Enhancing Soil Carbon Sequestration on Phosphate Mine Lands in Florida by Planting Short-Rotation Bioenergy Crops

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ABSTRACT

Phosphate mines in northern and central Florida provide a valuable resource for the national and international production of agricultural fertilizers. However, separating phosphate-rich ore from the underlying sand and clay matrix creates large containment ponds or clay settling areas (CSA). The physical and chemical characteristics of CSAs make restoration a critical priority for post-mining activities. Therefore, to demonstrate the potential use of these areas for bioenergy crop production and carbon sequestration, a 50-ha demonstration planting consisting of *Eucalyptus grandis*, *E. amplifolia*, cottonwood, cypress, and slash pine hybrid trees was established on a CSA beginning in 2000 near Lakeland, Florida. Establishment costs may be as high as $1,250 per acre, including costs of site preparation and planting. Yield estimates for 2.5-year-old *E. grandis* planted in single rows varied from 10 to 16 dry tons of biomass per acre. In addition to providing a carbon-neutral option for mitigating rising CO2 in the atmosphere, an important opportunity exists for promoting soil carbon sequestration as a result of restoration. Our analysis, using a simple model that describes the soil carbon dynamics indicates the potential for long-term increases in soil carbon under bioenergy crop plantations. Science in support of these observations will require investigations aimed at (1) selecting tree species for site restoration, (2) identifying management practices to ensure plant survival and maximize growth, (3) improved characterization of below-ground biomass and determining inputs of roots to soil organic matter pools, (4) documenting the colonization of bulk and rhizosphere soils with micro-organisms beneficial to carbon and nitrogen cycling, and (5) quantifying changes in soil carbon and nitrogen stocks over time.

INTRODUCTION

Restoration of degraded and disturbed lands has long been viewed as a process through which multiple benefits could be achieved. However, while there has been ample research on the reclamation of mine lands, few studies have examined these lands as a resource for use in mitigating rising CO_2 concentrations in the atmosphere. Nonetheless, it is reasonable to believe that various carbon management strategies (e.g., bioenergy crops and soil carbon sequestration) could be implemented on these lands. Worldwide, for example, nearly 2×10^9 ha of lands are considered to be degraded to some degree (Oldeman and Vanengelen 1993) and may be capable of sequestering from 0.8 to 1.3 Gt C/year (Metting et al. 2001). In the United States alone, 0.63×10^6 ha of land are classified as disturbed mine lands, mostly land strip-mined for coal, with a carbon sequestration potential of 1.3 Tg C/year (Lal et al. 1998). Lands associated from other mining activities also have the potential to store an equal, if not greater, amount of carbon in soils, but studies documenting rates of carbon sequestration on such lands are largely lacking.

Nationally, Florida ranks fifth in the production of limestone, sand and gravel, clay, peat, heavy minerals, and phosphate. Mining occurs throughout the state, with phosphate mines located primarily in northern and central Florida. These mines supply one-quarter of the world's and three-quarters of the U.S. domestic needs. Nearly all of the phosphate mined is used for the national and international production of agricultural fertilizer. In 2000, an approximate $1.13 billion dollars worth of fertilizer was exported.

Phosphate ore is found 15 to 60 feet beneath the ground in a mixture of phosphate pebbles, sand and clay known as phosphate matrix. The sandy layer above the matrix, called the overburden, is removed using draglines. Equipped with large buckets, these draglines remove the overburden and then deposit the underlying matrix into shallow containment areas. There, water under high pressure is used to make a watery mixture called slurry, which is sent through pipes to a benefaction plant where phosphate rock is physically separated from the sand and clay in the matrix. Clay particles are then pumped through pipes into large clay settling areas (CSAs). Depth of clay can range from a few feet to 60 feet or more.

There are an estimated 65,000 ha of CSA lands in Central Florida. These lands remain undeveloped because they cannot structurally support buildings for commercial or residential development, and are difficult to develop for agricultural use (i.e., more costly than other land options). However, research has shown that CSAs are fertile, high in potassium and phosphorus (Stricker et al. 2000). Therefore, CSA lands provide a valuable, yet underutilized resource. The objectives of this report are to summarize research aimed at better understanding the use of CSA lands for growing short-rotation bioenergy crops as a renewable source of energy, and the dual use of these lands for carbon sequestration. Biomass derived from these crops can be used in co-firing power plants and in the production of transportation fuels, while CSA lands have properties (e.g., high moisture holding capacity and high clay content) that raise interesting questions regarding the rate and magnitude of soil carbon that can be potentially stored on these lands. Thus, researchers from Oak Ridge National Laboratory have begun to explore the use of CSA lands for carbon sequestration. This work builds upon research currently being conducted by scientists at the University of Florida and Common Purpose Institute in bioenergy crop production. We suggest that restoration of CSA lands represents a unique opportunity to couple carbon sequestration with the production of bioenergy crops, while achieving ecological, environmental, and societal benefits.

METHODOLOGY

A 50-ha short-rotation woody crops (SRWC) Energy Farm was established beginning in 2000 near Lakeland, FL to demonstrate the use of trees as a renewable source of energy. The site was a CSA which had been closed in the 1940's and subsequently infested by cogongrass (*Imperata cylindrica*). Several tree species have been planted (cypress, maple, and slash pine) at the site; however, the Energy Farm consists primarily of non-invasive *Eucalyptus grandis* and *E. amplifolia* progenies, and *Populus deltoides* (i.e., cottonwood), a fast-growing deciduous species native to the southeast U.S. including Florida. All trees planted to date represent advanced progenies and clones developed by scientists at the University of Florida and elsewhere (Meskimen et al. 1987, Rockwood et al. 1993).

Field studies at the Energy Farm include a clone-configuration-fertilizer study (SRWC-90), a *P. deltoides* clonal nursery, and demonstration and commercial plantings. SRWC-90 involves *P. deltoides*, *E. grandis*, and *E. amplifolia*, each represented by up to six genotypes, two planting configurations (single or double rows per bed), and two fertilizer levels (0 or 100 pounds/acre ammonium nitrate) in a split-plot design with configuration main plots, species subplots, and genotypes in 6-tree row subsubplots. Spacing is 11 feet between beds and 3 feet between trees on a bed. The initial planting was done in March 2001, and fertilizer treatments were implemented in June 2002. *Eucalyptus grandis*, *E. amplifolia*, and five *P. deltoides* clones were planted in two configurations in a demonstration area in April 2001. Each species was established at 3-foot spacing within single and double row blocks on top of five beds spaced 11 feet apart. Several commercial scale planting were also made. In addition to single tree row designs, which would use traditional harvesting equipment of skidders, feller-bunches, etc., multiple row planting/bed designs were also implemented to accept Claas-type harvesting equipment. One of the advantages of using this Claas equipment is the probable compatibility of the cutter head with existing Claas foragers used extensively within the forest and sugar cane industry, thereby reducing the need for a dedicated unit to harvest bioenergy crops. Tree size and survival in all studies were measured periodically. The relative distribution of biomass to shoots and roots was determined for two 1.5-year-old *E. grandis* trees (ca. 6 m in height) by excavation with a back-hoe. Trees were separated into stem, branches, leaves, coarse roots, and fine roots, and total dry mass of each component was determined after drying and weighing.

Samples for analysis of soil carbon concentration were taken from areas of the CSA where (1) cogongrass was the dominant vegetation and (2) from 2.5-year-old plantings of *E. grandis*. Soils were sampled from two depths; 10 to 20 cm and 40 to 50 cm. Soil samples were sealed in plastic bags and transported to the laboratory for analysis. Replicate soil samples were dried, sieved through a 6-mm mesh screen, and analyzed using an elemental analyzer (LECO CN-2000, LECO Corp., St. Joseph, MI). Soil carbon stocks were calculated by assuming a soil bulk density of 1.4 g cm^{-3}. Soil carbon concentrations measured in 10-20 and 40-50 cm deep soil increment were assumed to be representative of carbon concentrations over a 0-30 and 30-60 cm depth increment, respectively. In addition to direct measurements of soil carbon, a simple model of soil carbon dynamics was used to predict patterns of soil carbon accumulation for CSA lands. The model (Garten 2004) was simplified to include two pools (i.e., biomass and soil carbon). Above- and below-ground biomass data from 2.5-year-old *E. grandis* trees were used to estimate shoot and root biomass throughout a rotation length of 5 years. Over this time, maximum biomass production was set at 250 Mg/ha. The mean residence time (MRT) for soil carbon was set to 20 years, and all simulations with the model were conducted for 25 years or 5 rotations.

RESULTS

Establishment Costs: Actual costs associated with establishing the SRWC tree farm was ca. $1,250 per acre (Figure 1). Application of herbicides ($250), site preparation ($50), disking ($90), and preparation of planting beds ($300) represented major expenses; approximately 55% of the total costs. Other costs included the buying trees ($270), planting trees ($250), and fertilization ($40).

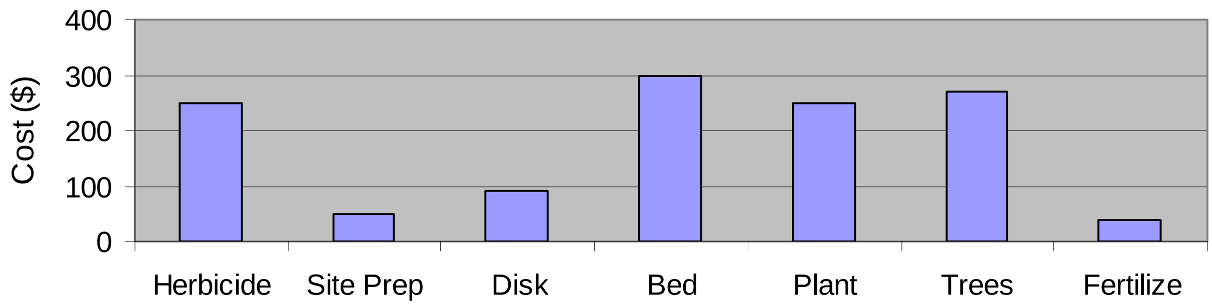

Figure 1. Component costs for establishing short-rotation woody crops on CSA lands in central Florida.

Tree Productivity and Biomass Distribution: Heights and stem diameters varied markedly among 2.5-year-old *P. deltoides*, *E. grandis*, and *E. amplifolia* (Table 1). All species grew well under both single and double row planting, although *E grandis* showed the greatest growth in terms of stem diameter and height. In 2.5 years, trees averaged 6.7 m in height and had stem diameters that ranged from 5 to 7.6 cm.

Table 1. Height and stem diameter for three tree species growing on CSA lands in central Florida.

Tree Species/Planting	Height (meters)	Diameter (cm)
P. deltoides		
Single row	1.3	0.7
Double row	4.0	2.9
E. grandis		
Single row	6.7	5 to 7.6
Double row	5.1	3.2
E. amplifolia		
Single row	4.1	3.4
Double row	4.6	3.1

Current "preliminary" estimates of yields in the commercial plantings suggest a low of 20 green tons (10 dry tons)/acre/year and a high of 32 green tons (16 dry tons)/acre/year for eucalypts with high survival at the end of the rotation. *E. grandis* has the potential to be the most productive species with thorough site preparation and fertilization, and properly timed harvest.

Destructive harvests were conducted to determine the relative distribution of biomass to stems, branches, leaves, and roots. Total biomass for 1.5-year-old *E. grandis* trees was 46 kg/tree. Distribution of whole-tree biomass was 36.6% to stems, 14.4% to branches, 10.5% to leaves, 35.9% to coarse roots, and finally 2.5% to fine roots. Approximately 62% of total whole-tree biomass was found above-ground, with the remaining 38% was allocated to below-ground tissues (Figure 2).

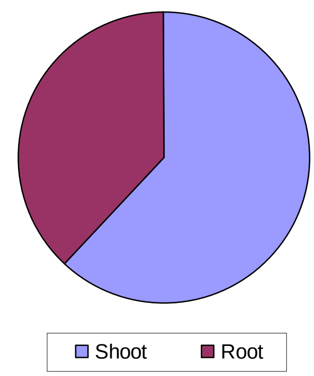

Figure 2. Relative allocation of biomass to shoots and roots in 1.5-year-old *E. grandis* trees.

Soil Carbon Measurements: Carbon concentration was higher in the upper 10-20 cm of soil than it was lower (i.e., 40-50 cm) in the soil profile (Table 2). This was true for soils sampled from beneath cogongrass and eucalyptus. However, soil carbon was considerably higher beneath 2.5-year-old *E. grandis* trees, with concentrations ca. 5.3 and 3.1% in the upper 10-20 and 40-50 cm, respectively. Estimated carbon stocks followed a similar pattern with stocks being higher in soils of the upper profile, and carbon stocks being considerably greater in soils sampled from the 2.5-year-old *E. grandis* plantation. Both the concentration and stock of carbon beneath *E. grandis* trees were several times higher than soils sampled beneath cogongrass.

Table 2. Soil carbon concentrations (and stocks) measured at two depths for both cogongrass and *E. grandis* growing on CSA lands in central Florida.

Soil property	Soil Depth (cm)	Congongrass	*Eucalyptus grandis*	% change
Carbon (%)	10-20	1.68 (0.57 – 2.87)	5.29 (4.44 – 6.02)	+215
	40-50	0.76 (0.45 – 1.05)	3.06 (2.58 – 3.51)	+303
Carbon stock (kg C m^{-2})	0-30	7.1 (2.6 – 11.6)	22.2 (19.2 – 25.2)	+214
	30-60	3.2 (2.0 – 4.4)	12.8 (11.2 – 14.4)	+304

Modeling Soil Carbon Sequestration: A simple model of soil carbon dynamics was used to estimate the long-term potential for storing carbon on CSA lands planted to *E. grandis*. Throughout each of five simulated rotations, total biomass increased to 245 Mg/ha, at which time the above-ground biomass was harvested (Figure 3). Because the growth of *E. grandis* as a bioenergy crop is envisioned to be a coppice system (i.e., trees re-grow form stump sprouts), roots from one rotation remain in the soil to decompose during subsequent rotations. Thus, biomass does not fall to zero at the end of each 5-years rotation. Increases in soil carbon are considerable throughout the simulation period; increasing from 7.1 kg C m^{-2} in the first year of the simulation to over 34.5 kg C m^{-2} after 25 years (summed over the two depth increments). The 25-year gain in soil carbon as simulated by our model is 27.4 kg C m^{-2} (i.e., 34.5 kg C m^{-2} – 7.1 kg C m^{-2}) or 274 Mg C ha^{-1}; averaging approximately 11.0 Mg C/ha/year. Extending our simulation to 50 years shows that gain in soil carbon is 35.4 kg C m^{-2} (i.e., 354 Mg C ha^{-1}), thus averaging an accumulation rate of 7.1 Mg C/ha/year. This decline is associated with what is typically observed as a saturation of soil carbon pools over time.

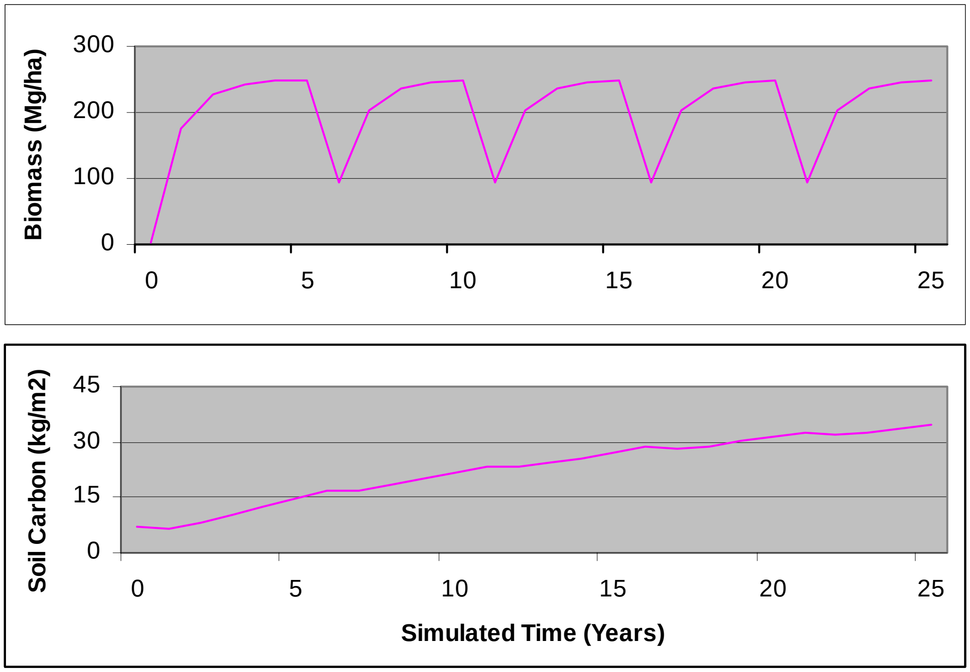

Figure 3. Biomass production and soil carbon accumulation as simulated for plantation-grown *Eucalyptus grandis* over a 25-year period.

DISCUSSION

Rates of carbon sequestration on following reclamation of degraded lands tend to be modest. Estimates from a 21-year chronosequence study in southwestern Ohio indicate that accumulation of soil organic carbon in reclaimed mine soils planted as forests were in the range of 1.5 Mg C /ha/year (Akala and Lal 2001). Lal et al. (1998) suggests that such rates could be higher, perhaps up to 4 to 5 Mg C/ha/year given the establishment of favorable plant species (i.e., legumes, grass, and trees). The results of our analysis are consistent with these observations, but differ in that CSA lands apparently possess considerably greater capacity to store carbon in soils than other more typically studied degraded mine lands. Although further analyses are required, our measurements and modeling exercise indicate that rates of soil carbon accumulation might range between 7 and 11 Mg C/ha/year. These rates would be several times higher than rates reported in previous studies.

One of the more intriguing questions to be asked in the context of our present investigation relates to what mechanisms contribute to the high rates of soil carbon accumulation beneath plantings of *E. grandis* on CSA lands. Deserts and arid shrub lands typically have carbon stocks on the order of 0.5 to 4.6 kg C m^{-2} (Cao and Woodward 1998); temperate deciduous and coniferous forests range between 2.7 and 15.3 kg C m^{-2} (Paul et al. 2003); and mixed-grass and short-grass prairie on the order of 5.2 to 10.9 kg C m^{-2} (Reeder and Schuman 2002). In contrast, soil carbon content of floodplain forests range from 15.6 kg C m^{-2} in early stages of succession to 55.9 kg C m^{-2} in late succession (Wigginton et al. 2000). It would appear that short-rotation woody crops planted to CSA lands, due either to their water holding capacity or high clay content, have carbon stocks similar to those of bottomland forests or wetlands. Soil texture (i.e., clay content) exerts a major control on the amount of slowly cycling carbon and therefore influences the storage and dynamics of soil carbon (Telles et al. 2003). Although not reported here, data for CSA soils indicate that 95 to 98% of the total carbon in soils beneath *E. grandis* is located in the mineral-associated organic matter (MOM) fraction. This is in contrast to soils from beneath cogongrass where only 23 to 38% of total carbon is in the MOM fraction. The turnover time of soil organic carbon in the MOM fraction is typically longer than that of the particulate organic matter (POM) fraction (Garten and Wullschleger 2000), thus providing additional evidence that CSA lands may have considerable capacity for carbon sequestration. A better understanding of the mechanisms that control this capacity will require additional studies aimed specifically at determining the turnover times of these two soil fractions.

CONCLUSIONS

The University of Florida/Common Purpose Institute (UF/CPI) Energy Farm demonstrates environmental and cost benefits of developing short-rotation woody crops on un/under-utilized CSA lands. The pilot studies described in this report are (1) documenting real world costs and yields of short-rotation woody crops, (2) developing guidelines for establishing and managing bioenergy crops on CSA lands, and (3) evaluating genetic, cultural, and harvesting options for further improving the cost effectiveness of trees planted as a renewable energy resource. Obviously, planting short-rotation woody crops as a post-mining restoration activity offers several valuable and unique advantages over abandonment. Rapid growth of planted trees effectively controls and/or eliminates shade intolerant cogongrass; assists in improving soil quality through increased soil organic matter formation; increases available nitrogen; and decreases soil compaction of the heavy clays. Furthermore, preliminary measurements of soil carbon indicate considerable potential for carbon sequestration on CSA lands. However, while we have begun to address important questions in this regard, many questions remain. Science in support of these observations will require investigations aimed at (1) selecting tree species for site restoration, (2) identifying management practices to ensure plant survival and maximize growth, (3) improved characterization of below-ground biomass and determining the inputs of roots to soil organic matter pools, (4) documenting the colonization of bulk and rhizosphere soils with micro-organisms beneficial to carbon and nitrogen cycling, and (5) quantifying changes in soil carbon concentrations and stocks over time.

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