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Soil Carbon Enhancement in Graded and Ungraded Reclaimed Minesoil Under Forest and Pasture in Ohio, USA

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ABSTRACT

Strip mining, a major industry in Ohio and elsewhere, causes drastic soil disturbance with severe adverse impacts on the soil and environment. Therefore, reclamation of mined soil is essential to enhancing soil quality and environment characteristics numerous benefits of reclaiming minesoil (e.g. water quality, C sequestration) are attributed to soil conservation and decrease in runoff and erosion risks. Thus, reclamative effects of establishing forest and pasture with and without topsoil application on soil quality and carbon sequestration were studied on minesoil in Ohio. The chronosequence sampled for soil organic carbon (SOC) sequestration without topsoil was greater than 30 years because of the implementation of the new strip mine law in 1972 after which, topsoil application on spoils became mandatory. However, chronosequence studies for the graded sites that had topsoil applied to it included 0 to 25-year period with 5-year increments. The SOC pool for 0 to 30 cm depth for the undisturbed control sites was 56.6 MgC ha^{-1} for forest and 66.3 MgC ha^{-1} for pasture. In comparison, the SOC pool in the reclaimed soil with topsoil application for 0 to 30 cm depth after 25 years was 58.9 MgC ha^{-1} for forest and 62.7 MgC ha^{-1} for pasture. Without topsoil application, the SOC pool in the 0 to 30 cm depth after 30 years of reclamation was 51.5 MgC ha^{-1} in forest and 58.9 MgC ha^{-1} in the pasture. With SOC sequestration of 25 to 35 MgC ha^{-1}, reclamation of 1.8 Mha of minesoil in the U.S. has a potential to sequester 45 to 63 Tg C.

INTRODUCTION

Some mining companies in Ohio reclaimed minesoils during 1930's and 1940's, even though the first reclamation law was not passed until 1948. These reclamative attempts were simple and ad hoc without adequate planning and the necessary follow-up. With the passage of a series of strip mining laws in Ohio between 1948 and 1965, it became mandatory for mining companies to reclaim the mined land. The most comprehensive and effective strip mining law in Ohio, largely pertaining to reclamation was passed in 1972 (ODNR, 1999). This law requires re-grading of the mine spoil to approximate pre-mining land contour, replacing the topsoil, and establishing a vegetative cover by the mine operator before the release of reclamation bond. The federal Surface Mining Control and Reclamation Act (SMCRA) of 1977, which brought this requirement to the federal level, followed the 1972 Ohio law. Pre-1972 reclaimed lands did not have any topsoil applied to the spoils and are termed "ungraded" (the topsoil was part of the total overburden and treated as part of the spoil) whereas post-1972 reclaimed lands have stored topsoil applied on spoil material and are termed "graded". Comparison of graded and ungraded mine lands for specific parameter is outlined in Table 1.

Table 1. Differences between graded and ungraded minesoil reclamation strategies (Holl and Cairns, 1994; Skousen et al., 1994).

Parameter	Graded	Ungraded
Topsoil	Topsoil stored before mining is applied on the spoils to an average depth of 25-30 cm	No topsoil applied separately on the spoil before 1972 in Ohio
Land use	Mostly forests	Mostly pasture and hayland
Soil structure	Presence of granular to subgranular structure after 10-15 years of reclamation. Coarse fragments at depths >30cm	Even distribution of coarse fragments and signs of soil development after 20 years of reclamation
Compaction	High	Low
Aeration	Very low in the upper layers and therefore anaerobic conditions may prevail in the subsoil below 30 cm depth	As the spoil is evenly distributed, aeration is high and homogenous
Macropore	Only in depths >30 cm	Throughout the soil profile
Infiltration rate	Low	High
pH	Mostly neutral to alkaline and sometimes acidic	Mostly acidic
Nutrient availability	Moderate	Low
Biomass productivity	Low in the early years of reclamation but may be high after 15-20 years	Consistently low
Soil Organic Carbon (SOC)	Overall sequestration high	Overall sequestration low

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Table 2. Plant species used in graded and ungraded systems under forest and pasture reclamation strategies (Holl and Cairns, 1994; Skousen et al., 1994).

Treatment	Graded	Ungraded
Forest	Most of the *Pinus* species. *P. flexilis, P. nigra, P. resinosa, P. sylvestris, P. taeda, P. Virginiana* and *Abies saccharum, Fraxinus americana, Juglans nigra. Leriodendron tulipifera*	Mixed hardwood species. *Abies spp.,Artemisia tridentata, Betula spp., Fraximus spp., Junipers spp., Malus spp., Picea spp., Pinus spp., Populus spp., Quercus spp., Robinia spp.,*
Pasture	*Andropogon gerardi, A. scoparius, Dactylis glomerata, Festuca arundinacea, Panicum virgatum, Phleum pratense, Lotus corniculatus, Medicago sativa,*	*Agrostis alba, Dactylis glomerata, Festuca elatior, Phleum pretense, Poa pretensis, Trifolium pretense, T. repens*

While increasing the cost, an important impact of these laws and acts was successful establishment of the vegetation on the reclaimed minesoil, which was adversely impacted (during the first 5 to 15 years) by soil compaction associated with intensive grading and low inherent soil fertility (Powell, 1988). The potential of SOC enhancement in minesoils is dependent on biomass productivity, root development in sub-soil and changes in mine soil properties resulting from overburden weathering (Haering et al., 1993). Improvement in soil aggregation is an important factor influencing SOC sequestration in soils (Boerner et al., 1998; Malik and Scullion, 1998; Lal, 1998).

Mining exacerbates soil degradation, and accentuates depletion of the SOC content of the disturbed soil. Therefore, SOC content of the disturbed soil is below their potential relevant to the specific ecosystem. Therefore, these experiments were designed to test the hypothesis that reclamation of disturbed minesoils can enhance SOC content and improve soil quality. In accord with this hypothesis, the objective of this study was to measure the rate and magnitude of increase in SOC pool through reclamation of disturbed minesoils.

Reclamation of Minesoil and SOC Enhancement

Reclamation activities in the Appalachian region during 1930s involved establishing tree cover of mixed hardwood species (Plass and Powell, 1988). Important factors considered in developing reforestation plans included climate, minesoil characteristics, and economic and regulatory compliance. In comparison, post-1972 reclamation strategies in Ohio involved establishing improved pastures, a mixture of vigorously growing grass species usually in combination with legumes (Ries and Stout, 1988). Traditional or unimproved pastures, which consist of volunteer grasses and legumes, have also been used. Specific soil-related constraints to minesoil reclamation were low pH, soil erosion, elemental toxicity (e.g. Al, Mn), and non-availability of N, P and K in the spoil (Barnhisel and Hower, 1997; Hossner, 1997). The data in Table 2 show common tree and pasture species grown for the two reclamative systems. The reclaimed forests and pasture are thinned and/or harvested from time to time, a practice that affects biomass productivity and SOC enhancement. The below ground biomass which contributes to SOC enhancement and sequestration is another factor that merits consideration, but the relevant data are not available.

MATERIALS AND METHODS

Site description and sampling

Measurements of SOC enhancements in reclaimed minesoils were done on sites in Morgan, Muskingum and Noble counties of Ohio. The reclaimed minesoils are owned and operated by Central Ohio Coal Company, a subsidiary of the American Electric Power Company. During 1930's, mining was relatively less detrimental to soil because the technology used was suitable only for the mining of shallow coal seams. Subsequent to shallow mining, the spoil (mixture of topsoil and overburden) was spread and the land planted to trees. Currently, the mining process involves clearing the secondary forest established since the first mining in the 1930's, removing and storing the topsoil, removing overburden and coal, grading and establishing the vegetative cover. Sites selected for the present study were mined completely, and subsequently put under final restorative land use. Predominant soils of the region are classified as fine, loamy, mixed mesic Aquultic/Ultic/Typic Haplustalfs. There is no classification of unreclaimed and reclaimed minesoils though the material is often classified on the basis of pH, texture, stoniness, dominant slope, effectiveness of the reclamation, land use, etc. (Carter *et al.,* 1974).

Soil samples were obtained both for the graded and the ungraded sites during 1997, also used as reference or baseline year. Soil sampling was the most difficult for the ungraded areas of both forest and pasture sites due to poor access and difficult location of these sites. A chronosequence consisting of 30, 35, 40, 45 and 50 year old reclaimed sites, corresponding to reclamation since 1967, '62, '57, '52 and '47, respectively, were chosen for ungraded sites. A comparative chronosequence of 0, 5, 10, 15, 20, and 25-year-old reclaimed sites corresponding to reclamation since 1997, '92, '87, '82, '77, and '72, respectively, were chosen for the graded sites. The criteria for choosing the sampling sites included similarity of topography and coal mining from similar geologic series thus assuring that there is negligible variation in spoil (overburden).

Table 3. Comparison of graded and ungraded system after 25 and 30 years of reclamation respectively

Ecosystem	Graded	Ungraded
Forest	Dark, many fine, very fine and medium roots with granular structure between 0 to 8 cm, some roots extend up to 20 cm, few coarse to thick roots extend beyond 30 cm, increased porosity, and hydraulic conductivity and less compaction, boundary with the spoil at 30 cm less apparent. Few rocks with more of weathered material with blocky to subangular structure in the spoil material.	A very distinct formation of dark horizon between 0 to 15 cm depth and good accumulation of litter on the surface. The roots extend in all directions, with strong evidence of soil development and weathering. The spoil is more homogenous. Roots penetrate to a depth of 1 m and sometimes grow laterally. A coarse sandy texture with high porosity. Soil pockets found deep in the profile contaminated with coal, shale and other spoil material.
Pasture	0 to 3 cm depth have granular structure and dark horizonation, possibly the formation of distinct A horizon, many roots between 0 to10 cm, medium roots with somewhat dense distribution between 10 to 30 cm depth. The spoil material is slightly weathered and the spoil horizon is distinct below 30 cm. The roots are few beyond 30cm depth and grow laterally along the coarse material.	The root system is prolific in the 0 to 20cm depth with a very distinct dark horizonation in the upper 0 to 5-cm depth. The profile is homogenous in the top 30 cm but has distinct coarse structure below. The roots do not penetrate beyond 60-cm depth and are limited by the coarse fragments.

Soil analysis

Soil samples were obtained for 0 to 15 and 15 to 30 cm depths by digging soil profiles using a backhoe. A total of three sub samples were obtained for each depth and composited. Soil bulk density was determined by the core method (Blake and Hartge, 1986), and corrected for gravel content assuming the particle density of 2.65 Mg m^{-3}. The whole soil samples were ground to pass through 0.5 mm sieve prior to determining the carbon content. An average sample amount of 0.4 to 0.5 g was used to analyze SOC content using the Walkley and Black method (Nelson and Sommers, 1986). The method was calibrated using standard soil samples of known SOC content. Soil aggregates larger than 2 mm were excluded from analyses as the sample contained only small amounts of soil, but had large proportion of gravel and organic litter and debris. The SOC content for 0 to 30-cm depth was calculated. It was difficult to obtain soil samples below that depth because of the large concentration of stones. Most roots were confined to the top 30-cm layer. The SOC pool was computed on a volume basis by multiplying C content (as fraction) with soil bulk density and sampling depth using the following equation (Lal, 1998),

$$\text{MgC ha}^{-1} = \text{C x Corrected } \rho_b \text{ (Mg m}^{-3}\text{) x 0.30 m x } 10^4 \text{ m}^2\text{ha}^{-1}$$

where ρ_b is soil bulk density.

Statistical analysis of the data was done to compute the analysis of variance (ANOVA) table. Differences among mean were assessed by using the least significant difference (LSD). The statistical package MINITAB v13.1 was used for all data analysis (Minitab, 2000).

RESULTS AND DISCUSSION

Description of the reclaimed sites

Soil structure improved over time in both forest and pasture, primarily due to the physical action of the roots and its impact on the development of the minesoil profile. Regardless of the vegetation, graded systems developed better soil profile than the ungraded system (Table 3).

Soil organic carbon pool

Total biomass productivity of the forests after 25 to 30 years of reclamation may be more than that of the pastures, yet the potential of pastures to sequester SOC maybe high (Lal, 1997). The SOC pool of undisturbed forest and pasture to 30 cm depth was 56.6 MgC ha^{-1} and 66.3 MgC ha^{-1}, respectively, and is assumed to be in equilibrium. The data showed that potential of the graded system to enhance SOC was higher than that of the ungraded system and that of the pasture was higher than the forest.

The SOC pool for 0 to 30 cm depth in the graded system increased from an initial level of 21.8 MgC ha^{-1} to 58.9 MgC ha^{-1} for the forest, and from 26.1 MgC ha^{-1} to 62.7 MgC ha^{-1} for the pasture system (Figure 1). Temporal changes in SOC pool under graded forest and pasture shown in Figure 1 indicate that SOC pool in 25 year old reclaimed forest sites exceeded that of the undisturbed forest by 2.25 MgC ha^{-1}. The SOC pool of the reclaimed pasture sites has yet to attain the steady state level of the undisturbed pasture, and is less by 3.6 MgC ha^{-1}, even after 25 years of reclamation. The rate of SOC enhancement for the graded system was 2.0 MgC ha^{-1} yr^{-1} for forest and 2.1 MgC ha^{-1} yr^{-1} for pasture.

The SOC pool for 0 to 30 cm depth in the ungraded system increased from 51.5 MgC ha^{-1} in the 30th year to 54.9 MgC ha^{-1} in the 50th year for the forest and from 58.9 MgC ha^{-1} to 61.5 MgC ha^{-1} for the pasture (Figure 2). Both ungraded forest and pasture systems had not attained the SOC pool of the undisturbed forest and pasture even after 50 years of reclamation. The difference in SOC pool was 1.7 MgC ha^{-1} between undisturbed forest and ungraded reclaimed forest of 50 years, and 4.8 MgC ha^{-1} between undisturbed pasture and ungraded reclaimed pasture of 50 years. The rate of SOC enhancement was 1.7 MgC ha^{-1} yr^{-1} for the ungraded forest and 1.9 MgC ha^{-1} yr^{-1} for the

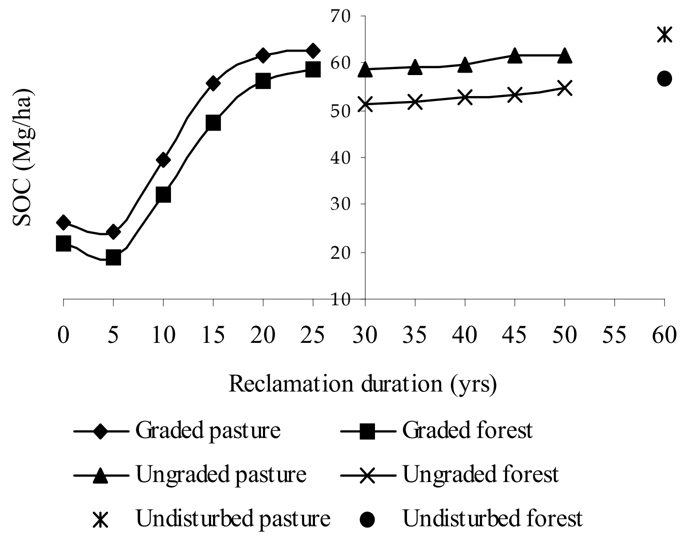

Figure 1. SOC pool in the different systems in comparison to undisturbed control pool.

Table 4. SOC pool (Mg ha^{-1}) difference between different systems.

Treatment	Graded [1]	Ungraded [2]	Difference (Graded - Ungraded)	LSD (0.05)
Forest	58.9	54.9	4.0	ns
Pasture	62.7	61.5	1.2	**
Difference (Pasture - Forest)	3.8	6.6		
LSD (0.05)	ns	***		

[1] - 25 years of reclamation; [2] - 50 years of reclamation; ns - not significant; * - significant.

ungraded pasture.

The data in Table 4 show that SOC sequestration potential is more for pasture than forest in both graded and ungraded systems. The SOC pool in pasture was more than that of the forest by 3.8 MgC ha^{-1} in the graded system after 25 years and by 6.6 MgC ha^{-1} in the ungraded system after 50 years of reclamation. There was no significant difference between graded forest and graded pasture at 95% level of probability. However, there was significant difference between ungraded forest and ungraded pasture at 95% level of probability. The potential of graded compared with ungraded forest system to enhance SOC was more by 4.0 MgC ha^{-1} and that of graded compared with ungraded pasture was more by 1.2 MgC ha^{-1}. There was no significant difference between graded forest and ungraded forest at 95% level of probability but there was significant difference between graded pasture and ungraded pasture at 95% level of probability.

CONCLUSIONS

Because of significant benefits to the environment, the strategy of ecosystem restoration has important policy implications. The data on restoration of drastically disturbed minesoils in Ohio show restoration potential of 25 to 35 MgC ha^{-1} over a 25-year period. If these rates were applicable on 1.8 Mha of drastically disturbed lands in the U.S., the total potential of C sequestration in these lands is 45 to 63 Tg over a 20 to 30-year period. In addition, there are also ancillary benefits with regards to soil erosion control, reduction in siltation of water reservoirs and waterways, and decrease in transport of pollutants to natural waters.

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