Florida Reclaimed Phosphate Mine Soils: Characteristics, Potential Uses, and Management Considerations[1]

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Phosphate is a critical nutrient for plant growth and an essential component of the agricultural fertilizer that helps sustain the world's growing population. Florida is a major producer of phosphate, and in 2010, seven mines in Florida produced approximately 10% of the world's phosphate supply and more than 65% of the phosphate for the United States (USGS 2011). Phosphate is typically extracted from the Earth via strip-mining, and thousands of acres are disturbed annually in Florida for production of phosphate rock. To date, more than 300,000 acres in Central Florida have been disturbed by phosphate mining (Brown 2005). The Florida Legislature has recognized that mining is a temporary land use, and all lands mined for phosphate after June 30, 1975 are subject to mandatory land reclamation (Florida Department of Environmental Protection [FDEP] 2006). The purpose of reclamation is to return the land to beneficial uses, such as agriculture, forestry, residential/commercial development, water supply projects, recreational areas, and restoration of native ecosystems. In excess of 190,000 acres in Florida have been or are subject to mandatory reclamation requirements (FDEP 2011).

The jobs and economic activity associated with mining depart from an area once the resource is exhausted. However, the legacy of mining is determined by the suitability of the post-mining landscape for beneficial uses. Communities affected by mining activities need to have reclamation efforts result in lands with high potential to provide sustainable economic opportunities. Soils mediate several important ecosystem functions, and soil properties strongly influence whether the land is suitable for particular uses. Therefore, landscape restoration efforts must include an assessment of soil properties to ensure targeted land uses are compatible.

This publication provides a general characterization of the various soil types resulting from phosphate mine reclamation conducted in accordance with the mandatory reclamation standards in effect since July 1, 1975. Although this document provides a broad overview of the soil types on reclaimed lands in Florida, methods of mining, processing, and mine waste disposal have varied with time and across landscapes. Site-specific surveys are necessary to properly characterize the properties of reclaimed soils on a specific site and determine their suitability for specific uses. Many mined areas in Florida were disturbed prior to the advent of mandatory reclamation regulations, and the post-mining landscapes and soils in these areas are highly variable.

The phosphate ore (matrix) found in Florida typically lies beneath a 15- to 50-foot layer of soft, sandy, or clayey overburden material. Therefore, phosphate mining in Florida requires that the overburden material be stripped off to expose the phosphate matrix. The phosphate matrix

1. This document is SL370, one of a series of the Soil and Water Science Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. Original publication date October 2012. Please visit the EDIS website at http://edis.ifas.ufl.edu.

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is typically 10- to 20-feet thick. Electric draglines are used to remove the overburden and expose the phosphate matrix. Then the phosphate matrix is excavated, slurried, and pumped to a beneficiation plant where the recoverable phosphate is separated from the clay and sand (Florida Institute of Phosphate Research [FIPR] 2012). The sands and clays each make up approximately one-third to one-half of the phosphate matrix and are disposed of in separate waste streams. Three common landform types are created via phosphate mine reclamation: 1) contoured overburden, 2) sand tailings, and 3) phosphatic clay areas. A fourth landform (sand/clay-mix) occurs to a limited extent, and it most closely resembles phosphatic clay settling areas.

The soils impacted by phosphate mining in Florida generally consist of sandy, acidic soils of marine origin. The mining and reclamation processes excavate, transport, process, and sort the earthen materials, and mechanically shape them into post-reclamation landforms. The reclaimed soils show little soil profile development and are properly classified as Entisols (United States Department of Agriculture - Soil Conservation Service 1990). Immediately following reclamation, the reclaimed soils typically have a near neutral to slightly alkaline pH. Clay content is often increased relative to native Florida soils. Initial nitrogen levels and organic matter content are low (Hawkins 1973), though substantial organic matter can be incorporated into newly-restored sites if topsoils are conserved and used for reclamation. Some reclaimed soils may be deficient in micronutrients, such as manganese (Bromwell and Carrier, Inc. 1989). Soil testing is recommended if the land will be used for agricultural production.

Landforms in Phosphate Mine Areas

1. Overburden

Immediately following extraction of the phosphate ore, the landscape consists of alternating rows of water-filled pits and mounds of mixed overburden spoil. The overburden is composed of sand and clay, and sometimes contains fragments of limestone. Substantial mixing occurs during mining and reclamation, and as a result, the overburden materials are highly variable. In general, the overburden soils have a more neutral pH than native Florida soils and are higher in clay content, plant nutrients, water-holding capacity (WHC), and cation exchange capacity (CEC). Soil organic matter (SOM) is generally low immediately following reclamation. Overburden areas do not receive additional backfill materials following mining. Removing the phosphate ore body from the landscape results in a deficit of material to be used for reclamation. The deficit of material often necessitates the creation of phosphate mine pit lakes in reclaimed overburden landforms.

2. Sand Tailings

Sand tailings are primarily quartz sands separated from the clay and recoverable phosphate during processing. Following processing, the sand tailings are hydraulically pumped back to mined-out pits. Once backfill has been completed, bulldozers may be used to establish the final design contours of the reclaimed landscape. The sands do not contain any phytotoxic substances and have high extractable concentrations of phosphate and calcium (Mislevy and Blue 1981a). Sand tailings exhibit minimal aggregation, and most of the pore space is due to macropores that occupy space between the sand grains. Sand tailings drain well, and as a result, leaching rates for cations and anions are high in upland areas. WHC and CEC are extremely low (CEC ~1.1cmol$_c$ kg^{-1}) (Bromwell and Carrier, Inc. 1989). The tailings are also low in organic matter and several nutrients (Mislevy and Blue 1981a), including potassium, and micronutrients, such as copper and manganese (Mislevy and Blue 1981b). Sand tailings can be droughty, and additional care may be necessary to establish the desired vegetation on upland sites composed of pure sand, particularly if dry conditions occur within the first few years of establishment.

Overburden spoil rows may be located at or just below the surficial sands. Repeating patterns of subsoil characteristics may be observed on some sand tailings sites because of the overburden's influence in the subsoil (see Figure 1). Overburden subsoil may provide additional WHC and

Figure 1. Sand tailings disposal site with an overburden "cap," in Hamilton County, Florida. Note the difference in subsoil due to the overburden spoil pile on the left side of the picture. Credits: M. Wilson

Figure 2. Sand tailings soil with a 1-2 foot overburden "cap," in Hamilton County, Florida. Credits: M. Wilson

nutrient content, and may support enhanced growth of some species. In some areas, the overburden spoil piles may be knocked down before deposition of the sand tailings, and the upper portion of the soil profile is composed of almost 100% sand tailings. Conversely, in some areas the tops of the overburden spoil mounds are used to create a 1–2 foot deep "cap" of overburden surface soil underlain by sand tailings material (see Figure 2).

Low CEC presents a challenge to growing crops on pure tailings (Mislevy, Blue, and Brolmann 1981), but low yields of forage can be produced (Mislevy and Blue 1981a). Mixing some overburden or phosphatic clays with the sand tailings could improve soil fertility, structure, and WHC. Where costs of this mixing process can be minimized, the long-term effects will likely persist with time creating a more productive and diverse landscape.

3. Phosphatic Clay

Phosphatic clay soils are formed on clay settling areas. The clay settling areas are retention basins where phosphatic clay wastes are settled and clear water is decanted and recycled. The clays become hydrated during processing, and the clay-water fraction occupies a substantially larger volume than the void where the phosphate matrix was originally removed (Bromwell and Carrier, Inc. 1989). Clay settling areas typically constitute approximately 40% of reclaimed landscapes and may be elevated up to 60 feet above grade. The settling area dam walls are created from overburden materials, and the exterior portions of phosphatic clay settling areas commonly are composed of overburden soils following reclamation.

The phosphatic clay includes some very fine sand and silt, but is composed predominantly of clay-size material. The soils of phosphatic clay areas will ultimately be classified as Vertisols. Phosphatic clay is high in natural apatite (24%–32% dry weight) and is also high in smectites, with minor components of attapulgite, mica, kaolinite, illite, palygorskite, wavelite, crandallite, vermiculite quartz, dolomite, and potassium-feldspar (Barwood 1982; Hawkins 1973). Phosphatic clays do not contain any phytotoxic substances (Mislevy, Blue, and Roessler 1989), are highly plastic, and have an extremely high surface area per unit volume. These clays are extremely high in phosphorus, calcium, and magnesium. WHC and CEC are high, and the pH is neutral to alkaline. Nitrogen and some micronutrients, such as copper, manganese, and zinc, may be lacking for agricultural production (Mislevy, Blue, and Roessler 1989; Bromwell and Carrier, Inc. 1989; Rahmani and Degner 1994).

Phosphatic clay soils have reduced air and water mobility, may exhibit expansion and contraction, and range from sticky when wet to extremely hard when dry. Clay soils have very low hydraulic conductivities, and when wet, they are prone to water logging and sticking to machinery, shoes, and tires. Farming the heavy, sticky clay is energy-intensive and inflicts substantial wear and tear on machinery. Any fertility and irrigation advantages of farming phosphatic clays are likely offset by higher labor and machinery costs. Regardless, the costs for agricultural production on phosphatic clay soils can be comparable to production on native Florida soils (Rahmani and Degner 1994). Sloped planting beds (macrobeds) have been used to enhance drainage on clay settling areas. Perennial peanut sod has been shown to help form a bed capable of supporting farming equipment during wet conditions. However, the macrobeds were lost within a few years because the clay continued to settle (Hanlon et al. 1994a).

Many crops have been successfully grown on phosphatic clay settling areas, including vegetables, forages, grains, ornamental trees, and turfgrass (Mulkey, Clouser, and Taylor 1994; Mislevy, Blue, and Roessler 1990). Forage concentrations for major nutrients are adequate for growing and finishing cattle (Mislevy, Blue, and Roessler 1990; Mislevy et al. 1990).

4. Sand/Clay Mix

Sand/clay-mix areas are formed by mixing dewatered sand tailings with thickened clays and depositing the mixture into settling areas (Bromwell and Carrier, Inc. 1989; Mislevy et al. 1991). Sand clay mix enhances consolidation, which means less storage volume is required in comparison to conventional clay settling areas, allowing the reclaimed land surface to be restored to near original grade (Bromwell and Carrier, Inc. 1989; Garlanger 1982). Mixing sand with the phosphatic clay also enhances soil permeability and dewatering rates. Adding tailings to the clays improves some physical properties, but the clays have an extremely plastic nature, which causes the sand/clay mixes to remain sensitive to soil moisture (Bromwell and Carrier, Inc. 1989). The sand/clay-mix areas retain the shrink/swell properties and associated land use limitations of phosphatic clay soils. Similar to the clay settling area soils, the soils of sand/clay-mix areas are likely to become Vertisols. Sand/clay-mix areas may contain sandy inclusions that are influenced less by the phosphatic clay component.

Sand/clay-mix soils have high concentrations of calcium (Ca), magnesium (Mg), and phosphorus (P). These soils also have very high CEC and WHC in comparison to the sandy soils typical of Peninsular Florida (Bromwell and Carrier, Inc. 1989). Potassium may be low, and corrective applications of micronutrients, such as boron and manganese, may be required for growing crops.

Debris Lands

Debris lands occur to a limited extent and are areas where a significant portion of the phosphate ore fraction has been disposed (Guidry et al. 1990). Beneficiation processes have greatly improved recovery of the phosphatic material, and no new debris lands are being created. Because debris lands are limited, little research has been performed on the properties of debris lands soils. Several debris parcels are being re-processed and will eventually be reclaimed to other landform types.

Management Considerations

Commercial and Residential Development

Sand tailings and overburden soils have proven suitable for residential and commercial development. Subdivisions, shopping centers, resorts, golf courses, and power plants have been constructed on reclaimed sand tailings and overburden areas. Because sand tailings soils have excellent suitability for development, local governments often request they be strategically placed in areas targeted as potential development corridors.

Phosphatic clay and sand/clay-mix soils are generally unsuitable for urban or suburban development because phosphatic clays exhibit pronounced shrink/swell characteristics even when consolidated (Mislevy et al. 1991). Phosphatic clays also need substantial time to dewater and consolidate (Mislevy et al. 1991; Bromwell and Carrier, Inc. 1989). Adding sand to phosphatic clays improves consolidation but does not sufficiently offset the phosphatic clays' instability to the degree that they become well-suited for commercial or residential development.

Agriculture and Forestry

Before phosphate mining, much of the land impacted by phosphate mining in Florida was used for agricultural production, such as pasture grasses, timber, citrus, and vegetable crops. Agriculture and forestry are major post-reclamation land uses, and all of the reclaimed soil types have potential for agricultural and forest production (Bromwell and Carrier, Inc. 1989; French et al. 1994; Jones, Eitzen, and Riddle 1994; Mislevy, Blue, and Roessler 1989; Mislevy, Blue, and Roessler 1990; Mislevy et al. 1991; Degner 1994).

Overburden soils generally contain sufficient nutrients and WHC for production of agricultural crops and pine tree plantations. Sand tailings have been successfully used to produce pine tree plantations and low yields of forage grasses. However, low WHC, CEC, and low availability of certain cations, such as potassium, may present some difficulties in getting trees and crops established on sand tailings soils. Using an overburden cap may enhance the ability to use sand tailings for agricultural production. Phosphatic clays are highly fertile but are difficult for producers to work with. Some biomass energy crops have been successfully established on reclaimed clay settling areas. Sand/clay-mix soils are also highly fertile and are much easier to work with than clays (Bromwell and Carrier, Inc. 1989).

Citrus production is also possible on mined phosphate land. Successful groves have been established on sites reclaimed with sand tailings, overburden, and sand/clay mix. Based on limited research, no extraordinary management tools are necessary for citrus production on reclaimed lands (Krezdorn, Oxford, and Moon 1987).

A Note on Soil Compaction

Compacted soils have been observed on some reclaimed lands. Soil compaction results in a loss of pore space, which decreases water and gas mobility, reduces root penetration, and may increase runoff. Soil is particularly susceptible to compaction when it is wet or has low organic matter content (United States Department of Agriculture – Natural Resources Conservation Service 2003). All reclaimed soil types, except pure sand tailings, have the potential for adverse soil compaction. A cone penetrometer can be used to determine whether a particular soil may be excessively compacted (Duiker 2002). Breaking up the compacted layers may be necessary to successfully revegetate some reclaimed sites (Nair et al. 2001).

Trace Element Concerns in Reclaimed Phosphate Mine Soils

Trace elements associated with phosphate ore that may be present in the reclaimed soils include arsenic, barium, cadmium, chromium, copper, lanthanum, lead, manganese, molybdenum, nickel, selenium, uranium, vanadium, and zinc (Bromwell and Carrier, Inc. 1989; Barwood 1982). Extensive water quality sampling has been conducted on reclaimed landscapes and none of these metals appear to be a concern for water quality. The FDEP requires groundwater and surface water testing for each of these elements in contemporary mining permits.

Some crops can take up cadmium from soil to unsafe concentrations. Because cadmium has been found to be somewhat elevated in some reclaimed soils, research has been conducted to determine whether cadmium uptake could be a problem for foods grown in reclaimed phosphate mine soils (Bromwell and Carrier, Inc. 1989). The research results indicate that cadmium concentrations in foods grown on sand/clay mixes were only slightly higher than background levels and were not high enough to pose a health risk. Cadmium uptake may be suppressed on phosphatic clay soils (Gonzalez, Sartain, and Miller 1992), as the alkaline pH and excellent metal binding ability (Singh, Ma, and Harris 2001; Singh, Ma, and Hendry 2006; Gonzalez, Sartain, and Miller 1992) of phosphatic clays may limit uptake of any hazardous metals present.

Changes in Soil Properties with Time

The process of soil development begins in reclaimed soils the moment they are created. Soil porosity increases with time as roots and other biota (such as earthworms, moles, and ant colonies) break up the soil and add to pools of SOM. Soil pH generally decreases with time while the availability of nitrogen generally increases. With time, the clay settling area (CSA) soils consolidate to a great degree, though this condition does not ameliorate the shrink/swell limitations of these soils. Enhanced vegetation growth has been documented on aged soils relative to newly-reclaimed soils (Paulic and Rushton 1991). Possible reasons for enhanced tree growth on older sites include the advanced state of dewatering on older sites, better development of microbial communities in older soils, and increased nutrient availability to the tree roots (Paulic and Rushton 1991).

Building SOM is a critical component of landscape restoration for agricultural or ecological purposes. SOM enhances water infiltration, WHC, and CEC. SOM acts as a nutrient pool and can make certain elements, such as iron (Fe) and P, more available to plants. SOM is important to the formation of soil structure and macropores, decreases soil bulk density, enhances soil aeration, eases root penetration, and increases the biomass of the soil microbial community (Ingram et al. 2005). A continual increase in root biomass and SOM occurs through time in reclaimed soils, but does not appear to reach a maximum within 60 years (Wallace and Best 1988). Rapid recovery of SOM has been documented in reclaimed wetlands (Nair et al. 2001).

The activities of earthworms, insects, and small mammals provide important soil functions such as soil aeration, drainage, and nutrient cycling. The soil microbial community also influences many aspects of soil ecology, and microbes have been used to document recovery in reclaimed soils (e.g., Insam and Domsch 1988; Graham and Haynes 2004; Ingram et al. 2005). Little research has been done on the recolonization of reclaimed phosphate mine soils in Florida by soil macrofauna or the soil microbial community. Additional knowledge on this subject could prove beneficial for understanding the processes associated with restoration of soil functions on reclaimed phosphate-mined lands.

Mycorrhizae are fungi that form symbiotic and often mutual relationships with plants. These fungi are important in agroecosystems as well as in native ecosystems (Sylvia and Hartel 2005). Elevated phosphate content in the reclaimed soils may suppress mycorrhizal activity. However, Wallace and Best (1988) found that mycorrhizae colonization on unreclaimed overburden spoil occurs rapidly following mining cessation. Most species sampled at three-year-old sites exhibited extensive mycorrhizae colonization. In fact, mycorrhizal colonization was observed to be more prevalent in three-year-old reclaimed sites than in native communities. Additionally, Sylvia (1990) found that inoculation of plants with mycorrhizae before planting in reclaimed sites had no effect on plant growth, though he concluded that insufficient information was available to draw strong conclusions on whether large-scale inoculation with mycorrhizal fungi could be an effective tool for restoration of reclaimed phosphate mine soils. Some researchers have suggested that the mycorrhizal species commonly found in the early-successional reclaimed phosphate-mined lands may not be efficient for promoting growth of the often late-successional types of trees commonly planted on many reclaimed community types (Wallace and Best

1988). Additional research is needed to determine whether large-scale inoculation with mycorrhizae would be a cost-effective tool for restoration of native community types or agricultural crops on reclaimed phosphate-mined lands.

The Effects of Soil Amendments on Reclaimed Phosphate Mine Soils

Land application of waste materials provides the dual benefits of cost-effective waste disposal and extraction of additional value from waste material in the form of enhanced soil properties. Several types of soil amendments have been tested on reclaimed phosphate mine lands including compost, municipal waste, and sewage sludge. Applying these amendments to reclaimed phosphate mine lands has enhanced CEC, WHC, SOM, and the concentrations of several cations, including potassium (Hortenstine and Rothwell 1972; Mislevy, Blue, and Brolmann 1981; Mislevy and Blue 1981a). The amendments appear to benefit vegetation establishment and enhance crop yields. However, the positive effects of the soil amendments are only significant the first few years following application, and amendments do not result in any significant long-term crop yield enhancement or benefits to the function of reclaimed soils (Mislevy and Blue 1981a).

Ecological Restoration

Strip mining is one of the most intense types of land disturbance, and complete replication of all native community types that existed before mining is not feasible. There is little or no "ecological memory" in reclaimed mined lands. Regardless, ecological communities have been restored so they are similar to native landscapes, and restoration technology and methodology improve with each passing year. Examples of quality restoration exist for many native community types, including scrub, sandhill, bayhead, pine flatwoods, hardwood hammock, depressional marshes, basin swamps, basin marshes, floodplains, and lake swamps. Reclaimed phosphate mine lands also have been shown to support a diversity of fish and wildlife (Durbin et al. 2008). Many factors (e.g., landscape position, hydrology, and quality of vegetative material) influence the success or failure of ecological restoration projects (Paulic and Rushton 1991). A major limitation to returning mined landscapes to native habitats is the lack of a normal seedbank (Odum et al. 1991).

To a large degree, soil acidity and nutrient availability are responsible for maintaining plant associations in nature, and the nutrient and acidity properties of soils must be considered when planning ecological restoration projects. For example, restoring a low-nutrient, acidic system on phosphatic clays or sand/clay mix would be difficult. Species such as pond cypress (*Taxodium ascendens*) and loblolly bay (*Gordonia lasianthus*), which are common to acidic, low nutrient wetlands have not performed well on CSA soils (Rushton 1991; Paulic and Rushton 1991). The most successful tree plantings on CSAs have been species typical of mixed swamps along floodplains (Paulic and Rushton 1991).

Most reclaimed mine soils are deficient in nitrogen immediately following reclamation (Mislevy, Blue, and Roessler 1989; Tamang 2005). Restored communities often pass through a stage where the vegetation community is heavily influenced by species adapted to low-nitrogen environments. Soil nitrogen cycling and availability should increase with age as SOM increases and the soil microbial community develops. Incorporating a green manure crop or a leguminous cover crop may add SOM and nitrogen, preclude erosion, and retard the establishment of invasive exotic vegetation. Adding slow release fertilizer may enhance seedling establishment (Paulic and Rushton 1991) on young sites.

Applying topsoil to ecological restoration areas has many benefits, including transfer of a native seedbank, addition of SOM, enhancement of nutrient availability, and enhancement of WHC (see Figure 3). Federal reclamation regulations for coal mines require that topsoils be removed, protected, and reused (Surface Mining Control and

Figure 3. Reusing topsoil provides many benefits to the properties of restored soils and is an effective way to stabilize disturbed lands and restore native ecosystems. In this picture taken in Hardee County, Florida, the area in the foreground is reclaimed land that was amended with topsoil after approximately one growing season.
Credits: M. Wilson

Figure 4. In Hardee County, Florida, wetland muck was recently placed on top of a sand tailings substrate in an area being restored to a freshwater marsh. Credits: M. Wilson

Reclamation Act of 1977, 2006). In contrast, Florida's phosphate mine reclamation law allows topsoils to be discarded as mining wastes, though the use of topsoil is "encouraged." Many phosphate mine reclamationists currently make extensive use of topsoil (see Figure 4), despite the lack of a mandate to do so. Applying topsoil has been observed to be an effective means of revegetating other types of reclaimed mined lands in Florida, such as heavy mineral mines (Matt Wilson, personal observation). The effects of incorporating native B-horizon material onto sand tailings reclamation projects should be investigated.

Hydrology has substantial influence on the type of native community that will be favored on a particular site and is arguably the most important factor affecting the success or failure of many ecological restoration projects on phosphate-mined lands. Most native Florida community types are maintained by a narrow range of hydrological conditions, and too much water can be as harmful as too little (Paulic and Rushton 1991). The type of soil used to construct a reclaimed site influences site hydrology. For example, Brown et al. (2010) concluded that wetlands developing on sand-capped CSAs experienced less direct surface runoff and were maintained by baseflow hydrology in comparison to the surface runoff-driven hydrology of wetlands forming on non-capped CSAs.

Reclaimed basins generally exhibit a slower response to rainfall recharge (Bromwell and Carrier, Inc. 1989), and increased stream flow has been observed in some reclaimed basins (Schreuder, Earls, and Dunmeyer 2006). Integrated surface and ground water modeling are commonly employed to assist with reclamation planning. For many reclaimed areas, hydrologic modeling reports are readily available from either the phosphate companies or the Florida Department of Environmental Protection's Bureau of Mining and Minerals Regulation (FDEP-BMMR).

Many successful ecological restoration projects have been completed on overburden, sand tailings, capped sand tailings, and sand/clay-mix soils. The inability of sand tailings to retain moisture is a major challenge for reclamation (Bromwell and Carrier, Inc. 1989) but has been overcome on many sites. In fact, of the reclamation soil types available, uncapped sand tailings probably most closely resemble native Florida soils with respect to texture and hydrology, especially if overburden subsoil remains somewhat near the surface beneath the layer of sand.

Clay settling areas pose several serious challenges to ecological restoration. The clays are somewhat unstable for several decades following the initiation of reclamation. Phosphatic clay soils are also prone to water logging. Continued settling occurs with time on CSAs, and wetland restoration projects (and even some areas targeted to become uplands) are likely to eventually subside and transition to open water/willow swamp areas that do not resemble native wetlands. Elevation of the clay settling areas above natural grade results in isolation from the surrounding landscape, and an adequate supply of water-borne seeds is unlikely to reach the site (Paulic and Rushton 1991). The lack of adequate seed material to the CSAs may be a major factor responsible for the states of arrested ecological succession that have been observed on many CSA sites.

Radiation Concerns for Reclaimed Soils

Elevated levels of uranium occur with the phosphate deposits in Central Florida (Hanlon, Hochmuth, and Jerez 1988; Guidry et al. 1990). The mining and reclamation processes result in radioactive elements moving closer to the land surface. Radiation levels on reclaimed phosphate mine lands are elevated relative to native Florida soils. Uranium has a low solubility and is typically not an environmental hazard. However, some members of the uranium decay series, such as ^{226}Radium and ^{222}Radon (and the radon daughter products ^{210}Lead and ^{210}Polonium), can be contaminants of concern. Soils from phosphatic clay and debris parcels exhibit the highest levels of radioactivity (Guidry et al. 1990; Mislevy, Blue, and Roessler 1989; Bromwell and Carrier, Inc. 1989). Despite the increase in radioactive elements, the radiation levels of reclaimed soils are still much lower than the levels found in many other parts of the United States (Guidry et al. 1990; FIPR 2012). Extensive water quality sampling has been conducted on reclaimed lands and no evidence indicates that radioactive elements are a threat to water quality.

Because development is a major post-reclamation land use, elevated levels of radon could be a concern. The United States Environmental Protection Agency (EPA) has set a standard of 4 picocuries of radon per liter of indoor air (pCi/L). Radon in buildings is a concern on all phosphate-bearing areas whether mined or not, and radon concentrations in excess of the 4 pCi/L standard have been detected in homes throughout Florida. In areas where radon is a concern, homes can be constructed to prevent the entry of most radon from the soil into the structure (Guidry et al. 1990). Many homes have been built on reclaimed lands, and testing has revealed that the 4 pCi/L standard is not exceeded most of the time. Whether the 4 pCi/L standard was exceeded in homes constructed on reclaimed phosphate mine lands depended mainly on the method of home construction (FIPR 2012).

Many contaminants, including radioactive elements such as ^{226}Radium, can be taken up by crops and enter the food chain. Because agricultural production is a significant land use on reclaimed phosphate mine lands, the FIPR sponsored and conducted extensive research to address the concerns of radioactivity in foods produced on reclaimed phosphate lands. Radionuclide content studies have been performed for milk, meat, vegetable, and agronomic crops (Million et al. 1994; Guidry et al. 1990). These studies agree that levels of ^{226}Radium are elevated in foods grown on reclaimed phosphatic CSAs, but the concentrations are small and do not pose any threat to human health (Hanlon 1994; Guidry et al. 1990; Mislevy, Blue, and Roessler 1989). Even using a worst-case scenario in which a theoretical individual consumed all of his food from clay and debris lands (which exhibit the highest radionuclide soil concentrations), the individual would receive a dose of radiation that would be considered negligible (National Council on Radiation and Protection Measurements 1987; Hanlon 1994; Guidry et al. 1990). In addition, the radionuclides do not appear to bioaccumulate in animals consuming plants grown on reclaimed lands, and consumption of products, such as milk and meat, from beef animals fed forage grown on reclaimed phosphate land has not been demonstrated to present a food safety problem (Hanlon 1994; Guidry et al. 1990; Staples et al. 1994; Stricker et al. 1994).

Crop type has a large influence on radionuclide uptake (Hanlon 1994; Guidry et al. 1990; Bromwell and Carrier, Inc. 1989). Multiple studies (e.g., Bromwell and Carrier, Inc. 1989; Guidry et al. 1990) indicate that leafy portions of plants accumulate radionuclides more so than grains, fruits, and roots/tubers. The properties of the phosphatic clays may suppress the uptake of radionuclides into crops, as foods grown on phosphatic clays have been shown to accumulate lower levels of radionuclides than foods grown on debris land, even though radionuclides are higher on phosphatic clay soils (Guidry et al. 1990).

Summary

The soils of reclaimed phosphate mine landscapes typically can be characterized by the type of landform from which these soils are created. There are four major landforms: 1) overburden, 2) sand tailings, 3) clay settling areas, and 4) sand/clay-mix areas. These soil types can all be distinguished from one another by their general properties and suitabilities for specific post-reclamation land uses. The purpose of reclamation is to return the mined landscape back to a beneficial use following mining. Several post-reclamation land use types, such as agriculture, forestry, residential/commercial development, and ecological restoration, have been successfully established on reclaimed mine soils. The post-reclamation soil type heavily influences how suitable the land is for a particular post-reclamation land use. The soil types should be evaluated before converting the reclaimed lands to a particular land use. The best source of information regarding the soils on a particular site is an onsite evaluation of soil properties. Additional information on the mining and reclamation histories of mined sites may also be available from the phosphate mining companies and also from the FDEP-BMMR.

References

Barwood, H.L. 1982. “Mineralogy and Chemistry of Phosphatic Clays.” In *Phosphatic Clay Workshop*, edited by S.W. Clark. Publ. no. 02-020-012. Bartow, FL: Florida Institute of Phosphate Research.

Bromwell and Carrier, Inc. 1989. *Production of High-Value Cash Crops on Mixtures of Sand Tailings and Waste Phosphatic Clays*. Publ. No. 03-075-080. Bartow, FL: Florida Institute of Phosphate Research.

Brown, M.T. 2005. “Landscape Restoration Following Phosphate Mining: 30 Years of Co-evolution of Science, Industry and Regulation.” *Ecol. Eng.* 24: 309-29.

Brown, M.T., M. Boyd, W. Ingwersen, S. King, and D. McLaughlin. 2010. *Wetlands on Clay Settling Areas*. Publ.

No. 03-148-238. Bartow, FL: Florida Institute of Phosphate Research.

Duiker, S.W. 2002. "Diagnosing Soil Compaction Using a Penetrometer." *Agronomy Facts* 63. University Park, PA: Penn St. College of Agric. Sci.

Durbin, D.J., S. Gonzales, H. Mushinsky, E. McCoy, R. Moore, N. Halstead, and K. Robbins. 2008. *Wildlife Habitat and Wildlife Utilization of Phosphate-Mined Lands*. Publ. No. 03-147-230. Bartow, FL: Florida Institute of Phosphate Research.

Florida Department of Environmental Protection (FDEP). 2006. *Mandatory Phosphate Mine Reclamation*. Florida Administrative Code (F.A.C.) Rule 62C-16.

FDEP. 2011. *Rate of Reclamation Report, July 1, 1975 through December 31, 2010*. Accessed September 26, 2012. http://www.dep.state.fl.us/water/mines/docs/2010ror.pdf.

Florida Industrial and Phosphate Research Institute (FIPR). 2012. *Phosphate Primer*. Environmental Quality Safety and Public Health. Accessed March 18, 2012. http://www1.fipr.state.fl.us/PhosphatePrimer/0/C5532E602A32126185256F88007C1F5E.

French, E.C., G.M. Prine, C.K. Hiebsch, R.D. Barnett, J.A. Stricker, D.B. Shibles, T.C. Riddle, and K.R. Woodard. 1994. "Multiple Cropping on Phosphatic Clay Soils in Polk County, Florida." In *The Polk County Mined Lands Agricultural Research and Demonstration Project*, edited by D. Shibles and J. Stricker. Publ. No. 03-088-107. Bartow, FL: Florida Institute of Phosphate Research.

Garlanger, J. 1982. "Engineering Properties of Phosphatic Clay." In *Phosphatic Clay Workshop*, edited by S.W. Clark. Publ. no. 02-020-012. Bartow, FL: Florida Institute of Phosphate Research.

Gonzalez, R.X., J.B. Sartain, and W.L. Miller. 1992. "Cadmium Availability and Extractability from Sewage Sludge as Affected by Waste Phosphatic Clay." *J. Env. Qual.* 21: 272-5.

Graham, M.H., and R.J. Haynes. 2004. "Organic Matter Status and the Size, Activity, and Metabolic Diversity of the Soil Microflora as Indicators of the Success of Rehabilitation of Mined Sand Dunes." *Biol. Fertil. Soils* 39: 429-37.

Guidry, J.J., C.E. Roessler, W.E. Bolch, J.T. McClave, C.C. Hewitt, and T.E. Abel. 1990. *Radioactivity of Foods Grown on Mined Phosphate Lands*. Publ. No. 05-028-088. Bartow, FL: Florida Institute of Phosphate Research.

Hanlon, E.A. 1994. "Naturally Occurring Radionuclides in Agricultural Products: An Overview." *J. Env. Qual.* 23: 630-2.

Hanlon, E.A., D.B. Shibles, and F. Mallory. 1994a. "Macrobed Construction." In *The Polk County Mined Lands Agricultural Research and Demonstration Project*, edited by D. Shibles and J. Stricker. Publ. No. 03-088-107. Bartow, FL: Florida Institute of Phosphate Research.

Hanlon, E.A., G.J. Hochmuth, and T.C. Riddle. 1994b. "Tillage Equipment Selection for Vegetable Bed Preparation." In *The Polk County Mined Lands Agricultural Research and Demonstration Project*, edited by D. Shibles and J. Stricker. Publ. No. 03-088-107. Bartow, FL: Florida Institute of Phosphate Research.

Hanlon, E.A., G.J. Hochmuth, and R.A. Jerez. 1988. "Radionuclide Studies." In *The Polk County Mined Lands Agricultural Research and Demonstration Project*, edited by D. Shibles and J. Stricker, 64-69. Publ. No. 03-088-107. Bartow, FL: Florida Institute of Phosphate Research.

Hawkins, G.J. 1973. *Physical, Chemical, and Mineralogical Properties of Phosphatic Clay Slimes from the Bone Valley Formation*. Master's Thesis, University of Florida.

Hortenstine, C.C., and D.F. Rothwell. 1972. "Use of Municipal Compost in Reclamation of Phosphate-Mining Sand Tailings." *J. Env. Qual.* 1(4): 415-18.

Ingram, L.J., G.E. Schuman, P.D. Stahl, and L.K. Spackman. 2005. "Microbial Respiration and Organic Carbon Indicate Nutrient Cycling Recovery in Reclaimed Soils." *Soil Sci. Soc. of Am. J.* 69: 1737-45.

Insam, H., and K.H. Domsch. 1988. "Relationship between Soil Organic Carbon and Microbial Biomass on Chronosequences of Reclamation Sites." *Microbial Ecology* 15(2): 177-88.

Jones, D., J. Eitzen, and T.C. Riddle. 1994. "Effect of Main Crop N Fertilizer on Ratoon Yield." In *The Polk County Mined Lands Agricultural Research and Demonstration Project*, edited by D. Shibles and J. Stricker. Publ. No. 03-088-107. Bartow, FL: Florida Institute of Phosphate Research.

Krezdorn, A.H., T.P. Oxford, and J.R. Moon. 1987. *An Investigation of the Current Status of Citrus Plantings on Reclaimed Phosphate Land in Central Florida*. Publ. No. 03-071-054. Bartow, FL: Florida Institute of Phosphate Research.

Million, J.B., J.B. Sartain, R.X. Gonzalez, and W.D. Carrier. 1994. "Radium-226 and Calcium Uptake by Crops Grown on Mixtures of Sand and Clay Tailings from Phosphate Mining." *J. Env. Qual.* 23: 671-6.

Mislevy, P., and W.G. Blue. 1981a. "Reclamation of Quartz Sand Tailings from Phosphate Mining: I. Tropical Forage Grasses." *J. Env. Qual.* 10(4): 449-53.

Mislevy, P., W.G. Blue, and J.B. Brolmann. 1981. "Reclamation of Quartz Sand Tailings from Phosphate Mining: II. Forage Legumes." *J. Env. Qual.* 10(4): 453-6.

Mislevy, P., and W.G. Blue. 1981b. "Reclamation of Quartz Sand Tailings from Phosphate Mining: III. Summer Annual Grasses." *J. Env. Qual.* 10(4): 457-60.

Mislevy, P., W.G. Blue, and C.E. Roessler. 1989. "Productivity of Clay Tailings from Phosphate Mining: I. Biomass Crops." *J. Env. Qual.* 18: 95-100.

Mislevy, P., W.G. Blue, and C.E. Roessler. 1990. "Productivity of Clay Tailings from Phosphate Mining: II. Forage Crops." *J. Env. Qual.* 19: 694-700.

Mislevy, P., W.G. Blue, C.E. Roessler, and F.G. Martin. 1991. "Productivity of Clay Tailings from Phosphate Mining: III. Grain Crops." *J. Env. Qual.* 20: 788-94.

Mulkey, W.D., R.L. Clouser, and T.G. Taylor. 1994. "Estimated Production Costs for Selected Vegetables Produced on Reclaimed Phosphatic Clay Soils." In *The Polk County Mined Lands Agricultural Research and Demonstration Project*, edited by D. Shibles and J. Stricker. Publ. No. 03-088-107. Bartow, FL: Florida Institute of Phosphate Research.

Nair, V.D., D.A. Graetz, K.R. Reddy, and O.G. Olila. 2001. "Soil Development in Phosphate-Mined Created Wetlands of Florida, USA." *Wetlands* 21(2): 232-9.

National Council on Radiation and Protection Measurements (NCRP). 1987. *Recommendations on Limits for Exposure to Ionizing Radiation*. Rep 91. Bethesda, MD: NCRP.

Odum, H.T., B.T. Rushton, M. Paulic, S. Everett, T. McClanahan, M. Munroe, and R.W. Wolfe. 1991. *Evaluation of Alternatives for Restoration of Soil and Vegetation on Phosphate Clay Settling Ponds*. Publ. No. 03-076-094. Bartow, FL: Florida Institute of Phosphate Research.

Paulic, M., and B.T. Rushton. 1991. "Long-Term Success of Planted Wetland Trees in Clay Settling Ponds." In *Evaluation of Alternatives for Restoration of Soil and Vegetation on Phosphate Clay Settling Ponds*. Publ. No. 03-076-094. Bartow, FL: Florida Institute of Phosphate Research.

Rahmani, M.R., and R. Degner. 1994. "Market Opportunities for Feed Grains and Alfalfa Hay Produced on Reclaimed Phosphatic Clay in Florida." In *The Polk County Mined Lands Agricultural Research and Demonstration Project*, edited by D. Shibles and J. Stricker. Publ. No. 03-088-107. Bartow, FL: Florida Institute of Phosphate Research.

Rushton, B.T. 1991. "Matching Tree Species to Site Conditions in Reclamation." In *Evaluation of Alternatives for Restoration of Soil and Vegetation on Phosphate Clay Settling Ponds*. Publ. No. 03-076-094. Bartow, FL: Florida Institute of Phosphate Research.

Schreuder, P.J., J.K. Earls, and J.M. Dunmeyer. 2006. *Impact of Phosphate Mining on Streamflow*. Publ. No. 03-145-220. Bartow, FL: Florida Institute of Phosphate Research.

Singh, S.P., L.Q. Ma, and W.G. Harris. 2001. "Heavy Metal Interactions with Phosphatic Clay: Sorption and Desorption Behavior." *J. Env. Qual.* 30: 1961-8.

Singh, S.P., L.Q. Ma, and M.J. Hendry. 2006. "Characterization of Aqueous Lead Removal by Phosphatic Clay: Equilibrium and Kinetic Studies." *Journal of Hazardous Materials* B136: 654-62.

Staples, C.R., R. Umana, J.A. Stricker, D.B. Shibles, M.J. Hayen, C.D. Hissem, D.S. Lough, and D.L. Demorest. 1994. "Radionuclides in Milk of Dairy Heifers Raised on Forages Harvested from Phosphate Mined Reclaimed Soils on Reclaimed Mined Land." *J. Env. Qual.* 23: 663-7.

Stricker, J.A., E.A. Hanlon, R.L. West, D.B. Shibles, S.L. Sumner, and R. Umana. 1994. "Naturally Occurring Radionuclides in Tissue from Beef Fed Phosphatic Clay-Grown Forages." *J. Env. Qual.* 23: 667-70.

Surface Mining Control and Reclamation Act of 1977 § 501, 30 U.S.C. § 1251 (2006).

Sylvia, D.M. 1990. "Inoculation of Native Woody Plants with Vesicular-Arbuscular Mycorrhizal Fungi for Phosphate Mine Land Reclamation." *Agriculture, Ecosystems, and Environment* 31: 253-61.

Sylvia, D.M., and P.G. Hartel. 2005. *Principles and Applications of Soil Microbiology*. Upper Saddle River, NJ: Pearson Education, Inc.

Tamang, B. 2005. *Vegetation and Soil Quality Changes Associated With Reclaiming Phosphate-Mine Clay Settling Areas With Fast-Growing Trees*. Master's Thesis, University of Florida.

United States Department of Agriculture – Natural Resources Conservation Service (USDA-NRCS). 2003. "Soil Compaction: Detection, Prevention, and Alleviation." *Soil Quality – Agronomy Tech*. Note 17. Auburn, AL: Soil Quality Institute.

United States Department of Agriculture - Soil Conservation Service. 1990. Soil Survey of Polk County, Florida. Accessed September 26, 2012. http://soildatamart.nrcs.usda.gov/manuscripts/FL105/0/Polk.pdf.

United States Geological Survey (USGS). 2011. "Phosphate Rock." *2010 Minerals Yearbook*. Accessed March 20, 2012. http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/myb1-2010-phosp.pdf.

Wallace, P.M., and G.R. Best. 1988. "Succession of Endomycorrhizal Fungi on Phosphate Strip Mined Lands." In *Enhancing Ecological Succession Following Phosphate Mining*. Publ. No. 03-008-064. Bartow, FL: Florida Institute of Phosphate Research.