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The influence of CO_2 mitigation incentives on profitability of eucalyptus production on clay settling areas in Florida

Matthew Langholtz[a,*], *Douglas R. Carter*[b], *Donald L. Rockwood*[b], *Janaki R.R. Alavalapati*[c]

[a]*BioResource Management, Inc., 3520 NW 43rd Street, Gainesville, FL 32606, USA*
[b]*School of Forest Resources and Conservation, University of Florida, P.O. Box 110410, Gainesville, FL 32611-0410, USA*
[c]*College of Natural Resources, Virginia Polytechnic Institute and State University, 313 Cheatham Hall, Blacksburg, VA 24061, USA*

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ABSTRACT

Fast growing, short-rotation tree crops provide unique opportunities to sequester carbon on phosphate-mined lands in central Florida and, if used as a biofuel, can reduce CO_2 emissions associated with electricity generation. Base case land expectation values (LEVs) of phosphate-mined land under *Eucalyptus amplifolia* (EA) forestry range from 762 to 6507 $\$\,ha^{-1}$ assuming real discount rates of 10% and 4%, respectively. Assuming 5 $\$\,Mg^{-1}$ C, these LEVs increase from 3% to 24% with incentives for *in situ* carbon sequestration benefits, or 21% to 73% given *in situ* carbon sequestration with additional incentives for reducing CO_2 emissions through the use of EA as an energy feedstock. Potential benefits from below-ground C sequestration and mine land reclamation are estimated to be worth an additional 5642–11,056 $\$\,ha^{-1}$.

1. Introduction

Central Florida produces 75% of the United States' and 25% of the world's phosphate supply, primarily used for fertilizer [1]. There are about 1,620 Mm^2 of phosphate-mined lands in Florida [2]. Phosphate was mined from more than 69 Mm^2 in central and north Florida from July 1975 through December 2002 and is increasing by 20 25 Mm^2 annually [3]. Here we quantify values of environmental services that may be provided by short-rotation woody crop (SRWC) plantations on phosphate-mined lands in Florida.

During phosphate mining, clays are washed from phosphate ore, and the resulting slurry of water and clay is pumped into clay settling areas (CSAs). CSAs comprise about 40% of the phosphate-mine lands and are 10–20 m deep. There are approximately 647 Mm^2 (160,000 acres) of undeveloped CSAs in central Florida [4]. These CSAs, classified as clayey Haplaquents [5], are characterized by poor drainage, high bulk density, high levels of P, K, and micronutrients, and pH of 7.0–8.3. They are commonly dominated by cogongrass (*Imperata cylindrica*), an invasive exotic species in Florida that is difficult to control [6]. CSAs can take about 15 y to dry and stabilize. While CSAs may be leased for cattle grazing for 35–40 $\$\,ha^{-1}\,y^{-1}$ they are typically left idle because of operational difficulties.

Langholtz et al. [7] calculate land expectation values (LEV) for *Eucalyptus amplifolia* (EA) on CSAs in central Florida. LEV

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[*] *Corresponding author*.
E-mail address: ml@bio-resource.com (M. Langholtz).

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expresses the discounted cash flow value of bare land in perpetual timber or biomass production. They report that EA production is likely to be profitable under reasonable scenarios, with LEVs ranging from 762 to 6507 $ ha^{-1} assuming real discount rates of 10% and 4%, respectively, establishment costs of 1800 $ ha^{-1}, planting costs of 1200 $ ha^{-1}, planting density of 8400 trees ha^{-1}, and a stumpage price of 20 $ dry Mg^{-1}. However, SRWC production on CSAs is currently in initial phases of development, and actual operational costs are not known. In light of this uncertainty, potential EA producers might seek innovative market opportunities to improve the profitability of this largely experimental silvicultural system. Markets for environmental services can improve the profitability of SRWC production on CSAs.

One environmental service that would be provided by the production of SRWCs on CSAs is atmospheric CO_2 mitigation. Global carbon trading has increased from 13 Tg CO_2 in 2001 to 2.5 Pg CO_2 in 2007 [8,9]. Establishing tree plantations on non-forested CSAs sequesters carbon by increasing the amount of C per area of land [10]. Chaturvedi and Sims [11] emphasize the benefit of sequestering C on land with low carbon density, such as deforested or degraded lands. An advantage of SRWC production on CSAs is the near-zero C density of the land prior to plantation establishment, as the land is bare of vegetation with little accumulation of soil organic carbon following mining. Even on 20–40 y-old CSAs, C density is likely to remain low if forest cover is not established. Research suggests that SRWCs sequester and maintain soil organic carbon (SOC) [12].

In addition to C sequestration *in situ*, if used as a dedicated feedstock supply system (DFSS) for biofuels, SRWC plantations can mitigate atmospheric CO_2 by displacement of CO_2 emissions associated with the combustion of fossil fuels [13–16]. The displacement of fossil fuels by biomass fuels can be a more effective way to mitigate atmospheric CO_2 than with sequestration. While *in situ* sequestration of C eventually reaches a plateau of accumulation in a climax stand and below-ground carbon, sustainably produced biomass used to displace fossil fuels can reduce CO_2 emissions in perpetuity. In the long-term, the cost per Mg of CO_2 is cheaper with displacement rather than sequestration, as land remains available for continued production in the future, rather than being taken out of production to avoid releasing sequestered carbon. Finally, reductions of net CO_2 emissions from fuel switching are not as risk prone as C sequestered *in situ*, which is susceptible to future events such as fire or land-use change. These benefits are elaborated by Eriksson et al., 2002 [17].

Though SRWC production on CSAs has been identified as an opportunity to produce income from a land base with low opportunity cost and provide environmental services [18], the impact of incentives for C sequestration and CO_2 emission reductions on the profitability of this SRWC system has not been studied. We extend Langholtz et al.'s [7] model by including an incentive for a) *in situ* sequestration for a mulch production scenario and b) *in situ* sequestration coupled with emission reduction through fossil fuel displacement for a biofuel production scenario. We then use these models to estimate profitability and determine optimal management of the SRWC production system.

2. Methodology

Langholtz et al. [7] assessed the profitability of EA cultivation on CSAs using a modified Faustmann model as described by Medema and Lyon [19], accounting for multiple growth stages (harvest rotations) for each coppice cycle (life of a tree) in calculating LEV. Hartman [20] internalized non-timber benefits (NTBs) into a Faustmann formula, and Smart and Burgess [21] internalized NTBs in calculations of LEV for SRWC systems. The basic Faustmann model modified by Medema and Lyon [19] to calculate net returns given a fixed number of stages (*n*) is

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

where

$t_0 = 0$
n = the number of stages, s,
$V(t)$ = the growth function for stage s at time t times biomass price,
r = the real discount rate,
C_s = costs of stage s at the start of the stage.

The application of Eq. (1) to evaluate SRWCs on CSAs excluding environmental services is described by Langholtz et al. [7]. Here we expand Eq. (1) to internalize the CO_2 mitigation service associated with each coppice stage of a coppice cycle projected in perpetuity.

Trees sequester atmospheric CO_2 in woody biomass as they grow. The value of standing above-ground C at time t for coppice stage s, assuming stage growth function $g(t)$, carbon content of 47% by weight [22], and multiplying by 1.7 to convert stem inside bark to total above-ground biomass (Mg ha^{-1}) [based on Refs. [23,24]] can be estimated as

$$\mathrm{CSA}_s(t)=g_s(t)\cdot C_p\cdot 0.8 \tag{2}$$

where $g_s(t)$ is the growth function for growth stage s as a function of time and C_p is the price of carbon. Once carbon is sequestered there is no further benefit from it, so the derivative of Eq. (2) is used to calculate the marginal benefit of the C sequestration service, yielding

$$\mathrm{CB}_s^A=\int_0^t\left(\frac{d}{dt}(\mathrm{CSA}_s(t))\cdot e^{(-r\cdot t)}\right)dt \tag{3}$$

where the above-ground C sequestration benefit of stage s is the definite integral of the flow of the carbon benefit discounted to the beginning of the stage, for the duration of the stage.

Central to the concept of carbon sequestration is the life span of the sequestered carbon, either in the ecosystem, or in products derived from harvests from the ecosystem [25]. As wood products burn or decay, sequestered carbon is re-emitted to the atmosphere in the form of CO_2, countering the benefit achieved by the sequestered C. This societal cost of the decay or oxidation of the sequestered carbon must be calculated and subtracted from Eq. (3). The rate of re-emission depends on the end use of the wood products. The two most likely products identified by an SRWC market survey in Polk County are mulch and bioenergy feedstock. The decay of C sequestered in these two products is accounted for differently.

The societal cost of CO_2 emissions from the decay of mulch harvested from stage s at age t, where y is the life of the biomass in years assuming linear decay, discounted first to the end of the growth stage at discount rate r is given as

$$C_s^M(t) = \left[\frac{CSA_s(t)}{y} \cdot \left(\frac{1-e^{(-r\cdot y)}}{r}\right)\right] \cdot e^{(-r\cdot t)} \tag{4}$$

For example, for y = 5, one-fifth of the harvested mulch would decay during each of five years. Subtracting the right hand side of Eq. (4) from the right hand side of Eq. (3) assuming that mulch decays in five years [26,27] yields

$$NTB_s^M = \left[\int_0^t \left(\frac{d}{dt}(CSA_s(t)) \cdot e^{(-r\cdot t)}\right) dt\right] - \left[\frac{CSA_s(t)}{5} \cdot \left(\frac{1-e^{(-r\cdot 5)}}{r}\right)\right] \cdot e^{(-r\cdot t)} \tag{5}$$

which is the integration of the marginal value of above-ground C sequestration discounted to the beginning of the growth stage, minus the societal cost of CO_2 emissions associated with mulch decay discounted first from the time of decay to the end of the growth stage and then discounted to the beginning of the growth stage. Though actual mulch decay is non-linear and may take longer than five years, the decay function in Eq. (4) was chosen to simplify the analysis and provide a conservative estimate of the net C sequestration benefit.

This NTB calculated in Eq. (5) is then included in the optimization model for each growth stage of the mulch scenario and discounted to the beginning of the coppice cycle. By incorporating Eq. (5) into Eq. (1), we get Eq. (6). To elucidate the discounting of each benefit and cost in the model, an example of Eq. (6) fixed for two stages is shown in Eq. (7), including the planting cost C^P at the beginning of the growth cycle, weeding cost C^W at the beginning of each growth stage, annual maintenance cost C_a and a one-time establishment cost C_i.

$$LEV_{mulch}(t) = \frac{\sum_{s=1}^{n}\left[V(t_s) \cdot e^{\left(-r\cdot \sum_{j=1}^{s} t_j\right)} + \left[\int_0^t \left(\frac{d}{dt}(CSA_s(t)) \cdot e^{(-r\cdot t)}\right) dt\right] \cdot e^{\left(-r\cdot \sum_{j=1}^{s} t_{j-1}\right)} - \left[\frac{CSA_s(t)}{5} \cdot \left(\frac{1-e^{(-r\cdot 5)}}{r}\right)\right] \cdot e^{\left(-r\cdot \sum_{j=1}^{s} t_j\right)} - C_s \cdot e^{\left(-r\cdot \sum_{j=1}^{s} t_{j-1}\right)}\right]}{1-e^{\left(-r\cdot \sum_{j=1}^{n} t_j\right)}} \tag{6}$$

$$LEV_{mulch}(t) = \frac{\begin{array}{l}\left(V(t_1) \cdot e^{(-r\cdot t_1)} + \left[\int_0^t \left(\frac{d}{dt}(CSA_s(t)) \cdot e^{(-r\cdot t)}\right) dt\right] - \left[\frac{CSA_s(t)}{5} \cdot \left(\frac{1-e^{(-r\cdot 5)}}{r}\right)\right] \cdot e^{(-r\cdot t_1)} - (C^P + C^W)\right) \\ +\left(V(t_2) \cdot e^{(-r\cdot (t_1+t_2))} + \left[\int_0^t \left(\frac{d}{dt}(CSA_s(t)) \cdot e^{(-r\cdot t)}\right) dt\right] \cdot e^{(-r\cdot t_1)} - \left[\frac{CSA_s(t)}{5} \cdot \left(\frac{1-e^{(-r\cdot 5)}}{r}\right)\right] \cdot e^{(-r\cdot (t_1+t_2))} - C^W \cdot e^{(-r\cdot t_1)}\right)\end{array}}{1-e^{(-r\cdot (t_1+t_2))}} - \left(\frac{C_a}{1-e^{-r}}\right) - C_i \tag{7}$$

Calculation of the societal costs associated with biofuel emissions must be handled differently than Eq. (4). SRWCs harvested as DFSSs for gasification or co-firing with coal are likely to be oxidized and returned to the atmosphere as CO_2 within zero to six months of harvest. However, as described above, CO_2 emissions from sustainably produced (i.e., closed-loop) biofuels are re-sequestered in the subsequent rotation, displacing the use of fossil fuels with closed-loop biofuel resulting in no net CO_2 emissions from biomass combustion, and reducing fossil fuel emissions. Thus, bioenergy from DFSSs produces no net CO_2 emissions, eliminating the need to calculate the costs of post-harvest biomass C decay. However, recognizing that there are fossil fuel inputs to the cultivation, harvest, and processing of SRWC DFSSs consuming up to 10% of the energy produced by the bioenergy system [28–30], 10% of the carbon sequestration benefit achieved at stage age t is discounted to the beginning of the stage and subtracted from the carbon benefit calculated by Eq. (3). Assuming this penalty is incurred at harvest at the end of each growth stage yields:

$$NTB_s^{BF} = \left[\int_0^t \left(\frac{d}{dt}(CSA_s(t)) \cdot e^{(-r\cdot t)}\right) dt\right] - [(0.1 \cdot CSA_s(t))] \cdot e^{(-r\cdot t)} \tag{8}$$

The net NTB calculated for each growth stage for the biofuel scenario in Eq. (8) is then added to Eq. (1), resulting in Eq. (9). Eq. (10) is an example of Eq. (9) fixed for two growth stages.

$$LEV_{biofuel}(t) = \frac{\sum_{s=1}^{n}\left[\begin{array}{l}V(t_s) \cdot e^{\left(-r\cdot \sum_{j=1}^{s} t_j\right)} + \left[\int_0^t \left(\frac{d}{dt}(CSA_s(t)) \cdot e^{(-r\cdot t)}\right) dt\right] \cdot e^{\left(-r\cdot \sum_{j=1}^{s} t_{j-1}\right)} \\ -[(0.1 \cdot CSA_s(t))] \cdot e^{\left(-r\cdot \sum_{j=1}^{s} t_j\right)} - C_s \cdot e^{\left(-r\cdot \sum_{j=1}^{s} t_{j-1}\right)}\end{array}\right]}{1-e^{\left(-r\cdot \sum_{j=1}^{n} t_j\right)}} \tag{9}$$

$$\mathrm{LEV_{biofuel}}(t)=\frac{\left[\begin{array}{l} V(t_1)\cdot e^{(-r\cdot t_1)}+\left[\int_0^t\left(\frac{d}{dt}(CSA_s(t))\cdot e^{(-r\cdot t)}\right)dt\right]-[(0.1\cdot CSA_s(t))]\cdot e^{(-r\cdot t_1)}-\left(C^P+C^W\right)\Bigg) \\ +\Bigg(V(t_2)\cdot e^{(-r\cdot(t_1+t_2))}+\left[\int_0^t\left(\frac{d}{dt}(CSA_s(t))\cdot e^{(-r\cdot t)}\right)dt\right]\cdot e^{(-r\cdot t_1)}-[(0.1\cdot CSA_s(t))]\cdot e^{(-r\cdot(t_1+t_2))}-C^W\cdot e^{(-r\cdot t_1)}\end{array}\right]}{1-e^{(-r\cdot(t_1+t_2))}}-\left(\frac{C_a}{1-e^{-r}}\right)-C_i \tag{10}$$

Thus, Eqs. (6) and (9) are used for incorporating C externalities in mulch and biofuel production scenarios, respectively. These models, with Eq. (1) for optimization without incorporation of externalities, are used to calculate LEV and optimum age of each of *n* number of growth stages. The process is repeated iteratively adding an additional growth stage for each scenario until the marginal benefit of the additional stage is negative, identifying the optimum number of growth stages per coppice cycle and associated LEVs. Finally, the sensitivity of these LEVs to variation in the model inputs is assessed. Effects of incentives for below-ground carbon sequestration and mine land reclamation are estimated separately.

3. Model inputs

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 [4]. Representative yields from SRWC-90 used in this analysis include EA at low (single row planting of 4200 trees ha^{-1}) and high (double row planting of 8400 trees ha^{-1}) planting densities, and we assume coppice yields declining 20% per stage. Derivation of the growth and yield function and explanation of the planting design, species selection, and coppice yields are described by Langholtz et al. [7].

The Kyoto Protocol was ratified by 140 nations on February 16th, 2005, strengthening ongoing efforts to reduce greenhouse gas emissions. Estimates for world carbon prices range from about 5 to 27 \$ Mg^{-1} C [31], with 5 \$ Mg^{-1} C typical of current forestry projects (Van Soestbergen, personal communication, September 11th, 2006). C prices assumed in this model range from 0 to 35 \$ Mg^{-1} C. To assess the impact of CO$_2$ mitigation incentives *vis-à-vis* the basic SRWC economic analysis, the model was run using the same range of assumptions as those described by Langholtz et al. [7], described in Table 1.

4. Results and sensitivity analysis

The above discussed model was optimized for the three scenarios (no NTB, *in situ* C sequestration in mulch production, and *in situ* C sequestration with CO$_2$ displacement derived from bioenergy production), under all combinations of discount rates (4%, 7%, and 10%), site preparation costs (900 and 1800 \$ ha^{-1}), planting costs (600 and 1200 \$ ha^{-1}), weed control costs (0 and 200 \$ ha^{-1}), planting density (4200 and 8400 trees ha^{-1}) and biomass stumpage prices (10, 20 and 30 \$ dry Mg^{-1} assuming whole-tree above-ground harvesting) for a fixed C sequestration incentive of 5 \$ Mg^{-1}. Additionally, at a base scenario (7% discount rate, 1800 \$ ha^{-1} site preparation cost, and 1200 \$ ha^{-1} planting cost), sensitivity of LEV and rotation age to increased C prices (15, 25 and 35 \$ Mg^{-1}) was tested. LEVs exclude below-ground C sequestration benefits which are estimated independently below.

Table 2 shows LEVs, optimum number of stages per cycle, and optimum stage lengths by NTB scenario and stumpage price assuming a base scenario of 7% discount rate, 1800 \$ ha^{-1} site preparation cost, 1200 \$ ha^{-1} planting cost and a carbon price of 5 \$ Mg^{-1} C. These results are comparable to LEVs of an SRWC system in the United Kingdom reported by Smart and Burgess [21] of 2395, 4634 and, 13,289 \$ ha^{-1} for market only, low NTB and high NTB model scenarios, respectively (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). Increasing stumpage price decreases the optimum number of stages per cycle (Table 2).

Raising incentives for CO$_2$ mitigation increases LEV (Table 3). Under a base scenario of 20 \$ dry Mg^{-1} stumpage price, 7% real discount rate, site preparation 1800 \$ ha^{-1}, planting cost 1200 \$ ha^{-1}, 8400 trees ha^{-1} planting density and no post-establishment weeding, increasing the price of C from 0 to 35 \$ Mg^{-1} increased LEVs from 2413 to 3788 and 2413 to 7915 \$ ha^{-1} for the mulch and biofuel scenarios, respectively. The marginal increase in LEV per dollar increment in C price is 39 and 157 \$ ha^{-1} in the mulch and biofuel scenarios, respectively. At a 4% discount rate, the marginal benefit in the biofuel scenario was both higher and more responsive to increases in C price, ranging from a marginal increase of 272 to 292 \$ ha^{-1} at 5 and 35 \$ Mg^{-1} C, respectively. The source of this increase was a transition from three to two stages as the price of carbon increased from 15 to 25 \$ Mg^{-1}. This reflects that the biofuel model is less penalized by post-harvest decay of sequestered C, thus increasing incentives for biofuel production rather than *in situ* sequestration.

Table 1 – Summary of model inputs.

Activity/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}
Real discount rate	N/A	4%, 7%, and 10%
Stumpage price	N/A	10, 20 and 30 \$ dry Mg^{-1}
Growth function	N/A	Low and high yield curves

Table 2 – LEV, optimum number of stages and optimum stage length for each stage by growth function, NTB benefit scenario, and biomass price under a base scenario of 7% discount rate, 1800 $ ha^{-1} site preparation cost, 1200 $ ha^{-1} planting cost and a carbon price of 5 $ Mg^{-1} C.

Planting density (TPH)	NTB scenario	10 $ dry Mg^{-1}		20 $ dry Mg^{-1}		30 $ dry Mg^{-1}	
		LEV ($ ha^{-1})	Optimum harvest age (y)	LEV ($ ha^{-1})	Optimum harvest age (y)	LEV ($ ha^{-1})	Optimum harvest age (y)
4200	None	−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
4200	Mulch	−2126	3.0, 3.1, 3.2, 3.3, 3.9	−659	2.9, 2.9, 2.8, 2.7	996	2.8, 2.8, 2.6
4200	Biofuel	−1885	3.0, 3.0, 3.1, 3.2, 3.3	−376	2.8, 2.8, 2.9, 2.7	1313	2.8, 2.7, 2.6
8400	None	−798	3.3, 3.3, 3.3, 3.1	2413	3.2, 3.1, 2.9	5864	3.1, 3.0
8400	Mulch	−616	3.3, 3.3, 3.3, 3.1	2608	3.2, 3.1, 2.9	6029	3.1, 3.0
8400	Biofuel	−88	3.3, 3.3, 3.2, 3.0	3197	3.2, 3.1, 2.9	6677	3.1, 3.0

The marginal impact of increasing discount rates between 4% and 10% ranged from −192 to −2581 $ ha^{-1} for a base scenario of 1800 $ ha^{-1} site preparation cost, 1200 $ ha^{-1} planting cost, carbon price of 5 $ Mg^{-1}, 8400 trees ha^{-1} planting density and no weeding costs (Table 4). More profitable scenarios are penalized more by higher discount rates.

Increases in discount rates from 4% to 7% and from 7% to 10% decreased optimum stage lengths by 0.1 y or less (Table 4). Increasing discount rates from 7% to 10% can increase the optimum number of growth stages per cycle. This effect is consistent with results from Smart and Burgess [21], who observe that in SRWC biomass systems the opportunity cost of the standing biomass is low relative to the opportunity cost of the land. Thus, increasing discount rate does not shorten rotations 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.

5. Additional benefits

Three additional environmental services provided by SRWC production on CSAs include 1) C sequestration in SOC, 2) C sequestration in roots, and 3) mine land reclamation. Because compensation for these services is speculative and their relationships with SRWC growth and harvest scheduling are not well known, they are estimated below as potential additional benefits. Compensation for these additional services would increase LEVs.

Currently available information about SOC accumulation on CSAs is limited to one reference. Wullschleger et al. [32] found that on a 25-y-old CSA, SOC under 2.5-y-old plantation of *Eucalyptus grandis* (EG) at a planting density of 9800 trees ha^{-1} accumulated 151 and 96 Mg ha^{-1} more than SOC under cogongrass in soil depths of 0–30 cm and 30–60 cm, respectively. Their model of soil carbon dynamics estimated that a SRWC EG plantation contributes to the storage of an additional 274 Mg ha^{-1} C after 25 y, reaching an additional 354 Mg ha^{-1} C after 50 y. A polynomial function fitted to the data simulation yields

$$\mathrm{SOC}(t) = -0.1668 \cdot t^2 + 15.084 \cdot t \qquad (11)$$

where SOC (Mg ha^{-1}) is expressed as a function of time t (years) after SRWC plantation establishment on a CSA. Eq. (11) is then used in the calculation of the NPV of the carbon sequestration service as the discounted marginal benefit to the year 45:

$$\mathrm{CB}^{\mathrm{SOC}} = \left[\int_0^t \left(\frac{d}{dt}(\mathrm{SOC}(t)) \cdot e^{(-r \cdot t)} \right) dt \right] \qquad (12)$$

Table 3 – LEV ($ ha^{-1}), optimum stage lengths, marginal benefit, and estimated below-ground benefit ($ ha^{-1}) by C sequestration incentive ($ Mg^{-1}).

$ Mg^{-1} C	LEV ($ ha^{-1})	Optimum stage lengths (y)	Marginal benefit (ΔLEV per $ C incentive)	Below-ground ($ ha^{-1})
	Mulch scenario			
0	2413	3.2, 3.1, 2.9	n/a	n/a
5	2608	3.2, 3.1, 2.9	39	893
15	3000	3.2, 3.1, 2.9	39	2679
25	3394	3.2, 3.1, 2.9	39	4466
35	3788	3.3, 3.2, 2.9	39	6271
	Biofuel scenario			
0	2413	3.2, 3.1, 2.9	n/a	n/a
5	3197	3.2, 3.1, 2.9	157	893
15	4769	3.2, 3.1, 2.8	157	2679
25	6342	3.2, 3.1, 2.8	157	4466
35	7915	3.2, 3.0, 2.8	157	6252

Table 4 – LEV (\$ ha^{-1}), change in LEV per 1% increase in discount rate, and optimum harvest scheduling (stage lengths and number of stages per cycle) assuming 1800 \$ ha^{-1} site preparation cost, 1200 \$ ha^{-1} planting cost, carbon price of 5 \$ Mg^{-1} C, 8400 trees ha^{-1} planting density and no weeding costs, without C sequestration incentives, *in situ* C sequestration for the mulch production scenario, and *in situ* C sequestration plus CO_2 emission reduction for the biofuel production scenario.

	% Discount rate	10 \$ dry Mg^{-1}			20 \$ dry Mg^{-1}			30 \$ dry Mg^{-1}		
		LEV (\$ ha^{-1})	ΔLEV/+1% discount	Optimum stage lengths (y)	LEV (\$ ha^{-1})	ΔLEV/+1% discount (\$ ha^{-1})	Optimum stage lengths (y)	LEV (\$ ha^{-1})	ΔLEV/+1% discount (\$ ha^{-1})	Optimum stage lengths (y)
No NTB	4%	619	–	3.4, 3.4, 3.3, 3.0	6507	–	3.2, 3.1, 2.9	12,960	–	3.2, 3.0
	7%	−798	−472	3.3, 3.3, 3.3, 3.1	2413	−1365	3.2, 3.1, 2.9	5864	−2365	3.1, 3.0
	10%	−1375	−192	3.2, 3.2, 3.3, 3.2, 2.9	762	−550	3.1, 3.1, 2.9	3057	−936	3.0, 3.0, 2.8
Mulch scenario	4%	810	–	3.4, 3.4, 3.3, 3.0	6715	–	3.2, 3.1, 2.9	13,140	–	3.2, 3.0
	7%	−616	−475	3.3, 3.3, 3.3, 3.1	2608	−1369	3.2, 3.1, 2.9	6029	−2370	3.1, 3.0
	10%	−1213	−199	3.3, 3.3, 3.3, 3.2, 3.8	946	−554	3.1, 3.1, 2.9	3239	−930	3.1, 3.0, 2.8
Biofuel scenario	4%	1832	–	3.4, 3.4, 3.3, 2.9	7869	–	3.2, 3.1, 2.9	14,419	–	3.1, 3.0
	7%	−88	−640	3.3, 3.3, 3.2, 3.0	3197	−1557	3.2, 3.1, 2.9	6677	−2581	3.1, 3.0
	10%	−880	−264	3.2, 3.3, 3.2, 3.1, 2.5	1315	−627	3.1, 3.1, 2.9	3611	−1022	3.1, 3.0, 2.7

Summing the discounted marginal benefits of SOC sequestration yields the values shown in Table 5.

C sequestration in root biomass can be estimated as a function of above-ground growth. Though the actual response of SRWC root biomass to harvest scheduling is not known, it could be assumed that root biomass peaks after the first harvest and remains steady in subsequent coppice stages and cycles, where decay of dead root systems is replaced by regrowth. Root systems of EG grown in a clay settling area in central Florida were 40% of the total biomass [23], or 68% of the above-ground biomass. Thus, carbon storage in roots can be estimated as the growth function multiplied by 1.7 to convert to total above-ground biomass, by 0.68 to estimate root biomass, and by 0.47 to convert biomass to carbon, or by a combined factor of the growth function multiplied by 0.54. Under sustained yield SRWC management, it could be assumed that biomass in root systems peaks during the coppice stage that produces the greatest above-ground biomass, and remains steady in subsequent coppice stages and cycles, where decay of dead root systems is replaced by regrowth. Anecdotal evidence from SRWC trials in central Florida suggest that greatest yields occur during the first coppice stage and decline in subsequent coppice stages. Therefore, the value of C sequestration in root systems from the first growth stage ($s = 1$) at time t can be defined as

$$C_1^R(t) = g(t)\cdot 0.54\cdot P_C \tag{13}$$

The derivative of Eq. (13) is the value of the carbon sequestered in roots discounted to plantation age 0:

$$CB_1^R = \left[\int_0^t \left(\frac{d}{dt}(C_1^R(t))\cdot e^{(-r\cdot t)}\right)dt\right] \tag{14}$$

Year t in Eq. (14) is determined by the length of the first growth stage. With better information about the response of root growth to harvest scheduling, Eq. (14) could be included in Eqs. (6) and (9). Lacking this information, we solve equations for lowest and highest optimum lengths of the first growth stage, and include this range of values in Table 5.

The actual SOC sequestration process is certainly more complicated than Eqs. (11) and (13) suggest. However, lacking better data, we use Eqs. (12) and (14) to estimate the additional benefit of below-ground (root + SOC) C sequestration.

As a result of high bulk density, high pH, and the invasion of cogongrass, CSAs are slow to naturally revegetate and are difficult to put into agricultural or forestry production. Chapter 378 of the 2004 State of Florida Statutes includes provisions for reimbursement of CSA reclamation costs, ranging from 4942–9884 \$ ha^{-1} [33]. Because it is not known if SRWC establishment would be recognized as a form of CSA reclamation, potential mined-land reclamation incentives are presented as possible additional benefits. Low and high total values for the three potential additional benefits are shown in Table 5, which illustrates great potential to increase LEVs.

Table 5 – Discounted values (\$ ha^{-1}) of C sequestration in soil organic carbon, C sequestration in root biomass, mined-land reclamation incentives, and low and high totals, assuming a C price of 5 \$ Mg^{-1} C, representing potential additional benefits that could be added to LEVs.

Discount rate	Soil organic carbon sequestration	Carbon sequestration in root biomass	Potential mined-land reclamation incentives	Low total	High total
4%	1014	123–158	4942–9884	6079	11,056
7%	751	117–149	4942–9884	5810	10,784
10%	589	111–140	4942–9884	5642	10,584

6. Conclusions

Assuming high establishment and planting costs (1800 and 1200 $ ha^{-1}, respectively), a moderate stumpage price (20 $ dry Mg^{-1}), a high planting density (8400 trees ha^{-1}) and excluding C sequestration incentives, 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 [7]. With the incorporation of an above-ground *in situ* C sequestration benefit of 5 $ Mg^{-1} C, LEVs increase 24% and 3% (to 946 and 6715 $ ha^{-1}). Recognizing the additional CO_2 mitigation benefits associated with the biofuel scenario increases LEVs 73% and 21% (to 1315 and 7869 $ ha^{-1}), assuming real discount rates of 10% and 4%, respectively. In addition, the societal value of below-ground C sequestration (roots + SOC at 5 $ Mg^{-1} C) is estimated at 700 and 1137 $ ha^{-1} at discount rates of 10% and 4%, respectively. Depending on future State of Florida legislation, mined-land reclamation incentives could provide an additional 4942–9884 $ ha^{-1}.

The influence of stumpage price, C sequestration benefit (CO_2 mitigation scenario or C price) or discount rate (from 4% to 10%) on optimum stage lengths is less than 1 y, and is probably operationally unimportant. Because of the short growth stages, penalties for post-harvest CO_2 emissions from product decay are discounted much less than those of conventional rotations of 20 or more years, countering benefits of *in situ* C sequestration, and underscoring the importance of recognizing the CO_2 mitigation benefit of displacing fossil fuels in the biofuel scenario.

It is important to recognize that the SRWC plantations evaluated here may or may not qualify for C mitigation incentives. There are varying levels of requirements in the project screening criteria of different reduction regimes. For example, only projects that are not profitable without carbon credits are approved for funding under the Kyoto Protocol. Considering that bioenergy projects in Florida will probably need a feedstock cost below 20 $ dry Mg^{-1} to be competitive with conventional fuels, our results indicate that at base case operational costs with a stumpage price of 10 $ dry Mg^{-1}, the-system is not profitable, with LEVs ranging from −2207 to −88 $ ha^{-1}. However, our results also suggest that every dollar increase in the price of carbon could increase LEVs by 157 $ ha^{-1} in the biofuel scenario, and possibly an additional 179 $ ha^{-1} for below-ground sequestration. Thus, currently unprofitable scenarios could become feasible as carbon benefits are increased. These results can be used to indicate the profitability of this biomass production system and, thus, its eligibility for C incentives under different regimes, and could be an important component of a methodology to validate carbon benefits of mined-land reclamation in Florida and elsewhere.

These results emphasize both the potential for DFSSs on CSAs to mitigate atmospheric CO_2, and for CO_2 mitigation incentives to contribute to the profitability of SRWC production. Increases in LEV from CO_2 displacement benefits are 3–6 times the increases gained from *in situ* sequestration in above-ground biomass. It would probably be impractical to provide incentives and penalties for the sequestration and decay of C for SRWC systems on a per-harvest basis, given the frequent harvest rate *vis-à-vis* conventional forestry systems. However, this model might be used to assess the present value of CO_2 mitigation benefits over the life of the stand, providing the opportunity to offer incentives without monitoring each biomass harvest. Though payment of C sequestration benefits independent of harvest monitoring could cause a divergence of private and socially optimum harvesting, these results suggest there is little difference in optimum harvest scheduling of private versus socially optimal SRWC production when accounting for C sequestration or CO_2 emission reduction. In fact, both optimum stage lengths and optimum stages per coppice cycle decrease in the biofuel production scenario, indicating that harvest monitoring might not be needed for a successful CO_2 mitigation program. In the biofuel production scenario, probably the easiest way to incorporate CO_2 mitigation benefits would be for utilities to pass on CO_2 emission reduction incentives to producers by increasing stumpage price.

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 discount rates of 10%, assuming some combination of adequate yields, stumpage prices, NTB incentives and/or operational costs are achieved.

7. Future research

Research is needed to verify the assumptions made in this analysis. The most immediate need is for a better understanding of growth response to treatment options such as weeding and fertilization. With more information, particularly with regards to below-ground C sequestration, growth functions and coppice growth, this model can be used to make case-specific evaluations. A better understanding of long-term impacts of SRWC production on CSAs and eligibility for mined-land reclamation incentives would be beneficial. Because reclamation incentives potentially surpass C sequestration benefits, valuation of reclamation benefits and incorporation of those values into the above analysis would be useful. In light of the 2004 hurricane season, a feasibility analysis incorporating risk assessment could be useful in assessing potential advantages of short rotations to reduce the probability of hurricane damage.

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