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Report Title: Carbon Sequestration in Reclaimed Mined Soils of Ohio

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ABSTRACT

This research project was aimed at assessing the soil organic carbon (SOC) sequestration potential of reclaimed minesoils (RMS). The experimental sites were characterized by distinct age chronosequences of RMS and were located in Guernsey, Morgan, Noble, and Muskingum Counties of Ohio. Restoration of disturbed land is followed by the application of nutrients to the soil to promote the vegetation development. Reclamation is important both for preserving the environmental quality and increasing agronomic yields. Since reclamation treatments have significant influence on the rate of soil development, a study on subplots was designed with the objectives of assessing the potential of different biosolids on soil organic C (SOC) sequestration rate, soil development, and changes in soil physical and water transmission properties. All sites are owned and maintained by American Electric Power (AEP). These sites were reclaimed by two techniques: (1) with topsoil application, and (2) without topsoil application, and were under continuous grass or forest cover.

Findings and Conclusions from the Research as a Whole

The spatial variability of chemical and physical properties at reclaimed mine sites without topsoil application was often high, and, therefore, valid statistical comparisons among sites of the age chronosequence severely altered. Taking many more soil samples is a requirement to address this high variability. Thus, the SOC sequestration over time at reclaimed coal mine sites without topsoil application can probably not be determined at economically justifiable expenditures. In addition, during this study a major difficulty in addressing SOC sequestration in RMS became evident. The SOC at all studied sites contains coal C from mining activities. Thus, changes in

SOC concentrations and pools over time in chronosequence studies are severely affected by unknown contributions of coal C to SOC at each site.

At reclaimed sites with topsoil application, the spatial variability in chemical and physical properties was lower. Thus, SOC sequestration over time can probably assessed with sufficient accuracy. Similar to the chronosequence without topsoil application, however, the contribution of coal C to SOC needs to be determined. For soil properties which are relatively stable over time, however, the spatial variability created by the reclamation practice needs also to be considered during soil sampling.

The soil properties at the subplots with biosolid application on the topsoil showed also a high spatial variability which severely interferes with the assessment of the potential of biosolid application in mined soil reclamation. Most importantly, the duration of this experiment was too short to detect any changes in SOC. Only if biosolid application results in increased root C inputs by promoting belowground productivity and by promoting the soil microbial biomass, increases in SOC in RMS after biosolid application may occur. On the other hand, N fertilization of RMS has also the potential to reduce SOC by promoting decomposition. Thus, long-term studies on larger plots are required to assess the potential of biosolid application for SOC sequestration on reclaimed mine sites. Similar to the plot-scale studies, separating coal C from SOC is a requirement for the assessment of the potential of biosolid application for SOC sequestration in RMS.

Models for predicting SOC over time could only be developed for RMS with topsoil application and under continuous grass cover. The following exponential regression models were obtained:

$SOC_{(0\text{-}15\ cm)}\ (g\ kg^{-1}) = 4.8439 * \ln(time) + 0.2785$

$SOC_{(15\text{-}30\ cm)}\ (g\ kg^{-1}) = 1.2265 * \ln(time) + 1.6583$

$SOC_{(0\text{-}15\ cm)}$ (Mg ha^{-1}) = 6.021 * ln (time) + 1.9565

$SOC_{(15\text{-}30\ cm)}$ (Mg ha^{-1}) = 1.9278 * ln (time) + 0.4997

The "SOC" values, however, must be corrected for coal C as was previously reported in many Technical Reports. Specifically, the major requirement to model SOC changes in RMS over time is the correction of SOC data for temporal invariant coal C contributions.

For all other sites in the age chronosequence (i.e., forest and grass sites without topsoil application; forest sites with topsoil application), the high spatial variability in soil properties did not allow the development of valid models. The soil sampling scheme used in this study was not adequate to address the spatial variability at the heterogeneous sites. In particular, it is probably impossible to determine and model SOC sequestration over time at economically justifiable expenditures for RMS under forest.

In summary, for subsequent studies on SOC sequestration in RMS the recommendations derived from this study include (i) separating coal C from SOC is essential, (ii) taking more soil samples per site to address the spatial variability, in particular at site reclaimed without topsoil application, (iii) sampling soil until the maximum rooting depth, (iv) determining root derived and soil microbial biomass derived C input, and (v) determine the biological, chemical and physical factors causing the long-term stabilization of SOC as sequestration is aimed to increase the proportion of the most stable SOC fraction. To assess the potential of biosolids for mine soil reclamation and, in particular, SOC sequestration long-term studies on larger-scales are required considering the recommendations listed above.

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1 Experimental Sites

The experimental sites identified were: (1) reclaimed prior to the 1972 Ohio Mineland Reclamation Act or the 1977 Surface Mining Reclamation and Control Act (SMRCA), under continuous grass and forest and without topsoil application, and (2) reclaimed after the 1972 Ohio Mineland Reclamation act, which made application of topsoil mandatory for reclamation, under continuous grass and forest (Table 1). These sites are maintained by the American Electric Power (AEP) Co., and are located along the borders of Guernsey, Morgan, Noble, and Muskingum Counties of Ohio. At three sites with topsoil application and under continuous grass cover, biosolids were applied (Table 5). At each site, sixteen plots (4m X 4m) were constructed (or marked) using randomized complete block design during May 2004. Five treatments were applied in triplicate to these plots at each site, (e.g., Fertilizer (F): 224-50-92 N-P-K; Manure (M): 27 kg/plot; Compost (C): 24 kg/plot; Compost + Fertilizer (CF): 12 kg/plot + Fertilizer (112-25-46 N-P-K); Compost + Manure (CM): 12 kg/plot + 13 kg/plot). Equivalent amounts of nitrogen on mass basis were applied on each plot. A control treatment (no application) in triplicate was also selected in each experimental site.

Table 1. Age chronosequence of reclaimed mine sites

Site	County	Vegetation	Treatment	Reclamation	ID
Active Site	Morgan	Grass	-	-	UMS
Active Site	Morgan	Grass	Topsoil	2003	R03-G
Switchgrass	Noble	Grass	Topsoil	1987	R87-G
Wilds	Muskingum	Grass	Topsoil	1978	R78-G
Spencer grass	Guernsey	Grass	No topsoil	1969	R69-G
Singer	Guernsey	Grass	No topsoil	1962	R62-G
Dyes fork	Morgan	Grass	No topsoil	1956	R56-G
Tilton's run	Muskingum/Noble	Forest	Topsoil	1994	R94-F
Cumberland tree	Guernsey	Forest	Topsoil	1982	R82-F
Mt. Carmel	Morgan	Forest	Topsoil	1973	R73-F
Spencer plantation	Guernsey	Forest	No topsoil	1969	R69-F
Campsite D	Morgan	Forest	No topsoil	1962	R62-F
Dyes fork	Morgan	Forest	No topsoil	1956	R56-F

UMS: Unmined site

2 Spatial Variability and Rate of SOC Sequestration for an Age Chronosequence of RMS

Table 2 and 3 provide an overview of Technical Reports (TRs) with chemical and physical data addressing the spatial variability and rate of SOC sequestration for an age chronosequence of RMS separated for sites with or without topsoil application and under grass or under forest cover. In Table 4, journal articles are listed that contain discussions about the spatial variability and rate of SOC sequestration for an age chronosequence of RMS.

Table 2. Technical reports with chemical data for an age chronosequence of RMS

Report	Site ID	Depth (cm)	pH	EC	TN	SOC	TN pool	SOC pool	SOC aggregates	TN aggregates	IC	HF-soluble SOC	$Na_2S_2O_8$-resistant SOC	NaOCl-resistant SOC
41903R01	UMS, R03-G, R87-G, R78-G, R69-G, R56-G, R56-F	0-15, 15-30	**x**	**x**	**x**	**x**								
41903R02	R03-G, R87-G, R78-G, R69-G, R56-G, R56-F	0-15, 15-30					**x**							
41903R03	R82-F, R78-G	0-15, 15-30, 30-50			**x**	**x**	**x**	**x**						
41903R04	R82-F, R78-G	0-15									**x**			
41903R05	R69-G, R62-F, R62-G, R56-F, R56-G	0-15, 15-30	**x**	**x**			**x**	**x**						
41903R06	R03-G, R73-F, R69-G, R62-G, R56-F	0-15, 15-30							**x**	**x**				
41903R09	UMS, R94-F, R82-F, R78-G, R69-F, R56-G	0-15, 15-30							**x**	**x**				

EC: Electrical conductivity; TN: Total nitrogen concentration; SOC: Soil organic carbon concentration; IC: Inorganic carbon

Table 2 continued

Report	Site ID	Depth (cm)	pH	EC	TN	SOC	TN pool	SOC pool	SOC aggregates	TN aggregates	IC	HF-soluble SOC	$Na_2S_2O_8$-resistant SOC	NaOCl-resistant SOC
41903R11	UMS, R03-G, R94-F, R87-G, R82-F, R78-G, R73-F, R69-G, R62-F, R62-G, R56-F	0-15, 15-30	**x**	**x**										
41903R12	R03-G, R73-F, R62-G, R56-F	0-15, 15-30			**x**	**x**	**x**	**x**						
41903R13	R03-G, R73-F, R69-F, R62-F, R62-G, R56-F	0-15, 15-30										**x**	**x**	
41903R14	UMS, R78-G	0-15, 15-30					**x**	**x**						
	R69-F, R62-F	0-15, 15-30											**x**	
41903R15	UMS, R78-G	0-15, 15-30											**x**	
41903R16	R87-G, R82-F	0-15, 15-30											**x**	
	R69-F, R62-F	0-15, 15-30												**x**
41903R17	R03-G, R73-F, R62-G	0-15, 15-30												**x**

EC: Electrical conductivity; TN: Total nitrogen concentration; SOC: Soil organic carbon concentration; IC: Inorganic carbon

Table 3. Technical reports with physical data for an age chronosequence of RMS

Report	Site ID	Depth (cm)	Texture	Coarse fraction	ρ_b	VTP	VSP	AWC	Ks	i_C	I	WSA	GMD	MWD
41903R02	UMS, R03-G, R87-G, R69-G, R56-F, R56-G	0-15	**x**			**x**	**x**	**x**	**x**					
	R56-G, R69-G	15-30			**x**									
41903R03	R82-F, R78-G	30-50			**x**									
41903R04	R82-F, R78-G	0-15, 15-30, 30-50	**x**			**x**	**x**	**x**		**x**	**x**			
41903R05	R69-F, R69-G, R62-F, R62-G, R56-F, R56-G	0-15, 15-30	**x**		**x**									
41903R06	R03-G, R73-F, R69-G, R62-F, R62-G, R56-F,	0-15, 15-30										**x**	**x**	**x**
41903R10	R94-F, R73-F, R69-F, R62-F, R62-G	0-15, 15-30				**x**		**x**	**x**					
41903R11	UMS, R03-G, R94-F, R87-G, R73-F, R69-F, R69-G, R62-F, R62-G, R56-F, R56-G	15-30	**x**											
41903R12	R03-G, R73-F, R62-G, R56-F	0-15, 15-30		**x**	**x**									
41903R13	R69-F, R62-F	0-15, 15-30		**x**										
41903R14	UMS, R78-G	0-15, 15-30		**x**	**x**									

ρ_b: Bulk density; VTP: Volume of transmission pores; VSP: Volume of storage pores; AWC: Available water capacity; Ks: Saturated hydraulic conductivity; i_c: Steady state infiltration rate; I: Cumulative infiltration; WSA: Water stable aggregation; GMD: Geometric mean diameter; MWD: Mean weight diameter

Table 4. Publications Discussing Spatial Variability and/or Rate of SOC Sequestration for an Age Chronosequence of RMS

Authors	Title	Reference
Shukla MK, Lal R	Temporal changes in soil organic carbon concentration and stocks in reclaimed minesoils of southeastern Ohio	Soil Science 2005; 170:1013-1021
Lorenz K, Lal R	Stabilization of organic carbon in chemically separated pools in reclaimed coal mine soils in Ohio	Geoderma 2007; 141:294-301
Shukla MK, Lal R, VanLeeuwen D	Spatial variability of aggregate-associated carbon and nitrogen contents in the reclaimed minesoils of eastern Ohio	Soil Science Society of America Journal 2007; 71:1748-1757

Findings and Conclusions from the Research

Spatial Variability of Soil Properties

The variability of soil properties is related to spatial, temporal, or management-related factors. Each of these factors can partially or fully contribute to the variability of a soil property. Surface mining for coal is a management-related factor that changes the topography permanently, alters the soil structure permanently and drastically, and disrupts surface and subsurface hydrologic regimes. The 1972 Ohio Mineland Reclamation Act and the 1977 Surface Mining Control and Reclamation Act (SMCRA) made it mandatory that topsoil is removed, stored separately and spread on the post-mine site as the last step of reclamation. The SMCRA requires that reclaimed sites have to be created that support organisms in approximately the same percentage and number as it did before mining began. The topography and hydrologic patterns need to be reconstructed. Furthermore, the morphology of reclaimed soils should be similar to the pre-mining soils. Thus, reclamation under the Ohio Mineland Reclamation Act and the SMCRA contributes to the spatial variability of soil properties. Prior to both Acts, however, reclamation practices were not regulated and the spatial variability in soil properties is expected to be higher.

Age Chronosequence of RMS without Topsoil Application

The high spatial variability in RMS without topsoil application contributed to highly variable differences among slope positions at sites of different reclamation duration and land use. Statistical analyses indicated that more random samples need be taken to properly consider the data distribution of the most soil properties. For example, at R62-G, no significant differences were observed among upper, middle and lower slope positions for sand, silt and clay contents, bulk density, SOC, and EC for both depths (TR41903R05). The TN pools were different among the three slope positions for 0- to 15-cm depth only. Soil EC was higher for lower than upper and middle slope positions for 0- to 15-cm depth. In R69-G, differences among slope positions were observed for sand and silt content, and TN pools but only for 0-15 cm depth. In this depth at R56-F, TN and SOC pools were different among slope positions as was the case for sand, silt and clay contents for 15- to 30-cm depth. At R62-F, differences among slope positions were observed for SOC and pH for 15- to 30-cm depth. Only for 15- to 30-cm at R69-F, differences were observed in SOC pools.

The aggregate properties were also highly spatial variable among slope positions at RMS without topsoil application. For example, at R69-G WSA was higher for the lower than the middle slope position (TR41903R06). The GMD did not differ, and MWD was higher for lower than middle slope. No differences were observed in WSA, GMD or MWD among different landscape positions in R62-G. For 15- to 30-cm depth at the sites under grass cover R69-G or R62-G, no significant differences were obtained in WSA, GMD or MWD among different landscape positions. However, WSA, GMD and MWD values were higher for 0- to 15-cm than 15- to 30-cm depth for all landscape positions and sites. For the forest sites R62-F or R57-F, no differences in WSA, GMD and MWD were obtained in three landscape positions for either depth. However, WSA values were consistently higher for 0- to 15-cm than 15- to 30-cm for all three landscape positions in each of the forested site. Most GMD and MWD values were also higher for 0- to 15-cm than 15- to 30-cm depth across landscape positions.

The number of random samples taken was not sufficient to properly consider spatial distribution of VTP and AWC for 0- to 15-cm than 15- to 30-cm depths at R69-F, R62-F and R62-G

(TR41903R10). Mean, median, standard deviation, kurtosis, skewness, minimum and maximum of VTP and AWC for R69-F, R62-F and R62-G indicated that data were not normally distributed in 0- to 15-cm and 15- to 30-cm depths.

The standard deviations for the percentage coarse fraction were often high among landscape positions in both depths at R62-G, R56-G and R56-F (TR41903R12). This indicates a high spatial variability of this soil property among upper, medium and lower slope positions. Furthermore, standard deviations for SOC pools in 0- to 15-cm and 15- to 30-cm depth were often high among landscape positions at R69-F and R62-F (TR41903R13).

The high spatial variability in soil properties among landscape positions severely affected also the characterization of SOC stabilization. The percentages of SOC associated with minerals in 0- to 15-cm depth at R56-F and R62-G were highly variable among landscape positions, and standard deviations were often high (TR41903R13). Similar to the HF-soluble SOC pool in 0- to 15-cm depth, the mineral-associated SOC pool in 15- to 30-cm depth at R56-F and R62-G was highly variable among landscape positions, and standard deviations were often high. The standard deviations of C:N ratios of the residues of the NaOCl treatment were extremely high for upper and lower slope positions in 15-30 cm depth at R62-F and R69-F (TR41903R16). At R69-F, standard deviations for percentages SOC resisting treatment with NaOCl in 0- to 15-cm and 15- to 30-cm depth were high for upper and lower slope positions. Among the three landscape positions, standard deviations were often high for the pool of SOC resisting NaOCl treatment in both depths at R62-F and R69-F. At R62-G, standard deviations of NaOCl-resistant C concentrations and pools in both depths were also high (TR41903R17).

In summary, the spatial variability of chemical and physical soil properties at reclaimed sites without topsoil application was often high. This variability severely affected any statistical comparison among sites of the age chronosequence. If taking many more soil samples is feasible to address this variability is questionable. Thus, it is not known if SOC sequestration over time can be studied at sites without any regulation of the reclamation practice. The SOC sequestration at reclaimed coal mine sites without topsoil application can probably not be determined at economically justifiable expenditures. In addition, during this study a major issue in addressing SOC sequestration in RMS became evident. The SOC contains coal C from mining activities. Thus, changes in SOC over time by chronosequence studies are severely affected by unknown contributions of coal C to SOC at each site. Up to 91% (!) of "SOC" in RMS in southeastern Ohio with topsoil application was coal C (Ussiri and Lal 2008).

Age Chronosequence of RMS with Topsoil Application

In contrast to reclaimed sites without topsoil application, the spatial variability of soil properties was expected to be lower at sites reclaimed with topsoil application. The reclamation practices and vegetation cover, however, were also a source of the spatial variability. For example, soil bulk density at R82-F showed strong spatial dependence for 0- to 15-cm depth (TR41903R03). However, ρ_b showed moderate to weak spatial dependence for 15- to 30-cm and 30- to 50-cm depths. Moderate to weak spatial dependence was also observed in all depths at R78-G. The SOC pools also showed strong spatial dependence for all three depths at R82-F. Otherwise at R78-G, SOC pools were moderately spatially dependent for all depths. The statistical variability was low in soil bulk density and high in SOC concentrations and pools for 0- to 15-cm, 15- to 30-cm and 30- to 50-cm depths for both sites R82-F and R78-G. The results of descriptive statistics showed that soil bulk density, TN concentrations and pools, and SOC concentrations and pools were all normally distributed. This was also the case for most of the data of sand, silt and clay percentages, VTP, VSP, AWC, i_c and I (TR41903R05). The statistical variability was moderate to low in most soil properties including particle size. However, water transmission properties showed high variability for R82-F and R78-G. Sand content showed strong spatial dependence for 0- to 15-cm depth from both sites. However, silt and clay contents showed moderate to weak spatial dependence for both sites. The spatial variability for the combined data also showed moderate to low spatial variation. These results suggest that spatial variability exists at R82-F and R78-G and need to be addresses for a reliable estimation of SOC sequestration over time.

Similar to soils reclaimed without topsoil application, the aggregate properties were highly spatial variable among slope positions at RMS with topsoil application. For example, in 0- to 15-cm depth at R03-G WSA was higher on upper than middle or lower landscape positions (TR41903R06). The GMD did not differ among landscape positions but MWD of aggregates was higher on upper than middle or lower slope. On the other hand, in 15- to 30-cm depth no differences among landscape positions in WSA, GMD and MWD were observed but values were lower than in 0- to 15-cm depth. For 0- to 15-cm depth, the SOC concentrations did not vary among different landscape positions for > 2.00 mm aggregate fractions (macroaggregate) as well as for 0.25- to 2.00-mm fraction (mesoaggregate). However, in the 0.053- to 0.25-mm fraction (microaggregate), SOC concentration was higher for lower than upper or middle slope position. On the other hand, in 15- to 30-cm depth no differences in SOC concentrations associated with aggregate fractions were observed among the three landscape positions. In 0- to 15-cm depth, TN concentrations did not vary among landscape positions for any aggregate fraction. But in 15- to

30-cm depth, TN concentrations were higher for lower than middle slope position for all three aggregate fractions. At a forest site reclaimed with topsoil application (R73-F), WSA, GMD, MWD, and SOC and TN concentrations of aggregate fractions in both depths were not different among landscape positions.

The statistical validity of the comparison of SOC and TN concentrations associated with aggregate fractions among R87-G, R82-F and R78-G needs also to be improved by randomly taking more soil samples (TR41903R09). Specifically, the data were often not normally distributed and the determination of mean values for SOC and TN concentrations of aggregate fractions severely affected. In contrast to 0- to 15-cm depth, however, the spatial variability of SOC and TN concentrations in the > 2.00 mm fraction, 0.25- to 2.00-mm fraction and 0.053- to 0.25-mm fraction was lower in 15- to 30-cm depth. Thus, the soil variability was higher in surface horizons due to reclamation but also vegetation establishment and dynamics.

The spatial dependence of SOC and TN concentrations in sand, silt, clay and aggregate fractions, and GMD, MWD and WSA at R87-G, R82-F and R78-G in 0- to 15-cm depth ranged from moderate to high (Shukla et al. 2007). The most measured properties showed a high variation but the soil sampling scheme was supposed to be adequate for most attributes. To assess the influence of time on the spatial dependence of SOC contents, however, repeated measurements in each site as well as at additional sites are needed.

At forest sites with topsoil application (R94-F, R73-F), the number of samples taken was often not sufficient to properly address spatial distribution of VTP and AWC (TR41903R10). But at the newly compared to the older reclaimed forest sites, it may be sufficient to take fewer samples to characterize the spatial variability of water transmission properties. For certain properties that are relatively stable over time, however, the spatial variability created by reclamation persists and requires that more samples are taken for comparison among landscape positions and time. For example, standard deviations for percentages coarse fraction were often high for upper, middle and lower landscape positions at R03-G and R73-F (TR41903R12). This was also the case for the 30 samples taken across the sites R78-G, R82-F and R87-G (TR41903R14, TR41903R15).

High variability of HF-soluble SOC and SOC resistant to $Na_2S_2O_8$ among landscape positions affected also comparisons of SOC stabilization among sites (TR41903R13 – TR41903R17, Lorenz and Lal 2007).

In summary, the spatial variability of chemical and physical properties at reclaimed sites with topsoil application was lower than at sites without topsoil application. Thus, SOC sequestration over time can probably assessed with sufficient accuracy. Similar to the chronosequence without topsoil application, however, the contribution of coal C to SOC needs to be determined. Furthermore, for soil properties which are relatively stable over time the spatial variability created by the reclamation practice need to be considered during soil sampling.

3 Assessment of the Potential of Biosolids in Mined Soil Reclamation

Table 5 provides an overview about reports with chemical and physical data for the assessment of the potential of biosolids in mined soil reclamation.

Table 5. Technical reports with chemical and physical data for an age chronosequence of RMS with biosolid application

Report	Site ID	Depth (cm)	TN	SOC	TN pool	SOC pool	ρ_b	VTP	VSP	AWC	i_5	i_c	I
41903R07	R94-G	0-15	**x**	**x**	**x**	**x**	**x**						
		15-30											
		30-50											
	R87-G	0-15	**x**	**x**	**x**	**x**	**x**						
		15-30											
		30-50											
	R82-G	0-15	**x**	**x**	**x**	**x**	**x**						
		15-30											
		30-50											
41903R08	R94-G	0-15						**x**	**x**	**x**	**x**	**x**	**x**
		15-30											
		30-50											
	R87-G	0-15						**x**	**x**	**x**	**x**	**x**	**x**
		15-30											
		30-50											
	R82-G	0-15						**x**	**x**	**x**	**x**	**x**	**x**
		15-30											
		30-50											

TN: Total nitrogen concentration; SOC: Soil organic carbon concentration ; ρ_b: Bulk density; VTP: Volume of transmission pores; VSP: Volume of storage pores; AWC: Available water capacity; i_5: Infiltration rate after 5 minutes; i_c: Steady state infiltration rate; I: Cumulative infiltration

Findings and Conclusions from the Research

Potential of Biosolids in Mined Soil Reclamation

Biosolids were applied to subplots under grass cover at the sites Tilton's Run, Switchgrass and Cumberland (Tables 1 and 5). Treatments included various mixtures of fertilizer, manure and compost but the amount of N applied with the biosolids was comparable (TR41903R07). Fertilization was expected to promote the establishment of a grass cover but SOC changes over time were not expected within the duration of this study.

The subplots where compost or a compost/manure mixture was applied often had lower bulk densities than the subplots with inorganic fertilization or the control plots (TR41903R07). Thus, biosolid application apparently improved soil physical properties for root growth. If enhanced root growth contributed to the lower bulk densities needs to be studied in more detail by studying root profiles. Furthermore, the chronosequence of reclaimed sites with biosolids was characterized by decreasing soil bulk density with time (TR41903R07). Specifically, ρ_b in 0- to 15-cm, 15- to 30-cm and 30- to 50-cm depth at the site reclaimed in 1994 (R94-G) was higher than at the site reclaimed 1987 (R87-G) or 1982 (R82-G). This indicates soil "loosening" properties of grass roots but similar to the subplots studies of root distribution and turnover are required to assess the influence of enhanced root growth after biosolid application.

The SOC and TN concentrations and pools among the majority of subplots within each site were not different (TR41903R07). The time until changes in SOC and TN occur after biosolid application is much longer than the duration of this study. Only if biosolid applications enhance

root-derived and soil microbial biomass derived C inputs, changes in SOC will be detectable as roots and microorganisms are the major sources for SOC (Rasse et al. 2005).
Similar to the whole plots with topsoil application, the subplots where biosolids were applied on the topsoil were characterized by a high spatial variability of soil properties (Section 3.1.; TR41903R08). For example, the infiltration rate after 5 min showed a high variability among R94-G, R87-G and R82-G. Most of the data for water transmission were, however, normally distributed. The differences between the sites in available water capacity were variable among 0- to 15-cm, 15- to 30-cm and 30- to 50-cm depth. Otherwise, VTP and VSP in 0- to 15-cm and 15- to 30-cm depth were comparable among sites. The infiltration rates were higher at R87-G than at R94-G, and lowest at R82-G.

In summary, the soil properties at the subplots with biosolid application on the topsoil of reclaimed sites showed a high spatial variability which severely interferes with the assessment of the potential of biosolid application in mined soil reclamation. Most importantly, the duration of this experiment was too short to detect any changes in SOC. Recent studies point to the importance of (i) root C, and (ii) microbial biomass C as the main sources for SOC. Thus, only if biosolid application results in increased root C inputs by promoting belowground productivity and by promoting the soil microbial biomass increases in SOC in RMS after biosolid application may occur. In contrast, N fertilization on RMS has also the potential to reduce SOC by promoting decomposition (Khan et al. 2007). Thus, long-term studies on larger plots are required to assess the potential of biosolid application for SOC sequestration in RMS. Similar to the plot-scale studies, separating coal C from SOC is a requirement for the assessment of the potential of biosolid application for SOC sequestration in RMS.

4 Temporal Variability of SOC Sequestration Rate and Pools in a Reclaimed Mine Soil Chronosequence

Findings and Conclusions from the Research: Predicting Soil Organic Carbon on Mined Lands over Time

Model input variables

As discussed in Section 3.1, the high spatial variability of soil properties at sites without topsoil application potentially severely interacts with efforts to model SOC changes over time. In fact, initial statistical test showed that at the reclaimed sites without topsoil application (R69-G, R62-G, R56-G, R69-F, R62-F, R56-F), the variability in SOC changes with time was too high to develop any significant predictive models. Similar observations for RMS in Ohio were reported by Akala and Lal (2001). Thus, only SOC changes over time at sites where the reclamation practice included topsoil application (R03-G, R87-G, R78-G, R94-F, R82-F, R73-F) were considered for the development of predictive models.

A subset of the chemical and physical data from the technical reports were used as input variables for the development of models for predicting SOC on mined lands with topsoil application. The input data included the SOC concentrations corrected for inorganic C, and reported in the technical reports 41903R12, 41903R13, 41903R14, and 41903R15. The bulk density (ρ_b) data included in the model development were corrected for the proportion of coarse fragments (> 2mm), and reported in the technical reports 41903R12, 41903R13, 41903R14, and 41903R15. The SOC pool data included in the tested models were based on the corrected SOC concentrations and bulk density data as reported in the technical reports 41903R12, 41903R13, 41903R14, and 41903R15. Furthermore, the data for soil reaction (pH) reported in the technical reports 41903R01, 41903R05, and 41903R11 were tested for their suitability as input variable to predict SOC. The soil texture data reported in the technical reports 41903R02, 41903R04, 41903R05, and 41903R11 were also included during model development. For predicting SOC changes over time, the data were modeled separately for reclaimed mine sites under grass (R03-G, R87-G, R78-G) and under forest cover (R94-F, R82-F, R73-F). Two predictive model approaches were tested for their suitability, i.e., (i) multiple linear regression models to model the relation between SOC and chemical and physical soil properties, and (ii) exponential regression models to model SOC changes with time. The Statistical Package for the Social Sciences (SPSS Inc., 2007) and Microsoft Office Excel 2003 were used to develop and test the model equations.

Grass Sites with Topsoil Application

For predicting SOC concentrations and pools in 0- to 15-cm and in 15- to 30-cm depths for R03-G, R87-G and R78-G, multiple regression models were developed by including the subset of chemical and physical data listed above. The model for predicting SOC concentrations in 0- to 15-cm depth and the model variable time were highly significant ($p<0.01$). However, 53% of the variance in SOC concentrations could be explained by the following model:

$$\mathbf{SOC_{(0\text{-}15\ cm)}\ (g\ kg^{-1}) = 0.759 * time - 0.089 * silt - 0.509 * clay + 1.026 * pH + 7.355\ (Eq.\ 1)}$$

The results of the Durbin-Watson-test indicated that the model for predicting SOC concentrations in 0- to 15-cm depth was valid (Table 6). The Beta coefficients indicate the importance of independent model variables for the explanation of the dependent variable SOC as dimensional differences between variables were eliminated by standardization. Thus, the variables time and clay were of main importance for explaining the model for predicting SOC concentrations in 0- to 15-cm depth.

The model for predicting SOC concentrations in 15- to 30-cm depth was significant ($p<0.01$), and highly significant ($p<0.01$) for the model variable time. However, 62% of the variance in SOC concentrations could be explained by the following model:

$$\mathbf{SOC_{(15\text{-}30\ cm)}\ (g\ kg^{-1}) = 0.188 * time - 0.045 * silt - 0.046 * clay - 0.186 * pH + 1.041\ (Eq.\ 2)}$$

The results of the Durbin-Watson-test indicated that the model for predicting SOC concentrations in 15- to 30-cm depth was valid (Table 6). The standardized coefficients for Beta indicated that the variables time and silt were of main importance for explaining the model for predicting SOC concentrations.

Multiple linear regression models were also developed to predict SOC pools in 0- to 15-cm and in 15- to 30-cm depths. The model for predicting SOC pools in 0- to 15-cm depth and the model variable time were highly significant ($p<0.01$). However, 45% of the variance in SOC pools could be explained by the following model:

$$\mathbf{SOC_{(0\text{-}15\ cm)}\ (Mg\ ha^{-1}) = 0.832 * time - 0.019 * silt - 0.486 * clay + 2.238 * pH - 2.476\ (Eq.\ 3)}$$

The results of the Durbin-Watson-test indicated that the model for predicting SOC pools in 0- to 15-cm depth was valid (Table 6). The standardized coefficients for Beta indicated that the variables time and pH were of main importance for explaining the model predictions for SOC pools in 0- to 15-cm depth.

The model for predicting SOC pools in 15- to 30-cm depth was not significant ($p>0.05$), but significant ($p<0.05$) for the model variable time. However, 53% of the variance in SOC pools could be explained by the following model:

$SOC_{(15\text{-}30\ cm)}$ ($Mg\ ha^{-1}$) = 0.271 * time + 0.095 * silt – 0.051 * clay – 0.213 * pH – 0.140 (Eq. 4)

The results of the Durbin-Watson-test indicated that the model for predicting SOC pools in 15- to 30-cm depth was valid (Table 6). The standardized coefficients for Beta indicated that the variables time and silt were of main importance for explaining the model predictions for SOC pools in 15- to 30-cm depth.

In summary, for predicting SOC concentrations and pools in 0- to 15-cm and 15- to 30-cm depths at the sites under grass cover and reclaimed with topsoil application (R03-G, R87-G, R78-G), the following **input variables** need to be determined:

Reclamation duration (time)

Silt content

Clay content

pH

Table 6. Quality of multiple linear regression model parameters for predicting soil organic carbon at grass sites with topsoil application.

Regression model	R^2	Durbin-Watson-test	Model variable	Beta
		0-15 cm		
SOC (g kg^{-1})	.531	1.580	Time	.746
			Silt	-.046
			Clay	-.163
			pH	.115
SOC (Mg ha^{-1})	.446	1.520	Time	.641
			Silt	-.008
			Clay	-.121
			pH	.197
		15-30 cm		
SOC (g kg^{-1})	.615	1.683	Time	.781
			Silt	.163
			Clay	-.087
			pH	-.091
SOC (Mg ha^{-1})	.533	1.748	Time	.679
			Silt	.206
			Clay	-.058
			pH	-.063

For predicting changes in SOC concentrations and pools in 0- to 15-cm and in 15- to 30-cm depths over time, exponential regression models were developed without assuming equilibrium SOC concentrations or pools (cf. Akala and Lal 2001). This follows the assumption that SOC in the reclaimed mine sites is not in equilibrium as the maximum reclamation duration was only 26 years (R78-G). Many modelers argue that the equilibrium assumption for SOC is generally wrong (Wutzler and Reichstein 2007). In particular, soils that have been disturbed several centuries ago are not in equilibrium because of the slowly ongoing accumulation of the slowest SOC pool.

The changes in SOC concentrations in 0- to 15-cm depth over time at the grass sites reclaimed with topsoil application (R03-G, R87-G, R78-G) could be predicted by applying an exponential model shown by Equation 5:

$$\mathbf{SOC_{(0\text{-}15\ cm)}\ (g\ kg^{-1}) = 4.8439 * ln\ (time) + 0.2785\ (Eq.\ 5)}$$

This model, however, explains only 38% of the variance in SOC changes over time.

For 15- to 30-cm depth, 55% of the variance in changes in SOC concentrations over time could be explained by Equation 6:

$$\mathbf{SOC_{(15\text{-}30\ cm)}\ (g\ kg^{-1}) = 1.2265 * ln\ (time) + 1.6583\ (Eq.\ 6)}$$

The changes in the SOC pool in 0- to 15-cm depth over time could be predicted by a model shown by Equation 7:

$$\mathbf{SOC_{(0\text{-}15\ cm)}\ (Mg\ ha^{-1}) = 6.021 * ln\ (time) + 1.9565\ (Eq.\ 7)}$$

This exponential model explains 36% of the variance in SOC pools in 0- to 15-cm depth over time.

For 15- to 30-cm depth, the model shown by Equation 8 could explain 50% of the variance in changes of the SOC pool over time:

$$\mathbf{SOC_{(15\text{-}30\ cm)}\ (Mg\ ha^{-1}) = 1.9278 * ln\ (time) + 0.4997\ (Eq.\ 8)}$$

In summary, models for predicting SOC over time at the grass sites with topsoil application could be developed. However, a higher percentage of the variance in changes in SOC concentrations and pools over time could be explained for 15- to 30-cm than for 0- to 15-cm depth. Possible reason is the higher spatial variability in the uppermost compared to the underlying horizon as a consequence of grass vegetation development with time (cf. Shukla et al. 2007).

Intended Application

The models for predicting SOC concentrations and pools in 0- to 15-cm and 15- to 30-cm depths, and for predicting SOC changes over time can be applied to reclaimed grass sites in southeastern Ohio. The validity of the data for SOC concentrations and pools, however, must be improved by separating coal C contributions. Furthermore, the sites need to be reclaimed with topsoil application according to the 1972 Ohio Mineland Reclamation Act or the 1977 Surface Mining

Reclamation and Control Act (SMRCA). The grassland reclamation practices should include sowing species associated with comparable belowground microbial biomass communities, and plant-derived C input such as rye grass (*Lolium perenne* L.), timothy (*Phleum pratense* L.), birdsfoot trefoil (*Lotus corniculatus* L.), orchard grass (*Dactylis glomerata* L.), blue grass (*Poa pratensis* L.), alfalfa (*Medicago sativa* L.) and mammoth clover (*Trifolium pratense* var. *perenne* L.). The reclaimed sites have to be mulched annually with approximately 5-7.5 Mg hay or straw per hectare, and fertilized with 224 kg of NPK (19-18-9) per hectare. The grassland reclamation practices mentioned above are typical for southeastern Ohio (pers. commun. Brian Cox, forester, American Electric Power).

If the model equations are valid for grassland sites reclaimed by similar reclamation practices but located in other eco-physiographic regions needs to be tested. In particular, differences in local climate interact with the major C input pathway to the soil, i.e., plant photosynthesis and subsequent root-derived and microbial biomass C inputs. Also, when the reclamation practices include C4 grasses and legumes SOC accumulation may be increased by 193% and 522%, respectively (Fornara and Tilman 2008). Thus, grassland reclamation practices promoting higher root biomass and greater root biomass accumulation from the presence of highly complementary functional groups (i.e., C4 grasses and legumes) may result in higher SOC accrual.

Forest Sites with Topsoil Application

Similar to the grassland sites, multiple regression models were tested for their suitability to predict SOC concentrations and pools in 0- to 15-cm and in 15- to 30-cm depths for forest sites with topsoil application (R94-F, R82-F, R73-F) by including a subset of chemical and physical data. However, the models for predicting SOC concentrations and pools in 15- to 30-cm depth for the three sites were not significant ($p>0.05$) and are not shown.

The model for predicting SOC concentrations in 0- to 15-cm depth and the model variable pH were highly significant ($p<0.01$), and significant ($p<0.05$) for the model variable time. However, 44% of the variance in SOC concentrations could be explained by the following model:

$$\mathbf{SOC_{(0\text{-}15\ cm)}\ (g\ kg^{-1}) = 0.379 * time - 0.124 * silt - 0.076 * clay + 3.901 * pH - 7.639}\quad \textbf{(Eq. 9)}$$

The results of the Durbin-Watson-test indicated that the model for predicting SOC concentrations in 0- to 15-cm depth was valid (Table 7). The standardized coefficients for Beta indicated that the variables time and pH were of main importance for explaining the model for predicting SOC concentrations in 0- to 15-cm depth.

Multiple linear regression models were developed to predict SOC pools in 0- to 15-cm depth. The model for predicting SOC pools in 0- to 15-cm depth, however, was not significant ($p>0.05$), but significant ($p<0.05$) for the model variable pH. Only 18% of the variance in SOC pools could be explained by the following model:

$$\mathbf{SOC_{(0\text{-}15\ cm)}\ (Mg\ ha^{-1}) = 0.255 * time - 0.118 * silt - 1.000 * clay + 5.343 * pH + 13.067}\quad \textbf{(Eq. 10)}$$

The results of the Durbin-Watson-test indicated that the model for predicting SOC pools in 0- to 15-cm depth was valid (Table 7). The standardized coefficients for Beta indicated that the variables pH and clay were of main importance for explaining the model predictions for SOC pools in 0- to 15-cm depth.

Table 7. Quality of multiple linear regression model parameters for predicting soil organic carbon at forest sites with topsoil application.

Regression model	R^2	Durbin-Watson-test	Model variable	Beta
		0-15 cm		
SOC (g kg^{-1})	.441	2.118	Time	.389
			Silt	-.090
			Clay	-.034
			pH	.440
SOC (Mg ha^{-1})	.175	2.021	Time	.305
			Silt	-.376
			Clay	.626
			pH	2.170

In summary, for predicting SOC concentrations in 0- to 15-cm depths at the sites under forest cover and reclaimed with topsoil application (R94-F, R82-F, R73-F), the following **input variables** need to be determined:

Reclamation duration (time)

pH

Similar to the grass sites, exponential regression models were tested for predicting changes in SOC concentrations and pools over time in 0- to 15-cm and in 15- to 30-cm depths at the forest sites. However, the changes in SOC concentrations and pools in both depths were almost constant between 10 years (R94-F) and 31 years (R73-F). Akala and Lal (2001) reported this also for forest sites without topsoil application. Thus, models for predicting SOC on mined lands over time and under forest reclaimed with topsoil application could not be developed.

In summary, changes in SOC concentrations and pools over time for reclaimed mine sites under forest cover could not be modeled. One reason is the high small scale variability of SOC which is already observed in un-reclaimed forests (cf. Schöning et al. 2006). This variability could not be addressed by the spatially distributed sampling of a maximum of 30 soil samples. Furthermore, the variability in SOC may increase with increase in soil depth. For example, more than 300 soil samples need to be taken to detect a 10% change in SOC pools to 0.96-m depth under forest not disturbed by reclamation (Schöning et al. 2006). Furthermore, the fundamental requirement for baseline data in assessing SOC changes over time have not been met by the sampling scheme used in this study (e.g., VandenBygaart and Angers 2006). Another reason is the contribution of coal C to SOC. Recently, Ussiri and Lal (2008) reported that up to 91% of OC in RMS in Ohio was coal C, and its contribution increased with increase in soil depth. However, it is not known how much coal C contributed to SOC at the studied forest sites R94-F, R82-F and R73-F. Thus, the temporal changes in SOC from 10 to 31 years cannot be detected against the possible large but almost constant contributions of coal C at this pseudo-chronosequence of reclaimed forest sites. A recent analysis of C sequestration potential in reclaimed mine sites in seven east-central states including Ohio is therefore highly questionable as SOC probably contained large proportions of coal C (Sperow 2006). **Separating coal C from SOC is therefore the major prerequisite to model SOC on mined lands over time.**

5 References

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