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The economic feasibility of reclaiming phosphate mined lands with short-rotation woody crops in Florida

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Abstract

Fast growing and short-rotation tree crops provide unique opportunities to reclaim phosphate-mined lands in central Florida. Optimum management of the eucalyptus short-rotation woody crop forestry system studied necessitates harvests every 2.5–3.6 years and replanting after 2–5 coppice harvests. The value of phosphate mined land under *Eucalyptus amplifolia* forestry ranges from \$762 to \$6507 ha^{-1} assuming discount rates of 10% and 4%, respectively, establishment costs of \$1800 ha^{-1}, planting costs of \$1200 ha^{-1}, planting density of 8400 tree ha^{-1}, and a stumpage price of \$20 dry Mg^{-1}.

JEL classification: Q230
Keywords: Clay settling areas; Faustmann; Non-timber benefit; Phosphate-mined land; Reclamation; Restoration; Short-rotation coppicing

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Introduction

Central Florida produces 75% of the United States' and 25% of the world's phosphate supply, primarily used for fertilizer (IMC Phosphates, 2002). There are about 162,000 ha of phosphate-mined lands in Florida (Segrest, 2003a). Phosphate was mined from more than 69,000 ha in central and north Florida from July 1975 to December 2002 and is increasing by 2000–2500 ha annually (Florida DEP, 2003).

As part of the phosphate mining process, clays are washed from phosphate ore, and the resulting slurry of water and clay is pumped into clay settling areas (CSAs). CSAs constitute about 40% of the phosphate-mined lands and are 10–20 m deep. There are approximately 64,700 ha of undeveloped CSAs in central Florida (Segrest, 2003b). These CSAs, classified as clayey Haplaquents (Mislevy et al., 1989), are characterized by high bulk density, poor drainage, high levels of P, K, and micronutrients, and pH of 7.0–8.3. They are commonly dominated by cogongrass (*Imperata cylindrica*), a costly invasive exotic species in Florida (Van Loan et al., 2002). CSAs can take about 15 years to dewater (stabilize and dry). While CSAs may be leased for cattle grazing for \$35–\$40 $\text{ha}^{-1}\,\text{year}^{-1}$, they are typically left idle because of operational difficulties.

Florida law requires that mining companies reclaim areas mined after July 1, 1975. Significant areas of uplands and wetlands have been reclaimed since the law was enacted (Segal et al., 2001). As of December 2003, 63% of the land mined since July 1, 1975 has been successfully reclaimed (Florida DEP, 2003). Reclamation and reuse of mined landscapes are major foci of the Florida Institute of Phosphate Research (FIPR), an independent State research agency that has spent almost \$11 million on phosphate mining related research.

Ongoing research and operational trials on a 50 ha CSA near Lakeland, FL suggests that CSAs can be used for the production of short-rotation woody crops (SRWCs). SRWC systems use fast-growing tree species that coppice (resprout from the stump), and typically involve 3–5 harvests before replanting, with 2–10 years between harvests. Preliminary results suggest that, given adequate site preparation, high density SRWC plantations of *Eucalyptus* spp. can exclude cogongrass, speed dewatering, increase soil organic matter and facilitate growth of native understory vegetation on CSAs (Tamang et al., 2005). Though not native species, *Eucalyptus amplifolia* (EA) and *Eucalyptus grandis* (EG) are non-invasive in Florida and have been produced commercially in south central Florida since the 1970s without spreading (Rockwood, 1996).

An assessment of eucalyptus markets was made in July 2004 in central Florida to identify products and prices to be used in this analysis. On-site and phone interviews were done with individuals from the Florida Division of Forestry, mulch industries, nurseries, electricity generation facilities, and potential biomass users. Potential products from eucalyptus grown on CSAs in Polk County include mulch, energy, timber, pallets, pulp and fiberboard. The most promising products are (1) mulch, having an existing multi-million dollar market in Polk County annually, and (2) feedstock for electricity generation, a prospective market with much potential for expansion. A range of price values and demand quantities were derived from the interviews, which suggest that stumpage prices for eucalyptus would range from \$11 to \$44 dry Mg^{-1}.

Large areas of CSAs in central FL require reclamation, which can be a significant cost to the phosphate mining industry. Due to their low opportunity cost and proximity to metropolitan centers, CSAs are well suited for biomass production (Stricker et al., 2003; Stricker, 1995). While the potential of SRWCs to restore productivity and ecosystem functions of CSAs was extensively studied (Rockwood et al., 2004; Segrest, 2003b; Tamang et al., 2005), very few attempts were made to systematically investigate the economic feasibility of this process. In this study, we build an optimization model to assess the profitability of reclaiming mined lands with eucalyptus and simulate it with various stumpage prices, operational costs, and discount rates.

Methods

The basic Faustmann model, which provides a convenient framework to estimate land value or land expectation value (LEV) under an even-aged tree plantation system, is defined as

$$\mathrm{LEV} = \frac{V(t)\mathrm{e}^{-rt} - C}{1 - \mathrm{e}^{-rt}}, \tag{1}$$

where $V(t)$ is the value of the stand at time t (i.e. price times volume), C the cost of stand establishment at the beginning of the rotation, and r the real discount rate. The optimum rotation age t^*, the time where marginal benefit of growth is no longer greater than but just equals the opportunity cost of the bare land and the opportunity cost of the stand, maximizes LEV (Chang, 1984). In order to determine optimum rotations of SRWC coppice systems, the above model requires a few modifications.

Following the terminology of Smart and Burgess (2000), a stage length describes the period of time between coppice harvests, while a cycle length describes the period of time and/or number of stages between replantings. Both the optimum duration of each stage as well as the optimum number of stages per cycle must be determined. Medema and Lyon (1985) modified the Faustmann model to solve for multiple stage lengths given a fixed number of stages (n):

$$\mathrm{LEV} = \frac{\sum_{s=1}^{n}\left[V(t_s)\mathrm{e}^{\left(-r\sum_{j=1}^{s} t_j\right)} - C_s\mathrm{e}^{\left(-r\sum_{j=1}^{s} t_{j-1}\right)}\right]}{1 - \mathrm{e}^{\left(-r\sum_{j=1}^{n} t_j\right)}}, \tag{2}$$

where $t_0 = 0$, n is the number of stages, s, $V(t)$ the stand value as a function of time t within stage s, r the real discount rate, C_s the costs of stage s at the start of the stage.

Eq. (2) defines net returns as the sum of the present value benefits of each stage less the sum of the present value costs of each stage for a fixed number of stages per cycle in perpetuity. C_s is cost, either the cost of replanting the coppice cycle, or the cost associated with each coppice stage-for example suppression of competing vegetation (weeding) costs. An example of Eq. (2) fixed for two stages ($n = 2$) is

$$\mathrm{LEV} = \left[\frac{(V(t_1)\mathrm{e}^{(-rt_1)} - (C_\mathrm{p} + C_\mathrm{w})) + (V(t_2)\mathrm{e}^{(-r(t_1+t_2))} - C_\mathrm{w}\mathrm{e}^{(-rt_1)})}{1 - \mathrm{e}^{(-r(t_1+t_2))}}\right] - \left(\frac{C_\mathrm{a}}{1 - \mathrm{e}^{-r}}\right) - C_r, \tag{3}$$

where t_1 and t_2 are the duration of stage one and stage two, respectively, C_p is the cost of planting at the beginning of the cycle, C_w is the cost of weeding at the beginning of the stage, C_a is the annual maintenance cost, and C_r is any additional year zero cost of establishment.

Solving for the optimum stage lengths and cycle lengths of coppicing SRWCs requires two parts. First, n is fixed and net returns and optimum stage lengths are determined for the fixed number of stages per cycle. Similar to the non-coppicing Faustmann model, the optimum coppice stage length is that where marginal benefits in growth just equal the opportunity cost of the stand plus the opportunity cost of delaying subsequent coppice cycles. Next, the optimum number of stages is found by determining at what value of n an additional coppice stage to the cycle has a marginal benefit less than zero.

Although an option is to restrict harvest ages to whole (integer) years, based on our earlier work (Langholtz et al., 2005) we estimate the model in continuous time and report results to the nearest 1/10th year. We feel that decimal years provide a level of precision appropriate for the analysis because (a) optimum rotations are less than 5 years, and (b) nearly constant growth of *Eucalyptus* spp. in subtropical central Florida results in little sub-annual variation.

Model inputs

Growth function

In the absence of published growth and yield functions of SRWCs, we have used comparable data collected from SRWC-90, a trial of SRWC *Eucalyptus* spp. on a CSA near Lakeland, Florida (Rockwood et al., 2005). Height and diameter measurements taken between August 2002 and January 2005 were converted to dry weights (see Appendix A). EA was identified as a likely candidate species due to (a) greater frost resistance than EG, which allows flexibility to plant in late summer during increased rainfall with minimum frost damage to small trees the subsequent winter, and (b) higher yields than EG despite being planted two months later. EG would likely be a preferable species for lower latitudes and/or where decay resistant heartwood for mulch production is desirable (Rockwood, 1998). Representative yields used in this analysis include EA species treatments EA-3 (single row planting of 4200 trees ha^{-1}) and EA-4, (double row planting of 8400 trees ha^{-1}) (Figs. 1 and 2 in Appendix A). Growth and yield functions representing EA-3 and EA-4 yields were used to fit the functional form shown in the appendix in Eq. (4) with parameters described in the appendix. Applying a factor of 1.7 to convert stemwood to total above-ground biomass (based on Patzek and Pimentel, 2005), maximum sustained yields are 17 and 32 dry Mg ha^{-1} year^{-1} for the EA-3 and EA-4 growth functions, respectively. These yields are comparable to 20–31 dry Mg ha^{-1} year estimated for eucalyptus in Florida (Rahmani et al., 1997) but slightly higher than the estimated 9–17 dry Mg ha^{-1} year^{-1} estimated by Klass (1998), who observes that yields could be improved with SRWC development in the southern US.

There is a dearth of information regarding coppice yields. Perlack et al. (1995) note that after about 20 years of improvement in *Eucalyptus* spp. coppice management in Brazil, coppice yields still decrease by about 15% for the second stage (first coppice) and 30% for the third stage (second coppice). While growth of the second stage of EA might be higher than that of the first stage due to the benefits derived from the previously established root system, coppice mortality associated with wind throw or weed competition might also increase, reducing per hectare yields. We assume coppice yields decline 20% per stage. This estimate is based on anecdotal evidence and is consistent with the methodology described by Medema and Lyon (1985) and applied by Langholtz et al. (2005). Due to uncertainty regarding coppice growth for EA on CSAs, we also assess the sensitivity of LEV and optimum management to an improved coppice scenario including the following coppice yields: 2nd stage (first coppice) 120% of growth function; 3rd stage (second coppice) 100% of growth function; 4th stage (third coppice) 80% of growth function, and 5th stage (fourth coppice) 60% of growth function.

Other inputs of the model

Operational costs on CSAs are higher than those of conventional forestry, as working conditions on sites with heavy clays and/or cogongrass infestation are problematic. A commercial trial of SRWC production on a CSA near Lakeland, Florida incurred costs of \$1800 ha^{-1} for site preparation and \$1200 ha^{-1} in planting costs. In this trial, mechanized planting costs of EA-3 and EA-4 planting configurations were the same. To assess the sensitivity of LEV to changes in operational costs, values of \$900 and \$1800 ha^{-1} for site preparation and \$600 and \$1200 ha^{-1} for planting and fertilization were used. In light of apparent growth response to weed control, a weeding cost of \$0 and \$200 ha^{-1} at the beginning of each growth stage was used. The values for various activities and their schedules used in the model are summarized in Table 1.

Results and sensitivity analysis

The above discussed model was run for all combinations of real discount rates (4%, 7%, and 10%), site preparation costs (\$900 and \$1800 ha^{-1}), planting costs

Table 1. Summary of model inputs

Activty/parameter	Schedule/timing	Values assumed
Site preparation	Once at initial establishment	\$900 and \$1800 ha^{-1}
Planting and fertilization	Beginning of each cycle	\$600 and \$1200 ha^{-1}
Weed control	Beginning of each stage	\$0 and \$200 ha^{-1}
Discount rate	N/A	4%, 7%, and 10%
Stumpage price	N/A	\$10, \$20 and \$30 dry Mg^{-1}
Growth function	N/A	EA-3 and EA-4 (see Appendix A)
Coppice yields	Duration of each stage	Expected and improved (see text)

(\$600 and \$1200 ha^{-1}), weed control costs (\$0 and \$200 ha^{-1}), growth functions (EA-3 and EA-4 planting densities) and biomass stumpage prices (\$10, \$20 and \$30 dry Mg^{-1}). The model was also run with improved coppice yields under a base scenario. Not surprisingly, results vary widely depending on assumptions as differences are magnified by frequent, short rotations. LEVs range from \$−2880 to \$21,109 assuming worst[1] and best[2] case scenarios, respectively. LEV reported for a SRWC system in the United Kingdom by Smart and Burgess (2000) is \$2392 ha^{-1} (4% discount rate, stumpage price of \$31 dry Mg^{-1}, establishment cost of \$1538 ha^{-1} and an exchange rate of \$1.54 per £ in November 2000).

Table 2 shows LEVs, optimum number of stages per cycle, and optimum stage lengths by growth function (EA-3 and EA-4) and stumpage price (\$10, \$20, and \$30 dry Mg^{-1}) assuming a base scenario of 7% discount rate, \$1800 ha^{-1} site preparation cost, and \$1200 ha^{-1} planting cost for both expected and improved coppice yields. Under these assumptions, marginal increases in LEV per dollar increment in stumpage price range from \$149–\$220 and \$321–\$429 under the EA-3 and EA-4 growth functions, respectively. Marginal benefits of increasing stumpage price are greater with the EA-4 function, as benefits of increased yield are magnified over multiple rotations. Under the improved coppice yield scenarios, LEVs in Table 2 increase by \$588–\$1792 and \$1108–\$2843 under the EA-3 and EA-4 growth functions, respectively.

The shortest[3] and longest[4] initial growth stages calculated from the parameters in Table 1 are 2.4 and 3.6 years, respectively. Ceteris paribus, increasing stumpage price decreases optimum stage lengths and optimum stages per cycle, as the opportunity cost of the value of the stand increases.

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[1] Real discount rate of 10%, stumpage price of \$10 dry Mg^{-1}, site preparation cost of \$1800 ha^{-1}, planting cost of \$1200 ha^{-1}, weed control cost of \$200 ha^{-1}, the EA-3 growth function (Eq. (4)), and expected coppice yields.

[2] Real discount rate of 4%, stumpage price of \$30 dry Mg^{-1}, site preparation cost of \$900 ha^{-1}, planting cost of \$600 ha^{-1}, no weed control cost, the EA-4 growth function (Eq. (4)), and improved coppice yields.

[3] Calculated under conditions of highest stumpage price and discount rate, lowest operational costs, the EA-3 growth function, and improved coppice yields, resulting in an LEV of 2797 ha^{-1}.

[4] Calculated under conditions of lowest stumpage price and discount rate, highest operational costs, EA-4 growth function, and expected coppice yields, resulting in an LEV of −937 ha^{-1}.

Table 2. LEV, optimum harvest ages and number of stages by biomass price assuming a base scenario of 7% discount rate, \$1800 ha^{-1} site preparation cost, \$1200 ha^{-1} planting cost, and no post-establishment weeding cost

Coppice yields	Growth function	\$10 dry Mg^{-1}		\$20 dry Mg^{-1}		\$30 dry Mg^{-1}	
		LEV (\$ ha^{-1})	Optimum harvest age for each stage (years)	LEV (\$ ha^{-1})	Optimum harvest age for each stage (years)	LEV (\$ ha^{-1})	Optimum harvest age for each stage (years)
Expected[a]	EA-3	−2207	3.0, 3.1, 3.2, 3.4, 4.2	−715	2.8, 2.9, 2.8, 2.7	895	2.8, 2.7, 2.6
	EA-4	−798	3.3, 3.3, 3.3, 3.1	2413	3.2, 3.1, 2.9	5864	3.1, 3.0
Improved[b]	EA-3	−1619	2.8, 2.9, 2.9, 3.0, 3.0	488	2.6, 2.8, 2.7, 2.7, 2.5	2687	2.6, 2.7, 2.6, 2.5
	EA-4	310	3.0, 3.2, 3.2, 3.1, 2.9	4417	2.9, 3.1, 3.0, 2.8	8707	2.8, 3.0, 2.9

[a] 80%, 60%, 40%, and 20% of original growth function for stages 2, 3, 4, and 5, respectively.

[b] 20%, 100%, 80%, and 60% of original growth function for stages 2, 3, 4, and 5, respectively.

Table 3. LEV, optimum number of stages per cycle, change in LEV in response to 1% increase in discount rate, and optimum stage lengths at stumpage prices of \$10, \$20, and \$30 dry Mg^{-1} and discount rates of 4%, 7%, and 10%, assuming \$1800 ha^{-1} site preparation cost, \$1200 ha^{-1} planting cost, EA-4 growth function, expected coppice yields and no weeding costs

	\$10 dry Mg^{-1}			\$20 dry Mg^{-1}			\$30 dry Mg^{-1}		
	4%	7%	10%	4%	7%	10%	4%	7%	10%
LEV (\$ ha^{-1})	\$619	−\$798	−\$1375	\$6507	\$2413	\$762	\$12,960	\$5864	\$3057
Optimum cycle length (years)	13.1	13.0	15.8	9.2	9.2	9.1	6.2	6.1	8.8
Optimum stage lengths (years)	3.4, 3.4, 3.3, 3.0	3.3, 3.3, 3.3, 3.1	3.2, 3.2, 3.3, 3.2, 2.9	3.2, 3.1, 2.9	3.2, 3.1, 2.9	3.1, 3.1, 2.9	3.2, 3.0	3.1, 3.0	3.0, 3.0, 2.8
ΔLEV/+1% discount rate	−\$656	−\$472	−\$192	−\$1908	−\$1365	−\$550	−\$3311	−\$2365	−\$936

The influence of discount rate on profitability and optimum management is summarized in Table 3. The marginal reduction of LEV per percent increase in the cost of capital between 4% and 7% is –\$23 under the least profitable scenario[5] and

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[5] Site preparation cost of \$1800 ha^{-1}, planting cost of \$1200 ha^{-1}, weed control cost of \$200 ha^{-1}, EA-3 growth function (Eq. (4)), expected coppice yields, and \$10 dry Mg^{-1} stumpage price.

Table 4. LEVs and marginal impact on LEVs given changes in site preparation, planting and weeding costs, assuming a 7% discount rate, EA-4 growth function and expected coppice yields

	Input values (\$ ha^{-1})	\$10 dry Mg^{-1}		\$20 dry Mg^{-1}		\$30 dry Mg^{-1}	
		LEV (\$ ha^{-1})	ΔLEV/Δ\$1 cost	LEV (\$ ha^{-1})	ΔLEV/Δ\$1 cost	LEV (\$ ha^{-1})	ΔLEV/Δ\$1 cost
Site preparation (low)	\$900	\$102		\$3313		\$6724	
Site preparation (high)	\$1800[a]	\$−798	−\$1	\$2413	−\$1	\$5824	−\$1
Planting (low)	\$600	\$306		\$3890		\$7621	
Planting (high)	\$1200[a]	\$−798	−\$2	\$2413	−\$2	\$5864	−\$3
Weeding (low)	\$0[a]	\$−798		\$2413		\$5864	
Weeding (high)	\$200	\$−1735	−\$5	\$1403	−\$5	\$4838	−\$5

[a] Base scenario assumptions.

−\$2711 under optimum[6] assumptions. For a base scenario of \$1800 ha^{-1} site preparation cost, \$1200 ha^{-1} planting cost, EA-4 growth function and no weeding costs, the marginal impact of increasing real discount rates one percent ranged from −\$192 to −\$2365. More profitable scenarios are penalized heavily by higher discount rates. Changing discount rates had little effect on optimum stage lengths. Increases in discount rates from 4% to 7% and from 7% to 10% decreased optimum stage lengths by one-tenth of a year or less. At increases from 7% to 10% the model selected an additional growth stage. This effect is consistent with results from Smart and Burgess (2000), who observed that, compared to conventional plantations, in SRWC biomass systems the opportunity cost of the land is proportionally greater than the opportunity cost of the standing biomass, and thus increasing discount rate does not shorten rotations the same as it would with a conventional system. Rather, LEVs are reduced, lowering the opportunity cost of the land relative to the marginal benefit of the stand growth, and stage lengths remain relatively unaffected, while the coppice cycle is extended to delay the cost of replanting.

Increases in operational costs decrease LEV (Table 4). Increases in site preparation costs, which are one-time up-front costs, have a dollar-for-dollar reduction in LEV. LEVs decrease \$2–\$3 per dollar increase in planting costs, with slightly higher marginal impacts at higher stumpage prices, reflecting shorter coppice cycles and increased planting frequency associated with higher stumpage prices. Increasing planting costs from \$600 to \$1200 ha^{-1} also increases optimum stage lengths by 1/10 of a year per growth stage plus an additional growth stage per cycle under the base case scenario. Weed control may be needed to insure high yields,

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[6] Site preparation cost of \$900 ha^{-1}, planting cost of \$600 ha^{-1}, no weed control cost, EA-4 growth function (Eq. (4)), expected coppice yields, and \$30 dry Mg^{-1} stumpage price.

though the exact impact of weed control on growth is not known. LEV is reduced \$5 for every dollar increase in weed control cost applied at the beginning of each growth stage.

LEVs of forestry and agriculture in Florida are in the range of LEVs calculated here. Stumpage prices of \$17 and \$21 dry Mg^{-1} are required to match the LEVs of \$1235 ha^{-1} (representative of LEVs of conventional forestry in Florida (Borders and Bailey, 2001)) and \$2470 ha^{-1} (representative of Florida agricultural land (Reynolds, 2005)), respectively.[7] *Eucalyptus* spp. production costs estimated here are higher than those estimated by Rahmani et al. (1997). We calculated farmgate costs of the above scenarios at \$39–\$43 dry Mg^{-1} assuming a harvest cost of \$22 dry Mg^{-1} (Rahmani et al., 1998), slightly higher than *Eucalyptus* spp. farm gate production costs for Florida of \$32–\$39 dry Mg^{-1} reported by Rahmani et al. (1997). A higher cost of production is expected given the cost of site preparation on CSAs vis-à-vis conventional agricultural lands.

Chapter 378 of the 2004 State of Florida Statutes includes provisions for reimbursement of CSA reclamation costs, ranging from \$4942 to \$9884 ha^{-1} (\$2000–\$4000 acre^{-1}) (State of Florida, 2004). Because it is not known if SRWC establishment would be recognized as a form of CSA reclamation, and because payment would not be a function of stand growth, mined land reclamation incentives are not included in this model. However, providing this reclamation compensation to SRWC systems would greatly contribute to the profitability of SRWC production on CSAs.

Discussion and conclusions

Even assuming high establishment and planting costs (\$1800 and \$1200 ha^{-1}, respectively) and a reasonable stumpage price (\$20 dry Mg^{-1}), production of EA on CSAs in central Florida is profitable, with LEVs ranging from \$762 to \$6507 ha^{-1} assuming discount rates of 10% and 4%, respectively. The influence of stumpage price or discount rate (from 4% to 10%) on optimum stage lengths is less than 1 year. We incorporated the model developed here into a deterministic decision support system in a Microsoft® Excel spreadsheet for end users who wish to assess the profitability of this system under condition-specific parameters in a user friendly format.

In light of uncertainty associated with SRWCs, potential financiers might expect a high rate of return on their investment. These results suggest that SRWCs can be profitable at real rates of 10%, assuming moderately high yields, moderate to high stumpage prices, and low operational costs are achieved. However, further research on SRWC production on CSAs is needed. One opportunity to improve the profitability of these systems is to incorporate incentives for the provision of

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[7] LEVs calculated assuming site preparation costs of \$1800 ha^{-1}, planting costs of \$1200 ha^{-1} and averaging the EA 3 and EA 4 growth functions, equivalent to 24 dry Mg ha^{-1} year^{-1}, and a discount rate of 5%.

environmental benefits, for example carbon sequestration and biodiversity. Additionally, this model could be improved with better knowledge about coppice yields, inputs (prices, operational costs, and reclamation benefits and incentives), and SRWC culture and management. In light of the 2004 and 2005 hurricane seasons, a feasibility analysis incorporating risk assessment could be useful in assessing potential advantages of SRWCs to reduce the probability of hurricane damage vis-à-vis conventional forestry.

Acknowledgments

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Appendix A

Growth and yield functions used in this analysis were developed from SRWC-90, a field trial of SRWC EA and EG on a CSA near Lakeland, FL. SRWC-90 involves planting configurations of single (4200 trees ha^{-1}) and double (8400 trees ha^{-1}) rows per bed, and fertilizer levels (unfertilized and fertilized on May 20th 2002 at a rate of 150 kg ammonium nitrate ha^{-1}) in a split-plot design with configuration main plots, species subplots, and clones in 6-tree row subplots for a total of 1920 trees including borders. Spacing in SRWC-90 is 3.4 m between beds, 0.9 m between trees on a bed, and 0.5 m between adjacent double row trees within a bed. The initial planting for the study was done in March 2001. Tree size and survival were measured on August 20, 2002, July 16, 2003, December 23, 2003, August 27, 2004, and January 11, 2005.

Through destructive sampling of 66 randomly selected trees in an operational area adjacent to the study site, we tested the Max and Burkhart segmented function equation with regression coefficients of Kotzee and Vonck (in Bredenkamp, 2000). Volumes were calculated from both measured and predicted diameters at 2 m intervals. The volumes calculated from prediction diameters were highly correlated with volumes calculated from measured diameters ($p < 0.0001$), while the independent variables DBH, species (EA vs. EG), and surviving density were insignificant ($\alpha > 0.05$). Measured and predicted volumes were normally distributed with constant variance and strongly correlated. The volume prediction equation was then applied to the DBH and height measurements taken on the SRWC-90 study at 1.1, 2.0, 2.5, 3.2 and 3.5 years of age. Predicted volumes were converted to per-hectare stemwood yields assuming specific gravity of 0.40 (Rockwood et al., 1995) (Fig. 2). Decreasing rates of productivity were observed on January 11, 2005 at 3.5 years of age, suggesting an optimizable function could be fit to the data for use in the model.

Treatments 3 (single row) and 4 (double row) were identified as being representative of moderately low and moderately high yields when compared to SRWC yields from other areas of the CSA, and EA was identified as a likely candidate species due to (a) greater frost resistance than EG, which allows flexibility

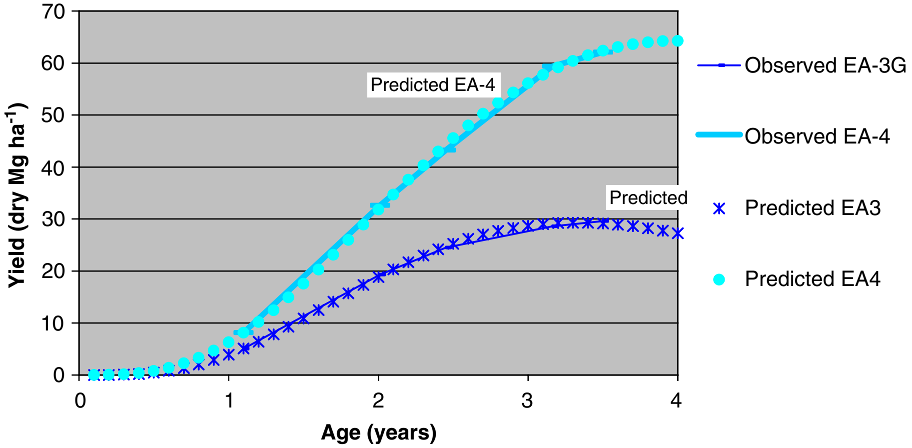

Fig. 1. Observed and predicted inside bark stem yields of EA-3 and EA-4, reflecting planting of 4200 (single row) and 8400 (double row) trees ha^{-1}, respectively.

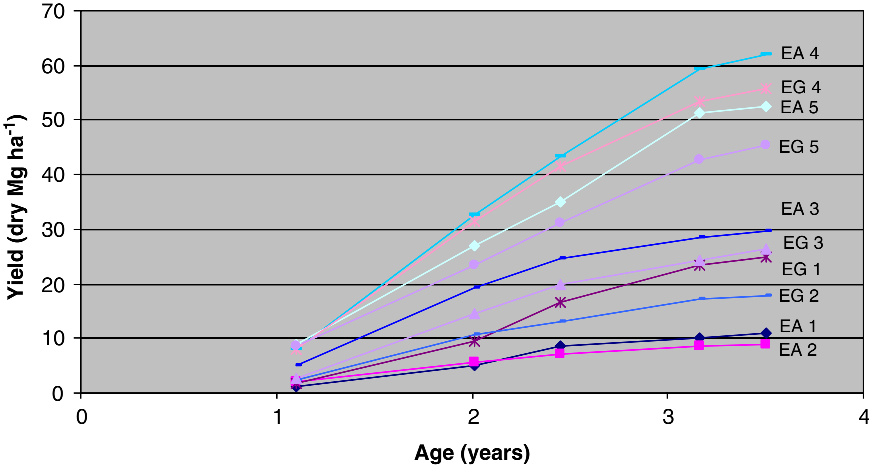

Fig. 2. Inside bark yields (dry Mg ha^{-1}) of EA and EG on a CSA near Lakeland, Florida for five treatments: (1) 4200 trees ha^{-1}, unfertilized, (2) 8400 trees ha^{-1}, unfertilized, (3) 4200 trees ha^{-1}, fertilized with 150 kg ha^{-1} ammonium nitrate on May 20 2002 at 11 months, (4) 8400 trees ha^{-1}, fertilized as treatment 3, and (5) same as treatment 2.

to plant in late summer during increased rainfall with minimum frost damage to small trees the subsequent winter and (b) higher yields than EG despite being planted two months later. Therefore, EA treatment 3 (EA-3) and EA treatment 4 (EA-4) were selected as representative single and double row planting yields. Nonlinear regression was used to fit the yield data to the functional form

$$B(t) = \mathrm{e}^{[b+c\ \ln(t)-d(t)]}, \tag{4}$$

where $B(t)$ is dry stemwood biomass ($\mathrm{Mg\,ha^{-1}}$) as a function of stand age t in years for the first stage, and b, c and d are the estimated parameters 2.57, 4.00 and 1.20 for EA-3 and 2.76, 3.67 and 0.92 for EA-4, respectively (Figs. 1 and 2) ($R^2 > .99$).

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