# Indicators of reclamation success for mineral sands mining in the USA

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ABSTRACT

Mineral sands mining in Virginia has potential to disturb over 4000 ha of prime farmland in Virginia and North Carolina, USA. Working cooperatively with Iluka Resources and local regulators, it was decided that an appropriate measure of “reclamation success” would be comparison of post-mining crop yields against (a) the 5-year running average for crop production in the local county (Dinwiddie, Virginia) and (b) against a local undisturbed prime farmland soil body of documented very high productivity. In 2004, we worked with Iluka to install a large (> 5 ha) replicated mine soil reconstruction experiment to evaluate several reclamation alternatives including topsoil substitution. Long-term results (2005 to 2012) have proven that reconstructed mine soils will consistently exceed local county 5-year average yields for all crops grown to date (corn, wheat and soybeans) but are typically 15 to 20% lower than adjacent prime farmlands under identical management. However, in 2012, for the first time, soybean yields on the reconstructed mine soils were higher than the adjacent prime farmlands and much higher than the 5-year county average. One important outcome of this research program (in 2010) was the fact that the company was able to gain approval for a "topsoil variance" from the state regulatory authority whereby carefully recombined tailings and slimes are coupled with lime, fertilizer and organic amendments (when available) to build a topsoil (A horizon) layer in situ rather than via conventional topsoil salvage, storage and replacement.

## 1 INTRODUCTION

Heavy mineral sands (HMS) consist of titanium bearing minerals, such as ilmenite ($FeTiO_3$) and zircon ($ZrSiO_2$), that 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 igneous and metamorphic rocks. 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 mineable ore is located under 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. However, significant accumulation of HMS occurs in the native topsoil. The HMS are more likely to accumulate in weathered surface soil horizons because they are more resistant to weathering than other aluminosilicates and quartz, coupled with the fact that quartz sands 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). Therefore, the overall goal 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. A secondary goal was to determine whether or not topsoil substitutes generated from organically amended tailings could be successfully employed at this site.

## 2. MATERIAL 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. This particular 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, 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 employed were:

1. LBS-CT (lime-stabilized biosolids, conventional tillage): Ripping, lime-stabilized biosolids at 78 Mg/ha in conventional tillage, and routine fertilization.
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 return, lime to topsoil, and routine fertilization.
4. C (control): Ripping, lime, P, and routine fertilization.

The research plots were established through the fall of 2004. Each plot was 15 x 183 m, with the dimensions set to allow relatively routine use of the agricultural equipment used by the contract farmer. Surface soil (to 15 cm) was excavated from the four TS plots and then all plots were deep ripped (90 cm) and chisel plowed (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 was returned to the four TS plots, and additional lime (6.72 Mg ha$^{-1}$) was applied and incorporated to 20 cm. Lime-stabilized biosolids (78 Mg ha$^{-1}$) were applied and incorporated to 20 cm on the LBS-NT and

Table 1: Selected dry-weight chemical properties of biosolids and topsoil amendments. Biosolids were added at 78 Mg ha$^{-1}$ to mixed tailings which were pH 5.0 and < 2 mg kg$^{-1}$ P extractable P. Thus, the biosolids were added at approximately 3.5% of the dry weight of the amended tailings.

| | 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 N | 32,700 | nd |
| Ammonia N | 4200 | nd |
| P | 15,467 | 9 |
| K | 1467 | 76 |
| Ca | 109,700 | 337 |
| Mg | 2500 | 57 |
| Fe | 44,933 | 123 |
| Mn | 318 | 7.5 |
| Cu | 205 | 2.1 |
| Zn | 455 | 1.5 |

LBS-CT plots. 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. 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. The UM study site was used to compare the success of reclamation treatments relative to undisturbed prime farmland. This particular site is part of some of the most productive farmland in Virginia, with historic record peanut yields, and therefore represents a very high standard of comparison. Crop yields also were compared to five-year (2003 - 2007) average crop yields for Dinwiddie County.

From 2005 through 2012, the experimental plots and comparison areas were placed in a corn-wheat/double-crop soybean rotation. Cotton was grown in 2009 and subsequently, the plots were returned to the typical corn/wheat/double-crop soybeans rotation for 2010-2012. Throughout the eight-year study period, the experimental plots and comparison areas were managed similarly with few exceptions. As necessary, all sites were irrigated (up to 3 times per season), and periodically received herbicides, fungicides and pesticides. Fertilizers were applied based on soil test results, and shallow ripping (~50cm) was applied on two occasions with a Case no-till ripper.

## 3. RESULTS AND DISCUSSION

### *3.1 Corn Yields (2005, 2007 and 2011)*

Mean corn yields for the four treatments from 2005, 2007 and 2011 are presented in Table 2 along with comparative yield data from the UM plots. In 2005, corn yields on LBS-NT and LBS-CT were similar (10.85 and 10.9 Mg ha$^{-1}$, respectively), and were significantly higher than the C (8.53 Mg ha$^{-1}$) and TS (3.79 Mg ha$^{-1}$) treatments ($p < 0.05$). 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 chemical markers, pH (5.68) and P (14 mg kg$^{-1}$), even after they received 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 returned by pans, leading to significant rutting and probable disturbance/smearing to 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 2). This relationship is consistent with previous work in which crop yields from reclaimed HMS mine soils were typically 70 to 80% of native soil crop yields (Daniels et al., 2003). The LBS and C treatments exceeded the five-year county average corn yield (6.28 Mg ha$^{-1}$); however, the research plots had the advantage of being frequently irrigated while the county yield data included non-irrigated and irrigated fields. Corn yields per treatment were lower in 2007 and 2011 than in 2005, with the exception of the TS plots. For example, in 2007, The C and TS treatments produced the highest average yields at 7.29 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 9.98 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. The first year (2005) corn on the LBS treatments had adequate N, as did the winter wheat crop that followed in 2005-2006. 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

Table 2: Mean corn, wheat, and soybean yields (13% moisture) and cotton lint yield by treatment for the Caraway-Winn Reclamation Research Farm and the Clarke Farm unmined control with Dinwiddie County averages indicated.

| Treatment | 2005 | 2006 | | 2007 | 2008 | | 2009 | 2010 | | 2011 | 2012 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Corn | Wheat | Soy-bean | Corn | Wheat | Soy-bean | Cotton | Wheat | Soy-bean | Corn | Wheat | Soy-bean |
| | ---------- bu ac$^{-1}$ (Mg ha$^{-1}$) ---------- | | | | | | | | | | | |
| LBS-NT | 173.9c[1] | 76.8b | 6.1[2] | 54.6b | 84.0c | 37.3b | --- | 41.0a | 16.4a | 75.7 a | 47.7a | 36.4c |
| | (10.90) | (5.16) | (0.41) | (3.43) | (5.64) | (2.51) | (1.18) | (2.76) | (1.10) | (4.75) | (3.20) | (2.45) |
| LBS-CT | 173.0c | 67.8ab | 6.5 | 57.6b | 93.3c | 36.0ab | --- | 40.6a | 14.3a | 84.6a | 47.2a | 37.1c |
| | (10.85) | (4.56) | (0.44) | (3.62) | (6.27) | (2.42) | (1.17) | (2.73) | (0.96) | (4.77) | (3.17) | (2.49) |
| TS (top- | 60.4a | 63.9a | 7.6 | 115.3a | 72.7b | 32.8ab | --- | 39.7a | 17.1a | 65.9a | 47.4a | 37.4c |
| soil) | (3.79) | (4.29) | (0.51) | (7.23) | (4.89) | (2.20) | (1.18) | (2.67) | (1.15) | (4.13) | (3.18) | (2.51) |
| C (control) | 136.0b | 60.9a | 5.6 | 116.3a | 69.0b | 31.5a | --- | 37.3a | 16.3a | 76.0a | 46.3a | 34.8b |
| | (8.53) | (4.09) | (0.38) | (7.30) | (4.64) | (2.12) | (1.05) | (2.51) | (1.10) | (5.30) | (3.11) | (2.34) |
| UM (un- | 224.0d | 102.7c | 37.7 | 158.1c | 58.1a | 47.7c | --- | 70.1b | 25.7b | 199.1b | 66.2b | 32.9a |
| mined) | (14.30) | (6.90) | (2.53) | (9.91) | (3.90) | (3.21) | (1.62) | (4.71) | (1.73) | (12.48) | (4.45) | (2.21) |
| County | 107 | 56 | 22 | 63 | 73 | 26 | --- | | 15 | 131 | 72 | 44 |
| Average | (6.7) | (3.76) | (1.47) | (3.9) | (4.90) | (1.75) | (1.18)[3] | na | (1.01) | (8.2) | (4.83) | (2.95) |

[1] Values followed by different letters are significantly different ($p<0.05$).
[2] CWRRF soybean yields for 2006 were very low in part because excessive wetness prohibited an appropriately timed harvest.
[3] State average (county average not available)

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.

### *3.2 Wheat Yields (2006, 2008, 2010 and 2012)*

In both 2006 and 2008, the LBS plots produced the highest treatment yields, while the TS and C plots produced significantly lower yields (Table 2). Soil fertility levels (data not shown) 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. These results indicate 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 operation. In 2010 and 2012, there were no significant 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 (3.70 Mg ha$^{-1}$) in both years. Yields for 2010 were much lower than previous years due to exceedingly dry and hot conditions which affected crop yields across the state. Yields across most treatments rebounded to more typical levels in 2012.

### *3.3 Soybean Yield (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. The UM yields were excellent (3.21 Mg ha$^{-1}$), reflecting the better physical condition of the unmined soil (Table 2). All mined land treatment yields exceeded the five-year county average (1.82 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 reconstruction treatments. Although regrading the depressions should ultimately improve crop yields, positive effects were not observed for the 2010 soybean harvest. However, in 2012, for the first time, soybean yields on the reconstructed mine soils were higher than the adjacent prime farmlands and much higher than the 5-year county average. This is first time in the history of this experiment that reconstructed mine soils have exceeded undisturbed prime farmlands and is taken as evidence that the overall quality of the mine soils is improving with time. Reports of reconstructed mine soils actually exceeding local native prime farmland soils in production of any major row crop are exceeding rare in the literature (Dunker et al., 1992) and most of the published work in that area was conducted in the mid-eastern USA coal basin in the 1980's.

### *3.4 Cotton Yield (2009)*

Average and lint yields are presented in Table 2. 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 settling. 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.

## 4. SUMMARY AND CONCLUSIONS

For local landowners and state regulatory authorities the major question regarding the sustainability of mining at this site was quite simple: *To what extent can the mining company reconstruct soils to return these lands to profitable agricultural production?* To address this issue, it was mutually decided that we would compare a range of mine soil reconstruction alternatives (with and without topsoil return) directly against (a) the very best undisturbed local prime farmlands, but that our minimum success target would be (b) the local county yield estimates for each row crop across all native soil types.

The biggest reclamation challenges associated with these mine soils are heavy compaction and lack of organic matter, which together restrict root growth and water holding. The benefits of ripping to alleviate compaction were readily apparent from the higher yields seen in the C plots following no-till ripping. Further improvement resulting from the incorporation of biosolids, which contributed to the development of soil structure and increased water holding, 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 was 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 continuously 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 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 of 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 20% should be expected in comparison to the most highly productive pre-mined soils. However, the fact that the 2012 soybean yield on the mined land actually exceeded local native prime farmlands clearly indicates that over the long term, return of 90% or more of pre-mining productivity levels may actually be possible.

One important outcome of this research program (in 2010) was the fact that the company was able to gain approval for a "topsoil variance" from the state regulatory authority whereby carefully recombined tailings and slimes are coupled with lime, fertilizer and organic amendments (when available) to build a topsoil (A horizon) layer in situ rather than via conventional topsoil salvage, storage and replacement. Once implemented, this will result in much higher mining royalty streams to landowners, higher local mineral severance tax revenues and improved profitability and long-term stability for the mining company. The research and demonstration program has also facilitated local landowner and farmer acceptance of the mining practices and provided at transparent assessment of potential post-mining productivity for them.

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