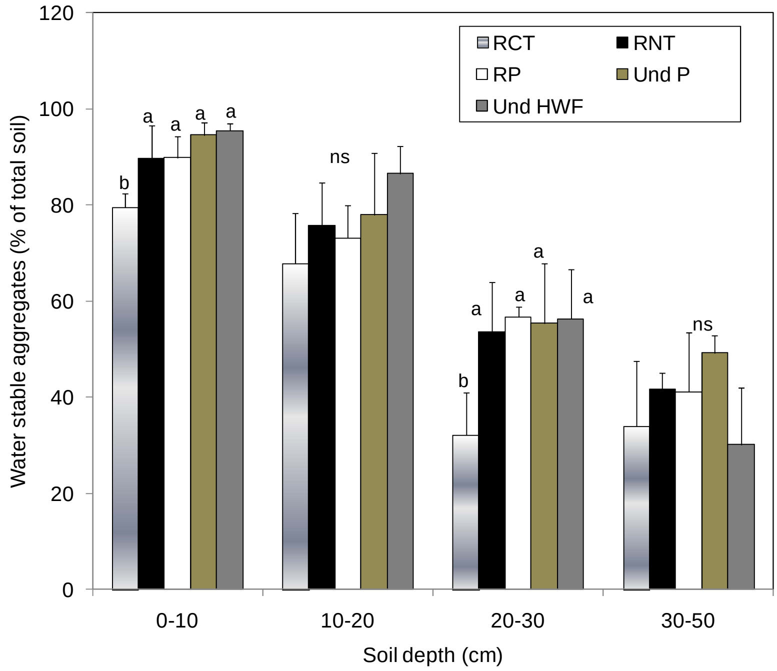

Figure 2. Land use effects on water-stable aggregates of the reclaimed cropland in Eastern Ohio. Error bars represent standard errors of the mean. For each depth group, same lower case numbers (or none) within the same column and sand same depth interval are not statistically significant at p = 0.05 level according to least significant difference (LSD).

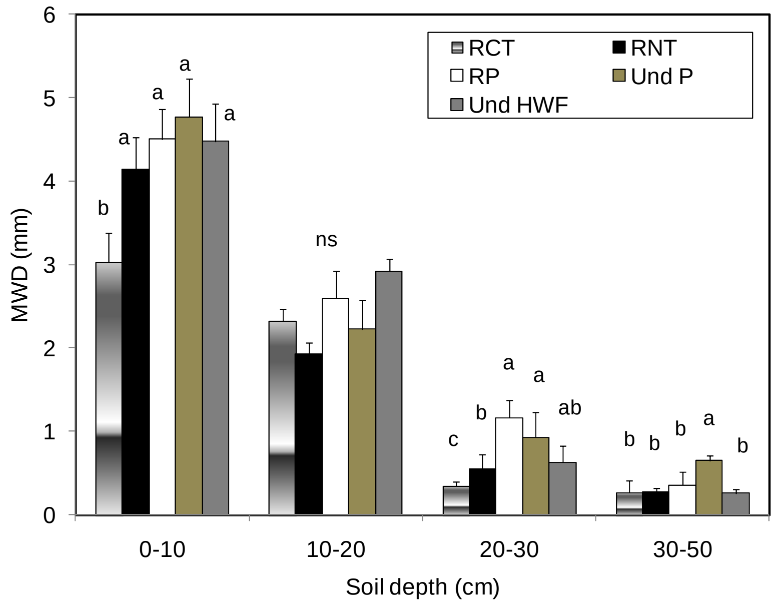

Figure 3. Land use effects on mean weighted diameter of soils from the reclaimed cropland of Eastern Ohio. Error bars represent standard errors of the mean. For each depth group, same lower case numbers (or none) within the same column and sand same depth interval are not statistically significant at p = 0.05 level according to least significant difference (LSD).

Among the reclaimed sites, WSA and MWD were significantly lower for the RCT in the 0 - 10 cm and 20 - 30 cm depths, than those under RNT and RP treatments (**Figures 2**, **4**). Tillage did not influence WSA and MWD in other depth layers. Decrease in WSA and MWD, following cultivation of RMSs suggested a reduced soil structure development in the RMS disturbed by cultivation compared to RNT and RP land uses. In addition, there were no significant differences among RP and undisturbed pasture, suggesting a complete recovery of

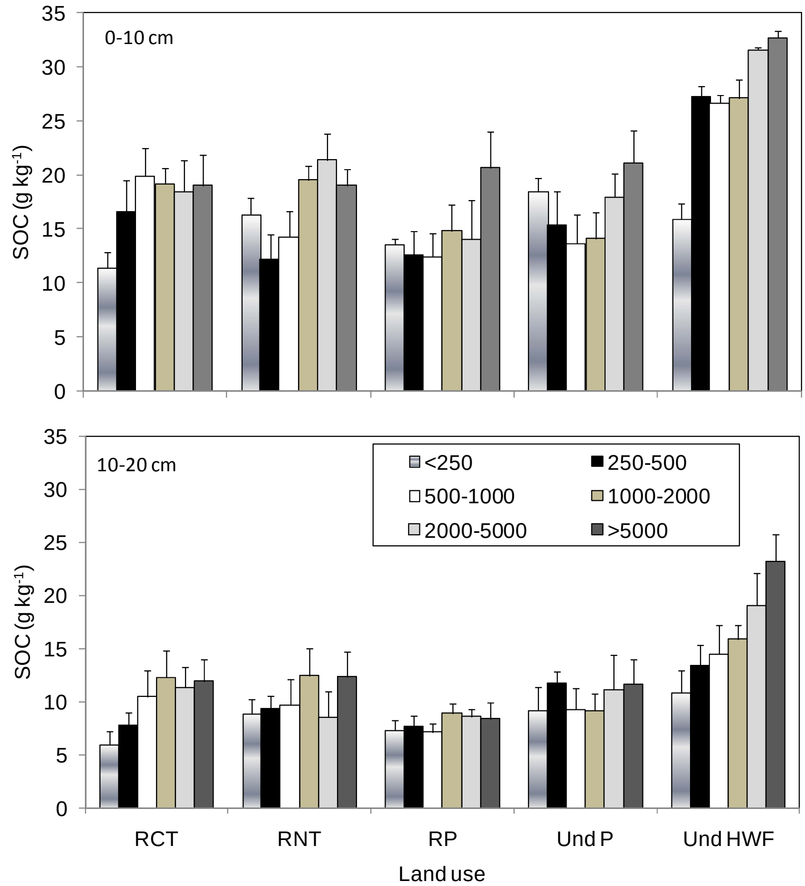

Figure 4. Effects of land use on soil organic carbon concentration of macroaggregates of the reclaimed cropland of Eastern Ohio. Error bars represent standard errors of the mean.

aggregate stability under pasture land use.

3.2. Soil Organic Carbon and Nitrogen Pools

The SOC and N concentrations were strongly stratified with soil depth (**Table 1**), and were the highest under the Und HWF on all depth layers compared to those from RMSs sites (**Table 1**). Among the RMSs sites, SOC concentration was higher under pasture in all depths than RCT and RNT treatments, except in 10 - 20 cm depth where SOC concentration was more under RCT land use ($p < 0.05$). Lower SOC concentration under RCT and RNT than RP treatments could be attributed to accelerated decomposition of SOM caused by soil disturbance associated with these agricultural practices. Total N concentration was significantly more under hardwood forest in the 0 - 10 cm layer, but no significant differences in N concentrations were observed among land uses in sub-soil layer (**Table 1**).

The N pools of the top 0 - 50 cm depth were the lowest under Und P (7.4 ± 1.1) than Und HWF (9.1 ± 1.2 $Mg \cdot N \cdot ha^{-1}$), and on the RMSs land uses RP (9.6 ± 0.2), RCT (9.0 ± 0.6) and RNT (7.8 ± 2.3 $Mg \cdot N \cdot ha^{-1}$; **Table 2**). Among the RMSs sites, the N pool was significantly lower under RNT than RCT and RP treatments. There were no significant differences among RNT and Und P land uses. In the 0 - 10 cm layer, the N pools were significantly greater under the RP than Und P site. However, there were no significant differences in N pools among RCT, RP, RNT or Und HWF in the top 0 - 10 cm depth. Only few changes in soil N pool were observed among land uses at lower depths (**Table 1**).

The SOC pool of the top 50 cm soil depth was the largest under the Und HWF (101.1 ± 3.0 $Mg \cdot C \cdot ha^{-1}$) and lowest under the Und P (64.2 ± 0.8 $Mg \cdot ha^{-1}$; **Table 1**). Among the RMSs sites, SOC pool of the top 50 cm depth was significantly more under RP (86.1 ± 2.4 $Mg \cdot ha^{-1}$) than RCT (75.4 ± 2.5 $Mg \cdot ha^{-1}$) and RNT treatments (66.5 $Mg \cdot ha^{-1}$; LSD = 7.7 $Mg \cdot ha^{-1}$, **Table 2**). Lower SOC pools under RNT and RCT than RP may be due to increase in the rate of SOM mineralization exacerbated by frequent disturbances caused by the farming operations (*i.e.* tilling and/or planting). Overall, the SOC pool decreased with increase in soil depth in all land uses.

Table 1. Land use effects on soil organic carbon, nitrogen, microbial biomass and mineralizable carbon of the reclaimed cropland of Eastern Ohio.

Land use	SOC	TN	C:N ratio	MBC	Min C
	-------($g \cdot kg^{-1}$ soil)-------			-------($g \cdot C \cdot kg^{-1}$ soil)---------	
0 - 10					
RCT	23.6 c	2.5 ab	9.37	0.36 b	4.10 c
RNT	24.3 c	2.0 c	9.33	0.29 c	4.82 a
RP	26.3 b	2.7 a	9.41	0.41b	4.46 b
Und P	20.2 d	2.2c	9.31	0.53a	4.46 b
Und HWF	34.5 a	2.8 a	12.32	0.53 a	5.12 a
10 - 20					
RCT	12.0 b	1.3	8.76	0.09 b	2.18
RNT	7.1 d	1.1	8.49	0.05 b	2.19
RP	10.1 c	1.2	8.83	0.20 a	2.71
Und P	11.9 b	1.2	9.58	0.17 a	2.14
Und HWF	19.7 a	1.7	11.21	0.21 a	2.58
20 - 30					
RCT	5.2 c	0.7	7.45		
RNT	3.6 d	0.7	7.71		
RP	6.7 c	0.7	9.36		
Und P	6.8 b	0.7	8.84		
Und HWF	11.4 a	1.1	10.33		
30 - 50					
RCT	4.0 b	0.6	6.98		
RNT	3.3 b	0.6	6.48		
RP	6.3 a	0.7	9.67		
Und P	3.4 b	0.5	6.67		
Und HWF	7.0 a	0.8	9.36		
0 - 20					
RCT	17.8	1.90		0.22	3.14
RNT	15.7	1.57		0.17	3.50
RP	18.2	1.98		0.29	3.30
Und P	16.1	1.70		0.36	4.09
Und HWF	27.1	2.23		0.37	3.85

Same lower case numbers (or none) within the same column and sand same depth interval are not statistically significant at $p = 0.05$ level according to least significant difference (LSD).

Table 2. Land use effects on soil organic carbon (SOC) and nitrogen pools of the reclaimed cropland in Eastern Ohio. Numbers in brackets are standard deviations.

Soil depth	Land use				
	RCT	RP	RNT	Und P	Und HWF
cm			SOC, $Mg \cdot ha^{-1}$		
0 - 10	29.8 (1.4)b	34.9 (1.0)ab	35.2 (5.0)ab	23.9 (1.2)c	38.2 (2.3)a
10 - 20	20.1 (1.8)b	16.1 (0.3)c	12.9 (1.5)d	17. 9 (1.3)bc	25.1 (1.3)a
20 - 30	9.7 (0.9)c	11.4 (0.8)b	6.6 (1.3)d	11.0 (0.1)bc	15.7 (0.5)a
30 - 50	15.7(0.3)b	23.8 (1.8)a	11.7 (2.4)c	11.4 (1.1)c	22.1 (2.4)a
Total	75.4 (2.5)c	86.1 (2.4)b	66.5 (7.4)d	64.2 (0.8)d	101.1 (3.0)a
			Total N, $Mg \cdot ha^{-1}$		
0 - 10	3.2 (0.4)ab	3.6 (0.2)a	3.0 (0.5)ab	2.6 (0.1)b	3.1 (0.3)ab
10 - 20	2.3 (0.1)	1.8 (0.1)	2.0 (0.9)	1.9 (0.5)	2.1 (0.1)
20 - 30	1.3 (0.2)	1.3 (0.2)	1.2 (0.6)	1.2 (0.2)	1.5 (0.2)
30 - 50	2.3 (0.3)	2.9 (0.2)	1.7 (0.5)	1.8 (0.6)	2.4 (0.6)
Total	9.0 (0.6)a	9.6 (0.2)a	7.8 (1.1)b	7.4 (1.1)b	9.1 (1.2)a

Same lower case numbers (or none) within the same column and sand same depth interval are not statistically significant at $p = 0.05$ level according to least significant difference (LSD).

However, there was a greater stratification of SOC pool in the RNT (53% of the SOC pool in the top 10 cm) than in other land uses. Similar stratification of SOC and N pools have also been reported under unmined agricultural soils [40,41]. These trends indicate that C and N stratification in soil under RNT is probably caused by accumulation of crop residues on the surface, and the lack of stratification under RCT may be due to incorporation of crop residues into the plow layer by tillage.

Similar to the bulk soil, the SOC concentrations in each aggregate-size class was also more in the top 10 cm layer, and generally decreased with increase in soil depth (**Figure 4**). With the exception of the >250 µm fraction in the 0 - 10 cm layer, the SOC concentration was generally more under Und HWF than in all other land uses for all aggregate size fractions. In the 0 - 10 cm depth, RCT contained more SOC concentrations in 0.25 - 0.5 mm and 0.5 - 1 mm aggregate sizes than those from RNT and RP treatments. In general, the SOC concentration was similar in the 1 - 2 mm fractions among RCT and RNT treatments but lower under RP treatment. In the 2 - 5 mm aggregate fraction, the RNT land use contained more SOC concentration than RCT and RP treatments. For aggregates >5 mm, the SOC concentration was more under RP than RCT and RNT treatments. In the 10 - 20 cm depth, the SOC concentration was the highest under Und HWF and the lowest under RP in all aggregate size fractions. Only minor differences in SOC concentration in aggregates were observed among other fractions and land uses. In addition, only little variations were observed in SOC concentration in the lower soil depths.

The RMSs could potentially act as a sink for atmospheric CO_2 [17,19,20,22,24]. Data from this study indicated that the RMSs under pasture accumulated SOC at higher rates than those under arable land use. Further, RMSs under pastoral land use increased SOC pool by 14% or 0.5 $Mg \cdot ha^{-1} \cdot yr^{-1}$ and 30% or 0.9 $Mg \cdot ha^{-1} \cdot yr^{-1}$ relative to RNT and RCT, respectively. This trend of higher SOC pool under managed pasture relative to arable land suggests that land use plays major role in SOC accumulation in RMSs. These data also suggest that even with similar nutrient input, RMSs under cropland do not maintain high SOC sequestration rates as observed under silviculture and pastoral land uses. Such a trend may be attributed to reduced aggregation in cultivated soils (**Figure 3**), thereby limiting aggregate-protected SOC in cropland soils.

3.3. Microbial Biomass and Mineralizable Carbon

Concentrations of MBC ranged from 0.29 to 0.53 $g \cdot C \cdot kg^{-1}$ in the 0 - 10 cm layer, and 0.05 to 0.21 $g \cdot C \cdot kg^{-1}$ in the 10 - 20 cm layer (**Table 1**). Among the reclaimed sites, the MBC was more under RP than RCT and RNT for both 0 - 10 and 10 - 20 cm soil depths. Overall, the MBC was more under the undisturbed soils than under the RMSs (**Table 1**). Microbial biomass C is a living component of SOC, a reservoir of nutrients and an important determinant of nutrient cycling in soils. The size, composition, activity, and ratio of MBC relative to SOC have been evaluated as indicators of state of the soil ecosystem with regard to degradation and recovery from disturbance [23,42]. These data suggest that disturbances associated with mining and reclamation were detrimental to microbial populations, resulting in reduction of MBC by 39%, 53% and 21% under RCT, RNT and RP compared to the undisturbed forest and pastoral sites for the first 22 years after mining. Similar results indicating 56% decline in MBC 20 years after reclamation and general decline in microbial community have been reported by Mummey *et al*. [26,27]. Soil microorganisms are sensitive to disturbances [43], and alteration of microbial community in terms of total biomass and species composition after mining and reclamation disturbances have also been reported [23,25,44]. In cultivated RMSs, tillage practices (NT and CT) had no significant influence on MBC in the 0 - 10 or 10 - 20 cm layers (**Table 1**). These results are contrary to those reported by Jacinthe and Lal [44] who observed significant increase in MBC in the 0 - 5 cm soil layer under NT compared to CT in reclaimed cropland of southwestern Indiana. Lack of response in this study may be attributed to application of cow manure at these sites which tends to favor microbial community restoration. The MBC was correlated with SOC and total N (**Figure 5**), suggesting that microorganisms in RMSs rely on soil organic matter (SOC and total N) as their main source of Cand energy.

The MIN-C concentration ranged from 4.1 to 5.5 $g \cdot C \cdot kg^{-1}$ and 2.2 to 2.6 $g \cdot C \cdot kg^{-1}$ for 0 - 10 and 10 - 20 cm depths, respectively (**Table 1**). The MIN-C accounted for up to 25% of the SOC concentration in the top 0 - 20 cm layer. The MIN-C concentration was significantly correlated with soil organic C and total N (**Figure 5**). The MIN-C concentration was nearly twice as much in the 0 - 10 cm layer compared to 10 - 20 cm layer. MN-C concentration was generally greater under the undisturbed sites (Und HWF and Und P) than the disturbed sites. The concentration of MIN-C did not differ significantly among the three land managements for the RMSs sites. Lower MIN-C under RMSs sites may be attributed to accelerated mineralization of SOC from the stored topsoil, which reduces mineralizable fraction of SOM.

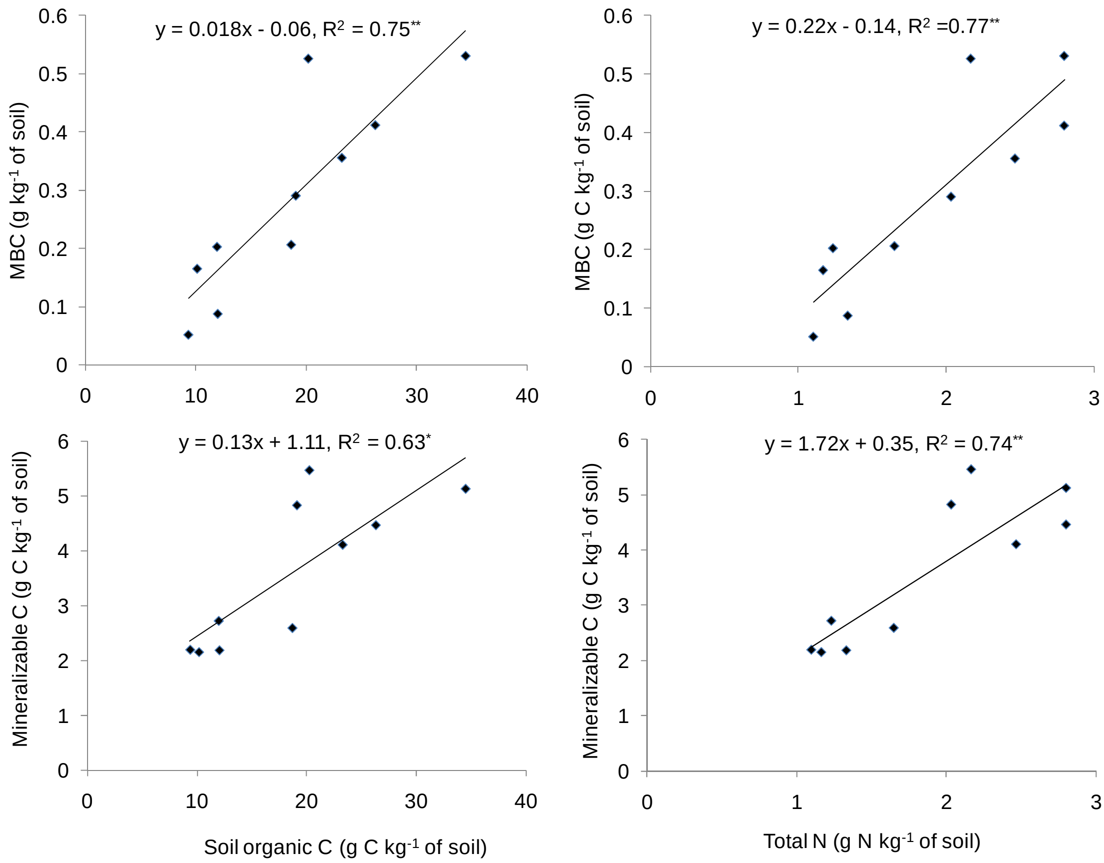

Figure 5. Relationships between soil microbial biomass carbon and soil organic carbon and total nitrogen in top 0 to 20 cm soil layer in reclaimed cropland of eastern Ohio.

4. Conclusion

Agricultural use is one of common post-reclamation land use in eastern Ohio. However, C dynamics and sequestration potential of RMSs under crop land is not well understood. This study evaluated tillage and pasture management on soil physical properties and SOC dynamics in 22 yrs old RMSs managed for agricultural use eastern Ohio. Results indicated that RMSs under no tillage and pasture had significantly greater water-stable aggregates and mean-weighted diameter in the top 10 cm soil layer than those under continuous tillage, suggesting improved soil structure under these land uses. The RMSs under pasture sequestered SOC at 30% higher rate or 0.9 $Mg \cdot ha^{-1} \cdot yr^{-1}$ than RMSs under conventional tillage. In addition, RMSs under pasture sequestered SOC at 14% higher rate or 0.5 $Mg \cdot ha^{-1} \cdot yr^{-1}$ than those under no tillage. Overall, the disturbances associated with mining and reclamation reduced the microbial biomass carbon by 21% to 39% compared to undisturbed pasture and forest land uses. The data from this study suggested that agricultural land use could be less efficient for microbial restoration and SOC sequestration compared to forest and grassland under RMSs. However, more data are needed to evaluate the impact of agriculture on ecosystem restoration and SOC sequestration in RMSs.

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