RECLAMATION OF MINERAL SANDS MINE AND TOPSOIL REPLACEMENT STUDY[1]

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Abstract: Iluka Resources Old Hickory mineral sands mining operation is located in Dinwiddie and Sussex Counties in southeastern Virginia. Pre-mining land use in the area is primarily agricultural, dominantly in row crops (soybeans, corn, peanuts, and cotton) and forage production. These farms are highly productive, and returning the land back to productivity is a key component to ensuring mine sustainability in the area. Collaborative efforts between industry, academia, and local landowners have led to several advances in reclamation techniques at the site. Co-deposition of tailings, deep ripping, use of soil amendments, and other reclamation techniques are discussed.

Additional Key Words: Iluka Resources, Ilmenite, Zircon, Prime farmland, Biosolids, Carraway-Winn Reclamation Research Farm, Tailings

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Introduction

Mining activities started in 1997 at the Old Hickory heavy mineral sands operation in southeastern Virginia. The deposit contains economic quantities of ilmenite and zircon, two minerals widely used in industry today. The ore body was formed 5-8 million years ago on an ancient shoreline where storm and wave action concentrated the valuable minerals (Carpenter and Carpenter, 1991). The deposit is located along the "fall zone" (Berquist and Goodwin, 1989), generally varies from 2 to 12 m (5 to 40 ft) in depth, and extends 8 km (5 miles) north to south and 1.6 km (1 mile) east to west. The ore body has an average heavy mineral grade of 7 % and a clay content of 35 %. The clay content can vary widely, ranging from as high as 50 percent to as low as 5 percent.

The surface mining process begins with the installation of perimeter sediment controls (silt fence, earthen berms, and sediment decant ponds. This is followed by clearing and grubbing of vegetation and/or structures on the parcel (Figs. 1 and 2). Efforts are made to remove root material to a depth of 45 cm (18 in), to reduce root-related processing issues. After root removal is complete, the topsoil is removed and stockpiled in berms around the exterior perimeter of the parcel, and in larger stockpiles that are outside of the mining boundary.

Figure 1: Land clearing.

Figure 2: Seeded topsoil and silt fence.

Thirty ton class excavators are used to excavate the material and place it into a mobile mining unit. This unit consists of a feed hopper that funnels material in to a large rotating classifier (shredder). Sandy material easily passes through aided by water jets. Rooty materials and clay are broken into pieces no larger than 45 cm by 7 cm (18 in by 3 in). The sized material is then dropped/washed into a large sump where additional water is added and a slurry is created. This slurry is then pumped through HDPE pipelines to the concentrator. A series of 500 horsepower centrifugal slurry booster pumps are spaced along the pipeline every 1200m to 1500 m (4000 to 5000 ft) depending on topography.

Processing of the material begins with screening the slurry to minus seven millimeter particle size. The undersize consists of sand and clay, which are separated by hydrocyclones. The sand is pumped across a series of spiral concentrators that progressively upgrade the amount of higher specific gravity mineral sands into a concentrate. The clay material is sent to a thickener where it is dewatered. The tailings from the spiral circuit are mixed with the thickened clay material and are pumped away from the plant at approximately 40% solids by weight and deposited in tailing impoundments.

Reclamation Overview

Following mining, the first step in mine reclamation is tailings impoundment construction. Earthen embankments are constructed within of the mining pits and occasionally surrounding the mining pits. These impoundments are designed to be < 7 m (20 ft) tall and contain < 6.17 ha-m (50 ac-ft) of slurry above natural ground. These size constraints are due to Virginia Department of Mines, Minerals and Energy (DMME) Mineral Mine Safety Laws.

Tailings Deposition

Tailings are deposited into impoundments over a 12 to 24 month period until the impoundments are filled. Slurry placement techniques have been modified over the years with the goal of depositing the most consistent blend of sand and clay throughout each impoundment as possible. By maintaining a good sand and clay mixture in each individual impoundment, reclamation can be completed easier than having to mix sand and clay materials that are separated by hundreds of meters. Techniques used to achieve this result are all intended to produce conditions that rapidly reduce the velocity of the tailing stream allowing the clay and sand to be deposited together. If the velocity of the stream discharged at the pipe outlet is not reduced quickly enough, the sand material is deposited close to the pipe outlet, and the clay material is transported toward the outlet of the impoundment, or throughout several adjoining impoundments. Some techniques utilized currently are: 1) Beach discharge – allowing the tailings stream to spread over a large area forcing the velocity to decrease at or near the discharge point, and 2) Sub-aqueous discharge – allowing the steam to discharge below the fluid surface of the impoundment. Sub-aqueous discharge increases the friction on the fluid, as compared to the friction generated when discharging into the air, creating a reduced velocity. Techniques such as these are helpful in maintaining consistent mixtures of sand and clay. Despite these efforts, some segregation is unavoidable, thus the discharge point is often moved around in the pond from as few as two locations to as many as five to six different locations to minimize the effect of segregation.

Dewatering

During slurry placement, impoundments are dewatered with decant structures known as weirs. These weirs are typically 1.5 m (4 ft) wide and 2 m (2 ft) tall with an open face toward the impoundment. The weir is used to adjust the level of the pond by decanting the clear water at the surface while keeping clay and sand material in the impoundment. The level is adjusted by the installing and removing 15 cm (6 in) riser boards. While the pond is receiving the initial tailings and the contained material has a lower density all the boards can be installed and removed over a period of two weeks. However, once the impoundment is near the end of its useable life and the contained material is higher in density, it may require months to be able to remove boards to adjust the impoundment level.

After the impoundments are filled and have as uniform as possible mixture of sand and clay, the tailings in the ponds are allowed to settle/stabilize while dewatering continues. At this point, the material in the impoundments is nearing 50-60% solids by weight. To assist and accelerate this dewatering process again several techniques are utilized. Tails are "shaken" which is the action of placing a bucket of an excavator 1 m (4-6 ft) into the surface and rapidly moving the bucket back and forth. This action liquefies the material and breaks the strata of sand and clay (formed during the tailing process) and allows water trapped in lower sand strata to migrate through the clay to the surface where it can be decanted off the surface of the pond. In addition to shaking tails, a technique of "ringing" the impoundments is used. Large trenches are excavated with long reach excavators. These trenches can be as narrow as 1 m (4 ft) or as wide as 3 m (10 ft) and vary in depth depending on the competency of the material. The intent of ringing is to ensure that minimal water will be perched on the surface of the impoundment and again breaking the strata to allow horizontal draining of the impoundment. Ringing (Fig. 3) is most beneficial when the material at the surface is able to be excavated, but still not competent enough to support the weight of regrading equipment.

Figure 3: Ring ditch constructed around the inside perimeter of an impoundment.

Regrading

Dewatering allows the slurry in the impoundment to dry sufficiently to allow heavy equipment to start working around the edges of the tailing surface. The ultimate goal of the regrading work is to create a surface that is stable, has positive drainage, and is able to support agricultural type equipment for future agricultural activities.

Regrading starts in the corner or area of the pond that had the highest sand to clay ratio and progresses toward the area of the pond with the highest clay to sand ratio. The area of an impoundment that will support equipment is graded by pushing the drier, stronger material toward the wetter less competent material. At some point, no more material can be pushed and the process of "dipping and spreading" starts. "Dipping and spreading" typically utilizes a long stick excavator to remove wet, unstable material from the impoundment and then places it onto the stable surface that has been previously graded. The dipped material is then spread out in lifts

15 to 30 cm (6 to 12 in) thick. This material is allowed to dry and is then graded with the rest of the stabilized area, advancing the face of the stabilized area. This process is continued until the entire impoundment surface area is stabilized. The material from the surrounding earthen embankment is also used as competent, dry material to mix with wet tailings and advance the face. After stabilization is complete on several adjacent impoundments, these impoundments are graded together into a single landform. The last step of the grading process is a final smoothing of the land surface. This is completed by dragging a large metal beam across the area. This beam is dragged back and forth and in circles with the goal of pulling slight highs into slight lows, performing fine grading that is not easily achieved with large earthmoving equipment. At completion of the regrading process, a surface has been created that is stable, drainable, and appealing to the eye. The new landform has been graded with an agriculture use in mind; the final surfaces of these reclaimed areas are designed with a minor slope across the surface (1% +/) to facilitate surface drainage. Where the desired slopes angles are unachievable (generally external slopes) the slope angle is increased to 3-4%, these slopes are installed with the use of pasture in mind, rather then crop management.

Challenges with Final Regraded Product

Several challenges have been identified over the years associated with the regrading practices. Often, these challenges have been addressed and new procedures implemented to mitigate their negative impacts.

Layered Deposition

Layered deposition of the slurried tailings often traps water at depth. As discussed earlier, the main contributor to layered deposition is excessive tailing velocity, creating an environment that allows the clay material to separate from the sand material during deposition. The short-term effect of layered deposition is believed to be minimal. However, the long term effects are differential settling due to differential dewatering of the various layers of tailings.

When the clay is allowed to segregate from the sand, high clay areas are challenging to regrade and difficult to maintain due to continued settling that persists with the ongoing dewatering. This dewatering is slow and a cause of settling issues after reclamation has been completed. A major contributor to this challenge has been identified as the “capping over” of wet material. When a large amount of dry material is available, it may be used to bridge or cap over wet material with a layer approx 1 m (3 ft) thick. In the short-term this can be a cost-effective and efficient method to quickly stabilize wet areas, but when studied over a longer period it has been observed that the clay will continue to release water, especially when proper sand packages are available to facilitate the drainage. When wet clay pockets are identified more time is now spent with the “dipping and spreading” technique to reduce potential settling/consolidation issues. In addition, the occurrence of pockets of clay is further reduced now due to improved tailing management techniques that reduces clay transport and the creation of pockets of clay during deposition.

Saprolite

The tailing impoundments are constructed with available earthen fill from the floor of the mined-out pit or from borrow areas that are outside of the mining boundary. As a result, a large number of the impoundments are constructed with saprolite (weathered bedrock) material. Saprolite is typically 70 % or more clay. As described above, this impoundment fill material is mixed with mine tailings during the regrading process. The lack of a sand component in this material causes challenges with the final soil surface as this material is poorly drained and has low bearing pressure when wet or loose. Saprolite is also a highly erodible material making site stabilization as well as erosion and sediment control more challenging.

Compaction

Compaction has been an invisible hindrance to reclamation for some time (Brooks, 2000; Meredith, 2007). Nearly all of the activities that are associated with the reclamation process compact the soil. For years, good compaction was viewed as a positive result of reclamation activities due to increased trafficability of the reclaimed surface. Research performed in conjunction with Virginia Tech identified that this compaction was negatively affecting post-reclamation productivity (Schroeder, 1997; Daniels, 2003). The highly compacted soil was very poorly drained and did not allow the plants to take up moisture properly and hindered root penetration. Compaction was also determined to be the cause of persistent wet areas in the reclamation areas caused by perched water trapped on the surface due to compaction of the subsoil (hardpan). Compacted soil also caused excessive runoff due to the low infiltration rates.

Increased runoff has the potential to negatively affect much larger areas downstream that are not always located on or near the reclamation site.

Nutrient Levels and pH

Soil nutrient levels are very deficient following regrading of mined areas, particularly with respect to P and K due to the significantly weathered nature of the deposit and soils mined. The pH of the returned tailings is typically 5.0 to 5.5 with significant exchangeable aluminum present (Schroeder, 1997). Prior to mining, managing these soils in their native state required large amounts of fertilizer and lime for crop production. The mining process takes nutrient deficient subsoil and 4.5 to 9m (15 to 30 ft) of material that is barren of nutrients; this material is then slurried, further combining any near surface nutrient enriched soil with deeper acidic materials. Soil samples collected from many regraded areas determined that the average pH of the reclaimed soil is 5.2 – 5.5, extractable P levels average 1-3 mg/kg, extractable potassium levels average 8-22 mg/kg, and the organic material in the soil is typically less then 0.5%. (Daniels et al. 2003)

Methods used to address challenges

The first step in addressing the preceding challenges was to realize that the challenges are somewhat inter-related and that all of the issues must be addressed with a single comprehensive plan. In 2004, Iluka formalized a new reclamation standard which was designed to create a sequence of events to be followed in all cases to address the challenges of reclamation; some of these are will be described.

Deep Ripping

Immediately following the final smoothing of the reclaimed surface, the entire area is deep ripped. This deep ripping is accomplished with a three shank ripper implement on a D-8 class dozer (Fig. 4). These shanks are capable of ripping to depths of 90 cm (3 ft). The ripping is completed by ripping each reclamation area in two directions at ninety degrees from each other. Deep ripping, breaks apart any compacted zones that may have been formed by heavy equipment during the preceding stages of reclamation. The deep ripping also provides a final mixing of the sand and clay to a depth of 90 cm (3 ft). The action of the deep ripping eliminates the compacted zones, allows for water to migrate through the soil and allows for better root penetration for plant establishment.

Figure 4: D-8 Deep Ripping

Subsoil Amendments

Historically, soil amendments were added to all reclamation areas on the final surface of the reclaimed area after all other steps had been completed (Daniels, 2003). The amendments were mixed to a depth of 15 to 25 cm (6 to 10 in), usually constrained by material hardness and limitations of farm tractors and implements. Current practice is to add amendments to the subsoil prior to deep ripping. This allows for better mixing of the lime and fertilizers to deeper depths than previously possible.

Topsoil Application

The topsoil, (A + E horizons) has been stripped, stored, and reapplied throughout reclamation activities at the Old Hickory operation. However, many of the practices of storage and application reduced the quality of the topsoil when reapplied or allowed non-topsoil saprolites and tailings/slimes to be mixed with the topsoil resource. The current practice of topsoil handling begins with the pre-mining topsoil removal and storage in berms that typically surround the mining area. After this material has been placed into berms it is seeded to ensure stability and reduce erosion. Mining, tailing, and regrading activities operate within this topsoil boundary berm, thus not disturbing it.

After the subsoil amendments (lime at 8 Mg/ha and P at 350 kg/ha) have been applied and incorporated, the topsoil is then returned over the amended subsoil. Several topsoil return techniques have been trialed including tractor/pull pan, scraper, dozer, and truck/dozer. The latter is currently the preferred method. Topsoil is removed from the stockpiles and loaded into trucks. The trucks dump the material in measured quantities into parallel windrows (Fig. 5), which are typically spaced one-hundred feet apart. After the material is placed in windrows any rutting caused by the truck haulage is smoothed out and the material is then spread from row to row. This method ensures that the topsoil materials depth is consistent throughout the area and that all areas receive an even distribution of approximately 15 cm (6 in) of topsoil.

Figure 5: Topsoil returned in windrows

Topsoil Amendments

Once topsoil has been spread, soil amendments are again added to the topsoil. The topsoil amendments include N, P, K and agricultural lime and are based upon soil tests of the stockpiled topsoil. With the addition of the topsoil and amendments, there is now a fertile horizon that will allow plant germination, and growth. This horizon is approximately 41 to 46 cm (16 to 18 in) in depth, extending into the subsoil layer. The quantity of soil amendments required for the topsoil is generally much less than required for the subsoil because the topsoil has been kept in a healthy state by seeding and maintenance of the topsoil storage berms.

Alternative Soil Amendments

Two alternative soil amendments have been used at the operation: green manure and biosolid/sewage sludge. The green manure trial was completed on approximately 8 ha (20 acres) of rehabilitated land. In the summer, soybeans and pearl millet were grown and winter wheat was grown during the cooler seasons. All plant material was cut and disked back into the soil to attempt to raise the contained organic material level. The green manure cycle was repeated for two and a half years. The practice did raise the amount of organic material in the soil, however, with further research it was determined that the number of years required to breakdown the plant material into usable organics made the process uneconomical. However, due to the benefits that green manuring does offer, current management practices used to maintain the reclaimed land is to mulch all grass clippings back into the pasture for the 2 year bond monitoring period. This 2 year monitoring period is dictated by the Virginia Department of Mines, Minerals, and Energy (DMME) reclamation regulations.(DMME 2003)

Additionally lime-stabilized biosolid/sewage sludge (Haering et al., 2000) has also been used quite successfully on the site. The application is limited to parcels where landowners allow (or request) the application and it has been permitted by the Virginia Department of Health. The application of biosolids greatly decreases the required application of lime and some macro nutrients, and replaces some of the tillage required for reclamation. The odor of the biosolids can be a significant deterrent to use and is often commented on by both employees and neighbors. To address this, biosolids are now immediately incorporated into the subsoil and then covered with topsoil as soon as possible as reclamation proceeds. This greatly reduces the odor while increasing the depth of organic-rich material from 15 cm (6 in) (topsoil organics only) to a depth of 36-41 cm (14 -16 in) (material treated with bio-solids plus 15 cm (6 in)of topsoil). We have experienced positive results and community comments with this new method of incorporation. Increasingly, landowners are requesting that biosolids be utilized on reclamation areas on their property. The company's success in utilizing biosolids has also influenced some local farmers to start applying biosolids on their farm fields, completely unrelated to the mining activities.

Carraway-Winn Reclamation Research Farm

In 2001, Iluka and Virginia Tech started a new relationship that would lead to several of the solutions to challenges in our reclamation practices. This cooperation started with soil and subsoil testing as well as determining the type and amount of soil amendments required to create a medium that that would sustain successful pasture growth. In 2004, Iluka, Virginia Tech, and Carraway Minerals (local landowner) entered into a cooperative agreement to begin work on a 40 ha (90 acre) research farm. The goals of this research farm were and still are to analyze the current reclamation techniques, identify additional potential for success, and define methods to improve potential shortfalls. Results from several years of soil reconstruction research are summarized by the Masters thesis "THE INFLUENCE OF SOIL RECONSTRUCTION METHODS ON MINERAL SANDS MINE SOIL PROPERTIES" (Meredith 2007).

Reclamation Research Farm Plan

With these goals in mind a plan was generated. This plan included the installation of a series of intensive row crop experiments that would provide data concerning the return of mined lands to row crop production, and what techniques would be most successful in maximizing crop yield. The plan also included the installation of a large forage experiment to study the same challenges with a focus on forage grasses due to the increased market for high-quality hay material versus limited local supplies. This was a very logical connection due to the fact that the current mining permit requires that land be released as pasture or grasslands. Another interest was timber and how the deep rooting would be effected by the reclaimed tailings material and structure.

Both the crop and forage experiments were set up to test the productivity on three reconstructed soil types: 1) Typical reclamation process – amended subsoil, amended topsoil; 2) Biosolids application – tailing/subsoil amended with biosolid material and additional P and K as necessary with no topsoil, and 3) No topsoil – amended subsoil only. All three methods were amended sufficiently with lime to adjust the pH to similar levels, and N-P-K as needed to insure optimum levels for germination and sustained growth for seeding and species of plants [forages, soybean, corn].

In the first two years of production from the experimental farm, a noticeable difference was seen between all three reconstructed soils. The topsoil areas had surprisingly low productivity. This low productivity was later determined to be associated with compaction, low pH and low initial P levels that were related to the techniques used in the placement of the topsoil. The fact that the topsoil originated from a forested source also led to some fertility limitations. The Biosolids plots had high productivity due to the high levels of organic matter and nitrogen in the soil. Productivity results from areas with no topsoil were consistent each year, and were able to maintain reasonable crop production levels in both years. Over the years, an increase in the topsoil plot yields has been noted due to additional deep ripping to reduce compaction as much as possible, and a relative decrease in the Biosolids plot yields associated with the depletion of the initial nitrogen levels. It is interesting to see that the plots are stabilizing and aligning themselves with the productivity of the control plots. This trend is apparent in the forage plots as well. Detail on these results can be found in the previously mentioned thesis by Meredith (2007).

<u>Productivity</u>

Productivity is shown on the chart below by year and crop. This chart shows the productivity of the crops harvested from 2005 through 2007. All units are reported in bushel per acre. The "% of unmined" column for each crop shows the percent of the yield as compared to the yield on the unmined plot.

	2005 Corn	% of unmined	2006 Wheat	% of unmined	2006 Soybean	% of unmined	2007 Corn	% of unmined
Biosolid Conventional	173	77%	68	67%	7	18%	58	36%
Biosolid No-Till	174	78%	77	75%	6	16%	55	35%
Topsoil	61	27%	64	63%	8	21%	116	73%
Control	136	61%	61	60%	6	16%	117	74%
Unmined	224		102		38		159	

Chart 1: Productivity from Research Farm

<u>Is Topsoil Removal/Return beneficial?</u>

The row-crop yield data presented above has raised several questions:

1) "Is the removal, storage, and re-application of the topsoil beneficial to the long term rehabilitation of mined lands?"
2) "Does the benefit of topsoil replacement warrant the associated expense?"

The discussion above has also brought into question the quality of topsoil prior to mining at the Old Hickory site. It has been determined that the topsoil that is removed and stockpiled in most cases is poor quality. The soils in the area have been farmed continuously for hundreds of years and require liming and addition of macronutrients yearly to produce a crop of economic yield. The soils are well drained. When this material is returned to mined lands, it does not appear to add many beneficial characteristics chemically or physically. The topsoil may have its largest impact in aesthetics were topsoil imparts a lighter brown color the bare surface that is similar to surrounding fields and is less red in color than the typical reclaimed subsoil.

There are some benefits that are associated with returning the topsoil that are harder to define and measure, however. These are associated with the microbial biomass and organisms that live in topsoil. The mining process completely removes these microbes and organisms from the processed material; regeneration of these microbes is a slow process. The importance of these microbes and organisms is not directly related to the short-term crop yield, but more so to the long-term accumulation of organic matter and regeneration of soil structure. Post-mining, the reclaimed land is generally described as structureless, highly variable, and having little pedogenic development (Schroeder, 1997; Daniels, 2003). The effects of vegetation growth, weathering, and wetting and drying over many years will be required to develop an environment that these microbes and organisms will thrive in as they did prior to mining.

<u>Conclusions</u>

Successful reclamation of lands mined for mineral sands is achievable with a sound understanding of the challenges that relate to soil productivity. Based on the data that has been collected to date, it is believed that the soil productivity levels can be maintained and possibly improved to higher levels with increased focus on challenging soil conditions (compaction, drainage, consistent sand/clay mixtures, and biosolid application where allowable). However, it is unlikely that these post-mining productivity levels will surpass pre-mining levels on a short term basis. Our results to date indicate that characteristics such as pH and nutrient levels have a greater impact on the yield of crop and forage stands than the presence of topsoil.

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.

Brooks, D. R. 2000. Reclamation of lands disturbed by mining of heavy minerals. pp. 725–754. *In* 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.

Daniels, W. L., P. D. Schroeder, S. M. Nagle, L. W. Zelazny, and M. M. Alley. 2003. Reclamation of prime farmland following mineral sands mining in Virginia. Mining Engineering, Dec. 2003: 42-48.

Department of Mines, Minerals and Energy, 2003, Virginia Reclamation Regulations For Mineral Mining, 2003 Edition, Virginia Department of Mines, Minerals and Energy, Charlottesville, VA

Department of Mines, Minerals and Energy, 2001, Mine Safety Laws of Virginia, 2001 Edition, Virginia Department of Mines, Minerals and Energy, Charlottesville, VA

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. of Agron. Monograph #41, Madison WI. 1082 p.

Meredith, K. R. 2007. The Influence of Soil Reconstruction Methods on Mineral Sands Mine Soil Properties. M.S. Thesis, Virginia Tech, Blacksburg. 247 p.

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.