RECLAMATION OF PRIME AGRICULTURAL LAND AFTER SURFACE MINING MINERAL SANDS FROM THE VIRGINIA COASTAL PLAIN: VARIABILITY IN PHYSICAL AND CHEMICAL PROPERTIES AND PRODUCTIVITY OF TAILINGS[1]

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Abstract: Minable quantities of Ti-bearing minerals occur in prime agricultural land in the Virginia Coastal Plain. Mining these soils and redistributing the tailings as a slurry has resulted in materials with poor physical and chemical properties in regard to agricultural productivity. This paper is focused on the spacial variability of tailings materials treated with various levels of yard waste compost (compost) or covered with topsoil. Treatments were applied to plots in a randomized complete block design with four replications. Each treatment received equal amounts of wood ash and fertility amendments. Minor amounts of spatial variability in tailings particle size distributions suggested an even distribution of tailings across the study area. Compost was added to tailings at rates of 1-12%. Coefficients of variation for 7 of the 10 organic carbon means from compost treatments were >35%, suggesting high variability. This variability can be attributed to the difficulty in spreading compost evenly across the plots. A systematic decrease in organic carbon occurred over a growing season in compost treated tailings as a result of microbial decomposition. Mechanical resistance measurements showed low to moderate variability, 88% of the means had coefficients of variability <30%. Compost treated tailings showed lower mechanical resistance and bulk density values. Soil pH, exchangeable bases, and cation exchange capacity increased with increasing amounts of compost. Addition of wood ash also increased the minesoil pH values. Tailings treated with topsoil showed the greatest amount of variability in corn and peanut yields over two years. Average yields of corn and peanuts grown on tailings amended with compost were at, or above, county averages.

Additional Key Words: Heavy Minerals; Corn; Peanuts; Yardwaste Compost; Wood Ash; Topsoil.

Introduction

Upper Coastal Plain soils, sediments, and paleosols of Virginia and North Carolina contain considerable concentrations of ilmenite, zircon, rutile, and leucoxene (Berquist 1987). Two areas in Virginia, known as the Brink and Old Hickory deposits, contain minable quantities of these heavy minerals in the sand fraction (Carpenter and Carpenter 1991), and are set to be mined within a few years. Soils containing mineral sands in these deposits, with respect to yields of corn and peanuts, are some of the most productive in the Atlantic Coastal Plain. Corn yields on soils planned for mineral sand mining can have average yields as high as 9600 kg/ha (Daniels et al. 1992). Therefore, reclamation of these prime agricultural lands is of the utmost importance.

The relative success or failure of the reclamation process has both economic and environmental ramifications. Successful surface mine reclamation provides protection of our natural resources such as ground and surface waters from pollution (Tate 1985). From an economic standpoint, successful reclamation results in good public relations, renewal of mining permits for future mining, and release of reclamation security bond monies. Federal law (U.S. Congress 1977) requires that prime agricultural land surface mined for coal must be returned to a productivity comparable to the original resource. Surface mining of mineral sands will most likely fall under similar mining regulations.

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Methods have not been established to reclaim prime agricultural land subjected to surface mining of heavy mineral sands in Upper Coastal Plain soils. Two methods are currently being considered to surface mine the mineral sands at the Brink Deposit. These methods are:

1) Stockpile the upper 50 cm of surface soil, mine the lower regolith, return the mine tailings to the land, and redistribute the surface soil over the mine tailings for reclamation.

2) Mine both the surface and subsurface soil and sediments, and return the tailings to the land for reclamation.

The first method, covering tailings, spoil, or overburden with topsoil, is a common practice in reclamation of prime agricultural land after coal surface mining (Power et al. 1981, Halvorson et al. 1986, Dunker and Jansen 1987, Barnhisel et al. 1988, Dunker et al. 1988, Caldwell et al. 1992, Henning 1992). Development of methods resulting in successful reclamation after mining both the surface and subsurface materials, however, would be the most profitable. Surface soils have the highest concentrations of mineral sands because minerals such as zircon and rutile are very resistant to weathering (Milnes and Fitzpatrick 1989). Therefore, if possible, these sources should be mined. In addition, because the surface material will not have to be removed separately, stockpiled, and then redistributed on the surface of the tailings, mining of both the surface and subsurface sediments in the overall scheme will require less time and energy.

Our research is focused toward developing reclamation methods for tailings in which both the surface and subsurface soils and sediments have been mined. The effects of the reclamation efforts can often be hidden or confounded by variability. Spatial variability is often divided into two components, systematic and random (Drees and Wilding 1973). Systematic variability in minesoils is that which can be explained by differences in treatments or natural processes such as weathering, leaching, and microbial decomposition. Random variability is related to unrecognizable differences in these effects, or error in treatment application, sampling, or analysis. The objectives of this paper are to describe the spatial variability in the physical and chemical properties of mineral sand tailings, and relate these properties to the variability in corn and peanut yields grown on the tailings.

Materials and Methods

Study Area

Our research site is located within the Brink mineral sand deposit in Greensville County, Virginia (Carpenter and Carpenter 1991). These deposits occur just east of the fall line that separates the Piedmont physiographic province from the Coastal Plain province to the east. Typic Hapludults and Typic and Plinthic Paleudults are the most common soils containing the heavy mineral sands (Edmonds et al. 1989).

An area of the Brink Deposit 30 x 60 m was excavated to a depth of 5 m to establish a reclamation study site. Materials were removed, treated in a manner simulating the separation of the mineral sands, and returned in a slurry form (tailings) to the mining site. Two sets of plots were established for planting of corn and peanuts. Areas consisting of a single treatment were 3 x 7 m in size. Treatments consisted of tailings (control), tailings amended with 1, 2, 4, 6, 12% yardwaste compost, and tailings capped with 45 cm of A horizon material (topsoil) stockpiled during mining (Fig. 1). Compost was added before planting in 1992 by hand and tilled into tailings to a depth of approximately 15 cm. Tailings plots treated with topsoil were excavated to 45 cm to remove tailings, and the stockpiled A horizon material was added with a skid-steer loader. These areas were then ripped to a depth of 60 cm with a chisel plow.

Soils were described and sampled from the walls of the simulated mining excavation pit. Samples were collected and analyzed from the upper 15 cm of each treatment. Particle size distribution was determined by pipette (Gee and Bauder 1986). Bulk density measurements were made from samples collected with a double cylinder sampler (Blake and Hartge 1986). Porosity was measured using a tension table (Danielson and Sutherland 1986). Mechanical resistance was measured in the field at depths of 5, 10, and 12.5 cm with a cone penetrometer (Bradford 1986). Saturated hydraulic conductivity (K_{sat}) was measured on saturated 5

Tailings Plot 1

R1	3	7	6	5	2	1	4
R2	1	6	5	7	2	3	4
R3	1	3	7	5	2	6	4
R4	5	3	1	6	2	7	6

Tailings Plot 2

R1	1	4	7	6	2	5	3
R2	5	7	3	4	2	6	1
R3	3	5	6	7	2	5	4
R4	5	1	7	4	2	3	6

Figure 1. Research Plots at Brink Site. Treatments: 1) Control; 2) Topsoil; 3) 1% compost; 4) 2% compost; 5) 4% compost; 6) 6% compost; and 7) 12% compost.

cm diameter cores maintained under a constant head (Klute and Dirksen 1986). Organic carbon was determined by dry combustion (Rabenhorst 1988). Cation exchange capacity (CEC) was determined from summation of the exchangeable cations and the extractable acidity (Rhoades 1982, Thomas 1982).

Wood ash was applied to the plots in 1992 and 1993 at rates of 2.2 t/A. Nitrogen (N), phosphorus (P), and potassium (K) were added to increase macronutrient fertility. Corn plots received 168 kg/ha of N in 1992 and 196 kg/ha in 1993. Sixty seven kg/ha of N was applied to the peanuts in 1992 and reduced to 33 kg/ha the following year. In 1992, 127 kg/ha of K was applied to both corn and peanuts. This was reduced to 112 kg/ha in 1993. Rates of P fertilization were 289 kg/ha in 1992 and 29 kg/ha in 1993 for both corn and peanuts. Zinc (Zn), as $ZnSO_4$, was applied in a foliar form in 1992 at a rate of 0.9 kg/ha. In 1993, 18 kg/ha of Zinc was applied to the minesoil. Dual 8E and AATREX were applied at rates of 4.2 kg/ha at time of corn planting to control weeds. Amendments to peanuts included: 8 kg/ha of Temik as a pesticide; Pursuit 2L and Dual 8E as herbicides; split application of 3368 kg/ha of gypsum as a soluble Ca source; and boron (B) and manganese (Mn) micronutrients.

The corn variety Pioneer 3140 was planted in both 1992 and 1993. The peanut variety VNC 851 was planted in 1992. In 1993, the peanut variety was changed to NC 7. Corn ears and peanuts were hand harvested and yields calculated from the center two rows of each treatment. Statistical analysis included calculations of means and coefficients of variation (CV) (Zar 1984).

Results and Discussion

Variability in Physical Properties

Texture, mechanical resistance, bulk density, porosity, hydraulic conductivity, and water holding capacity of the tailings are all important physical properties that need to be considered in regard to reclamation of mine tailings. The soil horizons from which the tailings originated have a range of textures from fine sand to sandy clay (Table 1). Particle size distributions (PSD) of the tailings are representative of the mixture of soil horizons from which they originated (Table 2). Mean sand content for the two tailings areas range from 70 to 75%, while clay contents ranged from 20 to 21%. Coefficients of variability (CV) were calculated for the means in order to enumerate the amount of variability in the various soil properties. Wilding and Drees (1983) grouped CV values into three classes: low variability, where CV values are <15%; moderate variability, 15-35%; and high variability, >35%. Percent silt for 7 of the 8 replications was <8%,

Table 1. Particle size distribution of a natural soil prior to surface mining.

Horizon	Depth	Sand						Silt	Clay	Textural Class
		VC	C	M	F	VF	Total			
	cm	%	%	%	%	%	%	%	%	
Ap	0-20	0.8	4.3	12.9	62.4	7.9	88.3	7.5	4.2	Fine Sand
Bt1	20-32	1.4	2.1	5.3	33.2	6.0	48.0	38.7	13.3	Loam
Bt2	32-83	1.5	1.6	3.8	27.9	4.6	39.4	46.2	14.4	Loam
Bt3	83-133	0.3	0.8	3.7	42.4	5.2	52.4	3.6	44.0	Sandy Clay
Bt4	133-185	0.0	0.8	4.6	49.0	2.8	57.2	3.6	39.2	Sandy Clay
2Bt5	185-235	0.3	1.7	20.5	48.9	1.9	73.4	2.0	24.6	Sandy Clay Loam
3C	235-290	12.7	14.2	13.5	39.7	1.8	81.7	1.6	16.7	Sandy Loam

Table 2. Particle size distribution for surface samples from unamended tailings (control). Coefficients of variation are in parentheses next to the mean.

Plot	Sand	Silt	Clay	Textural Class
	%	%	%	
		Tailings Plot 1		
R1-1	53	21	26.2	sandy clay loam
R2-1	71	5.5	23.9	sandy clay loam
R3-1	78	3.8	17.9	fine sandy loam
R4-1	79	7.2	14.3	fine sandy loam
Mean	70 (17)	12 (72)	20.9 (26)	sandy clay loam
		Tailings Plot 2		
R1-1	79	3.3	17.7	fine sandy loam
R2-1	78	3.7	18.6	fine sandy loam
R3-1	71	7	21.8	sandy clay loam
R4-1	74	5.1	20.8	sandy clay loam
Mean	75.5 (5)	4.8 (35)	19.7 (10)	fine sandy loam

therefore sand and clay are the dominant particle size fractions of the tailings. Clay and sand fractions show low to moderate amounts of variability. The minimal degree of spatial variability in sand and clay contents indicate that the tailings were deposited evenly across most of the study area. Observations of the in-place tailings also show a minimal amount of stratification.

Compost was added to the tailings at rates of 1, 2, 4, 6, and 12%. Tailings treated with compost were sampled prior to planting in 1992 and after harvesting and return of plant residues in the fall to examine variability in organic carbon (Table 3). The variation in means between spring and fall can be attributed to microbial decomposition of the compost causing a decrease in organic carbon content. A considerable amount of inherent variability in organic carbon content also occurs within most plots. Coefficients of variation for 7 of the 10 means are >35%, suggesting high variability. In addition, spring samples of the plots which were treated with 6% compost have a higher mean organic carbon content than those treated with 12% compost. This variability can be attributed to the difficulty in spreading compost evenly across the plots.

Table 3. Variability in organic carbon content within compost treatments. Samples were collected in the spring and fall of 1992. Coefficients of variation are in parentheses next to the means.

Treatment	Spring		Fall	
	Mean	Range	Mean	Range
	%	%	%	%
1% Compost	1.16 (9)	1.11-1.32	0.26 (41)	0.11-0.36
2% Compost	1.33 (20)	1.04-1.54	0.49 (61)	0.28-0.92
4% Compost	2.76 (64)	0.90-4.45	1.51 (25)	1.16-2.03
6% Compost	5.77 (54)	2.93-9.40	2.51 (37)	1.84-3.85
12% Compost	4.50 (42)	3.17-7.20	3.87 (51)	1.65-6.32

Additions of organic matter generally reduce bulk density values because of the lower specific density of organic material in comparison to mineral matter. This effect can be observed when comparing the bulk density values of the tailings material with that amended with compost (Table 4). Although organic carbon contents substantially declined for the tailings treated with 2 and 6% compost between 1992 and 1993 (Table 3), bulk density values did not increase. This suggests that other factors, such as minesoil structure development or pore space being created by root penetration, may be contributing to maintaining the low bulk density values of the tailings treated with compost. Coefficients of variation for the bulk density means are low (<14%) for all the treatments.

Table 4. Mean bulk density and range in values for tailings and tailings amended with compost. Means were calculated from 24 values. Coefficients of variations are in parentheses next to the means.

Treatment	1992		1993	
	Mean	Range	Mean	Range
	g/cm^3	g/cm^3	g/cm^3	g/cm^3
Tailings	1.46 (3)	1.39-1.52	1.44 (4)	1.35-1.50
2% Compost	1.38 (4)	1.30-1.45	1.37 (6)	1.23-1.46
6% Compost	1.23 (8)	1.11-1.39	1.18 (14)	1.09-1.49

Mechanical resistance is a good measurement of the resistance roots will encounter in the soil (Phillips and Kirkham 1962), and is affected by moisture content. With decreasing moisture content mechanical resistance increases (Terry 1953, Hemsath and Mazura 1974, MulQueen et al. 1977). This effect can be seen in the spring vs summer mechanical resistance measurements (Table 5).

Table 5. Mean mechanical resistance and moisture content. Coefficient of variation are reported in percent and in parentheses next to the means.

		Spring 1992		Summer 1992	
	Depth	Mechanical Resistance	Soil Moisture	Mechanical Resistance	Soil Moisture
	cm	MPa	%	MPa	%
Tailings					
Mean	5	0.30 (27)	15.9 (13)	1.50 (20)	8.7 (44)
Range	5	0.17-0.38	13.4-18.7	1.10-1.90	4.3-16.9
Mean	10	0.52 (22)	15.4 (19)	1.80 (21)	8.9 (24)
Range	10	0.38-0.66	10.2-19.1	1.15-2.07	4.9-13.1
Mean	12.5	1.15 (14)	15.7 (18)	2.00 (7)	10.6 (26)
Range	12.5	0.93-1.33	11.5-19.2	1.81-2.07	5.3-14.4
Tailing Amended with 2% Compost					
Mean	5	0.28 (28)	15.5 (23)	1.27 (30)	7.7 (24)
Range	5	0.19-0.40	10.1-19.5	0.62-1.93	5.7-10.9
Mean	10	0.42 (21)	16.2 (21)	1.75 (25)	9.6 (18)
Range	10	0.37-0.55	12.7-19.8	0.75-2.07	6.9-12.2
Mean	12.5	1.15 (16)	14.6 (42)	1.65 (46)	9.7 (21)
Range	12.5	0.88-1.57	13.1-21.2	0.97-2.07	7.1-12.9
Tailings Amended With 6% Compost					
Mean	5	0.29 (25)	31.7 (29)	0.93 (30)	15.8 (33)
Range	5	0.21-0.45	21.5-40.8	0.41-1.35	10.1-25.3
Mean	10	0.45 (22)	30.9 (85)	1.29 (34)	16.2 (33)
Range	10	0.33-0.59	9.2-42.5	0.79-2.07	7.9-25.2
Mean	12.5	1.06 (15)	244 (43)	1.73 (17)	13.2 (37)
Range	12.5	0.85-1.38	17.1-49.3	1.29-2.07	7.2-23.6

In general, mechanical resistance increases with depth. The cone penetrometer compacts soil as it is being pushed which increases the mechanical resistance (Hemsath and Mazurak 1974, MulQueen et al. 1977). Spring mechanical resistance measurements are very similar for equal depths for the three treatments. The summer mechanical resistance values, however, show that the addition of compost can reduce soil strength which is beneficial for plant roots. Mechanical resistance values over 2.1 MPa are considered too high for plant root penetration (Taylor and Gardner 1963, Taylor and Burnett 1964). Mean mechanical resistance measurements for the 10 and 12.5 cm depths of the unamended tailings are approaching 2.1 MPa.

Coefficients of variation for 88% of the mechanical resistance means are < 30% suggesting that variability in mechanical resistance measurements of mineral sand tailings and tailings treated with compost is low to moderate. Five of the 6 soil moisture CV values for means of tailings amended with 6% compost are >30%. These data suggest that the compost, which controls a considerable amount of the water holding capacity of the amended tailings, is not evenly distributed within the treatments. This conclusion is supported by the high variability in organic carbon content for the tailings amended with 6% compost (Table 3).

The addition of compost has increased both K_{sat} and porosity for the tailings (Table 6). The CV values for K_{sat} means of tailings treated with compost and the unamended tailings were extreme (71-180%). Coefficients of variation for porosity was much lower (4-6%). Tailings capped with topsoil had much lower mean K_{sat} values than the tailings treated with compost or unamended. Samples collected from tailings capped with topsoil also have the low soil porosity (38%). In addition, bulk density values for the topsoil over tailings ranged from 1.54 to 170 g/cm^3, and averaged 1.63 g/cm^3. The porosity, K_{sat}, and bulk density values suggest that compaction has occurred during placement of the topsoil over the tailings with the skid-steer loader.

Table 6. Variability in saturated hydraulic conductivity (K_{sat}) and porosity of selected tailings. Coefficient of variation are reported in percent and in parentheses next to the means.

Treatment	K_{sat} cm/hr		Porosity % Soil volume	
	Mean	**Range**	**Mean**	**Range**
Tailings	2.7 (71)	0.4-6.8	45 (4)	43-48
2% Compost	4.1 (88)	0.1-10.6	48 (5)	45-51
6% Compost	4.8 (180)	0.4-20.4	54 (6)	49-55
Topsoil	0.1 (9)	0.1-0.2	38 (6)	36-42

Variability in Chemical Properties

Mineral sand mine tailings are relatively acid (pH 4.3-4.8). Therefore, wood ash was added to the tailings. Additions of 2.2 t/A of wood ash in 1992 raised the pH of the tailings materials to 5.1 (Table 7). Our goal, however, was to reach a pH of 6.0. Therefore, in 1993, wood ash was again added to all of the plots. These additions raised the pH to desirable levels (Table 7). The 6 and 12% compost treatments have the highest pH values suggesting an increase in buffering capacity to the tailings by adding compost. Coefficients of variability for pH were very low for all treatments.

Addition of compost increased the levels of exchangeable Ca, Mg, and K, as well as increased the cation exchange capacity (CEC) of the amended tailings (Table 7). In the compost treatments a noticeable decrease in exchangeable Ca, Mg, and K is evident between spring 1992 and fall 1994. These differences can be related to plant uptake and leaching of the bases. Decreases in exchangeable Mg and K were about 50%. Calcium content did not decrease this much. The addition of Ca from the wood ash and gypsum added in 1993 kept the levels close to the 1992 values in the compost treatments, and increased the levels in the tailings and topsoil treatments. The decomposition of organic matter in the compost resulted in a decrease in CEC between spring 1992 and fall 1993. Most of the CV values for the exchangeable bases and CEC means showed low to moderate variability.

Table 7. Variability in pH, extractable bases, and cation exchange capacity (CEC). Samples were collected from the surface of the tailings. The 1993 samples were collected after harvesting corn. Coefficients of variation are reported in percent and are in parentheses.

Treatment	pH	Ca	Mg	K	Sum CEC
		------------meq/100 g----------------			
Spring 1992					
Tailings	5.1 (6)	1.42 (27)	0.27 (18)	0.23 (22)	6.6 (2)
Topsoil	4.6 (5)	1.09 (14)	0.27 (18)	0.23 (22)	4.9 (7)
1% compost	4.9 (2)	2.85 (34)	0.58 (28)	0.33 (25)	8.4 (41)
2% compost	4.9 (1)	3.15 (10)	0.68 (13)	0.35 (13)	10.1 (21)
4% compost	5.1 (3)	5.39 (13)	0.21 (12)	0.49 (5)	15.2 (11)
6% compost	5.2 (3)	8.71 (22)	2.18 (22)	0.85 (20)	20.9 (20)
12% compost	5.4 (4)	11.55 (20)	3.05 (18)	1.13 (13)	26.7 (20)
Fall 1993					
Tailings	5.9 (3)	1.75 (14)	0.15 (5)	0.15 (11)	4.2 (20)
Topsoil	5.8 (1)	1.24 (4)	1.12 (8)	0.12 (1)	3.1 (16)
1% compost	5.8 (3)	2.23 (21)	0.24 (30)	0.21 (24)	6.4 (36)
2% compost	6.2 (1)	2.69 (4)	0.25 (10)	0.18 (11)	5.4 (14)
4% compost	6.2 (1)	3.93 (24)	0.44 (22)	0.22 (20)	7.2 (17)
6% compost	6.2 (2)	6.41 (20)	0.93 (30)	0.31 (25)	11.4 (20)
12% compost	6.4 (1)	8.18 (13)	1.67 (11)	0.43 (11)	16.6 (13)

Crop Yields

Peanuts were grown on the lower tailings and corn on the upper plots in 1992. These two crops were rotated between plots in 1993. For the two years data, average yields of both corn and peanuts grown on the tailings amended with topsoil are the most variable (Figures 2 and 3). These average yields are also below the county average. All of the compost treatments showed average yields of both corn and peanuts at, or above, the county average based on two years data.

Conclusions

Prime agricultural lands in the upper Virginia coastal plain are rich in Ti-bearing minerals. The mining, distribution of tailings, and treatment of tailings with compost and topsoil has resulted in materials with minor to high degrees of spatial variability. Particle size distributions of tailings showed minimal amounts of variability indicating an even distribution of tailings. Variability in organic carbon content within compost treatments was high suggesting inconsistencies in the spreading of compost across the plots. Mechanical resistance measurements showed low to moderate variability. Variability in bulk density was low. Mechanical resistance and bulk density were reduced, and levels of pH, exchangeable bases, and cation exchange capacity were elevated with increasing amounts of compost. These data suggest that compost is

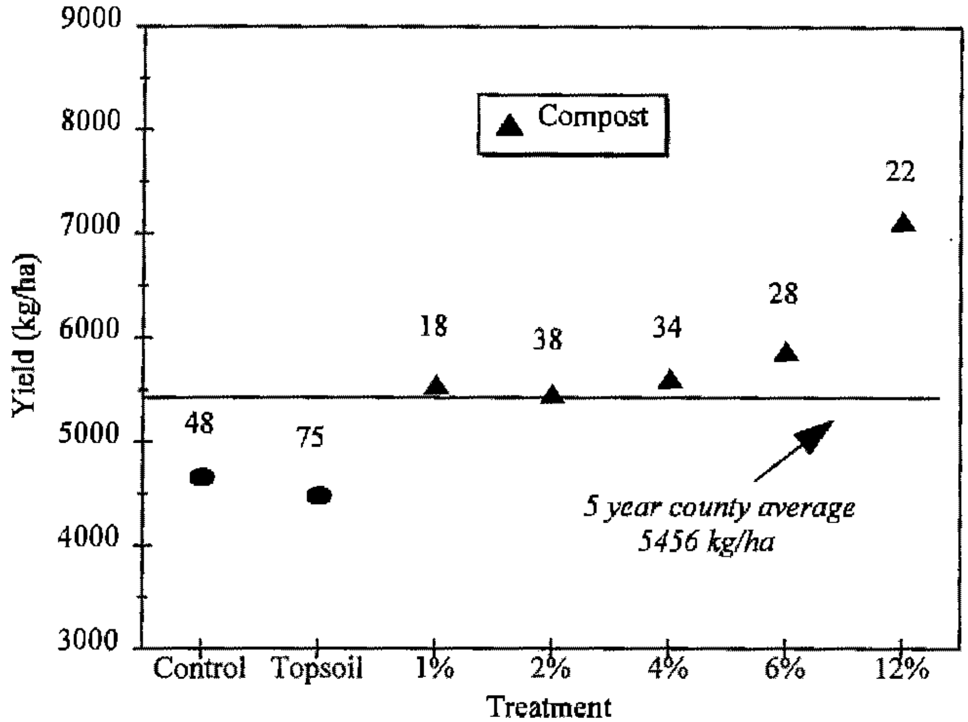

Figure 2. Mean yields of corn on tailings, tailings + topsoil, and tailings with various rates of compost. Coefficients of variability (cv) appear above the mean symbols.

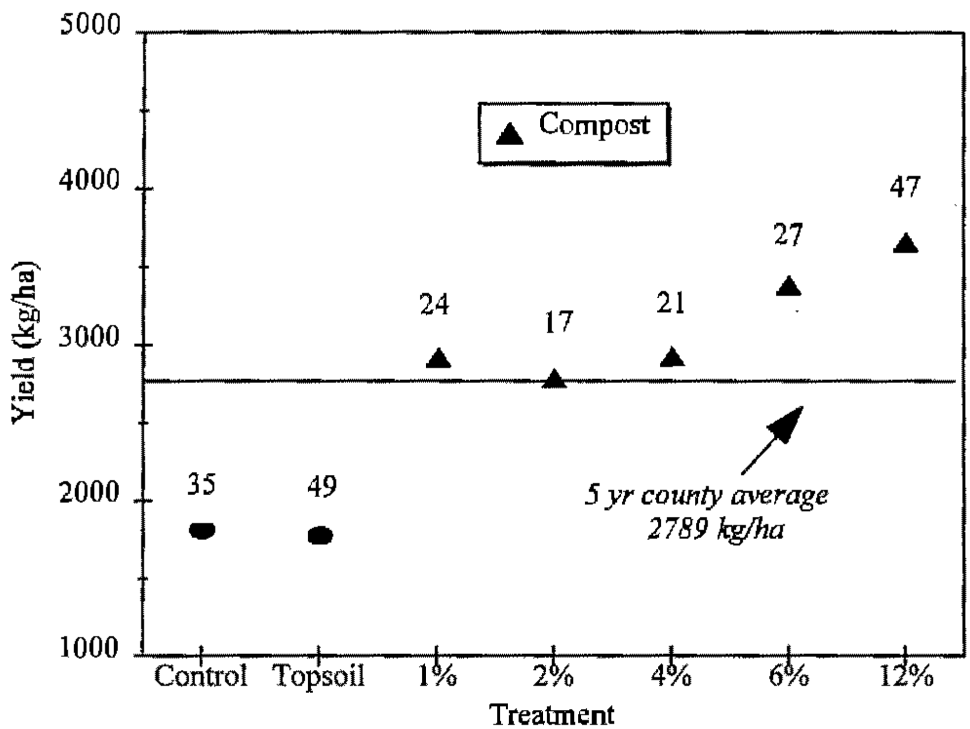

Figure 3. Mean yields of peanuts on tailings, tailings + topsoil, and tailings with various rates of compost. Coefficients of variability (cv) appear above mean symbols.

effective in improving the physical and chemical properties of the tailings. Tailings treated with topsoil showed the highest amount of variability in corn and peanut yields. These yields were also below county averages. Yields of corn and peanuts grown on tailings amended with compost were at, or above, county averages. These results suggest that the addition of compost to the tailings, rather than the more traditional approach of placing topsoil over the tailings, may be a better reclamation strategy.

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