Chapter

Carbon Sequestration by Eucalypts in Florida, USA: Management Options Including Biochar and Associated Economics

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Abstract

Growth and economic models for *E. grandis* in mulch wood rotations, for *E. grandis* and *E. grandis* x *E. urophylla* cultivars grown as short-rotation woody crops (SRWC), including coppicing, for *E. grandis* in windbreaks (WB), with and without soil amendments including biochar (BC) and the slow-release fertilizer Green Edge (SRF, GE), and for *E. grandis* in dendroremediation applications estimated the above- and belowground carbon sequestration potentials of these management options. The cultivars may sequester over 10 Mg of C/ha/year as SRWCs. Under assumed management costs and market conditions, SRWC management with BC is more profitable than operational culture if BC application costs are ≤$450/Mg. Longer rotations with less intensive management result in lower but still considerable sequestration and economic benefit. In WBs, *E. grandis* cultivars may sequester up to 34 Mg of C/ha in 3 years, with additional sequestration by amending soil with BC, GE, and BC + GE. Amending soil with BC derived from eucalypts is both a long-term sequestration strategy and an opportunity to increase plantation and crop productivity. Demand for sustainably produced BC is growing due to multiple applications beyond soil carbon sequestration.

Keywords: *Eucalyptus grandis*, *E. grandis* x *Eucalyptus urophylla* hybrid, mulch wood, short-rotation woody crops, carbon sequestration, management options, economic potential, biochar, slow-release fertilizer

1. Introduction

Eucalyptus species, the most widely planted hardwoods in the world [1], have considerable potential for sequestering carbon. For *E. urophylla* in Brazil and *E. globulus* in Spain, rotation length, number of coppice rotations, site quality, carbon credit, and discount rate influenced carbon sequestration value [2]. *E. urophylla* × *E. grandis* hybrids in subtropical China maximize sequestration in 12–15 year rotations [3]. In Pakistan, *E. camaldulensis* is one of the best sequestration options for marginal areas [4], and in northwest India, *E. tereticornis* used in agroforestry is a viable option for carbon mitigation [5]. In Portugal, sequestration by *E. globulus* plantations was smaller than that of their derived wood products [6].

In subtropical central and southern Florida, USA, (annual rainfall of ~1400 mm mainly during the summer, average maximum temperature of ~28°C, average minimum temperature of 18°C, and lowest temperature of −2°C), eucalypts have numerous potential applications. We previously described their potential for maximizing SRWC productivity through genetic improvement and site amendments, such as BC [7]. On former citrus and phosphate mined lands, *E. grandis* cultivars may have maximum mean annual increments (MAI_{max}) up to 78.2 green Mg/ha/year with an internal rate of returns (IRR) over 10% when grown as SRWCs [8].

BC improves many soil properties and thereby increases productivity [9–11], especially in sandy soils common to central and southern Florida [12, 13]. BC's numerous applications, including carbon sequestration [14], have considerable market potential.

Here, we expand our previous estimations of carbon sequestration by eucalypts with and without BC in Florida [15] by estimating (1) the economic potential for carbon sequestration by Eucalyptus planted in long-term mulch wood plantations, in more WBs, and in dendroremediation applications and (2) the responses to BC as a soil amendment with and without compost in additional field studies in Florida.

2. Materials and methods

Thirteen studies in central and southern Florida (27°–28°31′N, 80°–82°49′W) representing a range of *Eucalyptus* management options contributed to our analyses—(1) two *E. grandis* mulch wood studies, (2) two *E. grandis* cultivar planting density studies, (3) *E. grandis* x *E. urophylla* hybrid cultivar EH1 planting density demonstration, (4) EH1 fertilizer-planting density study at the Indian River Research and Education Center (IRREC), (5) five *E. grandis* WBs at Water Conserv II, Clermont, and the IRREC using BC, and (6) two *E. grandis* dendroremediation studies (**Table 1**).

2.1 *E. grandis* mulch wood plantations

In central and south Florida, *E. grandis* mulch wood plantations are typically established at moderate planting densities (1495–1794 trees/ha) with 7–10 year rotations and re-established after two or three coppice stages. Mulch wood plantation management intensity is low," with all cultural treatments, such as chemical site preparation, single-pass bedding, and N + P fertilization implemented prior to planting. Post-establishment silvicultural treatments, such as herbaceous chemical release and mid-rotation fertilization, are uncommon in most mulch wood plantations throughout the entire management cycle, including the coppice stages.

The carbon sequestration and yield potential of improved *E. grandis* open-pollinated (OP) family seedlings and cultivar G2 clones under low operational culture were based on field demonstration Studies 1A and 1B, respectively, established on bedded cutover flatwoods sites on poorly drained, sandy Spodic soils. The planting density was 1495 trees/ha at a tree spacing of ≈ 1.8 m within row × 3.7 m between beds. Stem wood green weight estimates were based on felled tree samples and stand-level, whole-stem green weight estimates were fitted to the equation below using nonlinear regression [8]:

$$B(t) = e^{\left[b + c \times \ln(t) - d \times t\right]} \tag{1}$$

Study	Location	Option	Genotype	Soil	Culture	Density	Age
1A	Palmdale	MW	Seedlings	Sandy	B, H, F	1495	8 yrs
1B	Palmdale	MW	Cultivars	Sandy	B, H, F	1495	7 yrs
2A	Ft Meade	SRWC	Cultivars	Clay	B, F, H, I	2148, 2872, 4305	48
2B	Indiantown	SRWC	Cultivars	Sandy	B, H	1436, 2148, 2872, 4305	48
3	Hobe Sound	SRWC	Cultivars	Sandy	B, F, H, I	1181, 2471	81
4	Ft Pierce	SRWC	Cultivars	Sandy	F, H	1196, 1794, 3588	47, 28
5A	Winter Garden	WB	Cultivars	Sandy	F, I	~2778	52
5B	Winter Garden	WB	Cultivars	Sandy	F, I	~2778	16
5C	Winter Garden	WB	Cultivars	Sandy	F, I	~2778	16
5D	Clermont	WB	Cultivars	Sandy	F, H, I	~3472	74
5E	Ft Pierce	WB	Cultivars	Sandy	F, BC, H, I	~4630	37
6A	Tampa	DR	Cultivars	Sandy	H, I	2778	44
6B	Belle Glade	DR	Cultivars	Muck	H, I	4444	12

Table 1.
Description of 13 Eucalyptus studies in Florida: location in FL, management option (mulch wood = MW, dendroremediation = DR). genotypes involved, soil type, culture (B = bedded, F = fertilized, H = herbicided, I = irrigated), planting density (trees/ha), and age (months) at final measurement.

where $B(t)$ = whole-stem green weight (metric tons/ha), t = stand age (years), and b, c, d are estimated parameters.

Stem wood carbon content was estimated as 25% of stem green weight. On sandy soils, 78% of total C sequestration for *E. grandis* was assumed to be in stem wood [16]. **Table 2** outlines the operational silvicultural treatments previously described, their associated costs, and stumpage and carbon price assumptions. Three coppice stages were assumed with coppice yields projected to be 80, 60, and 40% of the original stand for stages 2, 3, and 4, respectively.

2.2 *E. grandis* cultivar planting density studies

Studies 2A and 2B on a phosphate mine clay settling area and former citrus beds, respectively, assessed the effect of planting densities (**Table 1**) on the biomass production of three *E. grandis* cultivars (G2, G3, and G5). Stand-level whole-stem green weight estimates (based on felled and standing trees in Florida) for each planting density were calculated by Eq. (1) using nonlinear regression [8]. The carbon content of stem wood was again assumed to be 25% of stem green weight.

The economic assumptions in **Table 2** were coupled with the assumptions that 78% of total C sequestration for *E. grandis* on sandy soils is in stem wood [16] and that response to BC followed that observed in Study 5E. Yields in two coppice rotations

Activity	**Management option**	
	Mulch wood	**SRWC**
Land preparation (start-up cost)	\$618/ha	\$1236/ha
Chemical site prep (beginning of each cycle)	\$173/ha	\$297/ha
Weed control (beginning of coppice stage)		\$136/ha
Planting cost	\$0.08/tree	\$0.08/tree
Seedlings	\$0.30/tree	
Clones	\$0.70/tree	\$0.70/tree
Fertilization (beginning of each cycle)	\$223/ha	\$223/ha
BC application (one-time start-up cost—low)		\$750/Mg
BC application (one-time start-up cost—high)		\$1000/Mg
Stumpage price	\$13/green Mg	\$13/green Mg
Carbon credit [17]	\$5/Mg C	\$5/Mg C

Table 2.
Management costs and timber stumpage and carbon credit assumptions for two management options for E. grandis grown on sandy soils in central and southern Florida.

were projected to be 80 and 60% of the original stand for fertilization only and 90 and 80% of the original for fertilization + BC [18]. The application of BC priced at \$750 and \$1,000/ton assumed a 7% growth increase per ton of BC.

2.3 EH1 planting density study

Study 3, an intensively managed 8+ ha demonstration planted in May 2011 on sandy former citrus beds at two planting densities (**Table 1**) was monitored through December 2017. Stand-level whole-stem green weight equations [19] used periodic data through 81 months to model growth scenarios at the original two planting densities and an intermediate density of 1,794 trees/ha assuming original and two coppice rotations for each density, with the two coppices growing at 90% and 80% of the original planting. EH1 stem wood carbon content was assumed to be 25% of stem green weight, and 78% of total carbon sequestration was in stem wood.

2.4 EH1 fertilizer-planting density-coppicing study

EH1, planted in June 2015 on a sandy former pasture in five 3-row (26 trees/row) plots receiving one of five fertilizers (control, GE 6-4-0 + micronutrients at 112, 224, and 336 kg of N/ha rates, and diammonium phosphate equivalent to 336 kg of N/ha) and two replications of 5-tree row plots of three planting densities (1196, 1794, and 3588 trees/ha), was coppiced in June 2019. The interior row of each plot was periodically measured for tree size, and number of coppice stems/stool at least half the DBH of the largest stem, through November 2021.

Given eucalypt's high productivity and their use for traditional forest products and because economic feasibility is one of several conditions for a sustainable BC system [20], our financial analysis goal using Land Expectation Value (LEV) and IRR in Sections 2.1–2.4 was to estimate the cost of potential carbon sequestration by *Eucalyptus* genotypes with and without BC as a soil amendment.

2.5 *E. grandis* WBs

Two-row WB 5A, consisting of four *E. grandis* cultivars in 20-tree plots (two staggered rows 2.4 m apart with 10 trees at 1.5 m spacing within rows) systematically positioned in 14 replications, was established in June 2009 at Water Conserv II. All replications were irrigated with reclaimed water. The cultivars were measured periodically through 52 months for height and DBH. Assumed sequestration in roots was ≈10.3% of total aboveground sequestration [16].

In June 2012, two-row WBs (5B and 5C) composed of four *E. grandis* cultivars (G1, G2, G3, and G4) in one row and up to eight *Corymbia torelliana* progenies in an adjacent staggered row 2.4 m away were established around two Water Conserv II Rapid Infiltration Basins (RIB 2-3 and RIB 3-2). The trees were subsequently irrigated with reclaimed water. From the 290 clones of the cultivars replicated up to five times in row plots around RIB 2-3 and from the 308 clones replicated up to five times in row plots around RIB 3-2, typically 10-tree subsets in the row plots were measured periodically.

On March 30, 2014, two-row WB 5D was established at a citrus grove following Roundup application in mid-March. At 2.4 m spacing, 68 G3s were planted in the interior (north) row and 68 *C. torelliana* in the staggered (1.2 m offset) exterior (south) row. The trees were subsequently irrigated for 4 years and measured in May 2020.

Two-row WB 5E, consisting of three *E. grandis* cultivars in one row and four *C. torelliana* progenies in an adjacent row offset 1.2 m away, was established in July 2017 to assess BC and GE as silvicultural management options. Initially a randomized complete block design with four complete and one incomplete replications of the cultivars at 1.8 m within row spacing, in February 2018, all four complete replications received GE (6-4-0 + micronutrients equivalent to 336 kg of N/ha) and two interior replications also received 11.2 Mg/ha of GCS' Polchar BC by rotovating the two treatments into the soil to a 20 cm depth between and within 1.2 m of the two rows. The incomplete replication served as a control. The cultivars were measured periodically through June 2020.

2.6 *E. grandis* dendroremediation studies

Two dendroremediation studies (**Table 1**) represent the potential use of *Eucalyptus* for managing wastewater. Study 6A had 44-month-old *E. grandis* cultivars G2 and G3 at 2.4 × 1.5 m in sandy soil in a stormwater retention pond in Tampa, FL, at the Tampa Port Authority (TPA). Study 6B on muck soil at the Everglades Research and Education Center (EREC) at Belle Glade, FL, included two *E. grandis* cultivars (G3 and G4) planted at a 1.5 × 1.5 m inside an agricultural runoff collection pond and measured for tree size and survival at 12 months. Above- and below-ground carbon sequestration was estimated as described in Section 2.2.

2.7 Other BC field studies

Seven recent BC studies, all on sandy soil, are described in **Table 3**. GCS' Polchar BC was used for studies 7A, 7B, 7C, 7D, and 7E. Four studies (7A, 7C, 7D, 7F) involved levels of BC only, two (7B, 7E) also had GE alone and in combination with BC, and one (7G) included BC/compost mixes. The crops and soils were monitored periodically for up to two years.

Study 7E (**Table 3**) had two replications of four treatments: 0, GE equivalent to 336 kg of N/ha, 11.2 Mg/ha of GCS' Polchar BC, and GE + BC. The BC was banded

Study	Location	Amendments	Crop	Soil	Culture
7A	Gainesville	0, 11.2 mt/ha BC, 11.2 mt/ha BC twice	Vegetables	Sandy	Open field
7B	Gainesville	0, 11.2 mt/ha BC, GE, 11.2 mt/ha BC + GE	Perennial peanut	Sandy	Open field
7C	Old Town	0, 5.6, 11.2, 16.8, 22.4 mt/ha BC	Sorghum	Sandy	Open field
7D	Old Town	0, 11.2 mt/ha BC	Bahiagrass	Sandy	Open field
7E	Gainesville	0, 11.2 mt/ha BC twice, GE, 11.2 mt/ha BC twice BC + GE	Slash pine, Cypress	Sandy	Bedded
7F	Immokalee, Myakka City	0 and 286 kg/ha BC	Tomatoes	Sandy	Plasticulture/ Open field
7G	Immokalee	0, 446, and 892 kg/ha BC, BC at 2.5 and 5% plus compost at 4.5 Mg/ha	Citrus	Sandy	Open field

Table 3.
Description of field studies receiving BC, GE, and/or compost—location in FL, amendments, crop, soil type, and culture.

and incorporated into beds twice, and the GE was banded on top of fully formed beds. Soil samples were taken in January 2021 after all treatments has been applied.

The five experiments in Study 7F (**Table 3**) were conducted in two major commercial tomato production areas during the fall and winter of 2018–2019. Plastic beds (20 and 18 cm high in the middle and on the edges, respectively, and 81 cm wide) were formed at 1.8 m centers. Following formation, they were fertilized with a fertilizer/BC mixture (BC from coconut shells blended with the fertilizer at the blending facility at 268 lbs/ha), fumigated with 1,3-Dichloropropene and Chloropicrin (40:60) at a rate of 123 and 134 kg ha^{-1}, and covered with virtually impermeable film. In all trials, pre-plant dry fertilizer (ammonium nitrate, triple superphosphate, and potassium sulfate plus micronutrients) was broadcast as "bottom mix" and two fertilizer bands were applied on the bed shoulders as "top mix" for a total nitrogen-phosphorus-potassium (N-P-K) of 207-49-344 kg ha^{-1}. Fertigation supplemented the pre-plant fertilizer with 112-0-167 kg ha^{-1} N-P-K from tomato flowering to the first harvest. Roma-type tomatoes were harvested two to three times at the mature-green stage and graded into marketable sizes and weighed separately according to USDA specifications: extra-large (>7.00 cm), large (6.35–7.06 cm), and medium (5.72–6.43 cm).

Study 7G's three BC levels and two compost/BC mixes (**Table 3**) were applied annually to "Valencia" bud-grafted to "US812" planted in spring 2016. Tree growth measurements consisted of trunk diameter and fruit yield. Fruit mass per plot was assessed annually by weighing harvested fruit from entire plots using a Gator Deck scale (Scale Systems, Novi, MI).

3. Results

3.1 *E. grandis* mulch wood plantations

The MAI_{max} and biological rotation age for OP seedlings and G2 clones were 10.5 green Mg/ha/year at age 8.0 years and 16.5 green Mg/ha/year at age 7.0 years, respectively, and their associated total carbon sequestrations at MAI$_{max}$ were 27.0 and 37.0 Mg C/ha (**Figure 1**). The observed yields corresponded to site index (base age 8 years) values of 15.2 and 21.3 m for the seedlings and clones, respectively. LEVs at an 8% real discount rate, with and without carbon, ranged between −$731/ha and −$517/ha with IRRs between 4.3 and 5.9% (**Table 4**).

These yields for improved *E. grandis* OP seedlings were similar to earlier *E. grandis* spacing trial results in south Florida [21]. Under operational culture and without carbon credits, stumpage prices ≥ $15/green Mg would favor clonal deployment over family forestry with IRRs exceeding 6.1%. Clonal deployment could generate higher LEVs at stumpage prices as low as $13/green Mg with carbon credits included. Family forestry under operational culture and without carbon credits is favorable when stumpage prices are <$15/green Mg and can exceed a 6% IRR when stumpage prices are ≥$16.30/green Mg.

3.2 *E. grandis* cultivar planting density studies

On former citrus lands and phosphate mined clay settling areas in central and south Florida, *E. grandis* cultivars had MAI$_{max}$s as high as 78.2 green Mg/ha/year with

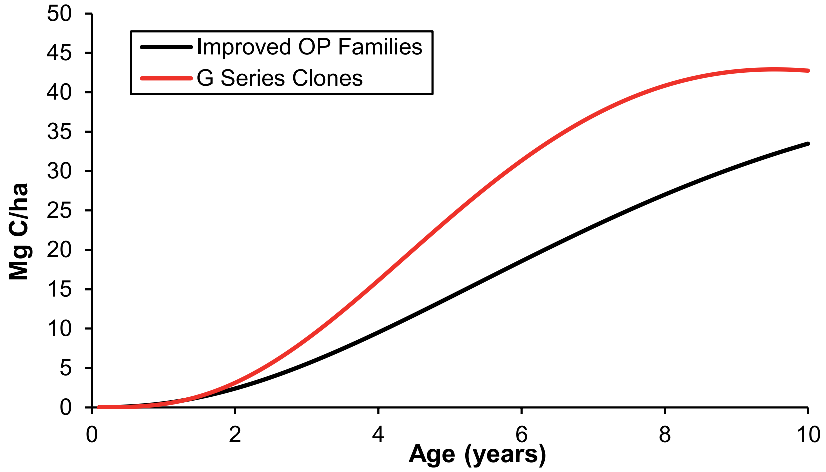

Figure 1.
Estimated total (stem + crown + roots) carbon sequestration (C, Mg/ha) for mulch wood plantations of E. grandis OP families and G2 clones established at 1,495 trees/ha on poorly drained, sandy Flatwoods sites in South Florida.

Genotype	OP families	G2 cultivar
Total carbon sequestration (C, Mg/ha)	27.0	37.0
MAI$_{max}$ (green Mg/ha/yr)—rotation age (yrs)	10.5–8.0	16.5–7.0
LEV ($/ha)—IRR (%) without carbon credit	−$652/ha—4.3	−$731/ha—4.9%
LEV ($/ha)—IRR (%) with carbon credit	−$519/ha—5.1%	−$517/ha—5.9%

Table 4.
Estimated total carbon sequestration at MAI$_{max}$, MAI$_{max}$, and associated rotation age, and LEVs at 8% real discount rate and associated IRRs with and without carbon credits, for mulch wood plantations of E. grandis genotypes OP families and G2 cultivar established at 1495 trees/ha on bedded flatwoods soils.

associated IRRs greater than 10% [8]. Total carbon sequestration estimates ranged from 38 to 95 Mg/ha at the time of MAI_{max}, with longer-term totals over 100 Mg/ha in 6 years, depending on cultivar, site, planting density, and harvest age.

The effects of adding BC as a soil amendment on sandy soils and of applying carbon credits were assessed (**Table 5**, **Figure 2**). Because BC increased growth and decreased time of MAI_{max}, estimated cumulative carbon sequestration with BC decreased as rotation length decreased; for example, at 2148 trees/ha, sequestration was 69.4 Mg/ha C in 4.9 years without BC and 61.9 Mg/ha C in 3.5 years with BC. Under current market conditions in central and southern Florida, intensive management with BC will be more profitable than operational culture if BC application costs are ≤\$450/Mg. If BC costs \$450/Mg, for example, then the LEV for 4305 trees/ha with BC will exceed the LEV of 2148 trees/ha under operational culture. Increased stumpage prices and carbon credits and/or lower silvicultural management costs favor an intensive BC regime under current application costs.

Increased stumpage price and low BC cost (\$750/Mg) favor a higher planting density under intensive management over the current mulch wood/moderate planting densities under operational culture. For example, a planting density of 4305 trees/

Response—associated response	**Planting density (trees/ha)**			
	1436	**2148**	**2872**	**4305**
Fertilization only				
Total carbon sequestration (C, Mg/ha)	52.7	69.4	73.2	77.4
MAI_{max} (green Mg/ha/yr) —rotation age (yrs)	39.0–4.3	45.1–4.9	51.8–4.5	63.2–3.9
LEV (\$/ha)—IRR (%) without carbon credit	282–8.8	413–8.9	216–8.4	−712 to 6.7
LEV (\$/ha)—IRR (%) with carbon credit	848–10.3	1054–10.3	963–9.9	216–8.4
Fertilization + 6.2 Mg/ha of BC				
Total carbon sequestration (C, Mg/ha)	55.5	61.9	69.5	92.6
MAI_{max} (green Mg/ha/yr)—rotation age (yrs)	55.2–3.2	56.3–3.5	73.8–3.0	92.1–3.2
Fertilization + 6.2 Mg/ha of BC @\$750/Mg				
LEV (\$/ha)—IRR (%) without carbon credit	−2217 to 5.6	−2803 to 5.2	−1914 to 6.2	−1464 to 6.7
LEV (\$/ha)—IRR (%) with carbon credit	−1306 to 6.6	−1885 to 6.1	−690 to 7.3	55–8.0
Fertilization + 6.2 Mg/ha of BC @\$1,000/Mg				
LEV (\$/ha)—IRR (%) without carbon credit	−3761 to 4.6	−4348 to 4.3	−3458 to 5.2	−3008 to 5.7
LEV (\$/ha)—IRR (%) with carbon credit	−2850 to 5.5	−3429 to 5.2	−2234 to 6.2	−1489 to 6.9

Table 5.
Estimated total (stem + crown + roots) carbon sequestration at MAI_{max}, MAI_{max}, *and associated rotation age, and LEV and associated IRR for E. grandis cultivars at two cultural intensities (fertilization and fertilization + BC), with and without carbon credits (\$5/Mg C), two BC prices (\$750 and 1000/Mg), and four planting densities on sandy soils in central and southern Florida.*

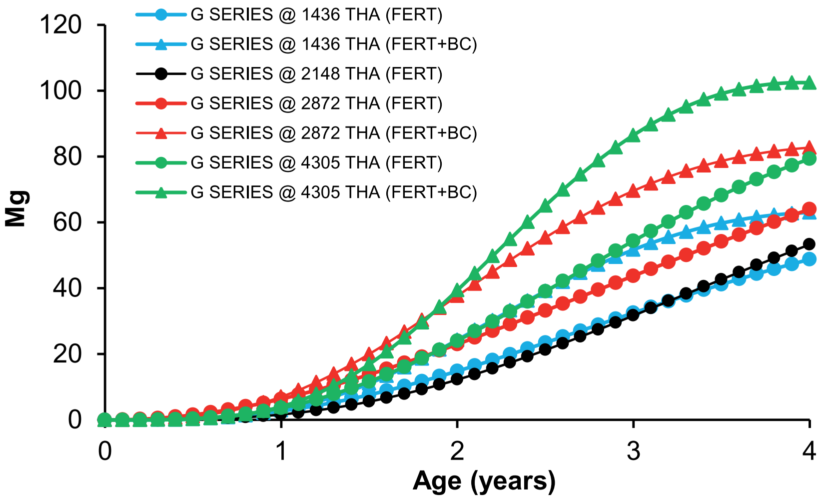

Figure 2.
Estimated total (stem + crown + roots) carbon sequestration (C, Mg/ha) for G Series E. grandis cultivars for 4 years under four planting densities and two cultural regimes (fertilization only vs. fertilizer + BC) on sandy bedded former citrus lands in central and southern Florida.

ha under an intensively managed BC regime can be more profitable (LEV = $3357/ha) than the moderate 2148 trees/ha planting density under operational culture (LEV = $2459/ha), assuming the $18/green Mg stumpage price observed in central and southern FL mulch wood markets (no carbon credits), BC application cost of $750/Mg, and 8% real discount rate (and the same management costs outlined in **Table 2**).

3.3 EH1 planting density study

Through 81 months, the higher 2471 tree/ha density increased the yield of intensively managed EH1 [7]. Maximum annual biomass yields and time to those maxima were directly and inversely, respectively, related to planting density: >58 green Mg/ha/year in 3.7 years at 2471 trees/ha vs. 44 at 5.0 years for 1181 trees/ha. Associated total carbon sequestration estimates followed somewhat similar trends: 77.2 Mg/ha C at 4.7 years for 2471 trees/ha vs. 75.8 Mg/ha at 5.5 years for 1181 trees/ha (**Table 6**, **Figure 3**). Assessing the economic feasibility of EH1 SRWCs at a stumpage price of $13/Mg and without BC, LEVs, and IRRs increased with carbon credit and were highest at an intermediate planting density.

3.4 EH1 fertilizer-planting density-coppicing study

Planting density consistently influenced tree size, and the highest planting density had the smallest tree DBH at the 47-month harvest of the original rotation ([7], **Table 7**). However, carbon sequestration at 47 months was greatest at the 3588 density.

While planting density usually did not influence coppice stem DBH and number, at 23 months, the DBHs of the largest coppice stem/stool (**Table 7**) were similar to tree DBH at the same age in the original rotation. Should that trend continue and the number of coppice stems/stool with DBH at least half that of the largest stem exceeds one, coppice carbon sequestration at each planting density would surpass that of the original rotation.

Response—associated response	Planting density (trees/ha)		
	1181	**1794**	**2471**
Total carbon sequestration (C, Mg/ha)	75.8	76.3	77.2
MAI_{max} (green Mg/ha/yr)—rotation age (yrs)	47.1–5.5	52.1–5.0	56.0–4.7
LEV ($/ha)—IRR (%) without carbon credit	2292–13.5	2913–15.0	1871–11.7
LEV ($/ha)—IRR (%) with carbon credit	2959–14.9	3665–16.6	2687–13.2

Table 6.
Estimated total carbon sequestration at MAI_{max}*,* MAI_{max} *and associated rotation age, and LEV at 8% real discount rate and associated IRR with and without carbon credits ($5/Mg C) for EH1 under operational culture without BC and three planting densities on sandy bedded former citrus lands in southern Florida.*

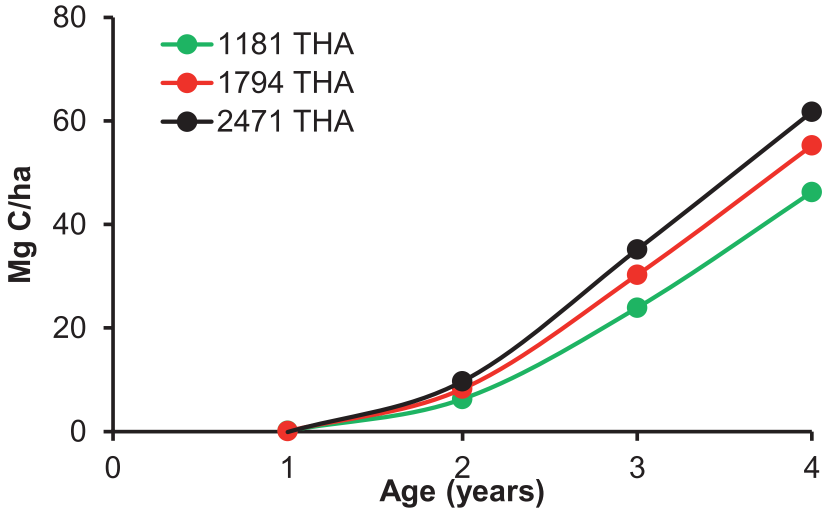

Figure 3.
Estimated total (stem + crown + roots) carbon sequestration (C, Mg/ha) for EH1 at three planting densities (trees/ha, THA) through 4 years in study 4 without BC.

Response	Planting density (trees/ha)		
	1196	**1794**	**3588**
47 months after planting			
DBH (cm)	15.4	13.5	11.4
Total carbon sequestration (Mg/ha C)	50.9	53.9	68.7
23-month-old Coppice			
DBH (cm)	8.3	8.4	6.4
No. of stems	4.1	3.8	2.7
Total carbon sequestration (Mg/ha C)	16.9	24.8	18.5

Table 7.
DBH and estimated total carbon sequestration of 47-month-old original and DBH and number of coppice stems of E. urophylla x E. grandis cultivar EH1 in Study 4.

3.5 *E. grandis* in WBs

WBs 5A, 5B, 5C, and 5D were measured from as young as 4 months to as old as 74 months (**Table 8**). Because the four *E. grandis* cultivars in WB 5A had similar sizes at each measurement age, their carbon sequestration estimates were averaged for each age. Sequestrations increased with age, reaching 12 Mg/ha C at 52 months. In WB 5B, because the cultivars were bigger in RIB 2–3, at 16 months, the cultivars had higher sequestration in RIB 2–3; both 16-month sequestration levels approximated the 18-month level in WB 5A. In WB 5C at age 74 months, cultivar G3 grew well and sequestered 33 Mg/ha C in just over 6 years.

Sequestration estimates in these three WBs were influenced by the planting density presumed for the three WBs. While the within-row spacing and distance between rows were known for each WB, the area occupied by each WB tree was speculative and was set to 652 trees/ha for each WB. Had a higher planting density been used, the sequestration estimates would be higher.

Soil amendments in WB 5E caused large early soil nutrient, tree nutrient, and tree growth responses by three *E. grandis* cultivars [7], with sequestration of up to 34 Mg/ha of C in 37 months with GE + BC (**Table 9**). GE and especially BC + GE greatly enhanced the nutrient properties of this inherently poor sandy soil.

GE greatly increased tree DBH and total carbon sequestration compared to the control, and GE + BC further increased DBH by 3.3 cm and C by 14 Mg/ha, respectively. Carbon sequestration from GE is primarily above ground while carbon sequestration by GE + BC is both above ground and in the soil. Assuming that all the BC applied remained in the soil, GE + BC increased total carbon sequestration by nearly 33% to some 45 Mg/ha of C.

Age (months)	Height (m)	DBH (cm)	Carbon sequestration (Mg/ha C)		
			Above ground	Below ground	Total
WB 5A: two *E. grandis* rows					
18	5.5	5.9	.69	.07	.76
25	7.4	7.2	1.53	.16	1.69
52	14.3	13.4	10.86	1.14	12.00
WB 5B—RIB 2-3: one *E. grandis* row, one *C. torelliana* row					
4	1.1				
8	2.0	1.0			
16	6.0	8.2	.83	.09	.92
WB 5C—RIB 3-2: one *E. grandis* Row, one *C. torelliana* row					
4	1.2				
8	1.8	.8			
16	4.9	7.2	.51	.05	.56
WB 5D: one *E. grandis* row, one *C. torelliana* row					
74	24.1	24.2	30.1	3.0	33.1

Table 8.
Tree height and DBH and estimated carbon sequestration at various ages of E. grandis cultivars in four WB studies.

Response—associated response	Treatment		
	Control	GE	GE + BC
DBH (cm)	5.8	10.3	13.6
Total carbon sequestration (C, Mg/ha)	2.8	19.6	33.6
MAI_{max} (green Mg/ha/year)—rotation age (years)	3.4–2.7	17.3–3.7	32.5–3.3

Table 9.
Tree DBH, estimated total carbon sequestration at 37 months, and MAI_{max} *and associated rotation age of E. grandis cultivars receiving Control, GE, GE + BC treatments in WB Study 5E.*

3.6 *E. grandis* dendroremediation studies

Studies 6A and 6B provided 12- and 44-month sequestration estimates, respectively (**Table 10**), for very different soil types and planting densities. Sequestration in 6A was 12 Mg/ha C at 44 months, or 12 Mg/ha C annually, on a sandy retention pond at 2778 trees/ha, while in 6B it was 12 Mg/ha C at 12 months on muck soil at 4444 trees/ha.

3.7 Other BC field studies

Five recent amendment studies involving BC, GE, and/or compost are summarized in **Table 11**. As suggested by Study 7A, notable soil and plant responses to BC may take up to 2 years, although BC immediately increased soil organic matter in Studies 7B, D, and E. Studies 7C and 7B had varied responses to BC rates.

In Study 7F, BC at 286 kg/ha only impacted the marketable yields in one out of five tomato trials (**Table 12**). Blending the BC with the broadcasting fertilizer application reduced the expense of an extra passing applying the BC; however, the rates were too low to produce an increase in marketable tomato yields. Similar studies indicate the use of BC was an effective and productive soil amendment as compared to compost [23–27]. Future trials with higher BC rates may impact tomato yields positively as may continue with yearly BC application at a lower rate.

Study 7G's first-year data indicated no differences in plant growth, but 892 kg/ha BC produced the highest fruit yields (**Table 13**), as application rates in this trial were too low to have a significant yield impact in the first year. Compost application in sandy

Cultivar	Height (m)	DBH (cm)	Survival (%)	Carbon sequestration (Mg/ha C)		
				Above	Below	Total
6A: 44-month-old at 2778 trees/ha [22]						
G2	9.6	6.7	67	7.2	0.7	7.9
G3	9.3	8.0	100	15.1	1.5	16.6
6B: 12-month-old at 4444 trees/ha						
G3	6.1	4.9	100	5.3	0.5	5.8
G4	5.7	4.2	100	3.3	0.3	3.6

Table 10.
Tree height, DBH, survival, and estimated above- and below-ground and total carbon sequestration of E. grandis cultivars in two dendroremediation studies.

Response	**BC Level (mt/ha)**					**GE**	**BC + GE**
	0	**5.6**	**11.2**	**16.8**	**22.4**		
7A—cauliflower (22 months after first BC application)							
Soil NO3-N (ppm)	2.45		3.44		2.19		
Leaf N (%)	4.68		5.29		4.70		
7B—perennial peanut (21 months after application)							
CEC (meq/100 g)	7.9		6.8			7.4	9.2
Soil OM (%)	1.42		1.93				
7C—sorghum (4 months after application)							
Soil NO3-N (kg/ha)	1.47	3.69	2.16	2.05	2.25		
Soil Ca (kg/ha)	3015	3094	3670	3255	3525		
Soil CEC (meq/100 g)	7.6	8.0	9.0	8.2	8.8		
7D—bahiagrass (13 months after application)							
Soil K (kg/ha)	21		166				
Soil OM (%)	0.8		1.3				
Soil CEC (meq/100 g)	5.0		9.1				
7E—slash pine/cypress (after application)							
Soil OM (%)	.60		1.06			.67	2.26
Soil CEC (meq/100 g)	3.1		4.4			3.3	6.7

Table 11.
Soil and plant responses in five BC and/or GE studies in Florida.

Tomato type	**Season**	**Number of harvests**	**Yield response**
Roma	Fall	2	Increase
Roma	Fall	2	No differences
Round	Fall	2	No differences
Round	Winter	3	No differences
Round	Fall	3	No differences

Table 12.
Effect of BC on the marketable yields of Roma and round-type tomatoes.

Soil Amendment		**Trunk diameter (cm)**	**Fruit yield (kg/ha)**
BC Level (kg/ha or %)	**Compost (%)**		
0	0	15.6	1600.0
446	0	15.1	2057.1
892	0	14.0	3200.0
2.5%	97.5	13.2	2514.3
5%	95.0	15.4	2057.1

Table 13.
First-year trunk diameter and fruit yield of Valencia/US812 in response to five BC/compost soil amendments.

soils had a positive impact on soil and crops elsewhere in Florida [28–32]. Long-term compost application at higher rates will promote soil health and increase yield [33, 34].

4. Discussion

The above- and below-ground carbon sequestration of productive eucalypts worldwide depends on site conditions and management options, such as genotype, cultural intensity, planting density, and rotation length (**Table 14**). Several types of *Eucalyptus* have promise as SRWCs in Florida [39, 40], including cultivars, such as *E. grandis* G3 and *E. grandis* x *E. urophylla* EH1. EH1 on former citrus beds and managed at relatively low intensity, for example, could sequester over 20 Mg of C/ha/year. The Florida WB and dendroremediation estimates are influenced by their assumed planting densities. Plantations, though, have well-defined planting densities that offer more reliable carbon sequestration values. As the other Florida examples demonstrate, sequestration estimates vary due to tree age, size, management, and genotype. Longer first and coppice rotations may maximize sequestration [3].

Our carbon sequestration estimates for *E. grandis* and *E. grandis* x *E. urophylla* in Florida approximated their potential, as several assumptions were involved. Green weights for *E. grandis* x *E. urophylla* were derived from Florida field data by a species-specific equation from Swaziland [19]. Stem wood carbon content was an assumed percentage of green weight. Above- and below-ground sequestration proportions

Species	Location	Management	Age	BC	C
E. grandis	Palmdale, FL	Seedlings, MW	8.0	No	27.0
E. grandis	Palmdale, FL	G2, MW	7.0	No	28.0
E. grandis	Ft Meade, FL	G3, SRWC	6.0	No	112.8
E. grandis	Indiantown, FL	G3, SRWC	3.9	No	77.3
E. grandis x urophylla	Hobe Sound, FL	EH1, SRWC	4.0	No	81.9
E. grandis x urophylla	Ft Pierce, FL	EH1, SRWC	3.9	No	68.7
E. grandis	Ft Pierce, FL	G3, double row WB	3.1	Yes	33.6
E. grandis	Winter Garden, FL	G3, double row WB	4.3	No	11.3
E. grandis	Winter Garden, FL	G3, double row WB	1.3	No	0.83
E. grandis	Winter Garden, FL	G3, double row WB	1.3	No	0.514
E. grandis	Clermont, FL	G3, double row WB	6.2	No	33.1
E. grandis	Tampa, FL	G3, DR	3.7	No	15.1
E. grandis	Belle Glade, FL	G3, DR	1.0	No	5.5
E. grandis	South Africa [35]		10	No	47
E. grandis	South Africa [35]		25	No	270
E. spp	Southern China [36]	Various	Var.	No	100
E. grandis x urophylla	Southern China [37]		6–8	No	>70
E. tereticornis	India [38]		4	No	116

Table 14.
Comparison of estimated above-ground carbon sequestration (C, Mg/ha) by Eucalyptus species in Florida with and without BC to sequestration elsewhere under varied managements and ages (years).

were based on *E. grandis* in Brazil [16]. Below-ground sequestration estimates assumed no soil C flux. Similar assumptions were used for sequestration estimates in South Africa [35] and China [36, 37].

In combination with the carbon sequestered in trees, cost estimates of sequestration in *Eucalyptus* plantations by using wood BC as a soil amendment were previously estimated at ~\$5/Mg of BC added per ha [7]. Using the intensively managed *E. grandis* plantation with 4305 trees/ha (**Table 4**), a single planting cycle, and three coppices, the estimated cost for using wood BC at \$750/ton as a soil amendment to accelerate sequestration is ~\$4/Mg of C sequestered. If a second planting cycle is included, the with and without BC cost comparisons are very similar. In a scenario with a minimum of two planting cycles and BC less than \$650/Mg, there is an economic incentive to use BC as a soil amendment to accelerate and increase carbon sequestration. These costs are less than the \$30–50/ton estimated in 2005 for US forestry sequestering up to 500 million tons of C/year [41]. In 2015, the California Air Resources Board listed C sequestration credits at \$12–13/ton [42].

Converting woody biomass into long-term forest products, such as BC, can be a critical component of carbon sequestration. BC produced from hardwoods has a soil residence time exceeding 1000 years [43]. In South Africa, carbon sequestration by *Eucalyptus* and their long-lived forest products may equally result in offsetting some 2% of the country's carbon emissions [35].

Because BC quality influences BC impact on soil properties and plant productivity, Study 5E used GCS' premium BC, which was produced from roundwood, was highly porous, and had high carbon content (93–95% fixed carbon on a dry weight (DW) basis), low ash content (2–3% DW), and high surface area (585–630 m^2/g).

BC enhances the nutrient properties of Florida's sandy soils as well as the nutrient status of *E. grandis*, especially when applied together with organic amendments, such as GE and/or chemical fertilizers. However, because soil C may decrease as *Eucalyptus* plantations mature [35], BC incorporation into plantation soil can be beneficial. BC application to the soil in Poland is viewed as an important component of the region's circular economy and means of counteracting climate change [44].

The relatively low levels of BC in Studies 7F and 7G had minimal impact on yield. Because both compost and BC improve soil physical properties (water-holding capacity, soil structure, and bulk density), soil chemical properties (cation exchange capacity and plant nutrient availability), and soil biological properties (microbial activity), they could, at higher levels, potentially mitigate symptoms of citrus greening, such as asymmetrical chlorosis of the leaves, foliar micronutrient deficiencies, root degeneration, leaf, and fruit drop and eventually dieback and sometimes death [45].

BC has benefited many crops. BC produced from *E. camaldulensis* increased critical soil properties and groundnut yield in Senegal [46]. BC applications have increased the yields of corn [47, 48], safflower [49], rice [50], cypress [51], and rubber [52]. BC-blended compost significantly improved crop quantity and quality in Europe [53]. In Florida, oak-derived BC as a soil amendment combined with standard fertilizers enhanced lettuce (*Lactuca sativa*) productivity in a greenhouse study [7], and Studies 7A-7E suggest that plant and soil nutrients may be enhanced by GE, BC, and/or BC + GE applications.

The SRF GE has also been used in several specialty crops, such as turfgrass, citrus, and landscape plants. Environmental concerns regarding quick release (soluble) fertilizers will continue to increase demand for SRFs like GE, which also add organic matter to the soil.

While BC soil amendments may generally enhance soil health and plant growth in forestry, agriculture, and other applications, responses will vary because BCs differ and are influenced by soil type, climate, vegetation, and management [54]. Agriculture is using BC to improve soil bulk density, root penetration, aggregate stability, water infiltration, water holding capacity or retention, nutrient leaching, pore distribution, organic matter, carbon sequestration, toxins and pollutants, soil disease pathogens, beneficial nematodes, nitrogen-mineralization rate and microbial biomass, respiration rate, and genetic diversity [55].

BC may remediate contaminated soils [56], restore degraded land, and increase agriculture efficiency and carbon fixation [57]. In Brazil, adding 4.2 t/ha/year of sugarcane BC in sugarcane fields could increase soil C by 2.35 t C/ha/year [58]. In European agriculture, BC + low input of nitrogen fertilizer provided the highest C sequestration (61.1 t CO2e/t of biomass) [59]. The renewed interest in biochar was stimulated by the discovery of high organic carbon and remarkably fertile soils in South America, especially Amazonia, that have been called "Amazonian Dark Earths or Terra Preta de Indio" (black Earth of Indians). These soils maintain fertility for years. Remarkably, these areas of the world are often characterized by low fertility and nutrient holding capacity. The fertility of the Amazonian Dark Earths is believed to be largely a consequence of charcoal/biochar applications by the indigenous tribes of the region and the benefits in the soils persisted for thousands of years.

BC is produced via pyrolysis, that is, heating wood in a very low oxygen environment to remove all moisture and volatiles, maximize carbon content, and minimize ash content while increasing porosity and maximizing surface area. BC pyrolysis technologies range from simple batches production techniques, such as open pits, mounds, and kilns, to continuous production systems using rotary kilns and retorts [7].

Given the trends toward sustainable business models and reducing the CO_2 footprint of production systems, the type of technology employed is an important consideration in BC production. As one moves up the technology scale, BC producers have the ability to control greater portions of the production process. A simple batch technology has limited ability to control the pyrolysis process compared to continuous production systems. Some of the operating metrics producers may want to control pyrolysis temperature, residence time, combustion of volatiles, and energy capture. To sustainably produce BC, operators will want to control all of these items and more, including, emissions and the source of feedstock.

While there is value in producing BC in remote areas to help support local agriculture or possibly even for export, many of these operations are not sustainable supply chains over the long term. The least sustainable producers are where the virgin forest is harvested to produce BC in open pits, mounds, or kilns. To truly be sustainable, pyrolysis operations should capture all components of value including fully combusting the volatiles inherent in the feedstock, converting this to a usable form of what is bioenergy, and then utilizing that energy in other applications (**Figure 4**). GCS is committed to these goals and the sustainable production of BC.

GCS' operations capture and utilize all components of value in BC production. With a commitment to sustainability and to further improve efficiency, GCS has designed its pyrolysis operations to be continuous, minimize the use of electricity, and capture and convert all volatiles into usable forms of energy for other applications. With a sustainable BC production process, carbon sequestered will have a greater beneficial impact.

Interest in and demand for BC documented in 2020 [7] are still growing due to improved BC production techniques, but BC's multiple applications vary widely in potential market size, timing, competitiveness, and pricing compared to alternative products (**Table 15**). With the need to replace the substantial loss of soil carbon due to modern agricultural practices [60] and considering the emerging carbon cascades [61], the applications and future potential markets become quite large. There are growing opportunities to utilize BC for (1) soil nutrient and water retention, (2) remediation of contaminated soils and water, (3) filler in concrete, asphalt, and tires, (4) acoustic and thermal insulation in walls, ceilings, and floors, (5) carbon fibers

Figure 4.
GCS' pyrolysis process with integrated heat capture and utilization.

Application	Market	Timing	Competition	Pricing
Soil carbon	Large	Current	Growing	Low
Specialty soil	Moderate	Emerging	Moderate	Moderate/high
Crop yield	Moderate	Current	High	Low/moderate
Carbon sequestration	Very large	Emerging	Moderate	Moderate
Nutrient retention	Large	Current	Moderate	Moderate
Water retention	Large	Current	Moderate	Moderate
Water purification	Large	Emerging	Low	High
General industrial	Large	Current	Moderate	Moderate
Specialty industrial	Moderate	Emerging	Low	High

Table 15.
Relative market, timing, competition, and pricing for BC applications.

and polymers, (6) protection against electrosmog, (7) filtration media, and (8) heavy metal adsorption. Growing trends in developing sustainable supply chains and reducing societal carbon footprint will help accelerate the growth of many of these markets.

5. Conclusions

Estimated carbon sequestration by *Eucalyptus* in Florida can be sizeable but depends on site conditions and management options. *Eucalyptus* managed in long rotations for mulch wood production sequesters less but still significant amounts of carbon. *Eucalyptus* cultivars are responsive to intensive culture in SRWC systems that may economically produce high-quality BC, which in turn can be a useful soil amendment for their culture and increase total carbon sequestration. In evaluating the tradeoffs of alternative management options to intensive SRWC culture, growers should consider soil type, planting density, and soil amendments. Amending soil with BC can both increase and accelerate total carbon sequestration and also help offset any carbon loss that takes place in growing *Eucalyptus*. Demand for sustainably produced BC is growing due to its multiple applications beyond soil carbon sequestration.

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Conflict of interest

The authors declare no conflict of interest.

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