DYNAMICS AND CHARACTERIZATION OF SOIL ORGANIC MATTER IN MINE SOILS SIXTEEN YEARS AFTER AMENDMENT WITH NATIVE SOIL, SAWDUST, AND SLUDGE

by

E. S. Bendfeldt, J. A. Burger*, W. L. Daniels, and C. M. Feldhake

Abstract: Soil organic matter (SOM) is an important indicator of soil quality and site productivity. Organic amendments may be a means for ameliorating mine soils and other soils that have been depleted of organic matter. In 1982, a mined site was amended with seven different surface treatments: a control, 30 cm of native soil, 112 Mg ha^{-1} sawdust, and municipal sewage sludge (SS) at rates of 22, 56, 112, and 224 Mg ha^{-1}. Four replicates of each treatment were installed as a randomized complete block design. Each replicate was subsequently split according to vegetation type: pitch x loblolly pine hybrid (*Pinus rigida* x *taeda*) trees and Kentucky-31 tall fescue (*Festuca arundinacea* Schreb.). Soil analyses of composite samples indicated that organic amendments initially improved C and N status of the mine soils, but after 16 years their levels converged to that of the control treatment. Tree volume and biomass were used as indices of the effects of organic matter content 16 years after initial amendment. Individual tree volumes of the sawdust and 22, 56, 112 Mg ha^{-1} SS treatments retained 18 to 26% more volume than the control. Overall, forage production was the same among treatments. Organic amendments improved initial soil fertility for crop establishment, but it appears that they will have little or no long-lasting effect on plant productivity.

Additional Key Words: organic amendments, reclamation, reforestation, soil fertility

Introduction

The disruption of natural ecosystems and the subsequent decline in soil productivity and water quality during coal mining operations were part of the impetus for the Surface Mining Control and Reclamation Act (SMCRA) of 1977. This legislation was also passed in anticipation of continued coal use and future land disturbances. A fundamental provision of the law requires that land disturbed by mining be reclaimed to its original use or one of higher value, and that its productivity be equal to or greater than it was before mining. Regulations based on this law require short-term success standards to judge if reclamation is adequate; however, due to the lack of full recovery of a functioning plant and soil system, initial productivity and 5-yr growth patterns may not be definitive indicators of general reclamation standards required by law. Sopper (1992) states that soil ecosystem stability is a function of soil organic matter (SOM) accumulation, transformations, and soil water and gas exchange processes that may require 30 years or more to come to equilibrium. Part of the intent of reclamation efforts is to restore soil functions as quickly as possible so vegetation can thrive and hydrological balance can be achieved. In order to accelerate the process, we hypothesized that organic amendments can be used to ameliorate mine soils and speed recovery to full productivity. We believe that knowledge of the dynamics and character of SOM and the role it plays in soil processes is critical for assessing whether short-term reclamation success standards are effectively representing long-term sustainable mine soil quality. To evaluate the dynamics of SOM within 16 years after reclamation, research was conducted on a mined site reconstructed with selected overburden material and amended with different organic surface treatments. Knowledge of the changing levels of SOM, associated soil properties, and subsequent vegetation response 16 yr after reclamation should help us judge the value of amending mine soils with organic materials.

---

[1] Paper presented at the 1999 National Meeting of the American Society for Surface Mining and Reclamation, Scottsdale, Arizona, August 13-19, 1999.

[2] E. S. Bendfeldt is a Graduate Research Assistant, J. A. Burger is Professor of Forestry, and W. L. Daniels is Professor of Crop and Soil Environmental Sciences at Virginia Polytechnic Institute and State University, Blacksburg, VA; and C. M. Feldhake is a Research Scientist, USDA-ARS, Beaver, WV.
*Corresponding author (jaburger@vt.edu).

Proceedings America Society of Mining and Reclamation, 1999 pp 225-235
DOI: 10.21000/JASMR99010225

https://doi.org/10.21000/JASMR99010225

Accordingly, the objectives of this study were:

1. To determine the effects of organic matter amendments on soil organic matter content, mineralizable nitrogen, and aggregate stability in mine soils after 16 years.
2. To determine the effects of these key soil quality variables on plant productivity.
3. To determine whether trees and herbaceous plants aggrade or degrade mine soil quality based on changing levels of the soil quality indicators.

Research Methods

Methods and Materials

The experiment was initiated in the coal mining region of southwestern Virginia in Wise County on the Powell River Project (37°00'N latitude and 82°41'W longitude). Mean annual precipitation and temperature is 1150 mm and 11°C. The soils on the site were classified as loamy-skeletal mixed mesic Typic Udorthents (Roberts, 1986). In April and May 1982, researchers from the Virginia Tech Crop and Soil Environmental Sciences (CSES) Department and Powell River Project personnel uniformly applied a 1m-deep base layer of 2:1 sandstone:siltstone overburden material over the study site prior to surface treatment applications. Seven organic amendment treatments were then applied, consisting of a control constructed of strictly overburden material, 30cm native soil composed of a mixture of A, E, B, C, and Cr horizon material from a neighboring forest soil, hardwood sawdust applied at 112 Mg ha^{-1}, and applications at the following rates 22, 56, 112, and 224 Mg ha^{-1} of aerobically digested municipal sewage sludge (SS). However, due to the detrimental effect the 224 Mg ha^{-1} sludge treatment had on initial tree seedling survival (Moss, 1986), the application rate was considered too high for tree establishment and was not analyzed in this study. The control, native soil, and sawdust plots each received additional fertilization with N-P-K at rates of 168, 147, and 137 kg ha^{-1}. The native soil plots were also limed at a rate of 7.8 Mg ha^{-1} to bring the pH (4.4) to a level comparable to the overburden material. The sawdust plots received an additional 336 kg ha^{-1} of slow release N (Isobutyl Di-Urea; IBDU) fertilizer to offset potential nitrogen immobilization caused by an initially high C:N ratio and increased microbial activity. All plots were mulched with 900 kg ha^{-1} straw, hydroseeded with 170 kg ha^{-1} KY-31 tall fescue (*Festuca arundinacea* L. Schreb.) seed and 940 kg ha^{-1} paper fiber mulch.

Four replicates of the surface treatments were installed as a randomized complete block design. Each replicate was subsequently split according to vegetation type to allow for parallel studies on the establishment and productivity of tree and herbaceous crops for reclamation ground covers. In April 1983, glyphosate (N-phosphonomethyl glycine) (Roundup 41S at 18.7 L ha^{-1}) was applied to the subplots designated for tree planting. Selective herbicide applications were annually applied (1982-1985) to the grass sub-plots to prevent the establishment of legumes and weeds. The tree sub-plots were originally planted to 12 pitch x loblolly pine hybrid (*Pinus rigida* x *taeda*) seedlings and 4 Loblolly pine (*P. taeda*) seedlings. During the second and third growing seasons (1984-1985), there was a significant treatment effect on seedling survival rates. The 112 and 224 Mg ha^{-1} SS treatments adversely affected seedling survival and were significantly lower than other treatments. After the fifth growing season, the composition of the herbaceous sub-plots were no longer maintained; leguminous and graminaceous species such as Sericea lespedeza (*Lespedeza cuneata* (Dum.) G.Don) and Orchardgrass (*Dactylus glomerata*) have seeded-in. The orchardgrass seed probably came from the straw mulch that was applied.

Soil Sampling and Characterization

Composite soil samples for each treatment combination of the organic amendment study were collected in March 1998 to a depth of 0-10 cm from three randomly-located subsamples within each subplot. Care was observed to avoid previous sampling sites by using a gridded map. Soils were air-dried and ground with a mortar and pestle to pass a 2 mm sieve; fine earth and coarse fractions were determined. Two bulk density soil cores were obtained from each subplot at a depth of 5-10cm using a double-cylinder, hammer-driven core sampler. Bulk density measurements for each core were measured on the fine earth fraction and whole soil. The fine earth fraction was determined by adjusting the total mass and volume of the cores according to coarse fragment content assuming a particle density of 2.65g cm^{-3}.

Total organic C and SOM was determined by the Walkley-Black wet oxidation method. (Nelson and Sommers, 1982). A companion dry combustion analysis of total organic C was performed using the Loss-on-Ignition Method (Sybron-Thermolyne Muffle Furnace, Inc.) at 550°C for 24hr. A light fraction determination of SOM content was made using a modified density flotation procedure of Strickland and Sollins (1987) and Gregorich and Ellert (1993). Oven-dried samples of the light fraction (<250 μm) were analyzed for total organic C by dry combustion with a LECO C analyzer. N was measured as NH_4^+-N colorimetrically on a Technicon Autoanalyzer II (Technicon Industrial systems, Tarrytown, NY) after a modified micro-Kjeldahl digestion (0.3g samples) (Strickland and Sollins,1987). Ash content was determined by placing an aliquot in a muffle furnace at 550° C for 4 hr.

Aggregate stability was determined using a wet sieving procedure (Kemper and Rosenau, 1986). Four grams of air-dried 1 and 2 mm aggregates were placed in sample cups with 70-μm screen bottoms and slowly wetted to approximate -33 kPa water potential capacity by aerosol misting. The samples were wet-sieved in the cups using de-ionized water, a stroke length of 1.3 cm, and a frequency of 35 cycles min^{-1} for 3 min. The stable and unstable aggregates were oven dried at 105°C, weighed, and the stable fraction was determined and calculated on a sand-free basis.

Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) were extracted with 1 M NH_4^+OAc solution buffered to pH 7 and concentrations determined by inductively coupled plasma spectrometry (ICP). Particle size analysis of the silt and clay fractions was performed by the hydrometer method (Gee and Bauder, 1986). Soil reactivity was determined with a pH electrode in a 2:1 water:soil extract. Exchangeable acidity was determined using a 1 N KCl replacing solution and titration to a phenolphthalien end point with a Mettler Dl2 auto-titrator (Mettler Instruments, Inc., Hightstown, NJ.). Available P was extracted with 0.5 M $NaHCO_3^-$ adjusted to pH 8.5. Extractable P concentration was determined using the modified Murphy-Riley ascorbic acid procedure and analyzed by spectrophotometry (Olsen and Sommers, 1982). Electrical conductivity (EC) was measured with a conductivity meter in a 5:1 water:soil extract and standardized to .01 M KCl reference solution (Rhoades, 1982). Subsamples were dried at 105°C for 24 hr to determine gravimetric moisture content.

Vegetation Sampling

In July 1997, tree survival rates were recorded. Tree heights and diameters were measured to obtain a relative volume index of individual tree growth, plot basal area and overall plot productivity. Heights of all the trees in the plot were measured to the nearest centimeter. Tree diameters at breast height (dbh $\approx$1.37 m above ground level) were measured to the nearest tenth of a centimeter. Trees were classified into dominant, co-dominant, and intermediate crown classes. Suppressed trees were not included in tree growth comparisons. After three growing seasons, Moss (1986) reported a significant treatment effect on seedling survival for the 112 and 224 Mg ha^{-1} sludge treated plots so tree height, diameter, basal area, and volumes were not statistically analyzed for treatment effects in 1997. Aboveground biomass was categorized into three vegetation classes (grass, legumes, and other) and separated within each plot. Composite samples for each cover class were obtained for each plot, dried to a constant weight at 65°C and weighed. Total biomass for each plot was then calculated.

Statistical Methods

The organic amendment study was a split block design, factor A being the six levels of organic amendment treatments (control, native soil, sawdust, and municipal SS at rates of 22, 56, and 112-Mg ha^{-2}), factor B the two levels of vegetation type (pitch x loblolly pine trees and herbaceous cover), and the interaction component of amendment x vegetation type. Analysis of variance was used to test treatment and vegetation type effects, and the interaction between treatment and vegetation type on soil fertility attributes and other soil parameters. Duncan's Multiple Range test was used for post-ANOVA mean separation comparisons at α = 0.1 level. PROC NLIN, a least squares non-linear regression procedure, was used to track and predict N mineralization potential and the rate change constant. All data analyses were performed using Statistical Analysis Systems software (SAS Institute Inc. Cary, NC).

Experimental Results and Discussion

Organic Matter Dynamics and Characterization

The organic matter content of the amended mine soils in this study varied after the first growing season commensurate with the amount of SOM added as part of the treatment (Figure 1). In 1982, the sawdust and 224 Mg ha^{-1} SS treatment plots contained the highest percentages of organic matter. The native soil treatment was a mixture of the A, E, B, C, and Cr horizons, therefore, SOM content was substantially lower than other treatments and actually no higher than the control treatment (Daniels et al., 1983). Soil organic matter in the sawdust-treated plots declined by almost one-half, while the plots treated with 112 Mg ha^{-1} SS treatments declined only slightly over the past 16 years. The other treatments accumulated more SOM with all treatments converging toward 4% SOM (Figure 1). The native-soil treated plots accumulated significantly less SOM than the control, suggesting a lower level of productivity; however, productivity levels were about the same through time. Soil organic matter accumulation was significantly higher under herbaceous vegetation than tree plots, 4.3 versus 3.8% (Table 1). Organic matter inputs by vegetation alone over the 16-yr period in the control plots resulted in SOM levels comparable to levels in the organically amended plots, indicating the importance of vegetation in the natural soil recovery process, and the relatively rapid rate of SOM incorporation in new mine soils.

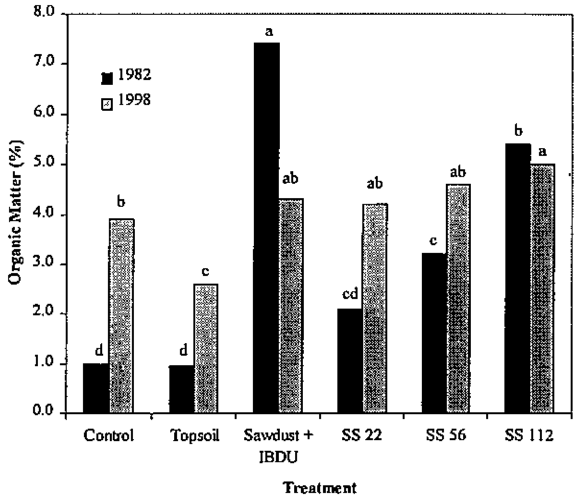

Figure 1. Comparison of soil organic matter content the year after amendment and 16 years later. Sludge rates are Mg ha^{-1}.

The rapid decline in organic matter content in the sawdust-amended plots may be attributed to the mineralization of the high level of biologically-reactive organic matter initially applied. Mostly stable, recalcitrant organic matter was added with the other treatments at levels below or near what appears to be the equilibrium SOM level consistent with the climate and the vegetation growing on these mine soils. It appears that around 100 Mg ha^{-1} sludge or sawdust or equivalent material can be added during reclamation to achieve SOM contents that will finally be achieved by vegetation inputs over time.

Characterization of the light fraction of organic matter showed that this fraction accounted for 1.9 to 2.9% of the whole soil on a dry weight basis (Table 1). The light fraction contains a significant percentage (51 to 68%) of whole soil organic matter, but the proportion was not significantly different among treatments and vegetation types. The sludge treatments had the least amount of nitrogen in the light fraction but the highest levels of total N, due to the greater level of organic matter decomposition (Table 1). This suggests that a greater amount of the total N in the SS treatments resides in the heavy fraction (specific density > 1.70 g cm^{-3}) of SOM.

Nitrogen Content and Mineralization Potential

Total Kjeldahl nitrogen was measured to assess the accumulation of N over time. Sludge (112 and 56 Mg ha^{-1}) treatments had the highest levels of total N at 1.90 and 1.65 g kg^{-1}. These two treatments were also higher in N content than other treatments when measured in 1984 and 1985. Overall levels in 1998 may be a residual effect of initial addition. The 56 Mg ha^{-1} sludge treatment was slightly higher in total N than reported by Moss (1986) indicating N accretion during the 13 yr period. In contrast, N levels of the 112 Mg ha^{-1} sludge treatment declined from 2.21 to 1.90g kg^{-1} over the same period. Nitrogen accretion occurred in all other treatments except the 112 Mg ha^{-1} SS treatment, indicating the influence of litterfall and root decomposition on total nitrogen. The native-soil treatment contained the lowest amount of total N in 1985 at 0.33g kg^{-1} and remains the lowest at 1.06 g kg^{-1} (Table 1). The native-soil and control treatments accumulated 0.62 and 0.45 g kg^{-1} total N during the past 13 years. The decline in total N in the 112 Mg ha^{-1} sludge treatment and increase in the other treatments suggests that the system may be equilibrating between 1 and 2 g kg^{-1}. It appears that about 15 years is needed for climate, moisture availability, and other edaphic features to have the same influence on overall organic matter decomposition, N accretion, system equilibrium, and mine soil quality as a one-time 100 Mg ha^{-1} application of organic amendment.

Nitrogen is usually deficient in mine soils and limits vegetation establishment and sustained productivity. Organic amendments can be used as a source of mineralizable material to enhance N levels and extend N availability through cycling. After 16 years, nitrogen mineralization potentials (N_0), determined by an aerobic incubation procedure, ranged from 102 to 183 mg kg^{-1} and were generally correlated with total N and C (Table 1). During the incubation period, mineralization of organic N was highest on the 112Mg ha^{-1} SS treatment and lowest on the native soil-treated plots. Moss (1986) measured the nitrogen mineralization potential of all treatments on the tree subplots at age 3; levels have increased substantially from that time. Potentially-mineralizable N on the control treatment increased from 6 to 139mg kg^{-1} over the 13 yr period. Anaerobically mineralizable nitrogen (Nmin) followed a similar trend during this period with slight declines in the organically amended plots and concomitant increases in the control and native soil-treated plots. The increase in carbon and nitrogen

Table 1. Soil organic matter, light fraction, total nitrogen, nitrogen mineralization potential (N_0) for 1985 and 1998, anaerobically mineralizable nitrogen (N_{min}), KCl extractable inorganic N, aggregate stability, and bulk density for amended mine soils collected in March, 1998.

Treatment	OM	Light Fraction OM	Organic Carbon	Light Fraction Carbon	TKN	Light Fraction Nitrogen	1985 N_0	1998 N_0	1998 Anaerobic N_{min}	NO_3-N	NH_4^+-N	Aggregate Stability	BD Fine Fraction	BD Whole Soil
	-------------- % of Whole Soil --------------				--------- g/kg ---------		------------------------------ mg/kg ------------------------------					%	-------- Mg m^{-3} --------	
Amendment (A)														
Control	3.9 b	2.0 bc*	2.3 b	0.7 ns	1.35 bc*	0.23 a	6 c	139 bc	60 bc	2.9 ns	6.7 ab	57 ab	1.24 b*	1.51 a
Native-soil	2.8 c	1.9 c	1.5 c	0.5	1.06 c	0.14 ab	10 c	102 d	45 c	2.4	6.1 b	52 b	1.38 a	1.51 a
Sawdust + IBDU†	4.3 ab	2.8 a	2.5 ab	0.9	1.32 bc	0.16 ab	74 b	119 cd	52 bc	3	7.5 ab	56 b	1.12 bc	1.35 b
Sludge (22 Mg/ha)	4.1 ab	2.2 abc	2.4 ab	0.6	1.43 b	0.10 b	54 b	134 bcd	63 ab	2.5	7.2 ab	61 a	1.14 bc	1.41 ab
Sludge (56 Mg/ha)	4.5 ab	2.7 ab	2.7 ab	0.9	1.65 ab	0.15 b	72 b	160 ab	64 ab	3				
Sludge (112 Mg/ha)	4.8 a	2.9 a	2.9 a	1.0	1.90 a	0.15 b	125 a	183 a	81 a	3.1	8.5 a	65 a	1.09 c	1.27 b
Vegetation Type (V)														
Herbaceous	4.3 a	2.5 a	2.6 a	0.8 a	1.60 a	0.18 a		154 a	74 a	3.0 ns	7.5 ns	59 a	1.18 a	1.41 a
Trees	3.8 b	2.3 a	2.5 a	0.9 a	1.32 a	0.15 a		125 a	48 b	2.7	7.3	59 a	1.19 a	1.39 a
A x V	ns	p=.0093	ns	ns	ns	ns		ns	ns	ns	ns	p=0.0635	ns	ns

* Means within columns followed by the same letter were not significantly different (alpha = 0.10).

† IBDU = Isobutyl Di-urea applied as a source of slow-release nitrogen.

accumulation on the unamended control plots and corresponding increase in nitrogen mineralization and apparent microbial activity suggest an overall improvement in mine soil quality due to the effect of vegetation inputs alone. The light fraction, the labile and readily decomposable portion of SOM, comprised a large percentage of the whole SOM of the control treatment, indicating the presence of more mineralizable material. Over the 16-yr period, the 56 and 112 Mg ha^{-1} sludge treatments still retain slightly higher nitrogen mineralization potentials than other treatments, but the range has narrowed compared to 1985 levels (Table 1).

KCl extractable inorganic N (NO_3^--N and NH_4^+-N) was well correlated with total N. Ammonium (NH_4^+-N) was predominant in the inorganic fraction, indicating rather fresh N inputs from litter and root decomposition. Weathering and hydrated conditions within the interlayer of the siltstone exchange complex may have contributed to the release of NH_4^+ that was previously geologically fixed (McBride, 1994); however, organic substrates are more probable sources of NH_4^+. Ammonium-N (NH_4^+-N) levels ranged from 6.1 to 8.5mg kg^{-1} and were three to four times higher than 1985 levels. Nitrate-N was relatively low and not significantly different across treatments, ranging from 2.4 to 3.1mg kg^{-1}. Soil samples were collected in early spring. The low NO_3^--N levels may have been due to the wet spring weather and cold temperatures at the time of sampling that would inhibit nitrification. Overall, the sum of KCl extractable nitrogen (NO_3^--N + NH_4^+-N) was similar across treatments at about 10mg kg^{-1}.

Aggregate Stability

The formation of soil aggregates is an important function of microbial activity and involves the incorporation of organic matter into the soil matrix. Aggregate stability is a critical factor in the prevention of water and wind erosion. A primary goal of reclamation is to stabilize any exposed mined land as quickly and efficiently as possible to prevent erosion and sedimentation. Establishing vegetation achieves this immediate goal, but further development of stable aggregates is important for proper soil function and optimum plant growth.

Aggregate stability varied slightly among treatments ($p = 0.0549$), ranged from 52 to 65%, and was well correlated with SOM content (Table 1). The SS treatments had the highest level of stable aggregates, and the native soil treatment had the lowest amount of water stable aggregates. The sawdust treatment was similar to the control. Because aggregate stability was well correlated with current levels of SOM, it is a function of soil development over time rather than the type or amount of amendment.

Soil cation exchange capacity is strongly influenced by SOM content especially in young mine soils. The ECEC levels ranged from 1.7 to 2.8 cmol$_+$ kg^{-1} and were, again, well correlated with organic matter content. Effective CEC was significantly higher on the tree subplots (2.7 vs. 2.1 cmol$_+$ kg^{-1}) suggesting slightly better retention and cycling of base cations through time. It follows that exchangeable cation levels were low if ECEC were low, but base saturation was fairly high at 65 to 92%. The base cation levels were lower than previously reported by Roberts et al. (1988) and Moss et al. (1989), indicating that leaching may have occurred over the past 13 years. Harrison et al. (1996) cite a study where significant losses of K, Ca, and Mg occurred after fertilization with biosolids apparently due to NH_4^+ replacement of base cations on the exchange sites. The rather high levels of KCl extractable NH_4^+-N suggests a similar potential for NH_4^+ replacement on the cation exchange sites of these mine soils as well. Extractable P was very low across all treatments, but increased with increasing levels of SS (Table 2). Nearly doubling the extractable P levels may be the greatest long-lasting effect of the sludge treatment.

Soil pH for all treatments ranged from 6.3 to 7.2. The native soil treatment had the highest pH at 7.2 because it was limed initially to raise the pH from approximately 4.5 to a level comparable (7.5) to the 2:1 sandstone:siltstone overburden materials. Soil bulk density for the fine earth fraction ranged from 1.09 to 1.38 Mg m^3. Bulk density decreased with increasing amounts of added organic amendment. The bulk density of the native soil plots was significantly higher than other treatments. These results suggest that the organic amendments have had a relatively long-term positive effect on soil bulk density compared to the native soil treatment which is one of the most common reclamation materials. The overburden material may have had a high concentration of soluble salt initially (Moss, 1986); however, electrical conductivity of soil in all treatments was negligible. Exchangeable acidity ranged from 0.2 to 1.0 cmol$_+$ kg^{-1} for the site; it was still significantly lower on the native soil treatment 16 years after liming. The high base saturation of the native-soil treated plots appears to be attributable to the low level of exchangeable acidity present (0.2 cmol$_+$ kg^{-1}). The other treatments had three to five times the exchangeable acidity (Table 2).

Table 2. **Concentration of macronutrients, effective cation exchange capacity, and base saturation for amended mine soils in southwest Virginia under different vegetation covers, March 1998.**

Treatment	ECEC	K	Mg	Ca	Na	Base Saturation	P	pH	Exchangeable Acidity	EC
	$\text{cmol}_+ \text{ kg}^{-1}$					%	mg/kg		$\text{cmol}_c \text{ kg}^{-1}$	uS cm^{-1}
Amendment (A)										
Control	2.5 a*	0.10 ns	0.33 ns	1.4 ns	0.038 a	74 b	31 bc	6.4 bc	0.7 a	49 b
Native-soil	1.7 b	0.09	0.32	1.1	0.035 ab	92 a	31 bc	7.2 a	0.2 b	46 b
Sawdust + IBDU †	2.8 a	0.09	0.32	1.4	0.035 ab	72 b	23 c	6.3 c	0.9 a	49 b
Sludge (22 Mg/ha)	2.7 a	0.10	0.34	1.3	0.034 ab	65 b	37 b	6.3 c	0.9 a	45 b
Sludge (56 Mg/ha)	2.5 a	0.08	0.34	1.2	0.030 ab	65 b	57 a	6.4 c	1.0 a	50 b
Sludge (112 Mg/ha)	2.2 ab	0.09	0.31	1.2	0.029 b	74 b	60 a	6.6 b	0.6 a	60 a
Vegetation Type (V)										
Herbaceous	2.1 b	0.09 a	0.33 a	1.1 a	0.030 b	76 a	40	6.6 a	0.5 a	51 a
Trees	2.7 a	0.09 a	0.33 a	1.4 a	0.036 a	72 a	39	6.5 b	0.8 a	49.a
A x V	ns	ns	ns	ns	p=.0795	p=.0212	p=.0927	ns	ns	ns

* Means within columns followed by the same letter were not significantly different (alpha = 0.10).

† IBDU = Isobutyl Di-urea applied as a source of slow-release nitrogen.

Tree Response

Tree and herbaceous vegetation productivity data are presented as indices of the effects organic amendments have had on plant productivity over time (Table 3). Initially, the high levels of organic matter in the 112 and 224 Mg ha^{-1} sewage treatments adversely affected tree survival. After 16 yr, survival was highest on the control plots, 69% of the original density of 16 trees per plot. Sawdust and native-soil treatment survival rates were not significantly different at 64 and 61%, respectively. Sewage sludge decreased tree survival compared to the control. Moss (1986) attributed the mortality to the deleterious effect of the high application rates. The present survival rates for the 112 and 224 Mg ha^{-1} SS are presented here to confirm the adverse treatment effect reported by Moss. Seedling survival for the 112 Mg ha^{-1} SS treated plots was 31%, while only 4 trees (25%) remained for the 224 Mg ha^{-1} sludge treatment. The pure loblolly pine genotype (25% of the total trees planted) suffered near complete mortality due to a very harsh winter in 1985 (Moss, 1986).

Table 3. 1997 average per-plot, survival, trees, height, diameter, and volume of pitch x loblolly pine trees growing on amended mine soils in Wise County, Virginia.

Treatment	Survival (%)	No. Trees	Basal Area (m^2 ha^{-1})	Height (m)	Diameter (cm)	Plot Volume (m^3)
Amendment:						
Control	69 a*	7	98 ns	7.2 ns	13.1 ab	0.20 b
Topsoil	61 ab	7	96	7.0	11.8 b	0.19 b
Sawdust + IBDU	64 ab	6	110	7.5	14.4 ab	0.23 a
SS 22	56 b	6	107	7.1	13.1 ab	0.22 ab
SS 56	58 b	6	116	7.4	15.0 a	0.24 a

In 1997, 15 growing seasons after establishment, cumulative basal area was the same across treatments regardless of tree density. Basal area ranged from 96 to 116 m^2 ha^{-1}. Actual resource allocation to basal area appears slightly better on plots amended with organic material. The native soil-treated plots had the lowest cumulative basal area and the 56 Mg ha^{-1} SS treatment the highest. Basal area on the sawdust plots was noticeably higher than other treatments after 8 growing seasons but appeared to decline from 1990 to 1996. The decline suggests that the positive effect of the initial amendments lasted 8 growing seasons and at that time the nutrient capital necessary for continued tree growth was reduced. During the same period, basal area continued to accumulate on all other treatments. From 1996 to 1997, cumulative basal area for all treatments increased sharply in response to a heavy limb pruning (Figure 2).

Diameter growth was markedly less on the native soil treatment at 11.8cm. Tree height for all treatments was comparable, ranging from 7.5m for the sawdust treatment to 7.0 m for native soil. Tree volume on the sawdust and SS amended plots was slightly higher compared to the control and native soil treatments. In 1997, tree volume per plot was comparable among the 56 Mg ha^{-1} SS, sawdust, 22 Mg ha^{-1} SS treated plots. Tree volume for the control and native soil treatments were the same, but contained significantly less volume than the organically-amended treatments ($p < 0.10$) (Table 3). The relative effect of these treatments on tree volume varied greatly over time (Figure 3) After the 1985 growing season, seedling volume on the sawdust plots was considerably greater than either the 22 or the 56 Mg ha^{-1} SS treatments (192.4cm^3 vs. 117.5 and 98.5cm^3, respectively). Data for the 112 Mg ha^{-1} SS treatments are presented but were not analyzed for treatment effect in this study due to the known detrimental effect these treatments had on tree survival (Moss, 1986).

The 1985 stem volume of trees on the sawdust treatment was 3.4 times or 340% greater than the control (Figure 3). This difference was similar to that reported by Schoenholtz (1990) who found that a wood chip-amended mine soil resulted in 203% more stem volume than an unamended control treatment. SS (22 and 56 Mg ha^{-1}) treatments were 1.48 and 1.15 times the control. However, after 3 yr, the tree volume on amended treatments began to converge toward the

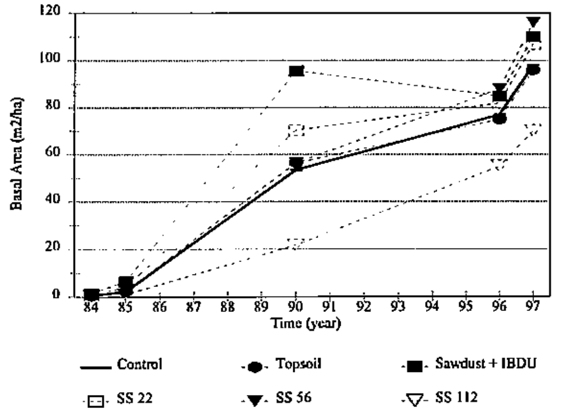

Figure 2. Cumulative basal area for pitch x loblolly pine trees growing on amended mine soils after 16 years.

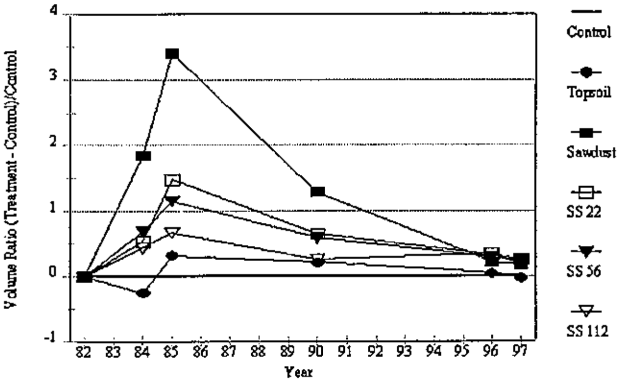

Figure 3. The relative stem volume of pitch x loblolly pine trees growing on amended mine soils after 16 years. Volume ratio determined by the equation (Treatment - Control)/Control.

control. In 1990, the sawdust treatment was only 129% greater than the control. In 1997, SS (22 and 56 Mg ha^{-1}) treatments were slightly higher than sawdust at 26 and 24%, respectively. At present, all organically-amended treatments contain 18 to 26% more stem volume than the control treatment. The relative stem volume of the native-soil treatment was below that of the control. Hence, the greater difference in performance by most treatments that was so obvious during the establishment period of this study was no longer evident, and the treatment response appears to have equilibrated to the level of the control (Figure 3). The decline in relative tree productivity was well correlated with the dynamics of organic matter content, aggregate stability, nitrogen mineralization, and associated properties.

Forage Response

Herbaceous ground cover crops are commonly used to reclaim mined sites to fulfill the revegetation requirements for bond release. For productive post-mining land use and ecosystem stability, the aim is to establish an environment in which vegetation can grow abundantly, prevent erosion, enhance nutrient cycling, and be self-perpetuating. Tall fescue was grown and maintained as the dominant vegetative community during the first 5 yr of the study. Leguminous species were eliminated from the sward. After 5 yr, management ceased, and the ground cover composition of the study plots changed as sericea lespedeza (*Sericea cuneata*), an early seral species in the mine fields, succeeded onto the site. Roberts et al. (1988) reported that tall fescue growth was particularly sparse on the control and native-soil treatments due to apparent N stress. Sparse growth offers an opportunity for species that can compete in N deficient sites to become established. Invasion of sericea lespedeza was most noticeable on the control and native soil plots compared to the other plots. The influence of this leguminous species on standing biomass yield was pronounced on all treatment plots except the 112 Mg ha^{-1} SS treatment (Figure 4). Standing biomass was highest on the native soil treatment (5.66 Mg ha^{-1}), where legumes accounted for 4.06 Mg ha^{-1} or 72 % of the total yield on a dry weight basis. Total biomass production of the native soil treatment was not significantly different from the three SS treatments. Biomass yields for all treatments was in the order of native soil ≥ SS (56 Mg ha^{-1}) ≥ SS (22 Mg ha^{-1}) = SS (112 Mg ha^{-1}) = control > sawdust. Growth response was lowest on the sawdust treatment at 2.6 Mg ha^{-1}.

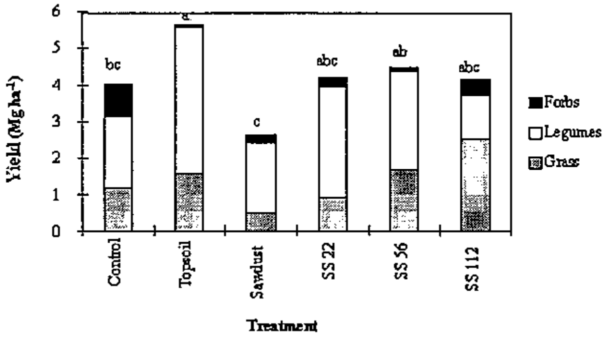

Figure 4. 1997 annual standing biomass and distribution of herbaceous cover.

The level of production declined since the initial amendments were applied. Earlier tall fescue biomass yields were presented by Roberts et al.(1988) and Haering et al., (1990), and are presented here to demonstrate the trend and fluctuations in annual yields (Figure 5). Roberts et al., (1988) reported tall fescue yields of 13.6 and 10.1 Mg ha^{-1} for the 1983 growing season. Overall biomass yields were lowest in 1987 ranging from 2.8 to 1.1 Mg ha^{-1}. The increase in biomass from 1987 to 1997 was most likely due to the increasing invasion of sericea lespedeza during the 10 yr period. Herbaceous vegetation productivity responded similarly to organic matter content as the trees and appears to be leveling off at 4.0 Mg ha^{-1} for all treatments except the sawdust treatment.

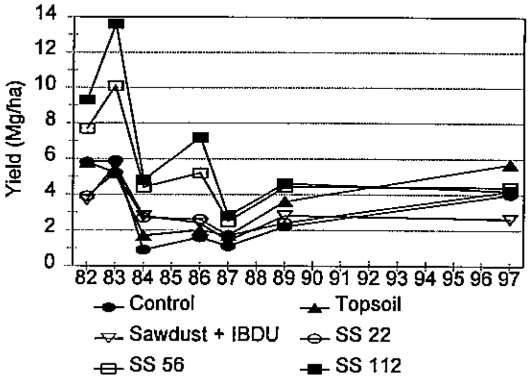

Figure 5. Comparison of annual standing biomass yields of herbaceous vegetation for organic amendments after 16 years.

Tree and plant productivity over time was closely correlated to the changes in organic matter content and N mineralization potential. Growth response of the grass demonstrates that SS treatments provide organic matter and N essential for high production, but if high inputs are not maintained, tall fescue drops out of the system in favor of a persistent legume. The rapid decline in growth after three to four years shows the need for augmentation with nutrient sources in order to maintain this agricultural species.

Conclusions

After 16 yr, the organic matter levels for all treatments except the native soil treatment have leveled off to about 4%. Total N content appears uniform across the site. The effects of organic matter amendments on mine soil quality and function were initially favorable and pronounced. However, organic matter content and productivity appears to be equilibrating. Climate, soil temperature, water availability, and other edaphic features appear to be more directly influencing organic matter decomposition, transformations, and associated properties than initial amendments. After 16 yr, mine soil quality and system function on this site appear to have equilibrated due to these factors. The results suggest organic amendments improved initial soil fertility for tall fescue establishment, but, over time, the amendment effect on soil fertility, with the exception of extractable phosphorus, dissipated. Nearly doubling the extractable P levels may be the greatest long-lasting effect of the sludge treatments on mine soils. Moreover, tree and vegetation response to organic amendments during the 16-yr period indicate additional soil fertility management and monitoring is necessary after 5 to 8 years for more intensive post-mining land uses. It appears that about 15 years is needed for climate, moisture availability, and other edaphic features to have the same influence on overall organic matter decomposition, N accretion, system equilibrium, and mine soil quality as a one-time 100 Mg ha^{-1} application of organic amendment.

Literature Cited

Bremner, J. M., and C. S. Mulvaney. 1982. Nitrogen - Total. p. 595-624. In A. L. Page, R. H. Miller, and D. R. Keeney (ed.) Methods of Soil Analysis. Part 2. 2nd ed. Agron. Monogr. No. 9. ASA and SSSA, Madison, WI.

Daniels, W. L., J. C. Bell, D. F. Amos, and G. D. McCart. 1983. First-year effects of rock type and surface treatments on mine soil properties and plant growth. p. 275-282. In Proc., Symp. on Surface Mining Hydrology, Sedimentology, and Reclamation, Lexington, KY. 5-10 Dec. 1982. Univ. of Kentucky, Lexington.

Gee, G. W., and J. W. Bauder. 1986. Particle-size analysis. p. 383-410. In A. Klute (ed.) Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. 2nd ed. Agron. Monogr. No. 9. ASA and SSSA, Madison, WI.

Gregorich, E. G., and B. H. Ellert. 1993. Light fraction and macroorganic matter in mineral soils. p. 397-407. In M. R. Carter (ed.). Soil Sampling and Methods of Analysis. Lewis Publ., Boca Raton, FL.

Haering, K., W. L. Daniels, J. A. Burger, and J. L. Torbert. 1990. Final Report: The effects of controlled overburden placement on topsoil substitute quality and bond release. Virginia Tech Research Div., Blacksburg.

Harrison, R. B., S. P. Gessel, D. Zabowski, C. L. Henry, D. Xue, D. W. Cole, and J. E. Compton. 1996. Mechanisms of negative impacts of three forest treatments on nutrient availability. Soil Sci. Soc. Am. J. 60:1622-1628.
https://doi.org/10.2136/sssaj1996.03615995006000060005x

Kemper, W. D., and R. C. Rosenau. 1986. Aggregate stability and size distribution. p. 425-442. In A. Klute (ed.). Methods of Soil Analysis. Part 1. 2nd ed. Agron. Monogr. No. 9. ASA and SSSA, Madison, WI.

McBride, M. C. 1994. Environmental Chemistry of Soils. Oxford University Press, Oxford, UK

Moss, S. A. 1986. Nitrogen availability and pine seedling growth in organically-amended mine soils. M.S. Thesis. Virginia Polytechnic Institute and State University, Blacksburg.

Moss, S. A., J. A. Burger, and W. L. Daniels. 1989. Pitch x loblolly pine growth in organically amended minesoils. J. Environ. Qual. 18:110-115.
https://doi.org/10.2134/jeq1989.00472425001800010020x

Nelson, D. W., and L. E. Sommers. 1982. Total carbon, organic carbon, and organic matter. p. 539-579. In A. L. Page, R. H. Miller, and D. R. Keeney (ed.) Methods of Soil Analysis. Part 2. 2nd ed. Agron. Monogr. No. 9. ASA and SSSA, Madison, WI.

Olsen, S. R., and L. E. Sommers. 1982. Phosphorus. p. 403-430. In A. L. Page, R. H. Miller, and D. R. Keeney (ed.) Methods of Soil Analysis. Part 2. 2nd ed. Agron. Monogr. No. 9. ASA and SSSA, Madison, WI.

Rhoades, J. D. 1982. Soluble salts. p. 167-179. In A. L. Page, R. H. Miller, and D. R. Keeney (ed.) Methods of Soil Analysis. Part 2. 2nd ed. Agron. Monogr. No. 9. ASA and SSSA, Madison, WI.

Roberts, J. A., W. L. Daniels, J. C. Bell, and D. C. Martens. 1988. Tall fescue production and nutrient status on Southwest Virginia mine soils. J. Environ. Qual. 17:55-62.
https://doi.org/10.2134/jeq1988.00472425001700010008x

Schoenholtz, S. H. 1990. Restoration of nitrogen and carbon cycling in an Appalachian mine spoil. Ph.D. Dissertation. Virginia Polytechnic Institute and State University, Blacksburg.

Sopper, W. E. 1992. Reclamation of mineland using municipal sludge. Adv. Soil Sci. 17:351-432.

Statistical Analysis System, Inc. (SAS). 1993. SAS Companion for the Microsoft Windows Environment. V. 6 ed. SAS Inst. Inc., Cary, NC.

Strickland, T. C., and P. Sollins. 1987. Improved method for separating light- and heavy-fraction organic material from soil. Soil Sci. Soc. Am. J. 51:1390-1393.
https://doi.org/10.2136/sssaj1987.03615995005100050056x