CHEMICAL AND PHYSICAL PROPERTIES OF MINERAL SANDS MINE SOILS IN SOUTHEASTERN VIRGINIA[1]

W. L. Daniels[2], Z. W. Orndorff, and P.D. Schroeder

Abstract. Significant areas of prime farmland in the upper Coastal Plain of Virginia and North Carolina will be disturbed by heavy mineral sands (Ti/Zr-bearing ilmenite, rutile, zircon) mining over the next 20 years. The physical and chemical properties of mine soils that result from the mining and reclamation process were studied in a replicated small plot experimental setting between 1994 and 1997 and in detailed transects over a succession of eight mining pits reclaimed between 1997 and 2002. Separation of sandy tailings from silt+clay slimes in dewatering pits leads to significant differences in soil texture, seasonal wetness and bearing capacity across the reclamation surfaces. Plant growth in sandy tailings areas is directly limited by low water holding capacity while that in finer textured zones is limited by the massive and laminated nature of the slimes. Compaction of the surface and subsurface also limits rooting in non-sandy reclaimed areas. Freshly deposited materials tend to be very low in pH (≤ 5.2) and in plant-available nutrients due to the highly weathered nature of the original deposit and the mineral separation processes employed. Native topsoil on-site is very high in heavy mineral content, and is therefore subject to being processed rather than saved for reclamation. An array of reclamation protocols have been implemented at the site including heavy liming and P application, deep ripping, and the utilization of biosolids to improve post-mining productivity. Revegetation of eight mining pits produced between 1997 and 2002 was positively affected by the utilization of topsoil, and extremes in surface texture limited revegetation where topsoils were not employed. Issues associated with differential settlement as the fills dewater over time, and the possibility of P leaching in areas of pure sandy tailings warrant further study.

Additional Key Words: Reclamation, titanium mining, tailings, slimes, biosolids, tillage, soil strength, soil fertility, soil acidity.

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Introduction

In 1997, Iluka Resources Inc. (formerly RGC USA Inc.) began active mining of the 2000 ha Old Hickory deposit of heavy mineral sands (Ti and Zr in ilmenite, leucoxene, rutile and zircon) in the Upper Coastal Plain of Virginia (Berquist and Goodwin, 1989; Carpenter and Carpenter, 1991). The deposit lies in Dinwiddie and Sussex Counties (see Fig. 1) in a relatively undissected landscape of Pliocene to perhaps early Pleistocene age. The heavy minerals are contained within the upper 5 to 20 m of highly weathered Coastal Plain soils lying abruptly over Piedmont igneous and metamorphic saprolites. Similar deposits have been located and leased for future mining in Greensville County, Virginia (Brink Deposit), and at multiple locations in North Carolina. Therefore, the long-term area of potential disturbance is great. Much of the recoverable mineralized area occurs under prime farmlands. This is an important peanut, soybean, tobacco, and (recently) cotton-producing region, and in fact, one farm in the center of the Old Hickory deposit was the top-yielding peanut producer for several years in the mid-1980's. Return of these lands to some form of agricultural production is a priority for the mining firm and the landowners, although post-mining productivity standards are not mandated by state law or the mining leases. To date, mineral sands mines have not been returned to row-crop agriculture anywhere in the world, but successes have been noted in return to pasture/hayland, wetland, native forests and heaths, and pine plantations in both the USA and Australia (Brooks, 1989).

Mineral sands processing in high clay deposits such as those found in Virginia generates coarse sand tailings along with an abundance of slimes (very fine sand, silt and clay) which must be recombined for effective disposal and reclamation (Brooks, 1989). Since the heavy mineral content of the native topsoil layer is typically quite high, both the mining company and the landowners have a direct interest in processing the A and E horizons along with the bulk of the mineral bearing sands. However, the importance of topsoil return is well-documented in prime farmland reclamation in other mining environments (Dunker et al., 1992). Therefore, a particular focus of our work on this project since 1990 has been to evaluate topsoil substitutes versus conventional topsoil return strategies. In precursor studies to the work reported here (Daniels et al., 1991, 1996), we evaluated soils reconstructed from tailings:slimes mixtures in 1.2 m reconstructed profiles in barrels in the greenhouse and found that the simulated mine soils could serve as suitable plant growth media if significant levels of P were added to offset fixation

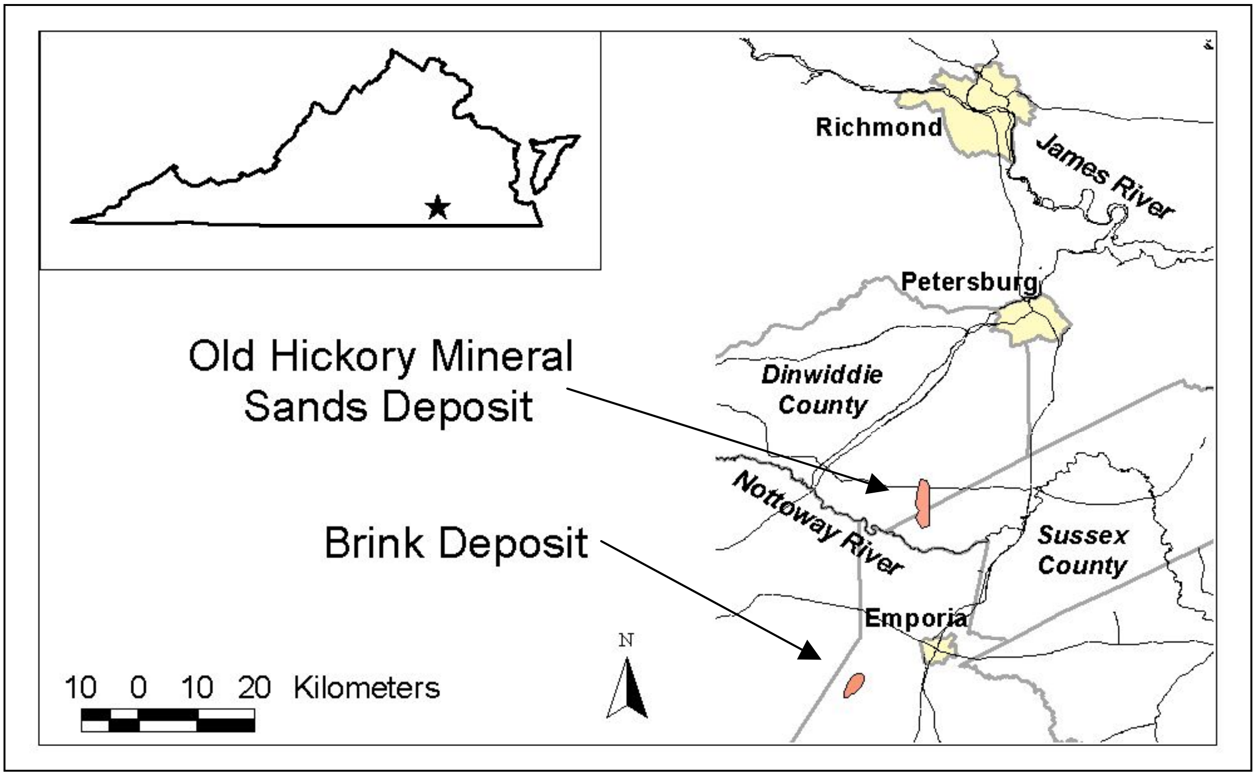

Figure 1. Location of Old Hickory mining area in southeastern Virginia. Similar large expanses of heavy minerals are leased for mining at Brink and in similar landscapes in North Carolina.

potentials along with appropriate pH adjustment via liming. In a follow-up study (Daniels et al., 1999) on pilot mining pits between 1995 and 1998, we compared the effects of thick (25 cm) topsoil return vs. topsoil substitution via the addition of 112 Mg/ha yardwaste compost to mixed tailings and slimes following heavy P-fertilization, liming, and ripping of the reclamation surface. Over a four-year cropping rotation, post-mining productivity compared to adjacent prime farmland plots was reduced by 23%, 3%, 27%, and 20% for each crop (wheat/soybeans/corn/cotton) in sequence. For a given crop in a given year, response to topsoiling versus compost addition to the surface varied, and neither treatment appeared superior.

In this paper, we summarize results from detailed rooting and mine soil characterization studies performed by Schroeder (1997) in the row-crop experiment cited above, and we report detailed soil characterization and observed field revegetation response from our study of eight large active mining pits that have been reclaimed and revegetated since 1997. Our overall objectives in this combined work have been to (1) determine the physical and chemical characteristics of these reclaimed mine soils, and (2) relate these properties to expected revegetation response and post-mining agricultural productivity potentials.

Methods and Materials

Pilot Mining Pit Soil Studies in 1995 and 1996

Detail on the layout and experimental design of the replicated pilot mining pit study is provided by Schroeder (1997) and Daniels et al. (1999), and an image of the processing layout and one of the pilot mining pits is provided in Fig. 2. Field experiments were installed on two pilot-scale (25 m X 60 m) mining pits in the late summer of 1995 and replicated on a directly adjacent undisturbed prime farmland area. Half of each mining pit was topsoiled (25 cm) while the remaining half was left as either (1) mixed tails/slimes or (2) re-graded subsoil over tails/slimes to simulate various pit closure scenarios. Both non-topsoiled half-pits received 112 Mg/ha of yard waste compost as a soil building amendment. The entire area was ripped/disked to ameliorate compaction and incorporate lime and fertilizer additions. The experiment was cropped through a wheat/soybeans/corn/cotton rotation over the 1995 to 1998 growing seasons. In 1995 and 1996, bulk soil samples were taken from every 25 cm of the reclaimed plot areas on a 4 x 5 m grid to a depth of 150 cm with a bucket auger, and composite samples of the 12 plots within each treatment (compost vs. topsoil) were taken to a depth of 15 cm with a soil probe. In mid-summer of 1996, following soybean harvest, 18 soil pits were excavated into the edges of randomly selected plots and completely described for soil morphology and rooting distribution (Bohm, 1979). Bulk samples of the 0-15 cm layer and all delineated horizons were taken for lab analysis and three intact cores were taken from each delineated horizon for bulk density determination, which was adjusted to account for the high particle densities. Root length was also evaluated in June of 1996 following wheat harvest by washing roots from intact soil cores. Full detail on all analyses is provided by Schroeder (1997).

Reclamation Pit Studies

The first excavations for the Old Hickory mining operations commenced in the summer of 1997 with the excavation of two small (4 to 6 ha) low grade mineral areas (Tailings Pits - TP 1 and 2), that were designed to accept tailings from the first-cut mining pits in higher grade areas.

Figure 2. Pilot processing plant and adjacent test pit in 1995. Spirals for sand separation are shown in middle background and the slimes thickener tank is on the left. Mixed tailings and slimes are being deposited in the foreground into one of the three test mining pits.

Subsequently, a series of mining pits ranging in size from 5 to 13 ha were mined and reclaimed as described later (see Fig. 3). The construction, physical composition, and reclamation treatments applied to the pits varied considerably. Eight reclaimed pits were sampled during the fall of 2001 and spring of 2002. At each pit, multiple auger borings were described and sampled from a regular grid to a depth of up to 150 cm. For pits 9702 and 9703, which are adjacent, samples were collected at 56 points along a grid with intervals of approximately 30 m. For each of the other five fields, samples were collected along 3 transects with an interval of approximately 30 m. This included 17 sampling points for the adjacent pits 9704-9705, 22 sampling points for pit 9801, 36 sampling points for pit 9806, 14 sampling points for Tailings 1, and 16 sampling points for Tailings 2.

In the field, profile descriptions were completed including horizon depths, texture, color, and consistence at each sampling point. Surface soil samples were collected from the upper 15 cm. If an abrupt boundary occurred within the upper 15 cm, then topsoil samples were separated to represent each material. Subsoil samples were collected as a composite sample of all materials occurring between 15 – 90 cm. In the laboratory, samples were air-dried, ground to pass a 2-mm sieve, and analyzed for pH, organic matter (Walkley and Black, 1934), particle size distribution by the pipette method (Gee and Bauder, 1986), and levels of dilute double acid extractable P, K, Ca, Mg, Zn, Mn, Cu, Fe, and B by Inductively Coupled Plasma Emission Spectroscopy (Donohue and Heckendorn, 1994).

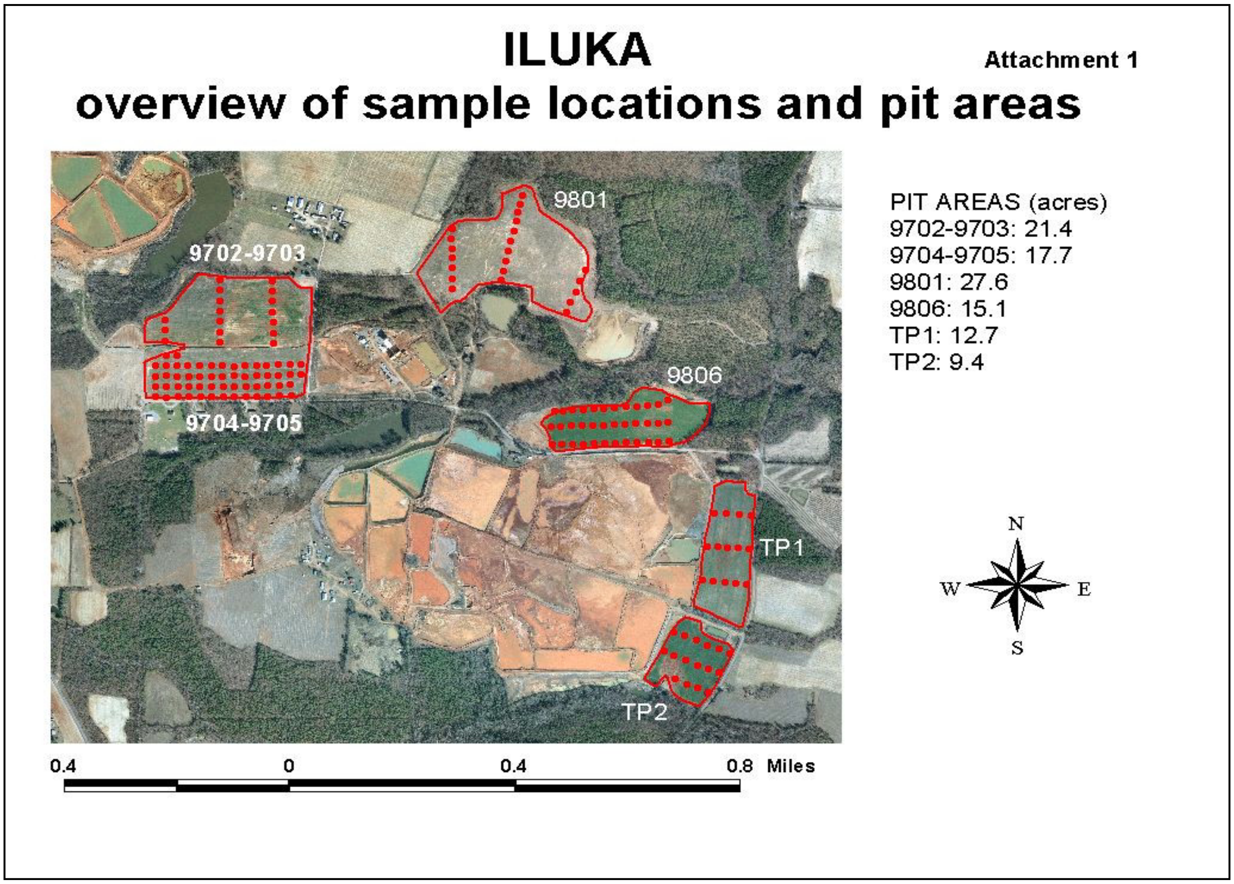

Figure 3. Aerial photo and pit map of the Old Hickory project area in late 2001. The pits sampled for this study are delineated, and the sampling transects appear as red dots. The area in the center is active mining. Light colored unmined areas are prime farmlands and wooded areas are predominantly wetlands or lower productivity (sloping and/or eroded/clayey) soils.

Results and Discussion

Overview of Mining, Processing, and Reclamation Procedures Employed at Old Hickory

Immediately before mining, any existing vegetation (e.g. forests or old fields) are removed and raked as necessary. Where topsoil is being salvaged, approximately 15 cm of A horizon material is bulldozed into windrows around the edges of the mining pits, and commonly becomes a portion of the enclosing dikes. Additional low-grade subsoil material is utilized to build enclosing dikes (up to 4 m above grade) as necessary. Mineral enriched weathered soil and underlying Coastal Plain sediments are dry-excavated using conventional loaders and haulers, dumped locally through a trommel-screen, and then pumped with water up to several km to the wet separation (concentrator) facility. The suspended soil/water mixture is then passed through sequences of separatory spirals (see Fig. 2) where the finer textured slimes (clays, silts, and some very fine sands) are separated away from the mineral bearing sand fraction. On average, the deposit generates from 35% to 45% slimes, depending on the weathering extent of the soil landscape unit being mined. The heavy mineral sands (particle density $\geq$ 4.0 g/cm^3) are further separated via spirals from the lighter host quartz. No additives or chemicals are used in the separatory process, but the soils are exposed to large amounts of process water and washing.

The two processed waste streams from the concentrator facility are dominantly Fe-coated quartz sands (tailings) from the spirals and the slimes which are partially dewatered in a thickener (see Fig. 2) via the addition of polymer flocculants. The tailings and thickened slimes are then pumped back to the reclamation pits in a 35 to 50% solids slurry. Detail on the mineralogy of these materials is provided by Van Wormhoudt (1993). The majority of the slimes fraction is Fe-coated kaolinite, but significant amounts of hydroxy-interlayered vermiculite and smectites do occur in some of the less weathered soils found in wetter and younger landscapes across the deposit, which negatively affect slime flocculation when encountered. At varying times between 1997 and 2000, tailings and slimes were either pumped combined or separately to the various pits to dewater as discussed below. However, due to mixing and shearing in pumping between the thickener discharge and the receiving pits, the slimes are re-dispersed when they discharge. This leads to significant segregation of sand tailings “beaches” or fans immediately below the discharge points (see Fig. 4) with finer textured silts and clays moving freely with water away from the discharge point. Surface water is decanted as quickly as possible from the pits and returned to the processing plant as make-up water. In recent years, the company has utilized multiple internal dikes and water control structures within dewatering pits to minimize lateral separation of the slimes away from the tailings (Fig. 4). For various operating reasons in 1997/1998, certain pits were backfilled with dominantly sandy tailings (e.g. 9801) while others (TP 1 and 2) received higher components of slimes. Regardless, the re-dispersion of the slimes has led to a significant swell factor in the overall mining removal/tailings deposition process, and the resultant landscapes are frequently higher than original grade. Settling with time is also expected for these areas, particularly as the high water containing slimes dewater fully, but this has not been rigorously documented to date.

Figure 4. Mining pit being backfilled with mixed tailings and slimes at Old Hickory. The light colored materials in the background are sandy tailings while finer-textured slimes have migrated to the calmer water environment in the foreground. Recent (post-2000) utilization of internal cross-dikes as seen here has minimized segregation to some extent. Material in the immediate right foreground is topsoil forming an enclosing dike.

Depending on weather conditions, it takes anywhere from several months to a year for the surface of the pits to dry down sufficiently to support machinery. Sandy tailings "beaches" are readily accessed while areas of high slimes contents take considerably longer to dewater to support tracked vehicles. Once accessible, the surface contour of the dewatered pits is graded with a bulldozer to ensure adequate surface drainage, and areas of highly contrasting materials are worked out to the best extent possible. This is often accomplished by dozing/ramping the enclosing dike materials up and over the final reclamation surface. Next, agricultural lime (4 to 10 Mg/ha) is applied depending on texture and pH, and P-fertilizer is applied at 350 kg/ha P_2O_5.

Depending on revegetation sequence, certain pits also received an additional 150 to 200 kg/ha P_2O_5 when indicated by low soil test P. These bulk soil amendments are then incorporated via a sequence of V-ripping followed by chisel-plowing and/or offset disking. The overall goal of this combined treatment is to physically loosen, lime and P-fertilize the mine soil materials to a depth of at least 30 cm. If topsoil has been retained in the lateral dikes, and is accessible, it is then returned at varying thickness over the conditioned subsoil materials, and disked again. Additional N-P-K fertilizers are then added to reclamation surface per the intended revegetation mixture, which has been mixed hayland/pasture (*Festuca arundinacea, Lotus corniculatus*, etc.) to date. Virginia Division of Mineral Mining (VDMM) regulations require two growing seasons of vegetative cover of sufficient quality to meet permit release standards. To date, pits TP1, 9702, 9704 and 9705 have met VDMM release standards.

Summary of Effects of Mine Soil Properties on Rooting and Productivity Observed in Pilot Plant Experiment in 1995 and 1996.

As detailed in our earlier paper (Daniels et al., 1999), crop yields in the replicated field experiment were approximately 20% lower than adjacent unmined ground over a four-year rotation period. Due to the extensive liming and fertilization regimes employed, these differences appeared to be due primarily to differences in physical properties and the subsoil rooting environment. Prominent segregation of tailings and slimes was obvious across the experimental pits when they dewatered, and efforts to physically remix the surface with a track loader were only partially successful in ameliorating surface texture variability. Detailed pit morphological observations by Schroeder (1997) also revealed significant layering of contrasting textural bands (slimes vs. tails) within the upper 1.5 m in 7 of 12 pits described in reconstructed soils. Perhaps more importantly, variability in subsoil clay content at 100 cm was extreme in the reconstructed soils when compared with the natural controls (Fig. 5).

As revealed by detailed root mapping from soil pits (Schroeder, 1997) rooting in the undisturbed control plots was significant to at least 150 cm, while rooting in all mine soils, regardless of treatment, was limited to the upper 50 cm. Bulk density ranged from 1.3 to 1.7 Mg/m^3 in the A horizons of all treatments, and was actually lower in the reconstructed mine soils than in the native soil. However, the subsoils (deeper than 25 cm) of the mine soils were structureless-massive with bulk densities ranging from 1.7 Mg/m^3 in sandy materials to

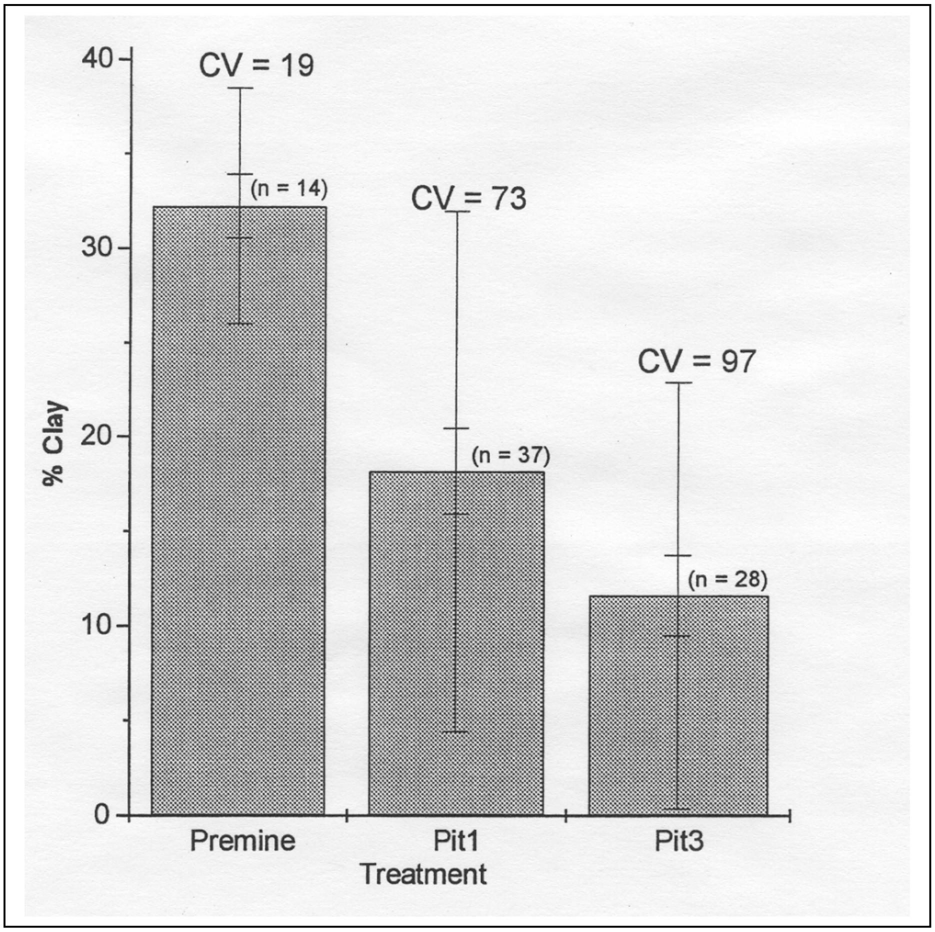

Figure 5. Variability in clay content in deep subsoils (100 cm) in pre-mining native soils (Typic Kandiudults: Faceville series) compared with reconstructed mine soils in experimental Pit 1 and Pit 3 as described in detail by Schroeder (1997). The mine soils are much lower in total clay content at this depth, and much more variable from point-to-point.

approximately 1.1 in pockets of slimes. The subsoils in the native soil materials were moderate to strong medium subangular blocky in structure with average bulk densities around 1.5 Mg/m^3. While increasing bulk density of the soil surface layers across all treatments in the experiment did have a significant negative effect ($p < 0.05$) on soybean yield in this experiment, the relationship was weak ($r^2 = 0.22$). However, the relationship between percent soil C and bulk density was very strong (see Fig. 6). Additionally, exchangeable cations and a number of other chemical parameters, as expected, were also strongly related to soil C content. Based upon the combined results from these studies, along with our previous greenhouse growth trials performed

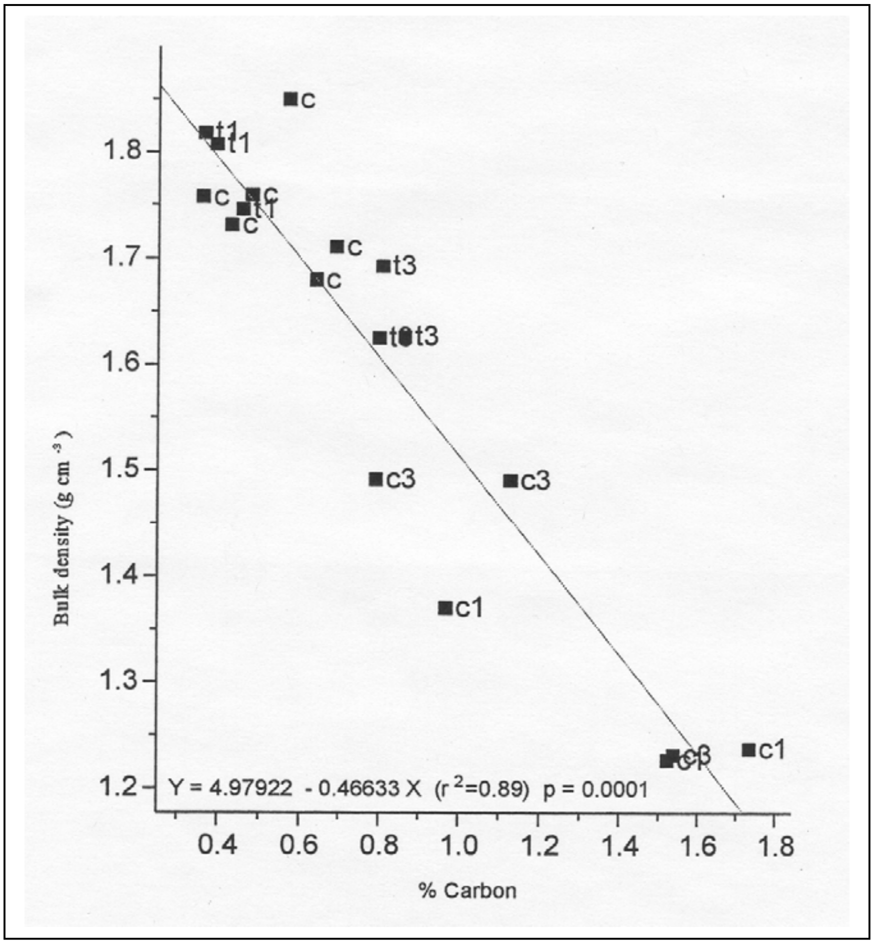

Figure 6. Linear relationship between increasing % C and decreasing bulk density due to improved aggregation in surface samples taken from 18 soil pits in natural soils (c's) and mining pit soils (t's) described by Schroeder (1997) in a long-tem field experiment at Old Hickory.

in deep barrels (Daniels et al., 1991, 1996), the development of adequate subsoil structure and associated macro-porosity over time appears to be a critical requirement for the return of these soils to high levels of row-crop productivity. Also, mine soil amendments or strategies that increase soil organic matter should be utilized where economic and feasible.

Mine Soil Properties and Variability in Reclaimed Mining Pits

When combined tailings and slimes from Old Hickory are freshly dewatered, they are generally pH 4.8 to 5.2 with 1 to 2 mg/kg extractable P, and essentially no organic matter or total N (Daniels et al., 1996; Schroeder, 1997). Overall soil pH in the surface layer for the eight reclaimed mining pits ranged from approximately 4.5 – 7.5 (Table 1) and from 4.8 to 5.3 in the subsoil layer (Table 2), reflecting the inherent acidity of the materials and the effects of liming in the surface layers. The median surface pH in pits 9702-9705 and TP 1 and 2 was between 6.0 and 6.8 as targeted following liming. The low pH (4.8) in the surface of pit 9806 was due to the fact that it was sampled before lime and fertilizer were applied. However, the low pH in pit 9801 was puzzling, since it had been limed at 3.5 Mg/ha approximately 18 months before sampling.

Extractable P, Ca, Mg, and K levels in the surface (Table 1) vs. subsurface samples (Table 2) also reflected the differential effects of fertilization and liming. It is notable, however that the surface soil levels of extractable P were still quite low (1 to 25 mg/kg) in relationship to fertilizer rates applied of 300 to 500 kg P_2O_5 per ha. In most instances, this is attributed primarily to very strong P-sorption which we documented earlier in these materials (Daniels et al., 1991). In pit 9806, the low P levels were again due to the lack of fertilization before sampling, but similar very low levels (1.0 mg/kg P) in pit 9801, which was supposedly heavily P-fertilized, were unexpected. Possible explanations include that (1) the recommended rate of P may not have been applied to this pit, or (2) the very sandy subsoil of this pit (see Table 3) allowed the P to leach. While the median surface texture of pit 9801 appeared to be quite similar to the other pits sampled (Table 3), detailed field examination revealed that the vast majority of the surface of this pit was exposed coarse sandy tailing which were somewhat under-represented in the sampling transects. The surface of this pit was also amended with additional slimes and finer-textured topsoil materials after the fertilizer and lime were applied, but before our transect samples were taken. The subsoil texture of this pit (96% medium and coarse sand), and an obvious lack of Fe-coatings on the sand grains would also support the possibility of P-leaching here. However, since the revegetation contractor's records confirm that P and lime was supposedly applied to this pit, more work is clearly needed to confirm whether or not P-leaching is a real possibility in these materials.

Acid extractable micronutrient levels were predictably low (Tables 1 and 2), particularly for Zn, Cu and B. While no obvious deficiency symptoms have been noted to date in the mixed grass/legume vegetation, the possibility of long-term micronutrient fertilization needs to be addressed. Organic matter in the surface soil typically ranged from 0.5 – 1.0%, with slightly higher values occurring in Tailings 1 and 2 (Table 3). These levels reflect the fact that the majority of all pits except 9801 and 9806 received at least 5 cm of topsoil over significant areas

Table 1. Nutrient levels and pH of surface soil samples (0 - 15 cm) for six reclaimed mining pits at the Old Hickory Project. Properties of adjacent natural soils are detailed by Schroeder (1997).

Pit		pH	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B
			---------------------------------- mg/kg ----------------------------------								
9702 - 9703	Min	5.0	2	31	162	48	0.2	3.1	0.2	5.2	0.1
	Max	7.6	89	128	1289	261	0.9	10.5	0.5	61.6	0.2
	Med	**6.8**	**15**	**60**	**472**	**101**	**0.4**	**5.8**	**0.2**	**12.3**	**0.2**
	Std dev	0.8	23.0	35.5	298	60.6	0.2	2.6	0.1	18.5	0.1
9704 - 9705	Min	5.0	1.0	18	208	36	0.3	2.8	0.2	7.8	0.1
	Max	7.1	102	415	2706	327	5.6	42	2.0	81	0.3
	Med	**5.9**	**25**	**132**	**433**	**81**	**0.9**	**11.7**	**0.5**	**41.7**	**0.1**
	Std dev	0.6	24.3	81.1	388	48.1	1.4	7.0	0.4	16.2	0.1
9801	Min	4.6	1.0	3.0	34	8	0.2	0.1	0.1	2.8	0.1
	Max	6.5	13	66	309	47	0.4	2.1	0.2	20.6	0.2
	Med	**4.9**	**1.0**	**7.5**	**60**	**15**	**0.2**	**0.3**	**0.1**	**4.2**	**0.1**
	Std dev	0.4	2.6	14.7	74	11.4	0.1	0.6	0.0	4.0	0.0
9806	Min	4.6	1.0	5	57	15	0.2	0.3	0.1	3.2	0.1
	Max	6.5	10	62	552	114	0.6	11.2	0.4	51	0.2
	Med	**4.8**	**1.0**	**17.5**	**145**	**39**	**0.4**	**1.8**	**0.2**	**6.35**	**0.1**
	Std dev	0.4	1.7	15.9	137	25.4	0.1	2.7	0.1	10.6	0.0
Tailings 1	Min	5.4	5.0	5.9	175	42	0.4	5.1	0.3	15.1	0.1
	Max	6.9	20	129	515	137	0.7	14.8	0.7	154.2	0.3
	Med	**6.2**	**13**	**93**	**465**	**95**	**0.6**	**8.5**	**0.5**	**30.9**	**0.2**
	Std dev	0.5	4.6	34.4	97	29.8	0.1	2.6	0.1	38.4	0.0
Tailings 2	Min	4.9	2.0	14	243	51	0.4	3.1	0.1	7.5	0.1
	Max	6.8	40	123	703	127	1.3	18.5	0.7	95.8	0.2
	Med	**6.0**	**19**	**53**	**483**	**93**	**0.8**	**11.3**	**0.5**	**67.1**	**0.2**
	Std dev	0.6	10.4	25.1	123	19.4	0.3	4.6	0.2	30.8	0.0

Table 2. Nutrient levels and pH of subsoil samples (15 – 90 cm) for six reclaimed mining pits at the Old Hickory Project. Properties of adjacent natural soils are detailed by Schroeder (1997).

Pit		pH	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B
			---------------------------------- mg/kg ----------------------------------								
9702 - 9703	Min	4.6	1.0	4.0	49	10	0.2	0.2	0.1	2.7	0.1
	Max	7.3	10	20	341	59	0.3	5.7	0.2	8.1	0.1
	Med	**5.1**	**1.0**	**12**	**101**	**23**	**0.3**	**0.8**	**0.2**	**4.8**	**0.1**
	Std dev	0.7	2.2	5.1	71	13.7	0.1	1.6	0.1	1.3	0.0
9704 - 9705	Min	4.5	1.0	8	77	18	0.2	0.4	0.1	4.4	0.1
	Max	7.0	16	163	950	162	1.7	19.9	1.0	68.1	0.2
	Med	**5.3**	**1.0**	**20.5**	**209**	**43**	**0.4**	**1.7**	**0.2**	**6.8**	**0.1**
	Std dev	0.6	3.4	29.5	169	32.5	0.3	3.9	0.2	12.3	0.1
9801	Min	4.6	1.0	3.0	34	8	0.2	0.1	0.1	2.8	0.1
	Max	6.5	13	66	309	47	0.4	2.1	0.2	20.6	0.2
	Med	**4.9**	**1.0**	**7.5**	**60**	**15**	**0.2**	**0.3**	**0.1**	**4.2**	**0.1**
	Std dev	0.4	2.6	14.7	74	11.4	0.1	0.6	0.0	4.0	0.0
9806	Min	4.6	1.0	5.0	57	15	0.2	0.3	0.1	3.2	0.1
	Max	6.5	10	62	552	114	0.6	11.2	0.4	51	0.2
	Med	**4.8**	**1.0**	**17.5**	**145**	**39**	**0.4**	**1.8**	**0.2**	**6.35**	**0.1**
	Std dev	0.4	1.7	15.9	137	25.4	0.1	2.7	0.1	10.6	0.0
Tailings 1	Min	4.5	1.0	10	80	22	0.2	2.3	0.1	4.4	0.1
	Max	5.9	20	109	447	69	1.3	23.2	0.8	241.2	0.3
	Med	**5.3**	**1.0**	**22**	**163**	**40**	**0.4**	**4.7**	**0.2**	**8.0**	**0.1**
	Std dev	0.5	5.4	34.9	123	16.6	0.3	6.0	0.2	76.2	0.1
Tailings 2	Min	4.2	1.0	8.0	83	21	0.2	1.0	0.1	4.4	0.1
	Max	5.8	42	116	491	95	1.4	12.2	0.7	116.7	0.2
	Med	**5.2**	**2.5**	**28.5**	**162**	**43**	**0.3**	**4.3**	**0.2**	**9.25**	**0.1**
	Std dev	0.4	10.0	33.1	109	24.6	0.3	4.0	0.1	30.3	0.0

Table 3. Particle size distribution and % organic matter (OM) for surface soil samples (0 – 15 cm) and subsoil samples (15 – 90 cm) for six reclaimed Old Hickory mining pits. Properties of adjacent natural soils are detailed by Schroeder (1997).

Pit		OM	Sand	Silt	Clay	OM	Sand	Silt	Clay
		---------% in surface soil -----------				----------% in subsoil ---------------			
9702 - 9703	Min	0.5	40	3.5	7.4	0.5	31.9	0.6	0.0
	Max	1.0	87.8	18.4	46.7	0.6	99.4	37.8	30.2
	Med	**0.6**	**78.1**	**9.7**	**12**	**0.5**	**93.4**	**3.9**	**2.2**
	Std dev	0.2	13.8	4.7	11.2	0.0	16.6	8.8	8.3
9704 - 9705	Min	0.5	42.1	2.7	0.1	0.6	58.4	9.7	1.9
	Max	1.0	95.2	23.8	42.8	6.0	82	28.8	22.4
	Med	**0.5**	**78.9**	**9.8**	**12.4**	**0.9**	**76.3**	**16.1**	**8.0**
	Std dev	0.1	15.0	5.7	11.5	0.7	5.2	3.6	3.9
9801	Min	0.6	55.7	0.3	0.1	0.5	52.5	0.1	0.0
	Max	1.1	94	20.6	34.1	0.7	99.4	12.5	34.9
	Med	**0.7**	**74.8**	**10**	**16**	**0.5**	**96.35**	**3.4**	**1.55**
	Std dev	0.1	12.3	5.3	9.7	0.1	15.9	3.5	12.7
9806	Min	0.5	14.3	4.0	2.5	0.5	44.9	0.2	0.0
	Max	1.1	88.5	25.5	65	0.9	98.5	21.6	33.5
	Med	**0.6**	**73.1**	**12**	**12.8**	**0.6**	**79.4**	**7.3**	**12.3**
	Std dev	0.1	20.8	5.9	16.4	0.1	15.8	6.8	9.9
Tailings 1	Min	0.6	54.9	11	5.0	0.5	44	6.6	4.2
	Max	1.7	83.9	26.3	20.7	2	89.2	35.2	34
	Med	**0.9**	**65.7**	**23.3**	**10.4**	**0.6**	**57.1**	**22**	**15.3**
	Std dev	0.3	10.5	5.7	5.5	0.4	14.2	10.7	10.5
Tailings 2	Min	0.5	33.2	3.8	4.6	0.5	43.4	5.9	0.0
	Max	1.6	91.6	37	50	2	92.7	31.5	39
	Med	**1.0**	**62**	**23.2**	**13**	**0.6**	**76.6**	**9.6**	**11.35**
	Std dev	0.3	12.5	8.2	11.6	0.4	14.2	7.3	11.3

of their final surfaces. Organic matter in the composite subsoil samples (15 to 90 cm) averaged around 0.5%, with slightly higher values occurring in Tailings 1 and 2. The source of this organic matter has not been defined at this time, but is most likely a mixture of topsoil inclusions with depth, adsorbed organics returned with the slimes, and contributions from initial rhizodeposition of organics from the revegetation plantings.

Surface soil textures were typically loamy sands and sandy loams (Table 3), although most of the pits exhibit a lateral gradational increase in clay content away from tailings discharge points. For example, in pit 9801, clay content increased from the middle of the field to both the east and the west, while for Tailings 2 the clay content increased from north to south. Most pits that were vegetated at the time of sampling were interspersed with varying amounts and sizes of bare, red, clayey patches. In particular, a large portion of the southwest corner of Tailings 2 was barren with dense clay exposed at the surface (Fig. 3). When first sampled, pits 9806 and Tailings 2 were quite wet at the surface, and portions of these fields were inaccessible. Soil wetness increased noticeably to the west in 9806, and increased slightly to the east and west in Tailings 2, due to slimes layering as discussed later. Subsoil textures ranged widely from fine clays to almost pure coarse and medium sands (Table 3). In some profiles, the texture was fairly consistent throughout the subsoil or gradually changed with depth, while in other profiles the subsoil consisted of alternating sandy and clayey layers with abrupt boundaries (Table 4). Some horizons actually consisted of two distinct textured materials that were physically mixed, such as clayey aggregates with sandy coatings or sands with large (5 to 30 cm) entrained slime blocks or aggregates. Pits 9702 – 9704 are most variable in the subsoil with many profiles containing a combination of clay, sandy clay loam, sandy loam and loamy sand layers. Pits 9801, 9806, and Tailings 1 and 2 are less variable with subsoil layers mostly consisting of sands, loamy sands and sandy loams, and clay content grading across the pit as described above. Black mineral sands were present at some sampling points, but were most prominent in Tailings 2, which was backfilled early in the life of the concentrator facility when the wet separatory processes were still being refined.

The soil profile described at three typical locations (Table 4) across the Old Hickory reclamation surfaces reveal a wide range of layering and horizonation depending on tailings/slimes discharge sequence, dewatering procedures employed, and the effects of final grading and/or topsoiling procedures. Table 4 also contains a description of a typical native pre-mining soil profile. While bulk density samples were not taken as a part of the detailed transect sampling described above, a limited point-sampling (5 locations each) from pits 9704, 9705 and TP 1 revealed that bulk density was frequently > 1.5 g/cm^3 within the upper 30 cm of finer textured materials, even after V-ripping and chisel plowing the previous year. This coupled with the massive nature of the finer textured materials led to very high soil strength and resistance to shovel and auger penetration under even moist conditions at many locations. Rooting was clearly limited by this combination of high density and massive structure. Sandier textures generally were not compacted to the same extent. Where topsoil was applied to pits, it averaged 8 to 15 cm in thickness, and was readily apparent in profile (see profile 3 in Table 4).

Table 4. Abbreviated profile descriptions for three typical mine soil pedons in reclaimed pits at Old Hickory and a typical undisturbed soil (Faceville series; fine, kaolinitic, thermic, Typic Kandiudults) before mining.

Profile 1. Dominantly sandy soil from pit 9801 with a slimes enriched surface.

A	0 – 8 cm; strong brown (7.5YR 5/8) sandy clay loam; friable.
C1	8 – 30 cm; very pale brown (10YR 8/4) sand; loose.
C2	30 – 59 cm; yellow (10YR 8/8) sand; loose.
C3	59 – 90 cm; reddish yellow (7.5YR 7/8) sand; loose.
C4	90 – 150+ cm; yellow (10YR 7/8); loose.

Profile 2. Dominantly clayey soil from pit 9806 with a tailings derived surface.

A	0 – 18 cm; yellow (10YR 8/8) sand; loose.
C	18 – 150+ cm; reddish yellow (7.5YR 7/6) clay; exceedingly firm

Profile 3. Mine soil with topsoil returned over alternating sandy/clayey layers from pit 9702-9703.

A	0 – 9 cm; dark yellow brown (10YR 4/4) sandy loam; loose.
C1	9 – 18 cm; red (2.5YR 4/6) clay; few distinct white (N/8) mottles; exceedingly firm.
C2	18 – 53 cm; reddish yellow (7.5YR 7/8) sand; loose.
C3	53 – 105 cm; yellowish red (5YR 4/6) sandy clay loam; friable.
C4	105 – 150+ cm; reddish yellow (7.5YR 6/6) sand; loose.

Profile 4. Native Faceville soil described in area adjacent to Pit 9801.

Ap	0 – 19 cm; brown (10YR 4/3) loamy sand; very friable.
E	19 – 27 cm; brown (10YR 5/4) loamy sand; very friable.
Bt1	27 – 59 cm; yellowish red (5YR 5/8) sandy clay loam; friable.
Bt2	59 – 89 cm; yellowish red (5YR 5/8) sandy clay loam/clay; friable.
Bt3	89 – 150+ cm; red (2.5YR 4/8) sandy clay loam; friable.

In certain pits (e.g. TP 1 and TP 2) the deposition of thick layers of slimes near the final reclamation surface led to significant areas of restricted infiltration and very wet conditions in late winter and following heavy summer rains. Surface water drainage and bearing capacity in wetter seasons across a number of pits appeared to be inadequate and will likely limit agricultural operations to some extent. It is unclear at this time whether this is due to actual final grading profiles or the differential settlement of the fills as the water-bearing slimes dewater and compress. This issue needs further monitoring and study.

The revegetation response on each reclaimed pit was observed monthly during the 1999 through 2002 growing seasons. In general, plant establishment and vigor was strongly controlled by (1) the presence or absence of topsoil, and (2) extremes in surface mine soil texture where topsoil was not employed. Where topsoil was re-applied to pits, vegetation establishment and persistence over time has been sufficient to meet VDMM bond release criteria with greater than 80% vegetated cover and a suitable diversity of the intended mixed forage stand. Where topsoil has not been applied, and either extremely sandy (> 80% sand) or high slimes (> 40% silt+clay) materials are exposed at the surface, plant establishment and persistence has been poor. On many occasions, vegetation over mixed tailings/slimes materials on a given pit would appear healthy on a given day, while any existent vegetation on adjacent areas of pure sands or slimes would show distinct symptoms of water stress. This region experienced record drought conditions in 2001 and 2002, however, which certainly amplified the observed vegetation response to surface soil conditions. In 2002, we initiated the utilization of biosolids surface amendment (40 to 80 Mg/ha) coupled with a second round of deep tillage to enhance the productivity of these mined lands, and initial field response in the fall of 2002 appeared quite favorable. Results from this soil modification research will be reported at a later date.

Summary and Conclusions

Mine soils generated by the overall mineral sands mining and reclamation process in eastern Virginia are highly acidic, low in nutrients, and highly variable in surface texture when initially dewatered and graded. Liming, heavy P-fertilization, and deep ripping are all essential to preparing the soil for revegetation. Replacement of native topsoil is a superior reclamation treatment, and where not feasible, addition of an appropriate organic amendment appears to be a comparable substitute. Until new procedures are developed to effectively flocculate and co-mingle the slimes fraction with the sandy tailings as they are dewatered, strong lateral and vertical variability of mine soil texture and associated chemical properties will be the expected condition, and will strongly differentiate revegetation success across reclaimed mining pits. These Fe-coated materials clearly need relatively heavy P applications (> 300 kg/ha) to offset strong P-fixation, but the possibility that P may be leaching from the surface soil within two seasons after application to pure sandy tailings warrants further study.

Where native topsoils are re-applied, they greatly decrease lateral variability in revegetation success, and a similar effect is expected from the application of organic amendments to non-topsoiled areas. The issue of differential settlement in the fills as they dewater, and its affects on both surface and internal drainage needs further study. Finally, our combined studies have reinforced previous findings from other surface mining environments that high subsoil densities coupled with weak structural development pose major long-term limitations to the return of prime farmlands to pre-mining productivity levels.

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