DIVISION S-4—SOIL FERTILITY & PLANT NUTRITION

Quality of Amended Mine Soils After Sixteen Years

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ABSTRACT

Soil quality research has focused on intensively managed agricultural and forest soils, but the concept and importance of soil quality is also pertinent to reclaimed mine soils and other disturbed ecosystems. Adding organic amendments has been used as a means for ameliorating mine soils and improving their quality, but the long-term effects of amendments on soil quality are not known. In 1982, a mined site was amended with seven different surface treatments: a control (nothing added), 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 plot was split and planted with pitch × loblolly pine hybrid (*Pinus rigida* × *taeda*) trees and Kentucky-31 tall fescue (*Festuca arundinacea* Schreb.). During the 16-yr period, organic matter content, total organic N, N mineralization potential, aggregate stability, and other physical and chemical properties were measured as mine soil quality indicators. The comparative ability of these organic amendments to positively affect organic matter content, total N, and other parameters was most apparent and pronounced after 5 yr. However, after 16 yr, soil organic matter (SOM) content and total N appeared to be equilibrating at ≈10 000 and 750 kg ha^{-1}, respectively. Organic matter inputs by vegetation alone across the 16-yr period in the control plots resulted in organic matter and N mineralization potential values comparable to levels in the organically-amended plots, indicating the overriding importance of vegetation in the soil recovery process. After 16 yr, there appears to be no lasting soil quality improvements due to addition of organic amendments to this mine soil. Amendments improved short-term production, but their cost of transport and application may be difficult to justify based on long-term soil quality improvement.

LONG-TERM RESTORATION of mine soil quality and ecosystem function of disturbed sites depends on reclamation that allows reestablishment of vegetation that can thrive and sustain itself. Conversely, Bradshaw (1987) points out that reconstruction of an ecosystem and mine soil quality depends on vegetation for improving the soil physical, chemical, and biological condition of disturbed sites. Therefore, a mine soil medium of sufficient quality is needed that allows adequate growth and productivity of reclamation species that will further improve mine soil properties.

In the process of defining and monitoring sustainable land management, soil scientists and practitioners have tried to identify specific soil physical, chemical, and biological indicators associated with soil quality, fertility, and health (Parr et al., 1992; Karlen and Stott, 1994; Larson and Pierce, 1994; Doran and Parkin, 1996). Soil properties identified by these authors as basic indicators, or part of a minimum data set of soil quality, are SOM, total organic N and C, aggregate stability, aeration, macroporosity, water holding capacity, microbial biomass, mineralizable C and N, bulk density, resistance to erosion, nutrient availability, pH, and electrical conductivity.

Many of the soil properties found in these soil quality minimum data sets are those that reportedly limit mine soil and plant productivity on mined sites. They include soil acidity (Daniels and Amos, 1981), N and P availability (Bradshaw, 1983; Marrs et al. 1983; Daniels and Zipper, 1988; Roberts et al., 1988b), micronutrient imbalance or toxicity, high electrical conductivity (Torbert et al., 1989), compaction, inadequate depth for rooting, and low water holding capacity (Torbert et al., 1988; Daniels and Amos, 1984).

Low mine soil fertility is nearly always a plant growth limiting factor on mined sites. Bradshaw (1983) recommended that 1000 kg ha^{-1} total soil N be recognized as a minimum standard for proper plant growth and ecosystem development. Marrs et al. (1983) explain that N accumulation is very slow in new ecosystems and that total soil N capital should be 10 to 20 times the annual plant uptake. Bradshaw (1983) further reports that P may be limited due to the high fixation capacities of exposed mine spoil composed of sandstone. This P binding potential of mine soils was clearly demonstrated in a study by Roberts et al. (1988a), who reported a P deficiency in tall fescue due to high soil P fixing capacity.

Seaker and Sopper (1988) stressed the importance of SOM accumulation, decomposition, and minimum levels of organic C and N contents for productive mine soils. In agriculture, crop residues, compost, manures, and synthetic fertilizers are traditional soil conditioners that are added to improve these soil properties and enhance soil function and quality. Most surface-mined sites lack organic matter levels necessary for optimum soil functioning. In the process of surface mining in the Appalachian region, topsoil is seldom recovered and replaced on the surface as a growth medium as required by federal and state laws. Mine operators obtain "topsoil waivers" that allow them to substitute mine spoils for the surface plant-growth medium, based on the argu-

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Published in Soil Sci. Soc. Am. J. 65:1736–1744 (2001).

Abbreviations: CEC, cation-exchange capacity; LF, light fraction, SOM, soil organic matter; SS, sewage sludge; TKN, total Kjeldahl N.

Table 1. Composition of sewage sludge applied as an organic amendment.

Macroproperties		Microelements	
	g kg^{-1}		mg kg^{-1}
NH_4^+–N	3	B	32
NO_3^-–N	0.024	Cd	6
Total N	26.0	Cu	245
Total P	6	Pb	175
Ca	37.0	Mn	320
Mg	3.8	Hg	3.5
K	8.8	Ni	80
Organic Matter	380	Zn	880
Total Solids	450		
pH	6.8		

Table 2. Total N, P, and K added at the time of study establishment as either chemical fertilizer or municipal sewage sludge.

Treatment†	N	P	K
		kg ha^{-1}	
Control, 2:1 sandstone:siltstone	168	147	137
30 cm native soil + lime, 7.8 Mg ha^{-1}	168	147	137
Sawdust, 112 Mg ha^{-1} + IBDU‡	504	147	137
Sewage sludge, 22 Mg ha^{-1}	582	29	56
Sewage sludge, 56 Mg ha^{-1}	1455	74	140
Sewage sludge, 112 Mg ha^{-1}	2910	147	280
Sewage sludge, 224 Mg ha^{-1}	5820	295	560

† Additional sources of organic matter that were uniformly applied to all treatments include 900 kg ha^{-1} straw mulch and 940 kg ha^{-1} paper fiber mulch.

‡ The sawdust treatment received an additional 336 N ha^{-1} as slow release Isobutyl Di-Urea (IBDU) fertilizer.

ment that native topsoils are too thin to recover, and that recovery operations are too difficult on steep slopes. Therefore, the depauperate nature of mine soils may benefit from addition of organic amendments that will initiate nutrient cycling and help overcome other chemical and physical limitations. Accordingly, we hypothesized that organic amendments applied on surface mined land would accelerate nutrient cycling, provide a receptive environment for vegetation, and improve overall soil quality and productivity. The specific objectives of this study were to determine the comparative ability of topsoil, sawdust, and SS soil amendments (i) to improve mine soil quality as measured by SOM content and quality, aggregate stability, and mineralizable N; and (ii) to determine the effect of these amendments on long-term changes in SOM content and related chemical and physical properties after 16 yr.

MATERIALS AND METHODS

Study Site Description and Design

The experiment was undertaken in Wise County, Virginia (37°00′ N, 82°41′ W). Long-term mean annual precipitation and temperature are 1150 mm and 11 °C, respectively. The mine soils were classified as loamy-skeletal mixed, mesic Typic Udorthents (Roberts, 1986). In 1982, a 1-m-deep base layer of 2:1 sandstone to siltstone overburden material was uniformly applied over the study site. Experimental plots, 7 × 3.5 m, were established in a randomized complete block design with four replications. Seven amendment treatments were applied, consisting of a control constructed of 2:1 sandstone to siltstone overburden material (standard mine soil), 30 cm native soil composed of a mixture of A, E, B, C, and Cr horizon material from a neighboring forest soil (Berks series: loamy-skeletal, mixed, active, mesic Typic Dystrudepts), hardwood sawdust applied at 112 Mg ha^{-1}, and applications of aerobically digested municipal SS at the following rates: 22, 56, 112, and 224 Mg ha^{-1}. The composition of the SS is shown in Table 1. Because of the detrimental effect the 224 Mg ha^{-1} sludge treatment had on initial tree seedling survival (Moss, 1986), results from the 224 Mg ha^{-1} treatment were not included in this study.

At the time of study establishment, the control, native soil, and sawdust plots all received additional N, P, and K at rates of 168, 147, and 137 kg ha^{-1}, respectively. The native soil plots were also limed at a rate of 7.8 Mg ha^{-1} to bring the native soil 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) fertilizer to offset potential nutrient immobilization caused by an initially high C:N ratio and increased microbial activity. Initial N, P, and K inputs for all treatments at time of study establishment are presented in Table 2.

All plots were seeded with 170 kg ha^{-1} KY-31 tall fescue seed and then mulched with 900 kg ha^{-1} straw and 940 kg ha^{-1} paper fiber. Whole plots were split by vegetation type (tall fescue vs. pine trees) to allow for parallel studies on the establishment and productivity of tree and agronomic crops. In April 1983, subplots were treated with glyphosate (N-phosphonomethyl glycine at 18.7 L ha^{-1}) and planted with pitch × loblolly pine hybrid seedlings. All grass and tree plots remained fully stocked during the 16-yr experimental period. Herbaceous competition was removed from the tree plots for several years prior to crown closure. During the last 5 yr of the study period, the grass plots were invaded to varying degrees by other grasses and herbs. Vegetation response to treatment was repeated elsewhere.

Field Sampling

The effects of topsoil, sawdust, municipal SS, and control treatments on soil properties were evaluated several times across a 16-yr period: (i) the first growing season after initial amendment, (ii) after 3 and 5 growing seasons, and (iii) 16 yr after initial amendment.

Composite soil samples, collected in 1982, 1987, and 1998, were composed of three randomly-located subsamples within each grass and tree subplot. Subsamples were collected from the surface horizon at a depth of 0 to 10 cm. Care was taken to avoid previous sampling sites by using a grid map. Soils were air-dried and sieved to pass a 2-mm sieve to determine fine earth and coarse fragment contents. Subsamples were collected and oven-dried at 105 °C for 24 h to determine gravimetric moisture content. In 1998, two bulk density cores were obtained from each subplot using a hammer-driven core sampler. Bulk density was determined for both the fine earth fraction and whole soil. The fine earth fraction was determined by adjusting the total mass and volume of the cores based on the coarse fragment content and assuming a particle density of 2.65 Mg m^{-3}. Micro- and macroporosity were determined using a tension table with a 50-cm tension (Kohnke, 1968). Available water at 33 kPa was obtained using a pressure plate (Klute, 1986). Bulk density core samples were oven-dried at 105 °C for 24 h to obtain unit mass per unit volume.

Soil Characterization and Laboratory Analysis

Particle size of the fine earth fraction was determined by the hydrometer method (Gee and Bauder, 1986). Total organic C and SOM were estimated using 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., Dubuque, IA) at 550 °C for 24 h. For soil samples collected in 1998, light and heavy fraction SOM were determined using the modified density flotation procedure of Strickland and Sollins (1987) and Gregorich and Ellert (1993). Aggregate stability of the 1998 samples was determined using a wet sieving procedure (Kemper and Rosenau, 1986). Nitrogen mineralization potential was estimated in 1985 and 1998 using an aerobic incubation procedure outlined by Stanford and Smith (1972) and later modified by Burger and Pritchett (1984). Inorganic plant available NH_4^+-N was determined using an anaerobic mineralization incubation procedure (Keeney, 1982).

Available P was extracted with 0.5 *M* $NaHCO_3^-$ adjusted to pH 8.5. Extractable P was determined using the modified Murphy-Riley ascorbic acid procedure and analyzed by spectrophotometry (Olsen and Sommers, 1982). 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. Soil reaction was determined with a pH electrode in a 2:1 water to soil extract. Exchangeable acidity was determined using a 1 *M* KCl replacing solution and titration to a phenolphthalene end point with a Mettler Dl2 auto-titrator (Mettler Instruments, Inc., Hightstown, NJ). Electrical conductivity was measured with a conductivity meter in a 5:1 water:soil extract and standardized to 0.01 *M* KCl reference solution (Rhoades, 1982).

Statistical Design and Data Analysis

Because there was no effect of vegetation type on soil quality indicators, soil data and treatment effects were analyzed as a split-block design with treatment means of the main effect pooled across vegetation types (herbaceous vegetation vs. pine trees). A general linear model procedure was used for an analysis of variance and determination of the effects of amendments on mine soil parameters (SAS Institute, 1993). When significant F-values were obtained ($P < 0.10$), Duncan's multiple range test was used to separate the mean responses of the treatments: control, topsoil, sawdust, and different levels of SS. A nonlinear procedure (PROC NLIN) was used to determine potentially mineralizable N (N_o) and the rate constant (k) for each treatment.

Dependent and independent variables were analyzed for significant correlations using PROC CORR procedure, and Pearson's correlation coefficients were computed. Multiple linear regression analysis was used to test the relationship of key soil variables (SOM content, aggregate stability, and N mineralization potential) to tree volume per plot and herbaceous biomass production. A stepwise selection procedure was used within the multiple linear regression analysis to determine the best model by optimizing R^2, mean square error (MSE), and the sum of squares of all predicted error.

RESULTS AND DISCUSSION

Soil Quality Indicators

Soil Organic Matter

In 1982, the year after the study was put in, SOM content of the amended mine soils was commensurate with the amount of SOM added as part of the treatment (Fig. 1). At 14 Mg ha^{-1}, the sawdust-treated plots contained the highest level of SOM. The SOM content of plots treated with SS increased linearly with increased application rates. The control and native soil-treated plots contained 2 Mg ha^{-1} SOM in the surface 10 cm, which were considerably lower than levels typical of forest soils (Pritchett and Fisher, 1987). The low level of SOM on the native soil-treated plots was due to a dilution effect from mixing the A, E, B, C, and C_r soil horizons and incorporation of this material with the minespoil. After five growing seasons (1987), SOM levels of all treatments (except sawdust) increased. Soil organic matter levels of the control, topsoil, and sludge (22 and 56 Mg ha^{-1}) more than doubled during this time. The increase in SOM is attributed to SOM inputs via root and litter cycling and decomposition of soil organisms.

By 1998, 16 yr after initial amendment, SOM concentration levels in the fine earth fraction for all treatments (except the native soil-treated plots) appeared to have equilibrated at around 8 to 10 Mg ha^{-1} (Fig. 1). Clapp et al. (1986) reported similar changes 4 yr after SS amendments were applied. No treatment had significantly more or less than the control, but the native soil

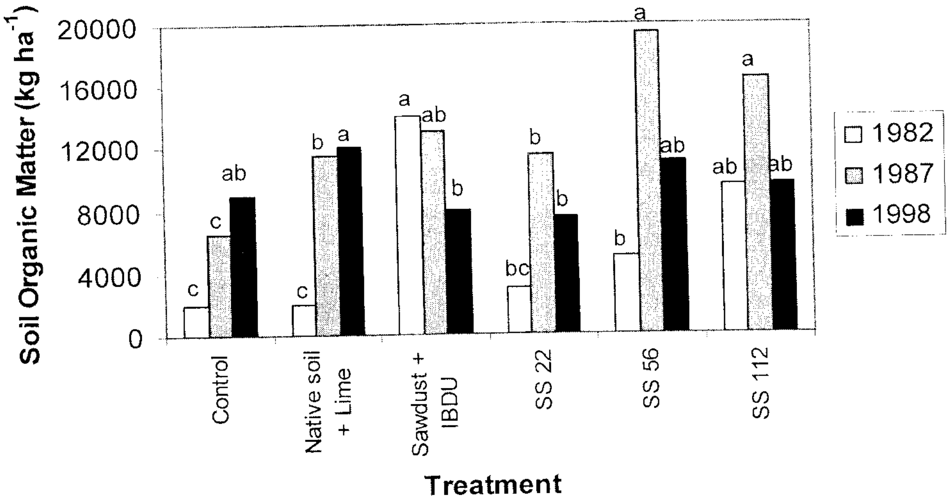

Fig. 1. Soil organic matter content (kg ha^{-1}) of organically-amended mine soils during 1982, 1987, and 1998. Means within years followed by the same letter were not significantly different. IBDU = isobutyl di-urea, SS = sewage sludge.

treatment contained 4 Mg ha^{-1} more than mine soils treated with sawdust or 22 Mg ha^{-1} SS. Organic matter inputs by vegetation alone across the 16-yr period in the control plots resulted in organic matter levels comparable to levels in the amended plots, indicating the importance of vegetation in the soil recovery process, and the relatively rapid rate of accumulation in new mine soils.

The increase in SOM content during the first 5 yr on the sludge-treated plots is attributed to the fertilization effect of the sludge causing high initial biomass productivity and vegetation inputs. The decline in SOM content of the amended plots corresponded with the decline in productivity of the vegetation after the fourth growing season. The decline in SOM content from 1987 to 1998 in the sewage-sludge treated plots suggests that the SOM inputs from vegetation were easily decomposable and were oxidized by biologically-mediated processes. The overall decline in SOM concentration of the sawdust-amended plots across 16 yr is attributed to decomposition and mineralization of the high level of biologically-reactive SOM initially applied. With time, as the new soil and plant system approaches an equilibrium, SOM levels should stabilize at a level consistent with the climate and the vegetation growing on the mine soils. After 16 yr, SOM levels of all treatments either increased or decreased within a range of 8 to 10 Mg ha^{-1}, as they approached an equilibrium SOM concentration level of 40 g kg^{-1} (4%), a level commonly found in native soils of the region. It appears that around 100 Mg ha^{-1} sludge or sawdust or equivalent material must be added at the time of reclamation to achieve initial organic matter contents equivalent to those that will finally be achieved by vegetation inputs alone after 16 yr.

After 16 yr, the light fraction (LF) organic matter accounted for 1.9 to 2.9% of the whole soil on a dry weight basis (Table 3). These LF estimates are comparable to levels reported by Christensen (1992) for natural soils. The LF contained a significant proportion (LF:SOM ratio) of whole SOM, but the proportion was not significantly different among treatments (Table 3). Overall, LF organic matter was more concentrated in the control, sawdust, and sludge-treated plots than in the native soil-treated plots.

We hypothesized that the SOM LF heavily influences soil quality indicators and may be a good indicator itself, and we hypothesized that the LF as a proportion of whole-soil OM content would be different among treatments. Indeed, LF was positively correlated with N mineralization potential ($r = 0.31$), anaerobically mineralizable N ($r = 0.34$), aggregate stability ($r = 0.27$), and total porosity ($r = 0.27$), which are commonly found in minimum data sets of soil quality.

Table 3. Soil organic matter (SOM), light fraction (LF) organic matter composition, heavy fraction organic matter, and aggregate stability after 16 yr.

Treatment	LF	LF:SOM	Aggregate stability
	% of whole soil		%
Control	2.0bc†	0.51ns‡	57ab
Native soil + lime	1.9c	0.68	52b
Sawdust + IBDU§	2.8a	0.65	56ab
Sludge, 22 Mg ha^{-1}	2.2abc	0.54	61a
Sludge, 56 Mg ha^{-1}	2.7ab	0.60	62ab
Sludge, 112 Mg ha^{-1}	2.9a	0.60	65a

† Means within columns followed by the same letter were not significantly different ($P < 0.10$).

‡ ns = not significant.

§ IBDU = isobutyl di-urea applied as a source of slow release of nitrogen.

Aggregate Stability After Sixteen Years

Aggregate stability of the 1998 samples was little different among treatments; it ranged from 52 to 65% (Table 3). The SS-treated plots had the highest levels of stable aggregates, and the native soil-treated plots had the lowest amount of water stable aggregates, probably due to the dilution effect of fewer coarse fragments (Table 7). Doubling the application of SS from 56 to 112 Mg ha^{-1} did not significantly increase aggregate stability. Aggregate stability of the treated mine soils was not significantly different from the control, indicating that natural organic inputs from vegetation alone might be as important in the formation of aggregates as any amendments used in this study.

Mineralizable Soil Nitrogen

Total Kjeldahl N (TKN) was measured to assess treatment effect on the accumulation of N. Organically-amended plots contained more total N than the control and native soil-treated plots in 1985, 5 yr after application (Moss et al., 1989) (Fig. 2). Total Kjeldahl N levels in the control and native soil treatments tripled in the ensuing 13 yr to levels comparable to the sludge treatments. The mean TKN concentration after 16 yr for the amended mine soils was 1.57g kg^{-1}. Nitrogen accretion on the control and native-soil-treated plots amounted to 680 and 920 kg ha^{-1}, respectively (Fig. 2). The decline in total N in the 112 Mg ha^{-1} sludge treatment plots, and subsequent increase in the unamended control plots, suggest that the system may be equilibrating at levels between 500 and 900 kg ha^{-1} (Fig. 2). These values are below the N level recommended by Bradshaw (1983), which suggests N may still be a limiting factor in this system. It appears that ≈15 yr is needed for climate, moisture availability, and other edaphic features to have the same influence on overall organic matter decomposition, N accretion, and system equilibrium as a one-time 112 Mg ha^{-1} application of organic amendment.

Nitrogen is usually deficient in mine soils, which limits vegetation establishment and sustained productivity. Organic amendments are used as a source of mineralizable material to enhance N levels and extend N availability through cycling. Moss (1986) analyzed the N content of the amended mine soils after three growing seasons. Nitrogen data for 1985 and 1998 are presented here to show the comparative ability of the various organic amendments to affect long-term N availability (Table 4). In 1985, N_0 for all treatments ranged from 6 to 125 mg kg^{-1} and was well correlated ($r^2 = 0.80$; $P > 0.0001$) with SOM (Moss, 1989). The N mineralization potentials of control and native soil-treated plots were