THE INFLUENCE OF SOIL RECONSTRUCTION TECHNIQUES ON MINERAL SANDS MINE SOILS IN VIRGINIA[1]

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Abstract: Significant deposits of heavy mineral sands (primarily ilmenite and zircon) are located in Virginia in Dinwiddie, Sussex and Greensville counties. Most deposits are located under prime farmland, and thus require intensive reclamation when mined. The objective of this study was to determine the effect of four different mine soil reconstruction methods on soil properties and associated rowcrop productivity. Treatments compared were 1) Biosolids-No Tillage, 2) Biosolids-Conventional Tillage, 3) Lime+NPK fertilized tailings (Control), and 4) 15-cm Topsoil+lime+NPK over lime+P treated tailings. Treated plots were cropped to corn (*Zea mays* L.) in 2005 and wheat (*Triticum aestivum* L.) in 2006. Yields were compared to nearby unmined prime farmland yields. Over both growing seasons, the two biosolids treatments produced the highest overall crop yields. The Topsoil treatment produced the lowest corn yields due to relatively poor physical and chemical conditions, but the effect was less obvious for the following wheat crop. Reclaimed land corn and wheat yields were higher than long-term county averages, but they were consistently lower than unmined plots under identical management. Detailed morphological study of 20 mine soil pedons revealed significant root-limiting subsoil compaction and textural stratification. The mine soils classified as Typic Udorthents (11), Typic Udifluvents (4) and Typic Dystrudepts (5). Overall, these mined lands can be successfully returned to intensive agricultural production with comparable yields to long-term county averages provided extensive soil amendment and remedial tillage protocols are implemented. However, a significant decrease (~25 to 35%) in initial productivity should be expected relative to unmined prime farmland.

Additional Key Words: biosolids, compaction, mine soils, reclamation, heavy minerals.

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Introduction

Heavy mineral sands (HMS) consist of titanium bearing minerals such as ilmenite ($Fe{\cdot}TiO_3$), and zircon ($ZrSiO_2$). The term "heavy" refers to the mineral's high specific gravity, $\geq$ 4.0 g/cm^3, relative to the host sands (quartz = 2.67 g/cm^3) (Brooks, 2000). HMS deposits are derived from fluvio-marine re-sorting of igneous, metamorphic and sedimentary rock derived sediments. Due to their high specific gravities, heavy minerals separate from lighter minerals via wave action and are subsequently concentrated in near-shore beach deposits (Lynd and Lefond, 1983), particularly during storm events. The dominant market mineral is TiO_2, (rutile) which is used as an opaque agent in paints. Titanium is also used in high strength metal applications and Zr is used as a refracting agent for high temperature ceramics and glazes.

Mineral Sand Deposits were discovered in Virginia and North Carolina in the late 1980's (Berquist and Goodwin, 1989; Carpenter and Carpenter, 1991). The largest ore body (2,550 ha) is known as the Old Hickory deposit and lies in the Upper Coastal Plain of Dinwiddie and Sussex Counties, Virginia; approximately 100 km (60 miles) south of Richmond and 175 km (110 miles) west of the Atlantic coastline (Schroeder, 1997). The beneficiation process of HMS varies greatly with the surrounding host materials and associated soil landscapes, thus the "Old Hickory" deposit in Virginia faces unique reclamation challenges. These include: (1) the high clay content of the pre-mining soil, and (2) the fact that most of the mineable ore is located under prime farmland (NRCS; 2008).

Prime farmland has the most favorable combination of physical, chemical, environmental properties for the production of food, fiber and oil crops (Grandt, 1988). Historically, this has been an important peanut-, soybean-, tobacco- and cotton-producing region. Heavy minerals are more resistant to weathering than other aluminosilicates and quartz, thus they are more likely to accumulate in weathered surface soil horizons over time. High accumulation of HMS coupled with the fact that quartz sands are more prone to wind and water erosion leads to significant accumulation of heavy minerals in the native topsoil, and that layer is often the most profitable material for HMS mining (Milnes and Fitzpatrick, 1989). As a result, there is great interest in the possibility of using organic amendments such as biosolids, an end-product of municipal wastewater treatment (Walker, 1994) or yardwaste compost as organic soil amendments to allow for topsoil substitution. However, current Virginia mining regulations require that the upper 15 cm of topsoil (A + E Horizons) be stockpiled and returned to the site after mining.

Current mining and reclamation practices at Old Hickory are detailed by Meredith (2007) and include dry pit mining of the ore-bearing soil and underlying Coastal Plain sediments, wet spiral separation of the minerals from the host soils, and then return of the slimes and tailings to the mined out pits where they are dewatered and re-graded to form post-mining landscapes. Native topsoil (15 cm) is salvaged and returned back over the graded pits. Deep ripping (90 cm) and applications of lime (4 to 8 Mg/ha) and P-fertilizers (350 kg/ha) are employed to ameliorate adverse subsoil chemical conditions before application of other soil amendments or topsoiling (Daniels, 2003).

Study Objectives

The overall goal of this study was to document the effects of various reconstruction techniques on mine soil properties and row-crop productivity on a mineral sands mine soils in southeastern Virginia. This study was designed with the following specific objectives:

1. To determine the effects of three different soil reconstruction practices on resultant mine soil morphological, physical and chemical properties. Specific reconstruction practices evaluated were topsoil return, organic amendment with biosolids, and direct utilization of limed and fertilized tailings.

2. To estimate the effects of mine soil reconstruction practices on row crop productivity, and to compare the productivity of the mine soils with nearby undisturbed prime farmland.

3. To document and measure the relationships between soil morphological, chemical and physical properties as influenced by differential soil reconstruction practices.

4. To describe and classify a range of mine soil pedons occurring on the Carraway-Winn Research Farm (CWRF) at Old Hickory.

In this paper, we present the overall crop yield results with reference to dominant effects of mine soil properties and treatments. Full detail on mine soil physical and chemical properties and mine soil reconstruction effects is given in Meredith (2007).

Research Methods and Materials

Virginia Tech worked with Iluka Resources and the Carraway-Winn family to create a demonstration research farm in 2003 and 2004. The experimental area chosen for this study (Figs. 1 and 2) was selected based upon its relatively uniform surface soil texture and color, and a general absence of poorly drained areas. The delineated area consisted of sixteen experimental plots with each plot approximately 180 m long and 15 m wide or approximately 0.25 ha.

Figure 1. Aerial view of Carraway-Winn property located on the Old Hickory Mine Site of Iluka Resources Inc. This image above was taken April 2006. Row Crop plots (at star in right center) were planted in winter wheat. Soil sampling transects ran down each plot center and plot treatment details are shown in Fig. 2.

Final treatments were installed in the fall of 2004. The overall design was a randomized complete block with four replicate blocks and four treatments per block. Each block was 59 x 183 m, with each plot measuring 15 x 183 m. The plot width was based on the width of the agricultural equipment used and the length was set to be long enough to allow relatively routine use of that same equipment without having to stop abruptly during harvest or modify normal management practices. All treatments received the same deep ripping tillage preparation before final treatments were installed. Prior to installation, all plots were deep ripped in two perpendicular directions with a multi-shank (3) ripper attachment mounted on a Caterpillar D-8 bulldozer to 90 cm, and one subsequent pass with a chisel plow (15 to 20-cm) was made over all the plots.

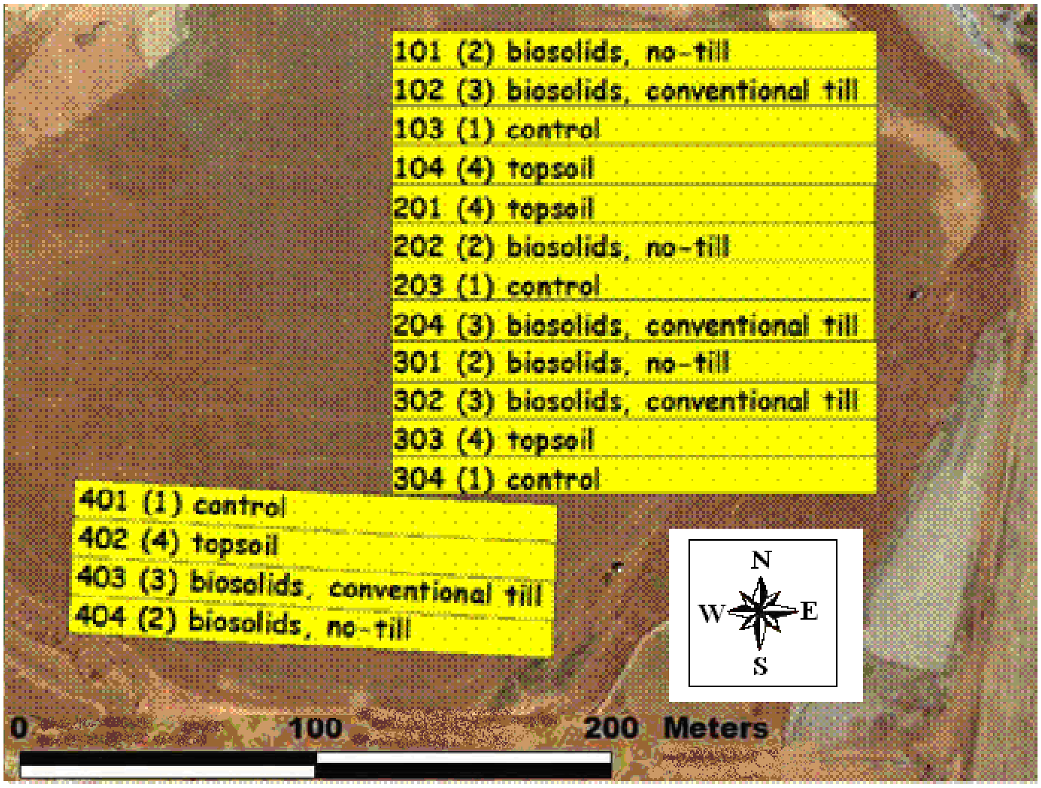

Figure 2. Diagram of soil reconstruction row crop experiment and overall plot design located on the Carraway-Winn Research Farm (CWRF) of the Old Hickory site. The area to the upper left is compacted and served as an external "no ripping treatment" control. Soil sampling transects (5 points each) were located from E to W down the center of each plot. These blocks/plots can be clearly seen in the SE corner of Fig. 1.

The four main soil reconstruction treatments were as follows:

1. **Biosolids no-till (Bio-NT)**: Ripping, lime-stabilized biosolids at 78 Mg/ha in no-till management, and P+K fertilization.
2. **Biosolids, conventional till (Bio-CT)**: Ripping, lime-stabilized biosolids at 78 Mg/ha in conventional till for row crops, and P+K fertilization.
3. **Control**: Ripping, lime (9 Mg/ha), 674 kg P_2O_5/ha, and N-P-K fertilization.
4. **Topsoil:** Ripping, lime+P to subsoil per Control, 15 cm of topsoil return, 6.7 Mg/ha lime added to topsoil + N-P-K fertilization.

Details on routine soil sampling and detailed soil fertility, liming, tillage and crop management protocols are provided by Meredith (2007). An external non-ripped comparative study area (compaction study) was delineated directly adjacent to three of the treatment blocks.

This area, which was not ripped, but was treated and managed identically to the Control plots, was 176 m in length (adjacent to the research blocks) and approximately 49 m wide. Finally, to enable comparisons of soil characteristics and crop yields from the CWRF with un-mined soils, an external control area was located 1 km away on the Clarke family farm on prime farmland soils (Orangeburg series; fine-loamy, kaolinitic, thermic Typic Kandiudults). Additionally, all corn plots were irrigated (2.5 cm each event) five times in 2005. This management difference needs to be emphasized since they are compared against a mix of irrigated and non-irrigated lands compiled into county averages as discussed later in the paper.

Corn was harvested in the fall of 2005 with a John Deere 9500 combine equipped with a five row-corn head, an Ag Leader Yield Monitor and Trimble GPS unit. Five center rows of each strip were harvested to represent the "treatment" yield. Coordinates from the GPS unit were collected at the time of grain mass and moisture readings and grain yields are expressed as bushels per acre at 15% moisture. A map of yield variation within each strip was developed using Ag Leader software and Arc GIS. Wheat was harvested in June of 2006. The central 4.6 m (15 ft) of each strip were harvested to represent the treatment yield.

Soil Sampling

Over the summer of 2005, the entire soil reconstruction research plot array was sampled. First-order soil sampling consisted of auger transects. A minimum of five equally spaced auger borings were made within each plot. All borings were spaced at approximately 35 m apart down the plot center line (from E to W; Fig. 2), and were carefully described and sampled for; 1) Mehlich I extractable nutrients and metals, 2), total C and N, 3), particle size analysis (USDA-NRCS, 2004), 4) horizon morphology (USDA-NRCS, 2004), and 5) rooting depth and abundance (USDA-NRCS, 2004). Full data sets are given in Meredith, 2007. Borings were made to a minimum depth of 2 m with composite samples taken every 25 cm. Additional bulk samples of defined horizons were also collected. In the laboratory, samples were air-dried, ground to pass a 10-mesh sieve, and analyzed for pH, organic matter and analyzed for pH in a 1:1 soil to water slurry. Exchangeable levels of P, K, Ca, Mg, Zn, Cu, Fe and B by an Inductively Coupled Plasma Emission Spectroscopy (ICPES) were also documented (Donohue and Heckendorn, 1996).

Detailed soil pit sampling was performed following wheat harvest between June 29th and August 10th, 2006. One pit location within each treatment plot was selected based on an overall analysis of the data collected from the auger borings. Representative samples of each plot were chosen based on analysis of auger profiles: Pits were located via the use of a handheld Garmin GPS12 and accuracy was approximately 1 to 5 meters. Pits were oriented in such a way to expose the effects of the deep cross ripping (if evident). Detailed morphological descriptions were made along the western pit face of each soil pit (Soil Survey Staff, 1993).

All data sets were first examined for normality and then analyzed with a two-way ANOVA (Treatment x Block) model followed by LSD mean separations where the initial F test p-value ≤ 0.05. Contrasts between treatments within the row-crop experiment and the Compacted area and the Clarke Farm control plots were done via 2-sample t-tests.

Results

Corn Establishment and Yields (2005)

The average corn seedling count and average corn seedling height in May of 2005 of the CWRF are shown in Table 1. There was no significant difference between the seedling counts; however, there was a significant difference between average seedling heights with the two Biosolid treatments producing the tallest seedlings and the Topsoil treatment producing the shortest plants.

Mean corn yields for the four treatments are presented in Table 2 along with comparative yield data for the Clarke Farm and Compacted Area. The Bio-NT and Bio-CT treatments produced the highest average crop yields of 10,904 kg/ha and 10,848 kg/ha, respectively. The Control treatment yielded 8,527 kg/ha, which was greater than the Topsoil treatment. Unexpectedly, the Topsoil treatment produced a very low yield at 3,785 kg/ha. Lower yields on the Topsoil treatment were most likely a result of low soil pH (5.68), low available P (14 mg/kg), compaction (B.D. > 1.6) during topsoil placement, and the formation of a surface crust that occurred after several heavy rains in April and May of 2005. The topsoil utilized for this experiment was stripped from an adjacent forested site and was initially acidic (pH 5.2) and very low in P (< 2 mg/kg extractable). These plots did receive significant lime and P fertilization in the fall of 2004, but were still much lower than optimum for both pH and available P in 2005 (Meredith, 2007).

Table 1 – Average corn seedling count and seedling height by treatment on May 18, 2005. Mean values followed by the same letter are not different ($p \leq 0.05$).

Plot	Seedling Count[1] (# of plants)		Seedling Height[2] (cm)	
	Avg. per plot	Treat. mean	Avg. per plot	Treat. Mean
Bio-CT				
102	104		18.5	
204	101		16.8	
302	95		20.1	
403	100	100 a	18.5	18.5 a
Bio-NT				
101	106		18.5	
202	99		17.5	
301	100		20.1	
404	104	102 a	19.8	18.8 a
Topsoil				
104	104		12.2	
201	100		11.4	
303	69		11.7	
402	96	92 a	12.7	11.9 b
Control				
103	107		13.7	
203	99		13.0	
304	101		11.9	
401	101	102 a	15.5	13.5 b
Clark Farm (unmined)[3]				
C	91		14.2	

[1] Seedling counts are based on 4 15-m transects per plot for the Clarke farm.

[2] Seedling heights are based on 20 observations per plot and 26 observations for the Clark Farm.

[3] The Clarke Farm was not delineated into plots at the time seedling counts and heights were observed; therefore C as reported here is for 4 random transects.

Lower yields in the Control plots (compared to the two Biosolids treatments) were most likely due to lower available N levels and organic matter, since plant-available N generally drives biomass accumulation in these systems given sufficient available water. Complete details on differences in soil chemical and physical properties across all treatments are available in Meredith (2007), and are summarized here where deemed appropriate.

Table 2 – Corn yield by treatment for 2005 and average yields between 2001 and 2005 for Dinwiddie County. Values followed by the same letter are not different ($p \leq 0.05$).

			Dinwiddie County Average (kg/ha)					
Treatment	Mean Crop Yield (kg/ha)	Mean Crop Yield bu/a*	Five Year Average	2001	2002	2003	2004	2005
Bio-CT	10,848a	172a	5,543	5,393	2,571	5,267	7,776	6,709
Bio-NT	10,904a	173a						
Control	8,527b	135b						
Topsoil	3,785c	60c						
Clarke Farm	14,360**	229**						
Compacted Area	6,070	96						

* bu/a at 15 % moisture

**Clarke Farm yields were based on an overall estimate from the yield monitor output from four random transects rather than four replicate plots.

The Clarke Farm and the Compacted Area produced 14,360 kg/ha and 6,070 kg/ha respectively, which were clearly much higher and lower, respectively, than the average Biosolids and Control treatment yields. County average yields for corn over a five-year period (Table 2) ranged from 2,571 to 7,776 kg/ha, the lowest yield occurring in 2002 (a drought year) and the highest occurring in 2004. Over the five-year period, average county corn yields were 5,543 kg/ha. The two Biosolids treatments (CT and NT) and the Control produced higher average yields (+ 97%, + 97% and + 54%, respectively) than the five-year-county-average, while the Topsoil treatment produced significantly less (- 32%) than the five-year-county-average.

Figure 3 presents a graphical representation of the CWRF corn yields (2005) taken along the center transect of each plot. From this figure, we can clearly see that lower yields occurred more often in the Topsoil treatments than the two Biosolids treatments. Additionally, we can see much lower yields for the Topsoil treatment in block three (highlighted in red) compared to the other three soil reconstruction treatments and the other three Topsoil treatments (blocks 1, 2 and 4 respectively). Overall, it is interesting to note that the Clarke Farm, under identical management conditions as the CWRF, produced much higher and spatially uniform yields than all experimental soil reconstruction treatments (Table 2 and Fig. 3).

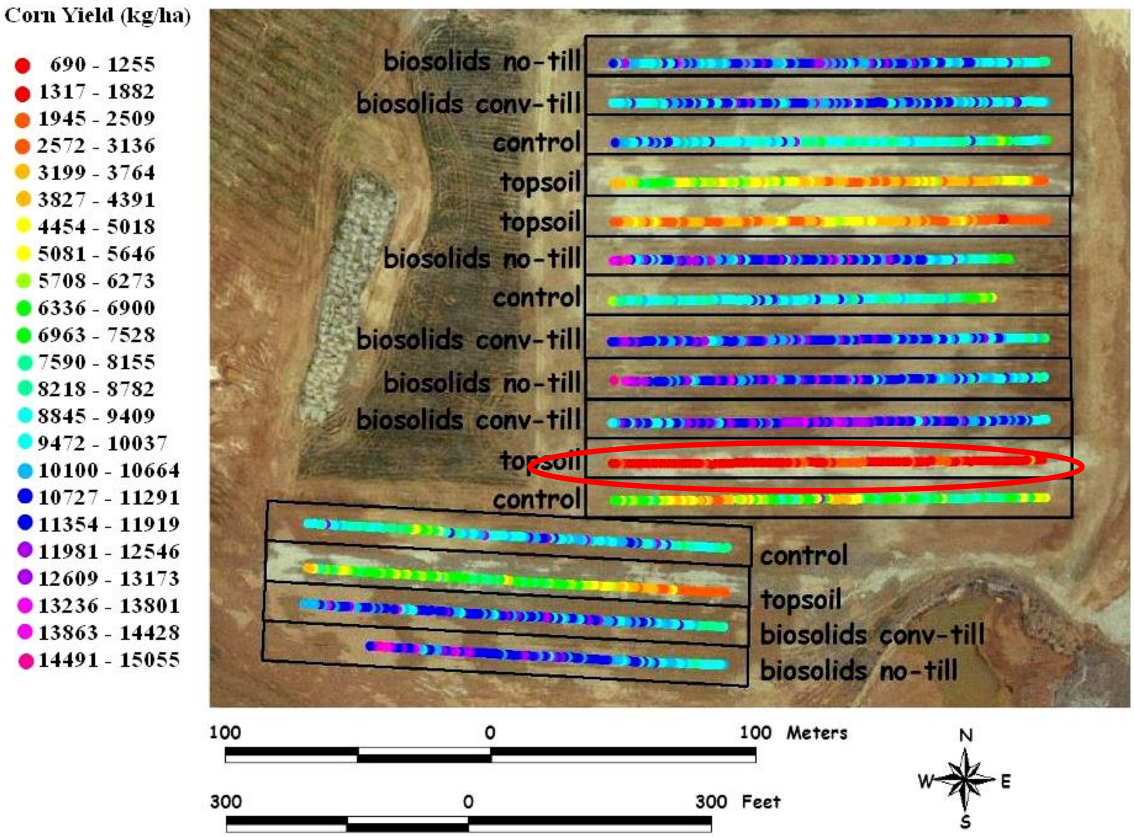

Figure 3 – Corn yields along the center transect of each plot located on the Carraway-Winn Research Farm (CWRF) of the Old Hickory site. The topsoil treatment in Block 3 (circled in red) was particularly low in yield and heavily compacted. Graphics courtesy of Pat Donovan.

<u>Winter Wheat Yields in 2006</u>

The Bio-NT treatment produced the highest amount of winter wheat in 2006, followed closely by Bio-CT with average yields of 5,326 kg/ha and 4,556 kg/ha respectively (Table 3). The Control and Topsoil treatments were significantly lower at 4,088 kg/ha and 4,291 kg/ha respectively. Note that the heavy yield suppression in the Topsoil treatment noted for corn (2005) was not evident in the following wheat crop, possibly due to disking/tillage of this treatment in the fall of 2005. Additionally, the Clarke Farm and the Compacted Area produced 6,900 kg/ha and 4,327 kg/ha respectively. Typical county-wide wheat yields on unmined farmland over a five-year period (Table 3) ranged from 2,889 to 4,165 kg/ha, with lowest yields in 2003. The Clarke Farm produced much higher comparative yields ($p < 0.0001$) than all experimental soil reconstruction treatments, but all four CWRF treatments produced higher average wheat yields (+ 48% -Bio-NT; + 27% -Bio-CT; + 20% - Topsoil; and + 14% - Control) than the five-year-county-average. Over the five-year period, Dinwiddie produced an average 3,588 kg/ha of wheat. Individual contrasts indicated that the Compacted Area yields were significantly lower than ($p < 0.0001$) the Clarke Farm; however they were not significantly different than the four CWRF soil reconstruction treatments.

Table 3 – Wheat yield in 2006 and five-year county averages for Dinwiddie, Virginia. Values followed by the same letter are not different ($p \leq 0.05$).

			Dinwiddie County Average (kg/ha)					
Treatment	Mean Crop Yield (kg/ha)	Mean Crop Yield bu/a*	Five Year Average	2001	2002	2003	2004	2005
Bio-CT	4,556b	67b	3,588	3,695	3,628	2,889	3,561	4,165
Bio-NT	5,326a	79a						
Control	4,088c	60c						
Topsoil	4,291c	62c						
Clarke Farm	6,900	102						
Compacted Area	4,327	64						

*bu/a at 15 % moisture

Soil Morphology and Taxonomy Study (2006)

The 20 soil profiles observed in 2006 were relatively simple in overall morphology, but highly variable in the number of subsoil horizons observed and their physical properties. The majority of pedons (7) were described with ^Ap-^C horizonation followed closely by ^Ap1-^Ap2 over ^C morphology (5), and ^Ap-^Bw (5) horizonation. Important subsurface features observed included densic layers (^Cd and ^Abd) and buried A (^Ab) horizon. Few pedogenic subsoil horizons were observed, but nine pedons did exhibit weakly expressed ^Bw horizonation. Of these nine Bw horizons, five were categorized as cambic, being 15 cm or more thick with a texture finer than loamy fine sand and at least 50% of their volume comprised of moderately well developed subangular blocky structure (Soil Survey Staff, 2006). Whether or not we can prove that this reflects *in situ* pedogenesis, the morphology exhibited meets cambic horizon criteria. Overall, eleven pedons were classified as Typic Udorthents, four classified as Typic Udifluvents, and five as Typic Dystrudepts (Table 4). Complete soil profile descriptions and data sets are available in Meredith (2007).

Although all soils observed in 2006 were deep-ripped in fall 2004 in two perpendicular directions (with and 90^{o} to plot axis), visual traces were only evident in two profiles, CWRF 102-3 (Bio-CT) and CWRF 104-5 (Control). Ripper traces were described based on the overall v-shape of the trace and the depth (~ 90 cm) at which traces were evident. It is interesting to note that of all 16 CWRF pedons; only two exhibited any visually obvious indication of deep-ripping. Ripping traces may not have been evident due to either 1) the majority of the soils may have been ripped while wet, which would have allowed the ripper traces to close immediately behind the shank and would have limited lateral soil shattering, or 2) alternatively, repeated vehicle passes and natural settling processes may have combined to re-consolidate the original ripper traces.

In one pedon (a Control plot), we described a wood ash and charcoal layer, with a black color (2.5Y/N) (Fig. 35). This layer, which varied in depth between 52 and 60 cm, was non root-limiting, structureless and rich in charcoal and woody debris. It was most likely a result of a slash fire of woody debris that was raked and picked from the forest topsoil materials that were transported from off-site. Artifacts (man-made objects) were found in CWRF 202-1, CWRF 303-2 and CWRF 402-3. CWRF 202-1 had a plastic sheeting that occurred between the ^Apu and ^Bwu horizon that most likely influenced the wavy boundary. CWRF 303-2 contained pieces of a plastic liner within the ^Apu layer, and CWRF 402-3 contained a small rubber hose (< 2 cm in diameter) located within the upper portion of the 2^Cu horizon. Few profiles exhibited any diagnostic subsurface horizonation beyond the cambic horizons described earlier. A densic layer, or non-cemented root limiting/restricting layer (e.g. a traffic/tillage pan), was described in five of the 20 profiles, however, densic properties and associated rooting limitations were observed in almost all described soil profiles.

Various profiles showed evidence of topsoil-like material throughout the subsurface; however, only one buried A horizon was described that appeared to be completely comprised of former topsoil. This occurred in pedon CWRF 201-2, which was a Topsoil treatment. Conversely, many other profiles showed evidence of buried and mixed topsoil material but were not assigned the subscript “b” due to their volume being less than 40% of the horizon. Interestingly, the buried A horizon occurred within a densic horizon. Three pedons exhibiting a range of observed morphologies are depicted in Fig. 4, 5, and 6. Much more detail on the vagaries and complexities of mine soil morphology, taxonomic complications, and interpretations of mining influences therein is reported by Meredith (2007) along with detailed profile descriptions and full data sets for the three profiles depicted here.

Table 4 – Taxonomic classification for Carraway-Winn Reclamation Research Farm and Compacted Area soil pedons.

Pit ID	Treatment	Classification
101-4	Bio-NT	Clayey over sandy, aniso, mixed, acid, thermic, Typic Udorthent
102-3	Bio-CT	Clayey over sandy, aniso, mixed, acid, thermic, Typic Dystrudept
103-2	Control	Coarse-loamy, mixed, nonacid, thermic, Typic Udifluvent
104-5	Topsoil	Clayey over sandy, mixed, acid, thermic, Typic Dystrudept
201-2	Topsoil	Loamy, mixed, nonacid, thermic, shallow, Typic Udorthent
202-1	Bio-NT	Coarse-loamy, mixed, nonacid, thermic, Typic Udorthent
203-3	Control	Loamy, mixed, nonacid, thermic, shallow, Typic, Udorthent
204-3	Bio-CT	Coarse-loamy, mixed, nonacid, thermic, Typic Udifluvent
301-3	Bio-NT	Fine-loamy, mixed, acid, thermic, Typic Dystrudept
302-3	Bio-CT	Coarse-loamy, mixed, acid, thermic, Typic, Dystrudept
303-2	Topsoil	Coarse-loamy over sandy, mixed, acid, thermic, Typic Dystrudept
304-1	Control	Fine-loamy, mixed, nonacid, thermic, Typic Udorthent
401-5	Control	Sandy over clayey, mixed, nonacid, thermic, Typic Udifluvent
402-3	Topsoil	Sandy, siliceous, nonacid, thermic, uncoated, Typic Udorthent
403-5	Bio-CT	Fine-loamy, mixed, acid, thermic, Typic Udorthent
404-1	Bio-NT	Sandy, siliceous, acid, thermic, uncoated, Typic Udorthent
EC 5-2	Compacted	Coarse-loamy, nonacid, mixed, thermic, shallow Typic Udorthent
EC 7-2	Compacted	Fine-loamy over sandy, mixed, acid, thermic, shallow, Typic Udorthent
EC 11-2	Compacted	Coarse-loamy, mixed, acid, thermic, shallow, Typic Udorthent
EC 12-2	Compacted	Sandy over clayey, aniso, mixed, acid, thermic, Typic Udifluvent

All pedons assumed to have a Udic moisture regime; no active redoximorphic features were noted.

Figure 5. Profile 302-3 (Bio-CT) is a Typic Dystrudept as indicated by weak development of a pedogenically-altered (Bw) horizon. This soil classified as an Inceptisol due to the presence of a cambic horizon with > 50% moderate subangular blocky structure between 12 and 44cm. This profile also showed typical sequence of finer textured high slimes material over sandy tailings at depth. Described horizons were ^Ap-^Bw1-^Bw2-^C1-^C2. Full description and data sets are reported in Meredith (2007).

Figure 6. Profile EC 11-2 is a typical plot of the Compacted Area. Please note that three of the compacted plots were classified as Typic Udorthents except for one soil which was a Typic Udifluvent. Note the complex layering and convoluted banding in the sandy tailings between 40 and 70 cm; this was most likely caused by surface re-grading of recently deposited tailings. Overall morphology was described as ^Ap-^Cd-^C1-^C2-^C3. Full description and data sets are in Meredith (2007).

Figure 7. Profile 203-3 (Control) was a Typic Udorthent with a prominent densic layer (Cd) at 30 to 59 cm. Please note the significant topsoil material prominent within the ^Cd layer. However, the inclusion of topsoil here was not sufficient to be dominant, so this was not described as Ab. Also note large angular blocks of red slimes material in deeper 2^C2/C1 horizon between 80 and 110 cm. These were most likely dried out into blocks over the underlying coarse tailings on an exposed tailings "beach" and then more sandy tailings were deposited over them. Overall described horizon sequence was ^Ap-^Bw-^Cd-2^C1-2^C2/C1-2^C3. Full description and data sets are in Meredith (2007).

Summary and Conclusions

The Control treatment constructed from regraded amended tailings and slimes produced higher corn yields (+54%) in 2005 than a five-year-county-average for Dinwiddie, Virginia. However, the Control produced significantly lower yields than the two Biosolids treatments which did not appear to vary from one another over the first two years of this study. The Topsoil return treatment produced significantly lower corn yield (-32%) than the five-year-county-average and the other three reconstruction treatments due to several interacting factors. First of all, the topsoil utilized came from a low quality forested source rather than agricultural fields. This lack of lime and fertilizer history, combined with physical problems due to significant grading-related soil compaction and formation of a surface crust appeared to directly limit corn growth and overall rooting depth.

The Clarke Farm, under identical management conditions to the four mine soil reconstruction techniques, produced 159 % more corn than the five-year-county-average, and +32 %, +32 %, +137 % and +279 % more than the Bio-CT, Bio-NT, Control and Topsoil treatments respectively. Additionally, the adjacent Compacted Area that did not receive the deep-ripping protocol produced 9 % more corn grain than the five-year-county-average and 41% more than the Topsoil treatment. In fairness, however, we must reiterate the fact that we irrigated our corn crop while the county average data are based upon non-irrigated and irrigated corn. In 2006, all four mine soil reconstruction treatments produced significantly higher wheat yields than the five-year-county-average; (Bio-NT - +48 %; Bio-CT - +27 %; Topsoil - +20 %; and Control - +14 %), respectively. In comparison, the Clarke Farm produced significantly higher winter wheat than all four soil reconstruction treatments, and 92% more than the five-year-county-average. The Compacted Area produced significantly higher wheat yields (+20 %) than the five-year-county-average; however, unlike the corn yields in 2005, it did not out-produce the Topsoil treatment. The increase in Topsoil productivity over the winter/spring of 2006 was most likely due to the fact that the Topsoil plots were chisel-plowed and disked to alleviate soil compaction and crusting after the 2005 harvest.

Relative to expected results and the scientific literature, the overall poor performance of the Topsoil treatment here was surprising. However, given that the Topsoil used was from a forested source, more research is needed to see if higher-grade topsoil could significantly improve upon the results reported here. It is also possible that the relative productivity of the

Topsoil treatment will improve over time due to liming and appropriate tillage and aggregation. Thus, topsoil addition success will also depend directly upon limiting the mechanical compaction caused during topsoil replacement.

From these combined results, we conclude that of the soil reconstruction methods studied here, the Biosolids amendment treatments were superior to the Control and Topsoil treatments with respect to crop yield potentials over the first two growing seasons. Schroeder (1997) reported similar positive results with a yardwaste compost amendment in earlier pilot scale experimental plots at Old Hickory. Although Schroeder did not use biosolids, extensive research summarized by Haering et al. (2000) for a range of mining environments confirms that biosolids have been widely used on mined lands with positive results, especially where the original topsoil is either low in organic matter, or when topsoil substitution occurs.

Overall, we expect that with application of best management practices such as initial deep ripping, liming and P applications, appropriate organic matter additions, and periodic follow-up tillage, these reconstructed soils can produce between 70 and 80% of local prime farmland average yields within several years after reclamation. Higher relative production levels may occur once the soils equilibrate and begin to develop subsoil structure and aggregation.

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Literature Cited

Berquist. C. R., Jr., and B. K. Goodwin. 1989. Terrace gravel, heavy mineral deposits, and faulted basement along and near the fall zone in southeast Virginia. Guidebook No. 5, Dept. of Geology, College of William and Mary, Williamsburg, VA.

Blake, G. R., 1965. Particle Density. pp. 371-373. *In* Black, C.A. (Ed.), Methods of Soil Analysis. Part II, American Society of Agronomy, Madison, Wisconsin.

Brooks, D. R. 2000. Reclamation of lands disturbed by mining of heavy minerals. pp. 725–754. *In* R. I. Barnhisel, et al. (Eds.). Reclamation of Drastically Disturbed Lands. American Soc. of Agron. Monograph #41, Madison WI.

Carpenter, R .H. and S. F. Carpenter. 1991. Heavy mineral deposits in the upper coastal plain of North Carolina and Virginia. Econ. Geol. 86:1657-1671. http://dx.doi.org/10.2113/gsecongeo.86.8.1657.

Daniels, W. L. 2003. Strategies for the return of heavy mineral sands mines to productive agricultural uses. *In* Z. Agioutantis, (ed.). Proceedings, Conf. on Sustainable Indicators in the Minerals Industry, SDIMI - 03. May 13-17, 2003, Milos, Greece. Pub. by Milos Conf. Center – George Eliotopous, Milos Island, Greece. ISBN: 960-87054-1-X.

Donohue, S. J. and S. E. Heckendorn. 1996. Laboratory procedures: Virginia Tech Soil Testing and Plant Analysis Laboratory. Virginia Coop. Ext. Bull. pp. 452-881. Blacksburg, VA

Grandt, A. F. 1988. Productivity of reclaimed lands - cropland. pp. 1321-135. *In* L.R. Hossner (Ed.) Reclamation of Surface Mined Lands. CRC Press, Boca Raton, FL.

Haering, K. C., W. L. Daniels and S. E. Feagley. 2000. Reclaiming mined land with biosolids, manures and papermill sludge. p. 615-644 *In* R. I. Barnhisel et al. (Eds.), Reclamation of Drastically Disturbed Lands. American Soc. Agron. Monograph #41, Madison WI. 1082 p.

Lynd, L. E., and S. J. Lefond. 1983. Titanium minerals. pp. 1303-1362. *In* S. J. Lefond (Ed.) Industrial Minerals and Rocks. 5th ed. American Institute of Mining, Metallurgical and Petroleum Engineers. Littleton, Co.

Meredith, K. R. 2007. The Influence of Soil Reconstruction Methods on Mineral Sands Mine Soil Properties. M.S. Thesis, Virginia Tech, Blacksburg. 247 p. http://www.lib.vt.edu/find/etds.php

Milnes, A. R., and R. W. Fitzpatrick. 1989. Titanium and zirconium minerals. pp. 1131-1205. *In* Minerals in Soil Environments, 2nd ed. J.B. Dixon and S.B. Weed (Eds.). Soil Sci. So. Am. Book Series 1, SSSA, Madison, WI

Schroeder, P. D. 1997. Restoration of Prime Farmland Disturbed by Mineral Sand Mining in the Upper Coastal Plain of Virginia. M.S. Thesis, Virginia Tech, Blacksburg, 164 pp.

Soil Survey Staff. 2006. Keys to Soil Taxonomy. 10th ed. USDA-NRCS, Washington, DC. http://soils.usda.gov/technical/classification/tax_keys/keys.pdf

Soil Survey Staff. 1993. Soil Survey Manual. USDA-SCS Agric. Handbook 436. U.S. Gov. Print Office, Washington, D.C.

USDA-NRCS. 2004. Soil Survey Laboratory Methods Manual. Soil Survey Inves. Report no. 42, Version 4.0. U.S. Dept. of Agric., Nat. Res. Cons. Svc., Natl. Soil Surv. Ctr. Lincoln, NB.

ftp://ftp-fc.sc.egov.usda.gov/NSSC/Lab_Methods_Manual/SSIR42_2004_view.pdf

USDA-NRCS. 2008. Web Soil Survey Portal. On-line soil survey for Dinwiddie County, Virginia. http://soils.usda.gov/survey/online_surveys/

Walker, J. M. 1994. Production, use and creative design of sewage sludge biosolids. pp. 67-74. *In* C. E. Clapp et al. (Eds.) Sewage Sludge: Land Utilization and the Environment. SSSA Misc. Publ. ASA, CSSA, and SSSA, Madison, WI.