ABSTRACT

Andrews, Ross Lester. Comparison of bucket-wheel spoil and phosphogypsum/clay blend as substrates for Nonriverine Wet Hardwood Forest restoration. (Under the direction of Dr. Stephen W. Broome).

Phosphate mining in Beaufort county, NC impacts a rare plant community type, Nonriverine Wet Hardwood Forest (NRWHF). Reclamation of land after mining utilizes three byproducts of mining and manufacturing: clay tailings containing dolomite, low pH phosphogypsum and bucket-wheel spoil from the surface 10 meters. The mine is backfilled with a blend of phosphogypsum and clay tailings, which may be left as the surface or capped with bucket-wheel spoil. The objective of this study was to determine the feasibility of using these byproducts as substrates for restoring NRWHF. A field study measured survival of 11 tree and 4 shrub species planted in replicated plots of blend or bucket-wheel spoil. After the first growing season, survival across all species was 92% on the blend and 81% on the bucket-wheel spoil. Survival at the end of the second growing season was 59% on the blend and 52% on the bucket-wheel spoil. A greenhouse experiment compared growth of four species of NRWHF oaks on bucket-wheel spoil, blend, local topsoil (sterilized and unsterilized), and a commercial potting mix. Half of the pots in each treatment were fertilized using a complete nutrient solution with 100 mg L⁻¹ N. Tree height and stem volume were significantly greater on topsoil than on bucket-wheel spoil and blend, but did not differ between bucket-wheel spoil and blend. Leaf chemical analysis found cadmium in both field and greenhouse plants. These results indicate that the use of topsoil from the advancing mine front will lead to successful restoration of NRWHF, thereby meeting the mine’s original goal of restoring bottomland hardwoods, improving wildlife habitat, and contributing to the conservation of a rare plant community.
COMPARISON OF BUCKET-WHEEL SPOIL AND PHOSPHOGYPSUM/CLAY BLEND AS SUBSTRATES FOR NONRIVERINE WET HARDWOOD FOREST RESTORATION

by
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SOIL SCIENCE

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DEDICATION

This thesis is dedicated to my wife, Sara Froyen Andrews, for her unceasing support.

Her consistent sense of humor and love creates an environment

in which I can pursue my dreams.
BIOGRAPHY

Ross Lester Andrews was born and raised in Charlottesville, Virginia near the Blue Ridge Mountains. Active in the Boy Scouts, Ross gained an appreciation and interest for ecology and natural systems. He received a BS in Biology from UNC Chapel Hill in 1997. While an undergraduate he did two “Research Experience for Undergraduates” summers projects, one in the Shenandoah National Park and one at Mountain Lake Biological Research Station near Blacksburg, Virginia. Ross was married to Sara Elizabeth Froyen in 1998 and then spent two years with her in Eugene, Oregon. While in Oregon he worked as a science teacher in the Northwest Youth Corps Outdoor School. In the fall of 2000 Ross and Sara moved to Raleigh where he began pursuing a Masters degree at NC State University.
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Introduction

The Aurora division of PCS Phosphate, located on the Pamlico River in eastern North Carolina, has mined over four thousand acres of forested and agricultural lands. Once the open pit mines are depleted of phosphate ore, the mined area is filled with a slurry of phosphogypsum and clay, two by-products of the mining and manufacturing process. After this blend material dewatered, it is colonized by Common Reed, *Phragmites australis*, and later Black Willow, *Salix nigra* and Wax Myrtle, *Myrica cerifera*. Clewell (1981), gives a description of plant succession on reclaimed phosphate mines in Florida where cattails dominate the initial stages:

“Cattails invade and quickly create a dense, vigorous monoculture which persists for about five years. Wildlife utilization plummets. Thereafter, the surface becomes sufficiently firm to allow the invasion of willows (*Salix caroliniana*). By about the tenth year after dewatering began, wax-myrtles (*Myrica cerifera*) and saltbush (*Baccharis halimifolia*) become established. Wildlife utilization remains low.”

Purpose

Soil Surveys of Beaufort County indicate that the soils on PCS land prior to mining included the Portsmouth, Roanoke and Tomotley series, all soils that support Nonriverine Wet Hardwood Forests, one of 104 natural communities identified in North Carolina (Schafale and Weakley 1990, Shafale 1999) (Appendix A and B). In the late nineteenth century this forest type was listed by Ashe and Pinchot (1897) as occupying a quarter of the swamplands in the Coastal Plain of NC. Today Nonriverine Wet Hardwood Forests (NRWHF) are listed by the NC Natural Heritage Program with a state priority S1 and a global priority G1, defined as being “Critically imperiled in North Carolina and globally because of extreme rarity or otherwise very vulnerable to extinction throughout its range” (Schafale, 1999). A survey of vegetation in Beaufort county by Blair (1967) found three of
the oak species that dominate NRWHF, *Quercus michauxii*, *Q. nigra* and *Q. falcata* var. *pagodaefolia* (*Q. pagoda*). He also found *Q. virginia* in Beaufort County; this species can be confused with *Q. laurifolia*, a fourth oak that is characteristic of NRWHF.

Although natural soils in Beaufort County are acidic, NRWHF are also known to grow on circumneutral soils with pH levels similar to those of the phosphogypsum-clay blend. Seasonal inundation and water levels up to one foot above the surface are also characteristic of NRWHF. PCS Phosphate has over 1,000 acres of wet area needing reclamation (Rob Jenner, Mine Services PCS Phosphate, personal communication, 2001). Given the site history of mined lands and the status of Nonriverine Wet Hardwood Forests, this plant community is a worthy target community for restoration. “Central to the issue of revegetation of phosphate mines is development of an understanding of the natural ecosystem prior to mining” (Bijan et. al.1989).

The original goal of mined land reclamation at PCS was to establish bottomland hardwood forests directly on the phosphogypsum/clay blend. Due to policy changes in 2001, PCS Phosphate is now planning to cover all areas to be reclaimed with bucket-wheel spoil. Bucket-wheel spoil is defined as soil material in the top 7-10 meters that is removed from the advancing mine by a bucket wheel excavator. Although numerous tree species have been tested at PCS since 1990 (Broome et al.), no substrates other than clay alone and the phosphogypsum/clay blend have been tested. Research on restoration of phosphorous mine sites in Florida has shown that amendments of topsoil significantly improve planting success (Clewell 1999). Since phosphate rock mined at PCS naturally contains cadmium and other trace metals (Wescott 1994), concentrations of Cd in the plant tissue of Nonriverine Wet Hardwood Forest trees is also of interest. The objectives of the research are to:
1) Compare survival of Nonriverine Wet Hardwood Forest community species on phosphogypsum/clay blend and on bucket wheel spoil in the field.

2) Compare seedling growth of 4 oak species of the Nonriverine Wet Hardwood Forest community on phosphogypsum/clay blend, bucket wheel spoil, local topsoil (sterilized and un-sterilized), and metro mix in the greenhouse.

3) Measure leaf tissue cadmium levels of NRWHF species planted on the bucket wheel spoil and phosphogypsum/clay blend in field and greenhouse experiments.

**Literature Review**

**Restoration of Nonriverine Wet Hardwoods Oaks**

Nonriverine Wet Hardwood Forests are a subset of the forest type bottomland hardwoods, the major forest type that occurs on floodplains in the lower Midwest and the Southeastern United States. Under the U.S. Fish and Wildlife Service wetland classification system (Cowardin 1979), bottomland hardwoods are classified as forested wetlands. NRWHF have the same species abundance as the swamp chestnut oak-cherrybark oak bottomland hardwood forest cover type defined by the Society of American Foresters. The hydrology of NRWHF is what makes them unique; they exist on poorly drained, wide inter-stream divides that retain moisture from precipitation instead of association with streams or rivers. NRWHF plant communities are often referred to as oak flats or precipitation flats. NRWHF are found on poorly drained clay soils with medium texture such as the Portsmouth and Tomotly series, both Typic Ochraquults (Appendix A). Pocosin vegetation growing on organic soils is often found adjacent to the mineral soils that support NRWHF (Schafale, personal communication 2001).

A great deal of research has been done on restoration of bottomland hardwood species on mine spoils and natural soils. Best (1983), tested application of amendments on
survival of 25 direct seeded tree species in phosphate mine overburden in Florida (70% of
tree species tested occur naturally in North Carolina). Straw mulch (organic matter), topsoil
and vesicular-arbuscular (VA) mycorrhizal inoculum treatments had a positive effect on the
relative growth, density, and diversity values of tree seedlings (defined as community
development index). “Perhaps the most important function of mulching is through its effect
of decreasing both surface soil moisture loss and soil crusting” (Best 1983). Application of
1,500 lbs per acre phosphogypsum had a negative effect on the community development
index. Clewell tested direct seeding of trees including bald cypress (Taxodium distichum)
and swamp tupelo (Nyssa biflora) on reclaimed mine lands at Brewster Phosphates in Polk
and Hillsborough counties in Florida. After one year, survival was 1-2% with heights of bald
cypress averaging 12-24 inches and swamp tupelo 6-9 inches.

A study on Quercus douglassii (blue oak) regeneration in California showed that the
presence of invasive annuals correlated with decreased shoot-emergence and survival due to
depletion of soil water (Gordon et al. 2000). The same results occurred with direct
manipulation of the water table. In a similar way, competition from Phragmites australis,
(common reed), on PCS lands likely decreases plant growth and survival. Tree growth
studies on reclaimed phosphate mine land in Florida compared tree growth rates on areas
with cattail and primrose willow (growth patterns similar to common reed) and areas where
primrose and cattail had recently been removed by cutting or herbicide application. After six
growing seasons bald cypress was 25% taller on sites without primrose willow.

Direct seeding for oak species on mined lands at PCS may be an economical
alternative to planting container stock. Direct seeding decreases cost and allows a longer
period of time for planting. Direct seeding with oaks after October typically results in
germination rates of 35% (Pope 1993). However, Tinus (1979), showed that on extremely stressed sites high maintenance and replacement costs should be considered. The price of producing trees that have outgrown the herbaceous competition after 10 years, including the maintenance expenses, not just the initial planting cost, must be considered. If container stock is used, the root to shoot ratio must be considered; root area must be able to support shoot development (Tinus 1979).

In direct seeding, acorns must be completely covered with soil for successful germination to occur (Pope 1993). Root development is more successful with direct seeding without the problem of twisted, pruned or pot bound roots often found in container stock. This leaves direct seeded trees much less susceptible to drought stress (Allen et al. 2001). Sown at a depth of 2 to 4 inches, seeding rates of 1,200 to 1,500 acorns per acre are recommended for mine spoil sites with heavy vegetative cover (Allen et al. 2001). Using a hand planter on 2.5 by 12 foot spacing, an individual can sow 7 to 8 acres a day. Specialty Truax brand large seed planters or modified agricultural planters can also be used. On freshly disked sites, broadcast seeding is effective and gives a more forest-like appearance. For large sites, aerial seeding can be successful with disking before and after seed application (Allen et al. 2001).

A viable method of restoring vegetation on mine spoil is applying topsoil from natural forest areas that contain a native seed bank to reclaimed lands. Plant propagules and viable seeds can survive in the top four inches of forest soils for several years. Topsoil should be transferred directly to the reclaimed area since stockpiling of soil will greatly reduce propagule survival. If any grass seed is planted for temporary stabilization on future
restoration sites, only annual grasses should be used to minimize competition with tree seedlings (Bijan et. al.1989).

Tomlinson, (1996) found that a 2.5 cm layer of mulch delayed emergence of northern red oak and led to greater seedling survival and root collar diameter. Although this experiment was done using ground corncobs and sawdust, other mulch materials could be effectively used at PCS. Testing areas with and without a humus layer, Nilsson et al. (1996), showed highest germination percentages for English Oak with a humus layer. An in house experiment by The Florida Institute of Phosphate Research on high sand mine soils similar to the bucket-wheel spoil showed that “hay cover significantly increases tree survival and growth if applied in a deep layer.”

**Shrub and Herbaceous layer**

In bottomland hardwood forests, such as Nonriverine Wet Hardwood Forests, trees make up the smallest component of vegetation in terms of number of plant species. In two bottomland hardwood forests, one in Kentucky and one in Florida, trees were only 27 and 10 percent, respectively, of plant species present (Allen et. al, 2001). Since undergrowth vegetation is such a large component of bottomland forests, 73 and 90 percent in the KY and FL examples, it is critical that these species be considered in restoration.

As well as being critical for cover, forage and nesting for wildlife, undergrowth vegetation adds complexity to biogeochemical cycling of nutrients. A greater diversity of root systems allows greater efficiency of cycling and conserving nutrients (Allen et al. 2001). Understory vegetation also promotes the survival of predacious arthropods and insects that lower mosquito populations and increase pollination of tree species. In long-term restoration,
shrub layer species should be planted after canopy species (trees) are established enough to provide shading (Allen et al. 2001).

**Tree Layer: Why Oaks?**

“Oaks are an important component of bottomland hardwood forests, valued for their timber quality, their hard mast production for wildlife and generally for their aesthetically pleasing growth habit” (Allen et al. 2001). Wildlife usage for oaks in bottomland forests is extremely high. “Bottomland hardwood sites support two to five times as many game animals as do upland pine sites” (Kennedy 1993). Of the oaks specific to Non-riverine Wet Hardwood Forests, *Quercus pagoda* (cherrybark oak) and *Quercus nigra* (water oak) foliage and/or fruit are used by the following animals: deer, turkey, squirrel, waterfowl, small mammals, quail (*Q nigra* only), and songbirds (*Q pagoda* only). Swamp Chestnut Oak, *Quercus michauxii* fruit and foliage are eaten by deer while the fruit is used by squirrels and other small mammals (Allen et al. 2001). It is more effective for restoration to focus on heavy acorn (hard-mast) producing species such as oaks because light-seeded species such as ash, maple and sweet gum are more likely to become established on their own by wind and water dispersal (Kennedy 1993).

**Tree growth studies related to blend as substrate**

A possible reason for slow tree growth on the blend compared to natural conditions are restrictive osmotic potentials limiting water and nutrient uptake due to high soluble salts, specifically Ca SO₄, found in the blend (Wescott 1994). In a study of stomatal conductance by MacLeod 1996, watering of trees with 10 ppt salinity (using instant ocean sea salt solution) significantly reduced photosynthesis. In a related study of watering with a 6 ppt sea salt solution, Conner et al. (1998), tested four oak species including NRWHF species water
oak and swamp chestnut oak, giving survival percentages of 45 and 5, respectively. High concentrations of Na (an element that is not a plant nutrient and can be toxic) present in seawater could lead to specific ion effects in addition to restrictive osmotic pressures.

In a 1990 study, Pezeshki found a correlation between stomatal response and photosynthesis rates with salinity levels in green ash seedlings. As salinity increased, stomatal response and photosynthesis rates decreased sharply. Stomatal response increase can indicate that ions have been transported into the plant and stored in vacuoles in the leaves. Pezeshki et al. 1995 cites “Photosynthetic capacity decreases in response to elevated salinity because of stomatal closure imposing diffusional limitations and metabolic inhibition.” This study also found that plant roots surrounded by higher salt concentrations (brackish water plants) had lower porosity.

Gilbert et al (1980) described a planting of 10,400 seedlings on reclaimed phosphate lands by International Minerals and Chemical Corporation (IMC) in Florida. In a range of mine spoils from constantly saturated to well drained, one year survival was approximately 85% for green ash (*Fraxinus pennsylvanica*), 62% for bald cypress (*Taxodium distichum*), 62% for red maple (*Acer rubrum*), and 72% for sweetgum (*Liquidambar styraciflua*).

Best and Erwin (1983), showed favorable results for survival of green ash (*Fraxinus pennsylvanica*), sycamore (*Platanus occidentalis*), red maple (*Acer rubrum*) and sweet gum (*Liquidambar styraciflua*), on reclaimed phosphate mine lands. After one growing season, of the 5,000+ of each species planted, survival rates were 98% for green ash, 90% for sycamore, 86% for red maple, and 83% for sweet gum.
Cadmium and Nonriverine Wet Hardwood Forests

Cadmium is present naturally in phosphate ore in the Pungo River Formation at PCS as well as in the ore of phosphate mines throughout the world. Cadmium associated with the ore at PCS is found in the phosphogypsum/clay blend after it is placed on reclaimed lands. Cadmium can be taken up by plant roots and may cause decline and mortality in some plant species. Cadmium is toxic to animals and can accumulate in the food chain if high levels are present in animal food sources such as foliage or fruits.

Cadmium can be a dangerous soil pollutant because it interferes with plant uptake, transport, and use of nutrients (Ca, Mg, P and K) and water. Most research in this area has been done on single plant species or varieties, mainly agronomic crops. In their Review of Cadmium Toxicity in Plants, Das et al (1997), give insight into the effect of elevated cadmium levels in soils. Stunting and chlorosis of plants are reported as the main visual symptoms. This results from the interaction between foliar iron and cadmium. Cadmium presence has been shown to suppress iron uptake (Haghiri 1973). Root et al (1975) support the assertion that cadmium chlorosis was influenced by changes in Zn: Fe ratios. Godbold (1985) also demonstrated that cadmium toxicity induces phosphorous deficiency and increased manganese transport problems.

Elevated cadmium concentration in plant tissues also has damaging cytogenic effects. Water Hyacinth, (Eichornia crassipes), exposed to 1.5-10mg L$^{-1}$ Cd for 24 hours had physiologicial and genetic damage (Rosas 1984). Overnell (1975) found .01-.1 mg L$^{-1}$ Cd decreased oxygen production and reduce the concentration of chlorophyll and ATP in several species of freshwater alga. Das (1997) cites that plants resistant to heavy metals such as
cadmium use metal binding proteins, called metallothioneins, to trap metal ions and prevent
them from being translocated or interfering with the transport of other minerals.

Differences in enzyme response from plant stress due to cadmium was cited by
Hertsein and Yager (1986) as a reason for variation between different plants in sensitivity to
cadmium. In a test of 10 agronomic crops, Kuboi (1987) found cadmium sensitivity to be
directly linked to botanical family and independent of soil pH. Levels of cadmium at which
chlorosis appeared were 80 mg L\(^{-1}\) for Japanese radish, 10 mg L\(^{-1}\) for soybean and 100 mg
L\(^{-1}\) Cd for pumpkin (Kuboi 1987).

Osteras (2000), investigated sensitivity and accumulation of cadmium in forest trees
native to Sweden. One genus from the Betulaceae botanical family studied by Osteras is
found in the NRWHF community. \textit{Betula} (birch) species were found to be the least sensitive
(out of birch, pine and spruce) to external and tissue levels of cadmium. Weight basis Cd
concentrations in media that gave a 5% yield reduction (averaged across plants from 3
regions) are 15 and 357 micrograms Cd (g FW\(^{-1}\), for shoots and roots, respectively. This is
relevant to the study site since \textit{Carpinus caroliniana} (ironwood), an important understory
tree in the NRWHF community is in the family Betulaceae. The authors conclude that lower
root sensitivity in \textit{Betula} may provide explanation for why birch is able to tolerate soils
contaminated with metals. Research showing evolved tolerance to metaliferous soils was
also reported by Denny and Wilkins (1987) for \textit{Betula} spp.

Another issue in determining the resistance of trees to metals is the role of
mycorrhizae. Wilkinson and Dickinson 2000, suggest that mycorrhizal fungi play a role in
promoting tree adaptation to contaminated soils by protecting the root tips of seedlings. This
‘sheathing’ effect was shown on three Ericaceous species with relatives that grow in
NRWHF, including *Vaccinium corymbosum*, (highbush blueberry). Beyond the sheathing effect, the authors suggest, “genetic variation already present in mycorrhizae may provide genotypes with competitive advantage in any given soil condition.” Wilkinson and Dickinson go on to say that the shorter life cycle of a fungus may facilitate genetic change within the root-mycorrhizae complex within the lifetime of an individual plant.” Mycorrhizae also helps plants adapt to local soil conditions by facilitating the up take of some chemicals while excluding the others. With appropriate mycorrhizae inoculation and sufficient time, long-lived and non-tolerant plants, potentially NRWHF trees at PCS, could develop a root-mycorrhizae strategy for survival on soils with high cadmium.

The literature presents ways of changing cadmium concentrations in soil solution through amendments. Xiong and Lu (1991), studied the effect of liming on plant accumulation of cadmium in upland and flooded conditions. The application of lime to cadmium rich soils was found to restrict plant uptake of Cd as well as transfer of Cd from roots to shoots. Since this study was done on a Typic Hapludult red clay with starting pH of 5.2, these data pertain more to the bucket wheel spoil and not the circumneutral phosphogypsum/clay blend. It is important to note that although under both water regimes lime decreased available cadmium considerably, excessive lime usage is reported to lead to zinc and other micronutrient deficiencies.

Due to its readily available binding sites, the addition of organic matter to metal-containing soils decreases in metal activity in the soil solution (Das et al. 1998). With organic matter and clays present in the soil, low molecular weight metal chelates are formed which keep free metal activity low. Street et al. (1997) showed that cadmium uptake in corn was less in acidic soils with high organic matter than in acidic soils with low organic matter.
In *Environmental Chemistry of Soils*, McBride (1994) confirms that mobility and bioavailability of cadmium in neutral to alkaline soils is lower than in acidic soils. Additionally Mcbride cites, “In continuously waterlogged soils the low solubility of cadmium sulfide results in low mobility,” thus limiting bioavailability of Cd.

In some areas of reclaimed mine land at PCS cadmium levels might be high enough to consider the use of hyperaccumulators to remediate the soil before restoring NRWHF communities. Hyperaccumulators are plants that take up and store in their tissues a higher than normal amount of a specific element or compound. Dahmani-Muller et al. (2000), discuss the herbacious species *Arabidopsis halleri* found naturally in metallophyte grasslands in northern France. This plant and others in similar soils found overlying ultramaphic rocks, or serpentine, exhibit high ability to extract and translocate metals to above ground parts. Where excessive levels of cadmium are found at PCS, one option is to consider planting hyperaccumulating species and harvesting them in order to remove cadmium before restoration of appropriate plant communities begins. A second alternative is to plant species that take up minimal amounts of cadmium.

Phosphogypsum/clay blend concentrations of approximately 16 mg/kg cadmium Wescott (1994) are within the range found in A horizons of naturally occurring serpentine soils. In the Austrian Alps, Wenzel (1998) found cadmium levels in Leptosols at 32mg/kg and in Regosols (18.2mg/kg). Cd concentrations in ultramaphic sites in Albania were found to range between 2 and 14 mg/kg (Shallari 1997). At three different serpentine sites in the Klamath Mountains in Oregon Burt (2001) found Cd levels of 26, 22 and 13 mg/kg.
Finally, the issue of cadmium variability in leaves at different positions on a given tree must be addressed. Luyssaert et al. (2000), tested sampling techniques on *Salix fragile* growing in dredge spoil in Belgium and reported variation of cadmium levels found in leaf tissue taken throughout an individual tree. After sampling at 292 different leaf locations on this willow species, a trend was found with high cadmium values (10.6 mg/kg) in the lower parts of the crown and low Cd concentrations (2.4 mg/kg) at the top of the crown. This reveals the error in standard leaf sampling practices of removing sun leaves from the highest point on the crown. The author concludes: “Leaf samples need to be taken at different heights of a few probabilistically selected trees” (Luyssaert et al. 2000).

**METHODS**

**Field Experiment**

Twenty species from the Nonriverine Wet Hardwood Forest community were planted on three-foot centers in a split plot design consisting of eight 10 m by 6 m rectangular plots in the wetland research area of Reclamation Area Three, R3 (See Appendix C, D). Four plots were chosen at random to be covered with a one-foot layer of bucket-wheel spoil from the upper 3 meters of the mined surface (plots 1, 4, 5 and 6). The remaining plots consisted of the preexisting blend material at the surface. Each plot contained three replicates of each plant. A list of trees, shrubs and herbaceous species found in Nonriverine Wet Hardwood Forests was compiled by Michael P. Schafale (Nonriverine Wet Hardwood Forests In North Carolina, Status and Trends, NC Natural Heritage Program, March 1999). Twenty species from the following list available as nursery stock were planted in late March, 2001: Trees:
*Liquidambar styraciflua*, Sweet Gum; *Liriodendron tulipifera*, Tulip Poplar; *Nyssa biflora*, Swamp Tupelo; *Quercus michauxii*, Swamp Chestnut Oak; *Quercus nigra*, Water Oak; *Quercus pagoda*, Cherry Bark Oak; *Quercus laurifolia*, Laurel Oak; *Pinus taeda*, Loblolly Pine; *Ulmus Americana*, American Elm; *Acer rubrum*, Red Maple; *Asimina triloba*, Common Pawpaw; *Carpinus caroliniana*, Ironwood; *Ilex opaca*, American Holly and *Persea palustris*, Red Bay. Shrubs: *Clethra alnifolia*, Sweet Pepperbush; *Lindera benzoin*, Common Spicebush; *Myrica cerifera*, Wax-myrtle; and *Vaccinium corymbosum*, Highbush Blueberry. Herbs: *Athyrium felix-femina*, Southern Lady Fern; *Osmunda regalis*, Royal Fern; *Saururus cernuus*, Lizard’s tail; *Woodwardia areolata*, Netted Chain Fern; *Woodwardia Virginica*, Virginia Chain Fern. All species were container stock except for *Quercus michauxii*, *Osmunda regalis* and *Woodwardia areolata* which were bare root plants.

Soil samples for each plot were taken prior to experimentation on the R3 wetland research area. Soil samples were mixed in a plastic bucket, air-dried and sent to the North Carolina Department of Agriculture Soil Testing Lab. The following measurements were taken at the end of each growing season on all plants: distance from crown to tallest terminal bud using an adjustable eight foot ruler and percent survival measured by observation and twig flexibility.

Leaf samples from Nonriverine Hardwood Forest tree and shrub species, selected at varying heights on each tree species, were analyzed for cadmium at the end of the one and two growing seasons. Leaf samples were dried and ground and then analyzed by the Analytical Services Laboratory at NCSU using their standard preparatory and digestive methods to perform mineral analysis for cadmium using inductively coupled plasma argon
emission (ICP). Atomic absorption spectrometry was used to determine cadmium concentrations below the ICP detection limit of 0.8 mg/kg.

Greenhouse Experiment

Two pounds of acorns of each of the following species were purchased from Louisiana Forest Seed Company, Inc.: *Quercus michauxii*, Swamp Chestnut Oak; *Quercus nigra*, Water Oak; *Quercus pagoda*, Cherrybark Oak; and *Quercus laurifolia*, Laurel Oak. This company was chosen because acorns of all four species were collected from the same region, in order to minimize seed variation due to provenance. Acorns were stored in a lab refrigerator at NCSU for forty days to satisfy the chilling requirement. A day before planting, acorns were individually inspected for density and durability. Soft and damaged acorns were discarded and 50 of each species were left to soak in distilled water overnight.

On March 17, 2002, forty-four acorns of each of the following NRWHF oak species were planted in a greenhouse experiment; *Quercus michauxii*, *Quercus nigra*, *Quercus pagoda*, and *Quercus laurifolia*. Bucket-wheel spoil, phosphogypsum/clay blend and native top soil were collected at PCS Phosphate and transported to Raleigh for use as substrates. The phosphogypsum/clay blend and native top soil were mixed in a large concrete mixer to assure uniformity. Five different treatments were assigned: metro mix (standard greenhouse potting mix), bucket wheel spoil, phosphogypsum/clay blend, native topsoil and sterilized native topsoil. Topsoil was used to approximate growth on undisturbed land and sterilized topsoil was used to control for biotic factors. All five substrate types in each replication were sampled and tested in the same manner as soil samples in the field study prior to the experiment.
Three gallon Treepots from Stuewe & Sons, Inc., measuring 20 cm wide and 32 cm deep were used to accommodate the long taproots of oak seedlings. Eleven replications of five substrates and four species each (twenty treatments) were set up in greenhouse #112 East at the Method Road facility in Raleigh, North Carolina. A random number generator determined placement within each replication for each of the twenty treatments. Plant height was measured regularly using an eight-foot adjustable ruler. After four months a fertilizer treatment was applied to half of the replications using Peters Professional water-soluble fertilizer (20-20-20) with micronutrients at a concentration of 100 mg/L \(^{-1}\) N. Each pot in the treatment group received 475 ml of fertilizer solution while the control group received 475 ml of water each week for eight weeks. Trees were watered daily except for the days of fertilizer application. At the end of the fertilizer treatment, root collar diameter was measured for all seedlings. The height of the tallest stem was measured on multiple-stemmed seedlings. Aboveground volume was calculated using the formula \(d^2 \times h = \text{volume}\).

**Statistical Methods**

Statistical analysis was done using the JMP computer program (SAS Institute 1988). Field survival data after one and two growing seasons were analyzed using a contingency table generated by JMP. Greenhouse seedling height means after 120 days were analyzed using the Tukey-Cramer test of means. Graphical representation of significance by green “means diamonds” shows population size by diamond width and 95% confidence interval by diamond height (Johnson 2000). If diamonds overlap in the vertical dimension, there is no significant difference between the mean values. Stem volume in the greenhouse experiment was also analyzed in this manner. Interactions between substrate and tree species height or
stem volume were tested according to p value and F ratio. Interactions between substrate and fertilizer treatment and five months growth without fertilizer were analyzed in the same fashion.

Results

Field Experiment

In July of 2001, three months after planting field plots, the dike keeping water out of the R3 wetland research pond failed. Since the eight plots in the field experiment were spaced in two rows adjacent to the pond, only the lowest four plots were affected. PCS mine engineering staff was unable to fix the dike before significant damage was done to the four lower plots. The lower plots were inundated for more than 5 weeks during the growing season and all but a few individual plants were lost. Cattails, algae on phragmites stems and standing water were evident along the edge of the low plots five months after the dike broke. Due to this unforeseen circumstance data was taken from only the 4 remaining plots.

Fortunately an equal number of each treatment survived, two blend plots and two bucket-wheel spoil plots for a total of 240 plants, 3 replicates per plot and 60 plants per plot. The five herbaceous species planted were excluded from the data set due to their immediate and high mortality without the shade of an established canopy.

Soil test results taken in the field revealed high nutrient concentrations in the blend and significantly lower concentrations of the same nutrients in the bucket-wheel spoil (Table 1). Extremely high phosphorous levels were found in the blend; this is understandable due to the association of phosphogypsum and clay tailings with phosphate ore. The K, Ca, Mg and S levels were also greater than those found in the bucket-wheel spoil. Sulfur levels of 10,221
mg/dm³ in the blend are exceptionally high. Micronutrient levels are less disparate ranging from two to five times higher in the blend. It is important to note that pH levels found in the bucket-wheel spoil are higher than expected because the sample was taken from the top 3 m only, rather than the top 10 m. Physical attributes of the two substrates include the following: the blend, a high moisture holding capacity, low bulk density and silt-loam texture; the bucket-wheel spoil, a low moisture holding capacity, high bulk density and loamy sand texture (over 80% sand).

Table 1 Field substrate chemical properties

<table>
<thead>
<tr>
<th>Substrate</th>
<th>PH</th>
<th>P</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
<th>Mn</th>
<th>Zn</th>
<th>Cu</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blend</td>
<td>6.2</td>
<td>1,474</td>
<td>1.48</td>
<td>66.9</td>
<td>8.68</td>
<td>5.3</td>
<td>6.6</td>
<td>25.4</td>
<td>1.01</td>
<td>10221</td>
</tr>
<tr>
<td>Top 3 m BWS</td>
<td>7.5</td>
<td>97</td>
<td>.25</td>
<td>49.5</td>
<td>1.37</td>
<td>.75</td>
<td>12.3</td>
<td>4.7</td>
<td>.74</td>
<td>5478</td>
</tr>
<tr>
<td>Local topsoil</td>
<td>4.8</td>
<td>74</td>
<td>.20</td>
<td>4.4</td>
<td>.82</td>
<td>.64</td>
<td>3.9</td>
<td>2.6</td>
<td>.8</td>
<td>NA</td>
</tr>
</tbody>
</table>

After the first growing season, there was little difference of survival between plants grown on the blend (92%) and the bucket-wheel spoil (81%). In Fig. 1, plant species are divided into two groups. Shrubs and one understory tree are clustered at the lower end of the Y axis (near the origin) and the canopy trees are on the higher end of the Y axis. Two shrub species showed differences in survival rates between the blend and the bucket-wheel spoil. *Clethra alnifolia* had a survival rate of 100% on the blend and 50% on the bucket-wheel
spoil. Survival of *Vaccinium corymbosum*, was 83% on the blend and 50% on the bucket-wheel spoil. Among canopy tree species only *Nyssa biflora* was affected by substrate. Survival was 100% on the blend and 67% on the bucket-wheel spoil. There was little or no difference between survival on the bucket-wheel spoil and the blend for the other tree species.

Figure 1. Percent survival at the end of the first growing season
Low survival rates of *Vaccinium corymbosum* and *Liriodendron tulipifera* were likely due to flood waters near the downhill side of the plots. Both species are found in the dry end of the 0 to 1 foot water level range of the Non-riverine Wet Hardwood Forest community. They are also commonly known to exist in other mesic sites throughout North Carolina. It is important to note that after the first growing season all four oak species had greater than 80% survival on both substrates.

![Figure 2. Percent survival at the end of the second growing season](chart.png)
Survival after the second growing season was significantly less (59% on the blend and 52% on the bucket-wheel spoil). It is likely that severe drought (summer of 2002) and increasing resource competition due to the invasive grass common reed (*Phragmites australis*) contributed to low survival. Lower survival on the bucket-wheel spoil was possibly due to its low water holding capacity. Since 14 of the 15 species planted were grown in containers, it is likely that more than one growing season was necessary for plant root systems to grow beyond the root ball and come in contact with the bucket-wheel spoil or blend material. Thus, it is possible that the substrate treatment effect was only seen after the second growing season.

Differences in survival rates on blend and bucket-wheel spoil were evident in both shrub and tree species after the second growing season. *Clethra alnifolia* had twice the survival on blend as it did on bucket-wheel, (the same ratio as the first growing season except the survival percentages on each substrate decreased). *Vaccinium corymbosum*, had low survival, 17% on both substrates perhaps due to the lingering effects of flooded conditions on the edge of the remaining plots. Among tree species, *Nyssa biflora* had a survival rate of 100% on the blend and 67% on the bucket-wheel spoil. Notably, *Liquidambar styraciflua* showed twice the survival on blend (67%) as on bucket-wheel spoil (33%) in the second growing season (compared to equal survival rates after the first growing season). Survival of *Quercus pagoda* (50%) and *Liriodendron tulipifera* (16.67)% was the same on bucket-wheel spoil and blend. All four oak species had survival greater than 50% on both substrates after the second growing season.
Table 2. Leaf cadmium in plants grown on field substrates (values in mg kg\(^{-1}\) Cd)

<table>
<thead>
<tr>
<th>Species</th>
<th>Blend Year 1</th>
<th>Blend Year 2</th>
<th>Top 3 m BWS Year 1</th>
<th>Top 3 m BWS Year 2</th>
<th>Natural Area*</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Acer rubrum</em></td>
<td>2.86</td>
<td>---</td>
<td>1.75</td>
<td>3.30</td>
<td>&lt;.8</td>
</tr>
<tr>
<td><em>Liquidambar styraciflua</em></td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>.64</td>
<td>&lt;.8</td>
</tr>
<tr>
<td><em>Myrica cerifera</em></td>
<td>1.34</td>
<td>1.26</td>
<td>.50</td>
<td>1.73</td>
<td>---</td>
</tr>
<tr>
<td><em>Persea palustris</em></td>
<td>5.67</td>
<td>11.21</td>
<td>3.01</td>
<td>6.58</td>
<td>---</td>
</tr>
<tr>
<td><em>Pinus teada</em></td>
<td>---</td>
<td>1.91</td>
<td>---</td>
<td>2.68</td>
<td>1.0</td>
</tr>
<tr>
<td><em>Quercus laurifolia</em></td>
<td>---</td>
<td>.44</td>
<td>---</td>
<td>.14</td>
<td>---</td>
</tr>
<tr>
<td><em>Quercus michauxii</em></td>
<td>.14</td>
<td>6.57</td>
<td>.28</td>
<td>.42</td>
<td>&lt;.8</td>
</tr>
<tr>
<td><em>Quercus nigra</em></td>
<td>---</td>
<td>9.43</td>
<td>---</td>
<td>4.99</td>
<td>3.1</td>
</tr>
<tr>
<td><em>Quercus pagoda</em></td>
<td>---</td>
<td>2.82</td>
<td>---</td>
<td>4.91</td>
<td>---</td>
</tr>
</tbody>
</table>

*Broome, 1990 Report to PCS Phosphate, Aurora Division.

**Cadmium**

Leaf cadmium levels for trees grown on both substrates were taken after one and two growing seasons (Table 2). Blank spaces indicate trees that had an insufficient amount of leaves for analysis at time of sampling. The increase in cadmium levels of plants grown on the blend from year one to year two is possibly due to growth of roots beyond the container-formed root ball. It is possible that root extension beyond the root ball in the second year also penetrated beyond the one foot covering of bucket-wheel spoil. This would explain the *Persea palustris* (6.58 mg kg\(^{-1}\)) and the *Quercus nigra* and *Q. Pagoda* (4.99, 4.91 mg kg\(^{-1}\), respectively) values in bucket-wheel spoil after the second growing season. Since the bucket-wheel spoil is surface material that is not associated with phosphate rock, cadmium
presence in the first-year leaf samples is surprising. However, the highest first year cadmium level of 3.01 mg kg\(^{-1}\) for *Persea palustris* is no higher than the highest level of naturally occurring leaf cadmium recorded on adjacent undisturbed lands, 3.1 mg kg\(^{-1}\) found in *Quercus nigra*, Broome (1990).

**Greenhouse Experiment**

The contrast between the chemical analysis for the blend and the bucket-wheel spoil in the greenhouse is similar to the soil test results of field substrates (table 3). However, for the greenhouse experiment, the top 10 m of the bucket-wheel spoil provided by PCS had a pH of 4.2, which was significantly lower than the 7.5 value found for the top 3 m of bucket-wheel spoil provided for the field experiment. Phosphorous, calcium and manganese values in the upper 10 m were more than an order of magnitude less than those found in the surface 3 m of the bucket-wheel spoil. All other macro and micronutrient levels were significantly less in the upper 10 m layer than those found in the upper 3 m of the bucket-wheel spoil. Physical characteristics were the same as reported in the field.

Table 3. Greenhouse substrate chemical properties

<table>
<thead>
<tr>
<th>Substrate</th>
<th>pH</th>
<th>P mg/dm(^3)</th>
<th>K Meq/100cm(^3)</th>
<th>Ca Meq/100cm(^3)</th>
<th>Mg Meq/100cm(^3)</th>
<th>Na Meq/100cm(^3)</th>
<th>Mn mg/dm(^3)</th>
<th>Zn mg/dm(^3)</th>
<th>Cu mg/dm(^3)</th>
<th>Cd mg/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blend</td>
<td>6.7</td>
<td>872</td>
<td>1.2</td>
<td>65.7</td>
<td>4.9</td>
<td>2.6</td>
<td>5.7</td>
<td>23.9</td>
<td>.79</td>
<td>16</td>
</tr>
<tr>
<td>Top 10 m BWS</td>
<td>4.2</td>
<td>8</td>
<td>.06</td>
<td>2.8</td>
<td>.26</td>
<td>.22</td>
<td>1.4</td>
<td>1.2</td>
<td>.67</td>
<td>6</td>
</tr>
<tr>
<td>Local topsoil*</td>
<td>4.8</td>
<td>74</td>
<td>.20</td>
<td>4.4</td>
<td>.82</td>
<td>.64</td>
<td>3.9</td>
<td>2.6</td>
<td>.8</td>
<td>.15*</td>
</tr>
<tr>
<td>Metro-Mix</td>
<td>7.2</td>
<td>11</td>
<td>.30</td>
<td>7.7</td>
<td>4.24</td>
<td>1.0</td>
<td>13.1</td>
<td>.95</td>
<td>2.8</td>
<td>0</td>
</tr>
<tr>
<td><em>Sterilized and unsterilized topsoils combined for chemical analysis</em>* Alloway 1990</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Germination of all four oak species was significantly lower on blend and bucket-wheel spoil than on topsoil and metro mix (Fig. 3). Germination was also lower on bucket-wheel spoil than the blend. Salt concentration may have been the reason for low germination on the blend. It is possible that the low moisture holding capacity of the bucket-wheel spoil (due to high sand content) contributed to low germination. Billings (1938) found a high correlation ($r = .85$) between density of oak reproduction and water holding capacity in old-field succession. If large scale restoration of NRWHF trees is done by seed at PCS on the blend or bucket-wheel spoil, a one foot layer of topsoil will help increase germination rates.

![Figure 3. Germination rates of acorns by substrate](image-url)
After 120 days, height of trees grown on topsoil was significantly greater than trees grown on both bucket wheel spoil and blend. There was no significant height difference between trees grown on bucket-wheel spoil, blend or metro mix (Fig. 4).

![Figure 4. Seedling height by substrate across all species, 120 days](image)

Among oak species, growth of *Quercus laurifolia* and *Quercus pagoda* were significantly greater than *Quercus michauxii* and *Quercus nigra* on all substrates (Fig 5). No differences were found between growth of *Quercus laurifolia* and *Quercus pagoda* or between *Quercus michauxii* and *Quercus nigra*. 
Observations after 120 days growth showed light green to slightly yellowish leaves on several seedlings planted in the metro mix and in the bucket-wheel spoil. Several seedlings in blend material germinated but died after the first flush of growth. These individuals often sprouted a second time. This new shoot was a flush or two (flush is distance between nodes) behind and significantly shorter in height than neighboring seedlings. A white mildew identified as “powdery mildew” was found on several Quercus pagoda seedlings in replications seven and eight. This could have been a result of high humidity or excessive moisture. Leaf tips of some Quercus pagoda and Quercus laurifolia seedlings were browning and curling at the edges.
After the first 120 days of growth in the greenhouse, overall seedling height had significant interactions with substrate at the .05 level. The p value was .04 and the F ratio 1.9. The F ratio value is right on the edge of significance according to the rule of 2 test. However, the use of Akaike’s Information Criterion allows a more in depth inspection of this value (Miller 2002). The Akaike’s Information Criterion (AIC) is taken with and without interactions included in the model. A lower AIC value, 4036, is found with interactions in the model (compared to 4218 without interactions). The lower AIC value indicates that the interactions are significant (Miller 2002). Tables of substrate and species interactions for all data sets are found in appendix E.

Figure 6. Substrate-species interaction for height, 120 days
Since the interaction term in the model is significant it indicates that certain species reacted differently to each of the five substrates; therefore we examined growth of each species on each substrate separately (Fig 6). On topsoil, height of *Quercus pagoda* was greater than the other species (p value .001). On the other substrates *Quercus laurifolia* was greater. This is an indication that *Q. laurifolia* is more adapted to the stress imposed by low nutrients in the bucket-wheel spoil and high salts in the blend. This is corroborated by observational evidence that *Quercus laurifolia* is found more often on sandy, nutrient poor sites in the coastal plain. *Quercus laurifolia* is also the oak that extends the closest to river mouths, perhaps indicating greater salt tolerance (Michael Schafale, personal communication).

To investigate data from the greenhouse fertilizer treatments, an ANOVA model for seedling height was compiled using species, substrate and replications, giving degrees of freedom of 3, 4 and 5, respectively. The adjusted R² value from this model was .63. The p value from the effects test was .67; this indicates lack of significance for replications in the model. The F ratio for reps is .63; this should be dismissed by the F test rule of 2. When we run the model with only substrate, the adjusted R² is .64, higher than the model with replications. When interaction between oak species and substrate is placed in the model the p value is .17 and the F ratio is 1.46. Both values indicate a lack of interaction between species and substrate even though the adjusted R² value with the species-substrate interaction is slightly higher at .666. Therefore we can conclude that no substrate and species interactions were significant in the fertilizer treatment.
Fig. 7 shows the change of height increase after eight fertilizer treatments. A 10 cm difference of seedling growth between trees with fertilizer and without fertilizer was found on the bucket-wheel spoil and on the metro-mix. Statistical analysis of change in height means between the two treatments determined that the changes in height for bucket-wheel spoil and metro mix are non-significant trends (Fig 8). This trend in fertilizer response is consistent with our soil test results (table 3) that indicated low plant nutrients in the bucket-wheel spoil and the metro-mix. The lack of height response to fertilizer on the topsoil and
the blend can be attributed to their greater nutrient levels (table 3), or in the case of the blend, the high soluble salts could have been a growth limiting factor.

A final measurement taken on aboveground growth at the end of the greenhouse experiment was stem volume. This allowed comparison of plant growth between trees of equal height with different diameters. After five months of growth on the five substrates, stem volume was an order of magnitude greater on both topsoil treatments than on either mine substrate (Fig. 9). High stem volume on sterilized topsoil could be due to soil microorganisms killed in the sterilization being used by seedlings as a nutrient source. There was no significant difference between stem-volume on the blend and bucket-wheel spoil.
Since the interaction term in the model for stem volume is significant (p value .001, F ratio 3.76) it indicates that certain species reacted differently to each of the five substrates; therefore we examined stem volume of each species on each substrate separately (Fig 10). On topsoil *Quercus laurifolia* had greater stem volume than the other species (individual interaction p value of .001). On bucket-wheel spoil and blend no individual species were
found to have greater stem volume than the other species. On the metro mix *Quercus laurifolia* showed greater stem volume than the other three species.

Poor growth on the blend is likely due to high soluble salt content. Gypsum (calcium sulfate) is a significant component of the blend. Sulfur levels were measured at 10,221 mg (dm$^3$)$^{-1}$ and calcium levels are also high at 65.7 meq 100g$^{-1}$, fifteen times greater than topsoil levels. High soluble salt levels would likely increase restrictive osmotic pressure acting on tree roots and prevent adequate uptake of water and nutrients even if both are

![Figure 10. Substrate-species interactions for stem volume](image-url)
present in good supply. Poor seedling growth on the bucket-wheel spoil is likely attributed to its low pH of 4.2 that could lead to aluminum toxicity. Low macronutrient levels of 8 mg (dm$^3$)$^{-1}$ and .06 Meq(100cm$^3$)$^{-1}$ for phosphorous and potassium are possible reasons for poor growth on bucket-wheel spoil as well.

**Cadmium**

Cadmium levels from leaves gathered from a range of positions on seedlings from each replication were tested at the end the greenhouse experiment (Table 4). Cadmium levels found in leaves of *Quercus nigra* (14.3 mg kg$^{-1}$) and *Quercus pagoda* (68.8 mg kg$^{-1}$) are significantly above natural leaf cadmium levels. The *Quercus pagoda* value is six times the highest field leaf cadmium value. Regrettably *Q. pagoda* was not tested in the field. Denny and Wilkins 1987 reveal tolerance for species in the Betulaceae family on high cadmium soils. Arduini 1996 studied the effects of Cd and Cu on 3 Mediterranean tree species, *Pinus pinea, P. pinaster* and *Fraxinus angustifolia*. *Pinus pinaster* was found to be more tolerant to cadmium than *Fraxinus angustifolia*. This research supports more testing of one of the NRWHF species in the same genus, *Pinus taeda* (loblolly pine) at PCS. Appendix F. shows tables of tree growth and survival on high Cd soils for selected tree species.

<table>
<thead>
<tr>
<th>Oak Species</th>
<th>Bucket-wheel spoil</th>
<th>Blend</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Q. michauxii</em></td>
<td>.07</td>
<td>.21</td>
</tr>
<tr>
<td><em>Q. nigra</em></td>
<td>.56</td>
<td>14.3</td>
</tr>
<tr>
<td><em>Q pagoda</em></td>
<td>.85</td>
<td>68.8</td>
</tr>
<tr>
<td><em>Q laurifolia</em></td>
<td>.39</td>
<td>.31</td>
</tr>
</tbody>
</table>

**Table 4. Greenhouse Leaf Cadmium Concentrations (mg kg$^{-1}$)**
Summary

Greater survival was found in plants grown in the blend than in the bucket-wheel spoil after two seasons of growth in the field. In the greenhouse, germination rates of acorns of all four species on topsoil were almost double those on bucket-wheel spoil and 1.5 times greater than those on the blend. Oak seedlings grown from acorns had significantly greater tree height and stem volume on topsoil and sterilized topsoil than on both mine substrates for all species. No significant difference between seedling height or stem volume was found between trees grown on the phosphogypsum/clay blend and the bucket-wheel spoil. A trend of increased height growth due to fertilizer was found for seedlings grown on the bucket-wheel spoil and on the metro mix. Significant interactions were found in the factorial design between substrate and species in height after 120 days and in stem volume.
Conclusions

Recommendations for Restoration of NRWHF at PCS Phosphate

Restoration of Nonriverine Wet Hardwood Forests on the blend would benefit from a deep cap of bucket-wheel spoil or other material to prevent the high cadmium uptake by *Quercus nigra* (14 mg/kg) and *Quercus pagoda* (68 mg/kg). Since the tap roots of bottomland oak species could potentially grow through a shallow cap, a layer 3 feet or more is preferable. A second option for restoration of Nonriverine Wet Hardwood Forests directly on the blend or in a shallow cap of bucket-wheel spoil is to exclude the two oak species with high cadmium uptake. Surveys of mature Nonriverine Wet Hardwood Forests indicate that often all four oak species do not exist in one population simultaneously. Thus a successful restoration of a Nonriverine Wet Hardwood Forest could be achieved at PCS without the presence of the high cadmium accumulating oak species.

If bucket-wheel spoil is used as a capping material, application of lime and fertilizer would be necessary to increase pH and add nutrients. On bucket-wheel spoil the low survival species *Liriodendron tulipifera, Lindera benzoin, and Vaccinium corybosum* should be excluded. Regardless of substrate used, control of the invasive common reed (*Phragmites australis*), before, during and after seedling planting is essential to promote tree survival and growth. If direct seeding of oaks is attempted at PCS, using topsoil from the advancing mine will significantly improve germination of acorns and tree growth. The use of the conveyor system presently transporting bucket-wheel spoil out of the mine pit could possibly be used to place top soil on reclaimed lands.
Further Research

Dehgan et al 1989 prepared a selection criteria list for tree and shrub species that could be grown successfully on reclaimed phosphate mine lands in Florida. Research on these species is likely to be fruitful since *Myrica cerifera* (Wax Mrytle), a plant common on PCS reclaimed land, was used as a model to investigate the attributes that allow a plant to grow successfully in disturbed soils of phosphate mines. In his study of four different phosphate mine substrates, Harrell (1987), discusses several Florida hardwood swamp species that are also native to the North Carolina coastal plain. Based on 50% survival after one year, bareroot *Quercus laurifolia* (Laurel Oak), and *Pinus palustris* (longleaf pine) are recommended for planting on sand tailing soils (92% sand, 8% clay). Since particle size analysis revealed 86% sand and 7% clay for bucket-wheel spoil at PCS, perhaps these findings are applicable to North Carolina phosphate mine substrates. Supporting this, Clewell’s 1983 sand tailings study on *Quercus laurifolia* had 71% survival and a mean height of 1.3 m after three years.

Another essential area of future research is “mulching” of native soil as a restoration technique for seeding native trees, shrubs and herbaceous species. Often called topsoiling, this method consists of spreading a foot of natural soil from the surface of an ecologically similar site nearby. Surface soil should be collected from areas recently cleared for mining, not topsoil from undisturbed areas, a method that would be destructive and unrealistic for large-scale reclamation (Best 1983).

Clewell (1983), showed tree density representing 44 trees per acre, including laurel oak and red maple three years after spreading one foot of topsoil from a natural riverine forest in the path of the advancing mine. Clewell cites that most trees sprouted from seeds
and some from stump or stem sections transferred in the topsoil. Several desirable herbaceous species, including *Saururus cernuus* (lizard’s tail), found in NRWHF were also seen three years after topsoil was spread. Segal et al. 2001, in a study of upland restoration of phosphate mine lands, described topsoiling as “a successful method for transferring a viable seed bank to a reclaimed area” (80% of seeds transferred were of desirable native species). Segal states “the addition of topsoil improved soil properties in the surface layer at the overburden site by decreasing bulk density and the C:N ratio while also increasing total carbon, nitrogen, Ca, Mg, K, Zn, Mn and Na” (Segal et al. 2001).
References


Billings, Dwight 1938. The structure and development of old field shortleaf pine stands and certain associated physical properties of the soil. pp 437-500 Ecological Monographs Vol 8, No. 3.


Godbold, D. L. and Hutterman, A. 1985. Effect of Zinc, Cadmium and Mercury on Root Elongation of P. abies Seedlings and the Significance of these Metals to Forest Dieback. Environmental Pollution 38, 375-381.


Herstein, U. and Jager, H.S. 1986. Tolerances of different populations of three grass species to cadmium and other metals. Environmental and Experimental Botany 26, 309-319


Xiong, Li-Ming and Lu, Ru-kun, 1992. Effect of liming on plant accumulation of cadmium under upland or flooded conditions. Environmental Pollution 79: 199-203
Appendix A. Soil survey near Porter Creek on PCS land
Appendix B. Site map near Porter Creek (same location as appendix A)
Appendix C. Wetland Research Area, R3, PCS Phosphate, Aurora NC

Appendix D. Plot Design of Field Experiment

Nonriverine Wet Hardwood Forest Plot Diagram

Downhill Gradient
Appendix E. INTERACTION TABLES

Table 1. Mean stem height (cm) for each treatment after 4 months

<table>
<thead>
<tr>
<th>Oak species</th>
<th>Topsoil</th>
<th>Sterilized Topsoil</th>
<th>Bucket-wheel spoil</th>
<th>Blend</th>
<th>Metro-mix</th>
<th>Species Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Q. michauxii</em></td>
<td>34.6</td>
<td>40.6</td>
<td>12.7</td>
<td>14.3</td>
<td>21.4</td>
<td>24.7</td>
</tr>
<tr>
<td><em>Q. nigra</em></td>
<td>33.4</td>
<td>44.5</td>
<td>10.1</td>
<td>13.3</td>
<td>15.2</td>
<td>23.3</td>
</tr>
<tr>
<td><em>Q. pagoda</em></td>
<td>51.3</td>
<td>49.4</td>
<td>12.4</td>
<td>16.8</td>
<td>29.3</td>
<td>31.8</td>
</tr>
<tr>
<td><em>Q laurifolia</em></td>
<td>33.1</td>
<td>56.6</td>
<td>26.0</td>
<td>25.0</td>
<td>40.9</td>
<td>36.3</td>
</tr>
<tr>
<td><strong>Substrate Mean</strong></td>
<td>29.8</td>
<td>47.8</td>
<td>15.3</td>
<td>17.3</td>
<td>26.7</td>
<td>----</td>
</tr>
</tbody>
</table>

Table 2. Mean height difference (cm) for each treatment after 8 fertilizer applications

<table>
<thead>
<tr>
<th>Oak species</th>
<th>Topsoil</th>
<th>Bucket-wheel spoil</th>
<th>Blend</th>
<th>Metro-mix</th>
<th>Species Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Q. michauxii</em></td>
<td>0</td>
<td>15.9</td>
<td>-3.0</td>
<td>-.3</td>
<td>3.2</td>
</tr>
<tr>
<td><em>Q. nigra</em></td>
<td>3.4</td>
<td>10.4</td>
<td>6.0</td>
<td>6.9</td>
<td>6.7</td>
</tr>
<tr>
<td><em>Q. pagoda</em></td>
<td>0</td>
<td>10.4</td>
<td>6.0</td>
<td>6.9</td>
<td>5.8</td>
</tr>
<tr>
<td><em>Q laurifolia</em></td>
<td>37.6</td>
<td>-7.6</td>
<td>-16.2</td>
<td>15.4</td>
<td>7.3</td>
</tr>
<tr>
<td><strong>Substrate Mean</strong></td>
<td>10.3</td>
<td>7.3</td>
<td>-1.8</td>
<td>7.2</td>
<td>---</td>
</tr>
</tbody>
</table>
Table 3. Mean stem volume (cm³) for each treatment after 6 months growth

<table>
<thead>
<tr>
<th>Oak species</th>
<th>Topsoil</th>
<th>Sterilized Topsoil</th>
<th>Bucket-wheel spoil</th>
<th>Blend</th>
<th>Metro-mix</th>
<th>Species Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Q. michauxii</em></td>
<td>7.19</td>
<td>12.84</td>
<td>1.52</td>
<td>0.81</td>
<td>2.37</td>
<td>4.9</td>
</tr>
<tr>
<td><em>Q. nigra</em></td>
<td>6.35</td>
<td>13.52</td>
<td>0.76</td>
<td>1.11</td>
<td>1.46</td>
<td>4.6</td>
</tr>
<tr>
<td><em>Q. pagoda</em></td>
<td>5.45</td>
<td>8.68</td>
<td>0.79</td>
<td>0.37</td>
<td>2.06</td>
<td>3.47</td>
</tr>
<tr>
<td><em>Q laurifolia</em></td>
<td>24.97</td>
<td>29.60</td>
<td>0.75</td>
<td>1.26</td>
<td>5.93</td>
<td>12.5</td>
</tr>
<tr>
<td><strong>Substrate Mean</strong></td>
<td>10.9</td>
<td>16.2</td>
<td>1.0</td>
<td>3.6</td>
<td>3.0</td>
<td>---</td>
</tr>
</tbody>
</table>

Table 4. Mean height response (cm) for each treatment after 6 months

<table>
<thead>
<tr>
<th>Oak species</th>
<th>Topsoil</th>
<th>Bucket-wheel spoil</th>
<th>Blend</th>
<th>Metro-mix</th>
<th>Species Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Q. michauxii</em></td>
<td>52.4</td>
<td>15.7</td>
<td>17.3</td>
<td>22.6</td>
<td>27</td>
</tr>
<tr>
<td><em>Q. nigra</em></td>
<td>70.2</td>
<td>16.7</td>
<td>26.7</td>
<td>15.1</td>
<td>32.2</td>
</tr>
<tr>
<td><em>Q. pagoda</em></td>
<td>54.6</td>
<td>0.03</td>
<td>18.9</td>
<td>26.5</td>
<td>25</td>
</tr>
<tr>
<td><em>Q laurifolia</em></td>
<td>87.8</td>
<td>18.1</td>
<td>54.9</td>
<td>41.1</td>
<td>50.5</td>
</tr>
<tr>
<td><strong>Substrate Mean</strong></td>
<td>66.3</td>
<td>12.6</td>
<td>29.5</td>
<td>23.8</td>
<td>---</td>
</tr>
</tbody>
</table>
Appendix F. Cadmium concentration and tree growth response tables.

<table>
<thead>
<tr>
<th>Soil Cd Conc. (top 25 cm)</th>
<th>Species</th>
<th>Height (cm)</th>
<th>% Mortality</th>
<th>Added Cd: 59.5 mg/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>Alnus glutinosa</em> Black Alder</td>
<td>82</td>
<td>106</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td><em>Fagus sylvatica</em> European Beech</td>
<td>30</td>
<td>84</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td><em>Fraxinus excelsior</em> Ash</td>
<td>25</td>
<td>53</td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td><em>Quercus robur</em> English Oak</td>
<td>19</td>
<td>52</td>
<td>20</td>
</tr>
</tbody>
</table>

*0.2 mg/kg in undisturbed soils (Greszt 1979).

<table>
<thead>
<tr>
<th>Soil Cd Conc. (top 30 cm)</th>
<th>Height (cm)*</th>
<th>Percent Mortality*</th>
<th>Leaf Cd Conc* (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.95 mg/kg Cd (natural soils)</td>
<td>25.4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>83.2 mg/kg Cd</td>
<td>6.48</td>
<td>29</td>
<td>5.76</td>
</tr>
<tr>
<td>415 mg/kg Cd</td>
<td>1.5</td>
<td>--</td>
<td>3.8</td>
</tr>
</tbody>
</table>

*Acer pseudoplatanus* L. seedlings, (Turner and Dickinson 1993).

<table>
<thead>
<tr>
<th>Cd Conc. added to soil</th>
<th>Height (cm)*</th>
<th>Total Biomass (g)*</th>
<th>Leaf Area (cm²)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 mg/kg</td>
<td>102.5</td>
<td>24</td>
<td>750</td>
</tr>
<tr>
<td>10 mg/kg</td>
<td>96.5</td>
<td>17.5</td>
<td>665</td>
</tr>
<tr>
<td>20 mg/kg</td>
<td>89</td>
<td>15</td>
<td>575</td>
</tr>
<tr>
<td>40 mg/kg</td>
<td>82.5</td>
<td>13</td>
<td>375</td>
</tr>
</tbody>
</table>

* Taxodium distichum* L. seedlings in sandy, drained soil (Fredenberg 1999).