EFFECTS OF PRIME FARMLAND SOIL RECONSTRUCTION METHODS ON POST-MINING PRODUCTIVITY OF MINERAL SANDS MINE SOILS IN VIRGINIA[1]

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Abstract. Significant areas of prime farmland in the upper Coastal Plain of Virginia have been disturbed by heavy mineral sands (Ti/Zr-bearing ilmenite, rutile, zircon) mining over the past 15 years. Mine soils created by the deposition of tailings and slimes in dewatering pits exhibit physical and chemical properties that limit agricultural use due to abrupt textural changes, heavy compaction from grading and the inherently low pH and available P of the processed subsoils. In 2004, the Carraway-Winn Reclamation Research Farm (CWRRF) was developed with Iluka Resources Inc. in Dinwiddie County to evaluate reconstruction strategies for returning mined land to agricultural production. In 2004, row crop plots were established in a randomized complete block design with 4 replications of 4 treatments: 1) LBS-CT – lime-stabilized biosolids (78 dry Mg ha^{-1}) with conventional tillage, 2) LBS-NT – lime-stabilized biosolids (78 dry Mg ha^{-1}) with no tillage, 3) TS – 15 cm of topsoil replacement with lime+NPK, and 4) C – control (tailings+lime+NPK). All treatments were deep ripped to 90 cm following grading and limed and fertilized annually to optimal levels. Two additional study sites, managed similarly to the treatment plots, included a compacted (no ripping) area (COMP) and a nearby unmined prime farmland (Orangeburg series) field (UM). Between 2005 and 2008, the plots were managed with a corn-wheat/double crop soybean rotation. In 2009, the plots were managed with cotton and in 2010 with wheat/double crop soybeans. During the initial four year corn-wheat/double crop soybean rotation, the two LBS treatments produced significantly higher yields than the TS or C treatments. No significant differences were observed among treatments for the 2009 cotton yield; however, erratically distributed settlement depressions adversely affected crop growth and harvest and led to high variability within each treatment. Similarly, no significant differences were observed for the 2010 wheat and soybean yields in a low rainfall year. Overall, yields from all four treatments typically exceeded 5-year local county averages, but were 25 to 40% lower than yields from the local prime farmland soil under identical management. Relatively low COMP yields illustrated the need for initial deep ripping and periodic tillage to improve physical conditions of these mine soils.

Additional Key Words: biosolids, compaction, titanium mining, topsoil replacement

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Introduction

Heavy mineral sands (HMS) consist of titanium bearing minerals, such as ilmenite ($FeTiO_3$) and zircon ($ZrSiO_2$), which have high specific gravities (> 4.5 g cm^{-3}) relative to the host sands (~2.67 g cm^{-3}; Brooks, 2000). The HMS deposits are derived from fluvio-marine resorting of sediments derived primarily from nearly igneous and metamorphic rocks of the Piedmont. 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).

Heavy mineral sands deposits were discovered in Virginia in the late 1980's (Berquist and Goodwin, 1989; Carpenter and Carpenter, 1991). The largest ore body in Virginia, the Old Hickory deposit, is positioned along the Atlantic Coastal Plain in the counties of Dinwiddie and Sussex. The deposit is located approximately 100 km south of Richmond and 175 km west of the Atlantic coastline and covers over 2,500 ha. The beneficiation process of HMS varies greatly with the surrounding host materials and associated soil landscapes, thus each mining site faces unique reclamation challenges. For Old Hickory, these include the high clay content of the pre-mining soil and the fact that most of the higher grade mineable ore is located in prime farmland.

Prime farmland has the most favorable combination of physical, chemical, and environmental properties for the production of food, fiber, and oil crops (Grandt, 1988). Historically, the Old Hickory area has been an important peanut (*Arachis hypogaea*)-, soybean (*Glycine max*)-, tobacco (*Nicotiana tabacum*)- and cotton (*Gossypium hirsutum*)- producing region. Virginia mining regulations require that topsoil, defined as the surface layer and underlying materials that can produce and sustain vegetation, be stockpiled and returned to the site after mining (4VAC25-31-410). However, significant accumulation of HMS occurs in the native topsoil. The HMS accumulate in weathered surface soil horizons because they are more resistant to weathering than common aluminosilicates and quartz, and the less dense quartz sands and silts are more prone to wind and water erosion. Since the surface soils are often the most profitable material for HMS mining (Milnes and Fitzpatrick, 1989) there is great interest in using topsoil substitution amendments such as municipal biosolids which enhance organic matter, nutrient pools, water holding capacity, and overall long-term productivity on mine soils (Haering et al., 2000). In addition, compaction which occurs during final grading is readily observed in these soils (Meredith, 2008; Orndorff et al., 2005) and adversely affects soil physical properties with respect to agricultural use, but may be alleviated with deep ripping. Therefore, the objective of this study was to evaluate 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.

Materials and Methods

In 2004, Virginia Tech collaborated with Iluka Resources Inc. (the mining company) and the Carraway-Winn family (the landowners) to create the Carraway-Winn Reclamation Research Farm (CWRRF) where the study was located (Fig. 1). This area was selected based on its relatively uniform surface soil color and texture (dominantly sandy loam and sandy clay loam), and a general absence of concave wet areas. The area was mined in 1998, and subsequently received the standard stabilization treatment, which included 9.96 Mg ha^{-1} lime, 392 kg ha^{-1} P_20_5, and seeding to an herbaceous cover. The experimental design was a randomized complete block with four replicate blocks and four treatments per block. Soil reconstruction treatments included:

1. LBS-CT (lime-stabilized biosolids, conventional tillage): Ripping, lime-stabilized biosolids (Table 1) at 78 Mg/ha in conventional tillage, and routine fertilization (described below).
2. LBS-NT (lime-stabilized biosolids, no-tillage): Ripping, lime-stabilized biosolids at 78 Mg/ha in no-till management, and routine fertilization.
3. TS (topsoil replacement): Ripping, lime and P to subsoil, 15 cm of topsoil (Table 1) added, lime to topsoil, and routine fertilization.
4. C (control): Ripping, lime, P, and routine fertilization.

The research plots were established in the fall of 2004. Each plot was 15 x 183 m, with dimensions set to allow relatively routine use of regular agricultural equipment. The entire area inside the plot boundaries was sprayed with 2.1 kg ha^{-1} Round-Up Ultra (glyphosphate, isopropylamine salt) and 1.2 L ha^{-1} 2,4-D (2,4-dichlorophenoxyacetic acid). Surface soil (to 15 cm) was excavated from the four TS plots, then all plots were deep ripped with bulldozer shanks to a depth of 90 cm and chisel plowed to 20 cm. Lime (8.96 Mg ha^{-1}) and P (672 kg ha^{-1}) were applied and incorporated to 20 cm on the TS and C plots. Topsoil (15 cm) was applied to the four TS plots, and additional lime (6.72 Mg ha^{-1}) was applied and incorporated to 20 cm. The topsoil material provided for use on the TS plots was not from the Carraway-Winn property and

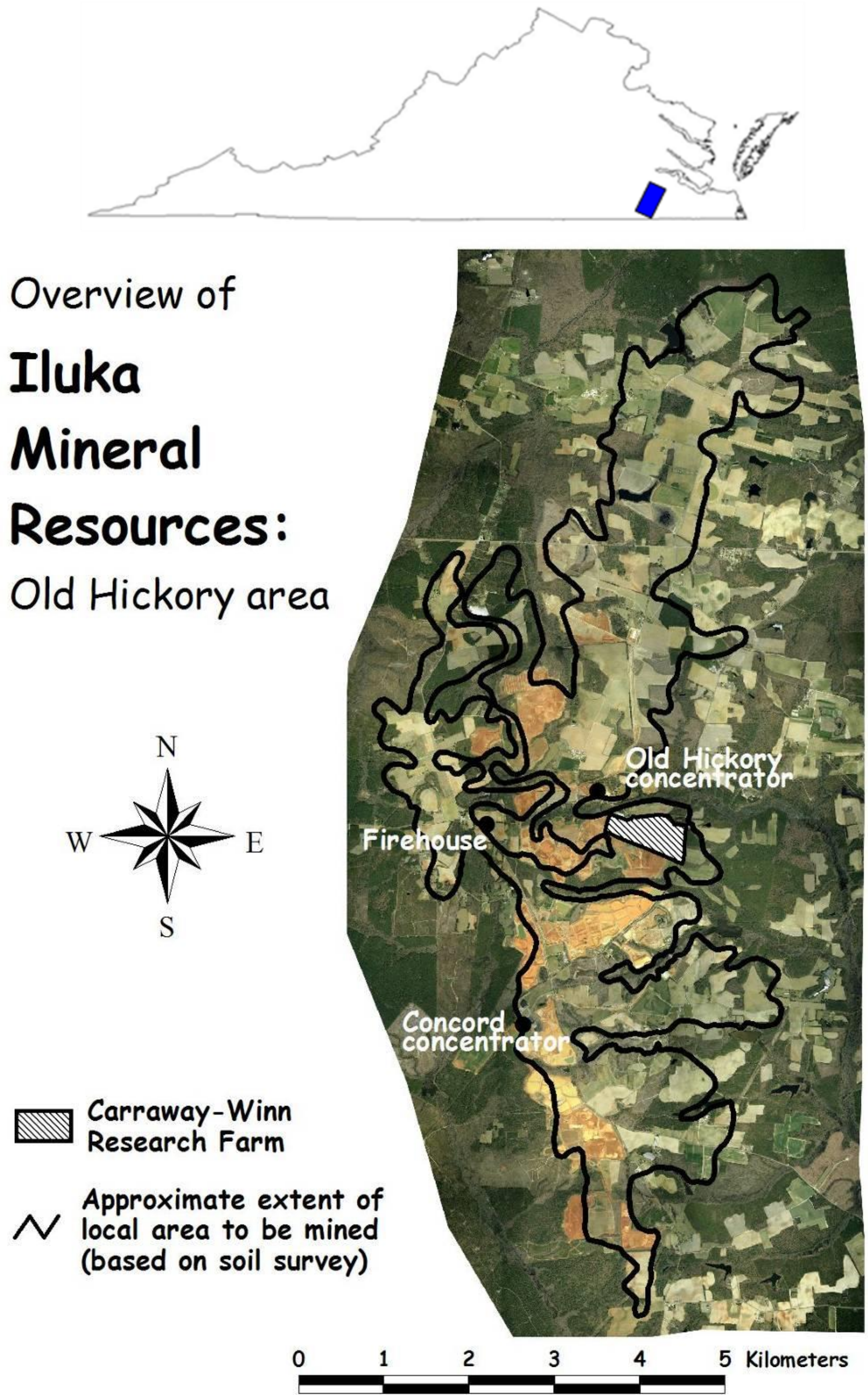

Figure 1. Location of heavy mineral deposits in Virginia and overview of Iluka Mineral Resources Old Hickory/Concord mining area.

Table 1. Selected dry-weight chemical properties of biosolids and topsoil amendments. Topsoil data represents pre-treatment conditions.

	Biosolids	Topsoil
pH	10.43	5.28
	Total	Mehlich-1
	---------- mg kg^{-1}---------	
Solids	317,033	nd
Calcium Carbonate Equivalence	158,867	nd
Total Kjehldahl nitrogen	32,700	nd
Ammonia N	4,200	nd
P	15,467	9
K	1,467	76
Ca	109,700	337
Mg	2,500	57
Fe	44,933	123
Mn	318	7.5
Cu	205	2.1
Zn	455	1.5

appeared to be of forest soil origin. Lime-stabilized biosolids (78 Mg ha^{-1}) were applied and incorporated to 20 cm on the LBS-NT and LBS-CT plots. The biosolids used in this study were low in heavy metals, had a CCE of 16% and are widely used in Virginia for routine agricultural land application. Chemical properties of the topsoil and biosolids amendments are presented in Table 1. All plots were smoothed and cleared of debris by multiple passes with a field cultivator.

After initial establishment of the research plots, a 49 x 176 m area directly adjacent to the three northern treatment blocks was delineated as the compaction study site (COMP). This area was treated identically to the C plots except that it was never ripped. The COMP plot was used to evaluate the benefits of ripping on crop yields on these heavily compacted mine soils. An unmined study site (UM) was delineated on the nearby Clarke Farm, approximately 1.2 km northwest from the CWRRF, and included four plots each measuring approximately 15 x 183 m on Orangeburg soils (Fine-loamy, kaolinitic, thermic, Typic Kandiudults). The UM study site was used to compare the success of reclamation treatments to undisturbed prime farmland. This particular site is part of some of the most productive farmland in Virginia, with historic Virginia record peanut yields, and therefore represents a very high standard for comparison. Crop yields also were compared to five-year average crop yields for Dinwiddie County.

From 2005 through 2008, the experimental plots and comparison areas were placed in a corn-wheat/double-crop soybean rotation. Cotton was grown in 2009, and then the plots were returned to wheat/double-crop soybeans for 2010. Corn (*Zea mays*) was planted in the spring of 2005 and 2007, with the center five rows (2005) and center ten rows (2007) harvested from each plot. Wheat (*Triticum aestivum* L.*)* was planted in the late fall of 2005, 2007, and 2009. In 2005 the corn residue was shredded prior to planting, whereas in 2007 the residue was left intact. Wheat was harvested from the central 4.6 m of each plot in the summers of 2006, 2008, and 2010. Double-crop soybeans were planted in 2006, 2008, and 2010. Due to severe wetness in the late fall of 2006 that crop could not be properly harvested. In 2008 and 2010, soybeans were harvested from the central 9.1 m of each plot. Cotton (Stoneville 4427; *Gossypium hirsutum* L.) was planted in 2009, and harvested from the central 8 rows of each plot for the four treatments on the CWRRF, and the central 4 rows for the UM plots. All plots were planted no till for the first corn crop (2005), while subsequent plantings were no-till except for the LBS-CT plots which were managed under conventional tillage. All crops were harvested using a combine equipped with an Ag Leader Yield Monitor and Trimble GPS unit allowing grain mass, moisture, and GPS coordinates to be collected simultaneously at 1.0 second intervals.

Throughout the six-year study period, the experimental plots and comparison areas were managed similarly with few exceptions. When necessary to preserve the crop, all sites were irrigated (maximum of 3 x 2.5 cm per season), no-till ripped (~50 cm), and periodically received herbicides, fungicides, and pesticides. Fertilizers were applied to achieve optimal nutrient levels for the yearly crop based on soil test results (discussed below) and standard recommendations by the Virginia Tech Soil Testing Laboratory. To evaluate the long-term N supply of the biosolids, the LBS plots did not receive any additional N fertilization during the first three growing seasons. Examples of the differential fertility regimes as applied vs. underlying soil test values from 2004 to 2007 are presented in Meredith (2008).

Composite surface (0 – 15 cm) soil samples along the centerline of each plot were collected after the plots were delineated, but prior to treatments, then annually in the late fall or early winter to determine fertilization needs. In the laboratory, all soil samples were air-dried, ground to pass a 10-mesh sieve, and analyzed for pH in a 1:1 soil:water solution using a combination electrode with an Orion PerpHecT logR Benchtop meter (model 370), and for concentrations of Mehlich-1 extractable B, Ca, Cu, Fe, K, Mg, Mn, P, and Zn by USEPA method SW 846 6010B, revision 2 (USEPA 2001), using a SpectroFlame Modula Tabletop ICP. A summary of soil chemical properties is presented in Table 2. In addition, during the summers of 2005 and 2006, extensive soil sampling was conducted which included auger transects along the centerline of

Table 2. Summary of soil characterization data. Elemental data from Mehlich I extracts.

	pH	P	K	Ca	Mg	Fe	Zn	Mn	Cu	B
		------------------------------- mg kg^{-1} -------------------------------								
Sept 2004†	7.0	16	71	602	114	15	4	1	0.7	0.2
June 2005										
LBS-CT	7.2	45	63	1762	107	74	4	7	2.1	0.4
LBS-NT	7.2	46	72	1933	113	63	4	7	2.3	0.4
TS	5.7	14	80	599	142	92	2	10	1.8	0.2
C	6.5	22	73	608	147	19	1	6	1.3	0.2
UM	5.8	51	89	451	54	18	3	5	0.8	0.3
COMP	6.7	13	65	541	107	20	1	6	0.8	0.2
Feb 2006										
LBS-CT	7.6	76	91	1725	107	92	4	8	2.1	0.4
LBS-NT	7.6	73	87	1906	110	92	5	9	2.5	0.4
TS	6.6	18	97	707	153	84	1	12	2.4	0.3
C	6.8	33	98	508	132	20	1	5	0.7	0.3
Sept 2007										
LBS-CT	7.9	74	77	2045	83	51	4	7	1.3	0.4
LBS-NT	7.9	78	83	2319	91	51	5	8	1.5	0.4
TS	7.2	15	73	754	156	46	1	9	0.3	0.2
C	7.3	26	80	530	145	12	0	5	0.2	0.2
UM	6.1	49	43	461	59	15	2	6	0.4	0.2
Dec 2008										
LBS-CT	7.6	52	62	1430	78	66	3	6	1.6	0.3
LBS-NT	7.6	56	66	1516	77	73	3	6	1.7	0.3
TS	7.1	11	77	684	152	51	1	10	0.8	0.2
C	7.2	14	70	490	133	17	0	5	0.6	0.2
UM	6.2	45	93	425	47	16	1	6	0.7	0.2

† Post stabilization, but prior to plot installation

each plot as well as detailed pit profile characterization and sampling. Detailed soil physical, chemical, and morphological properties observed before and after the reconstruction treatments will be presented in a separate publication and may be found in Meredith (2008).

Results and Discussion

Corn Yields (2005 and 2007)

Mean corn yields for the four treatments from 2005 and 2007 are presented in Table 3 along with comparative yield data from the COMP and UM plots. In 2005, corn yields on LBS-CT and LBS-NT were similar (10.85 and 10.90 Mg ha^{-1}, respectively), and were significantly higher than the C (8.53 Mg ha^{-1}) and TS (3.79 Mg ha^{-1}) treatments ($p < 0.05$). For this first crop, the LBS-CT and LBS-NT treatments were in fact managed identically due to first year tillage issues. Lower yields in the C plots likely resulted from lower nutrient concentrations, lower levels of organic matter, and associated reduced water holding capacity. The drastically reduced yield observed in the topsoil return plots appeared to result from a complex mixture of adverse soil properties. First, the topsoil materials did not originate from fields that had been intensively managed in agriculture and therefore were lower in two important fertility parameters, pH (5.7) and P (14 mg kg^{-1}), even after liming and fertilization prior to corn planting. Second, the topsoil materials formed a relatively hard surface crust immediately after seeding that probably affected early seedling growth and water relations. Third, the topsoil material was compacted in place upon its return. These plots were still quite wet with low bearing strength when the topsoil was applied by scraper pans, leading to significant rutting and probable disturbance/smearing into the previously ripped and loosened underlying tailings.

In comparison to the reclamation treatments, the UM plots produced a high corn yield of 14.36 Mg ha^{-1} (Table 3). This relationship is consistent with previous work in small plot experiments where crop yields on reclaimed HMS mine soils were typically 70 to 80% of adjacent undisturbed soils (Daniels et al., 2003). The LBS and C treatments exceeded the five-year county average corn yield (5.78 Mg ha^{-1}); however, the research plots had the advantage of being irrigated when threatened by drought while the county yield data include all soils in production and non-irrigated and irrigated fields. As expected, the LBS and C yields exceeded the COMP yield (6.07 Mg ha^{-1}) illustrating the importance of ripping to alleviate compaction in these mine soils. The prevalence of unusually poor soil conditions in the TS plots is emphasized even further by the low TS yield (3.79 Mg ha^{-1}) relative to the COMP area.

Table 3. Crop yields from the CWRR and a local unmined soil for years 2005-2010, and Dinwiddie County 5 year crop yield averages as applicable.

	Corn		Wheat			Soybeans		Cotton (lint)	
	2005	2007	2006	2008	2010	2008	2010	2009	
Treatment	Mg ha^{-1}								%
LBS-CT	10.85a†	3.62b	5.04a	5.97a	2.74a	2.24ab	0.96a	1.17a	0.424
LBS-NT	10.90a	3.43b	5.16a	5.65a	2.76a	2.51a	1.11a	1.18a	0.442
TS	3.79c	7.23a	4.29b	4.89b	2.68a	2.20ab	1.15a	1.18a	0.453
C	8.53b	7.30a	4.10b	4.64b	2.51a	2.11b	1.10a	1.05a	0.446
UM	14.36	9.91	6.90	3.90	4.72	3.20	1.73	1.62	0.400
COMP	6.07	3.18	4.33	nd	nd	1.75	nd	nd	nd
Dinwiddie Co. Average (2004 – 2008)	----- 5.78 -----								
Dinwiddie Co. Average (2006 – 2010)			---------- 4.19 ----------			----- 1.54 -----			

†Means in the same column followed by the same letter are not significantly different at $\alpha = 0.05$

Corn yields per treatment were lower in 2007 than in 2005, with the exception of the TS plots. The C and TS treatments produced the highest average yields at 7.30 Mg ha^{-1} and 7.23 Mg ha^{-1}, respectively. The LBS-CT and LBS-NT yields were significantly lower, at 3.62 Mg ha^{-1} and 3.43 Mg ha^{-1}, respectively. The UM area produced 9.91 Mg ha^{-1} while the COMP area produced only 3.18 Mg ha^{-1}.

Multiple reasons account for the lower crop yields in 2007. Extremely high temperatures during the day and night throughout July reduced yields relative to more optimal weather years. The LBS-CT and LBS-NT also were affected by severe N deficiency, which resulted from our efforts to explore the long-term N supply of the biosolids by not adding additional fertilizer N. These strips received high loading rates (78 dry Mg ha^{-1}) of biosolids when the experiment was established in 2004. Crop yields indicated that the first year (2005) corn and winter wheat (2005-2006) crops on the LBS treatments had adequate N. Since N-fixing soybeans were on the plots over the summer and fall of 2006, we presumed some carry-over of plant available N would remain from that crop plus the longer term residual N available from the initially heavy biosolids applications. However, N deficiency symptoms appeared in 2007 once the corn was approximately 60 cm tall. Since N deficiency controlled crop response in the LBS plots, any potential effects of the differential tillage treatments were not evident.

Relative to the UM yield (9.91 Mg ha^{-1}), the C and TS plots showed noticeable improvement from 2005 to 2007. In 2005, the C and TS yields were only 59% and 26%, respectively, of the UM area, whereas in 2007 these treatments yielded 77% of the UM area. The increased yields were likely due to improved physical conditions from chiseling and ripping in these plots. This is supported by comparison to the COMP area (identical to the C plots except it was not ripped) which produced only 3.18 Mg ha^{-1} (44% of the C yield). Aggregation of the originally massive tailings-derived soils was probably a factor as well. Improved yields in the TS plots also were due to lime and fertilizer treatments which improved soil chemical conditions in 2007 relative to 2005.

Wheat Yields (2006, 2008, 2010)

In both 2006 and 2008, the LBS plots produced the highest treatment yields, while the TS and C plots produced significantly lower yields (Table 3). Soil fertility levels were optimal for all plots, suggesting that the biosolids improved physical conditions in the LBS plots; however, the different tillage methods (LBS-CT vs LBS-NT) did not significantly affect crop yields. By 2006 the influence of initial deep ripping in 2004 appeared to have diminished as the C yield was similar to the COMP (not deep-ripped) yield. These results suggest that the soils were reconsolidating due to a lack of soil structure, especially below the immediate surface layer. Mine soils have little to no structure, and thus are susceptible to compaction from normal rainfall, settling, and field equipment operations. In 2010, there were no significant yield differences among the four reconstruction treatments.

Wheat production from all reconstruction treatment plots was higher in 2008 than 2006, and exceeded the five-year county average (4.19 Mg ha^{-1}) in both years with only one exception (C, 2006). Yields for 2010 were much lower than previous years due to exceedingly dry and hot conditions which affected crop yields across the state. In 2006, the UM yield (6.90 Mg ha^{-1}) was noticeably higher than the mined land treatment yields, but in 2008 it was surprisingly low (3.90 Mg ha^{-1}). This difference resulted from variable surficial corn residue impacts on planter performance which, for consistency, was set at the same depth for all plots (mined land vs. UM).

In 2005, the corn residue was shredded prior to planting the wheat which allowed the planter to function smoothly over all plots. In 2008, the corn residue was not shredded prior to planting the wheat. On the UM plots, the large volume of bulky corn stalks in 2008 apparently disrupted the planter and prevented consistent seeding across the plots, whereas the lower residue volume on the treatment plots did not interfere with performance of the planter. Therefore, the low yield of the UM plot in 2008 was probably not a function of soil properties but rather reflected the difficulty of planting no-till following an exceptional corn crop.

Soybean Yields (2008 and 2010)

The double-crop soybean yields for the 2008 season reflected good growing conditions and the effect of irrigation that was critical to the development of the soybeans. The LBS treatments produced slightly higher yields (>2.20 Mg ha^{-1}) than the TS treatment (2.20 Mg ha^{-1}) and C treatment (2.11 Mg ha^{-1}) due to the improved physical structure of the soils amended with biosolids. No-till (shallow) ripping prior to planting the soybeans appeared to alleviate some of the physical problems associated with the TS and C treatments, and the low COMP yield (1.75 Mg ha^{-1}) again demonstrated the importance of initial deep ripping and periodic tillage to remediate these mine soils. The UM yields were excellent (3.21 Mg ha^{-1}), reflecting the better physical condition of the unmined soil (Table 3). All treatment yields exceeded the five-year county average (1.54 Mg ha^{-1}). In 2010, no significant differences were observed among the mine soil reconstruction treatments, and yields were relatively low (45 – 55% lower than 2008) due to the exceedingly dry and hot conditions. In addition, just prior to the 2010 soybean planting, re-grading work was completed to fill in mine fill differential settlement depressions which occurred erratically throughout the mined land reconstruction treatments. Although re-grading the depressions should ultimately improve crop yields, positive effects were not observed for the 2010 soybean harvest. At the time of planting, the soil in the re-graded depressions was softer than surrounding areas causing the planter to push the soybeans too deep in the ground. Consequently, the re-graded areas had poor stand establishment. This limitation will decrease over time as the ground firms up through the winter and spring wetting and consolidation cycles.

Cotton Yield (2009)

Average lint percentages and lint yields are presented in Table 3. Cotton yields for all treatments were excellent (1.05 – 1.18 Mg ha^{-1}) with no statistically significant differences among the four reconstruction treatments. As seen with other crops, yields from the reconstruction treatment plots were lower (27 – 32%) than yields from the UM plots (1.62 Mg ha^{-1}). Although the C plots appeared to have a noticeably lower yield than the other three reconstruction treatments, the lack of a statistical difference may be due to high variability among the plots per treatment. Variability resulted from unevenness of the land due to the differential settlement described above. Depressions, which were visually apparent throughout the plots, reduced cotton growth where high rainfall in the spring created discrete ponded areas. Of the common agronomic crops for this region, cotton is particularly sensitive to excessive moisture, especially within the first month after planting. As indicated above, work was completed in 2010 to fill in these depressions and re-grade the ground surface.

Summary and Conclusions

The CWRRF was established in 2004 to evaluate the effects of various soil reconstruction techniques on the physical and chemical characteristics of mineral sands mine soils, and associated row crop productivity. This study focused specifically on corn, wheat, and double-crop soybean yields from four different reclamation treatments – biosolids with conventional tillage (LBS-CT), biosolids with no-tillage (LBS-NT), topsoil replacement (TS), and a control (C) – as well as yields from a compacted area which was never ripped (COMP) and a nearby unmined area (UM).

The biggest reclamation challenges associated with these mine soils are heavy compaction and lack of organic matter, which together restrict root growth and soil water holding capacity. The benefits of ripping to alleviate compaction were readily apparent from the higher yields seen in the C plots relative to the COMP area. Further improvement from the incorporation of biosolids, which contributed to the development of soil structure and increased water holding capacity, was apparent by the significantly higher yields produced from both LBS treatments from 2005 - 2008. In comparing no tillage with conventional tillage, no significant differences were observed between the LBS-NT and LBS-CT plots. Nitrogen availability from the biosolids alone was adequate through the first two growing seasons, but severe N deficiencies in the 2007 corn crop revealed the need for subsequent N applications. Although topsoil replacement was expected to improve crop yields, positive effects from the presumed optimal texture and biological activity were overpowered by several complicating factors which included the use of lower quality topsoil with low pH and low P, compaction during topsoil application, and surface crusting that inhibited germination. After the 2005 corn harvest, plowing and disking reduced compaction and improved subsequent yields on the TS plots, however the TS treatment never produced a significantly higher yield than the mine tailing derived control. Despite the addition of natural organic matter via topsoil, low water holding capacity was presumably a problem in the TS plots.

With few exceptions, crop yields from the four reclamation treatments routinely exceeded local (Dinwiddie County) five-year county averages. However, in making this comparison it is important to note that the research crops had the advantage of being irrigated when necessary to protect against crop failure, while the county average data were based on the combined data for all non-irrigated and irrigated croplands. In comparison to native unmined land, crop yields from the treatment plots typically were reduced by 25 to 40%, and the greatest one-time reduction was as high as 74%. In fairness, we must reiterate that the UM plots were located on extremely productive Virginia farmland and therefore represent a very high standard for comparison. Intensive soil reconstruction that includes ripping, chiseling, and the incorporation of organic matter, will allow for the return of these heavily compacted mine soil to agricultural use; however, a minimum yield decrease of 25% over the initial five years following soil reconstruction should be expected in comparison to the most highly productive pre-mined soils. However, we hypothesize that over longer periods of time, mine soil productivity may slowly increase due to improved aggregation of the surface and subsoil horizons assuming optimal tillage and fertility management practices are followed.

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