Chapter

Forest Trees for Biochar and Carbon Sequestration: Production and Benefits

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Abstract

Many tree species worldwide are suitable for making biochar (BC), with planted eucalypts in particular being very productive and extensive. Above- and below-ground carbon sequestration by Eucalyptus plantations depends on plantation management options. An intensively managed cultivar could sequester over 100 mt of C/ha at a cost of $21–40/mt. BC production systems ranging in size from small mobile units to large centralized facilities and many kiln technologies influence the quality and price of the BC produced as well as the ability to control emissions. While BC from wood has many applications, its use as a soil amendment in forest plantations is appealing as a long-term sequestration strategy and opportunity to grow more robust trees and increase survival rates. Research in Florida USA and elsewhere addresses responses of forest and agronomic crops to wood BC soil amendments with and without other fertilizers. In combination with the carbon sequestered through tree growth, sequestration of 2.5 mt/ha of wood BC as a soil amendment in Eucalyptus plantations has estimated costs ranging from $3.30–5.49/ton of C.

Keywords: biochar, trees, Eucalyptus, production systems, carbon sequestration, soil amendment

1. Introduction

BC's multiple uses (www.biochar-international.org) and numerous benefits [1] include soil and crop improvement, carbon sequestration, retention of nutrients and water, reduced leaching, water purification as well as general and specialty industrial applications, and interest in and demand for BC are growing [2]. From a global BC market value of $1.04 billion in 2016, the market is projected to grow at ~13% annually to a value of $3.2 billion in 2025 [3].

Focusing on Florida USA, we previously published on eucalypts' suitability as a BC feedstock and assessed BC's potential for improving soil properties, tree nutrition, and tree growth [4].

In this chapter, we review (1) the advantages of forest trees for BC by documenting the availability and relative suitability of major tree species, particularly eucalypts (*Eucalyptus*) and related species, (2) carbon sequestration by planted

Eucalyptus, (3) BC production systems ranging in size and the associated quality of BC, (4) promising BC applications, (5) recent and ongoing BC research, and (6) carbon sequestration potential and associated cost of *Eucalyptus* plantations using wood BC as a soil amendment.

2. Forest trees for biochar

Many tree species worldwide are suitable for making BC, with planted eucalypts in particular being very productive and extensive. Eucalypts are the world's most valuable and widely planted hardwoods (20 million ha in 2018 [5], up to 21.7 million ha in 61 countries by 2030 [6]) and have numerous potential applications [7, 8]. In Florida, several *Eucalyptus* species, including cultivars of *E. grandis* and *E. grandis* × *E. urophylla*, have promise as short rotation woody crops (SRWC, [9, 10]).

BCs from *E. grandis* × *E. urophylla* cultivar EH1, *Corymbia torelliana*, *E. grandis* cultivar G2, *E. amplifolia*, and *Quercus virginiana*, were similar and suitable for commercial BC production ([4], **Table 1**). Compared to high quality European *Quercus* spp., all five Florida trees were similar for recalcitrant carbon but higher in pH and water holding.

Other evaluations of BCs made from various woods and other feedstocks indicate that feedstock and pyrolysis condition influence properties important for using BC as a soil amendment [11, 12]. Since key objectives in BC production include minimizing the combustion of carbon, maximizing carbon content, and minimizing ash, consistency of feedstock and the production operating environment are imperative.

Property	Florida tree					Europe
	G2	CT	EH1	EA	QV	Qsp
Volatile matter (% of DW*)	83.3	85.0	85.9	82.5	83.3	
Fixed carbon (% of DW)	15.7	14.4	13.7	17.0	15.5	
Ash (% of green weight)	1.00	0.54	0.37	0.50	1.15	
Moisture content (% of DW)	36.4	48.0	43.1	30.1	33.1	
C (% of DW)	49.2	49.7	49.8	50.8	49.1	
O (% of DW)	43.0	43.1	43.1	42.0	43.1	
H (% of DW)	6.5	6.5	6.5	6.5	6.4	
N (% of DW)	0.21	0.17	0.17	0.26	0.29	
Cl (% of DW)	0.07	0.02	0.02	0.02	0.00	
S (% of DW)	0.01	0.00	0.00	0.01	0.00	
Recalcitrant carbon (%**)	76.0	71.6	74.0	70.8	71.8	67.6
pH	10.6	10.4	10.5	11.1	11.9	8.2
EC (mmhos/cm)	0.57	1.76	1.56	3.88	1.14	3.33
Water holding (ml/100 g)	75.9	78.8	79.8	69.0	68.5	43.4
Carbonate value (%)	2.6	2.5	5.6	16.7	2.5	—

**Dry weight (DW).*
***Estimated at 80% of fixed carbon on a dry ash-free basis.*

Table 1.
Properties of BC made from Florida E. grandis *cultivar G2, C. torelliana (CT),* E. grandis × *E. urophylla cultivar EH1,* E. amplifolia *(EA), and* Q. virginiana *(Qv), and European Q. sp. (Qsp) test trees (adapted from [4]).*

3. Carbon sequestration by planted *Eucalyptus*

Eucalyptus planting density trials have assessed the effect of stand density on biomass production. On former citrus lands and phosphate mined clay settling areas in central and south Florida, *E. grandis* cultivars can have maximum mean annual biomass increments (MAI_{max}) as high as 78.2 green mt/ha/year with associated internal rates of return greater than 10% [13]. Through 81 months, the intensively managed *E. grandis* × *E. urophylla* cultivar EH1 planted on former citrus beds at two planting densities yielded more at 2471 trees/ha than at 1181 trees/ha. Annual yield at 2471 trees/ha was over 58 green mt/ha/year in 3.7 years compared to 44 mt/ha/year at 5.0 years. However, planting density also inversely affected average tree Diameter Breast Height (DBH) as the higher planting density produced smaller trees.

To estimate carbon sequestration over a rotation in Florida, we applied carbon allocations for *E. grandis* in Brazil [14] and *E. grandis* × *E. urophylla* in China [15] to Florida tree data. The resulting total carbon sequestration estimates ranged from 38 to 95 mt/ha at the time of peak annual accumulation (**Table 2**), with longer-term totals over 100 mt/ha in 6 years, again depending on cultivar, site, planting density, and harvest age (**Figure 1**).

Sequestration estimates by *Eucalyptus* elsewhere vary. *Eucalyptus* plantations in southern China sequestered ~100 mt C/ha [16]. *E. urophylla* × *E. grandis* planted in southern China accumulated >70 mt C/ha in 6–8 years [15]. In South Africa, 10- and 25-year-old *E. grandis* plantations may store 47 and 270 mt C/ha [17]. *Eucalyptus tereticornis* plantations may accumulate up to 129 mt C/ha in 4 years [18].

Planting density (trees/ha)	Tree component				Rotation age at MAI_{max} (years)
	Stem (wood + bark)	Crown	Roots	Total	
G3 on clay settling areas					
2533	61.2	4.3	6.8	72.3	4.3
5066	80.5	5.6	8.9	95.0	4.2
8841	32.3	2.2	3.6	38.1	3.4
EH1 on former citrus beds with intensive culture					
1181	63.4	6.7	5.7	75.8	5.5
2471	64.5	6.9	5.8	77.2	4.7

Table 2.
Predicted carbon sequestration (mt/ha) by tree components at maximum mean annual increment (MAI_{max}) rotation age for cultivars G3 and EH1 at three and two planting densities, respectively.

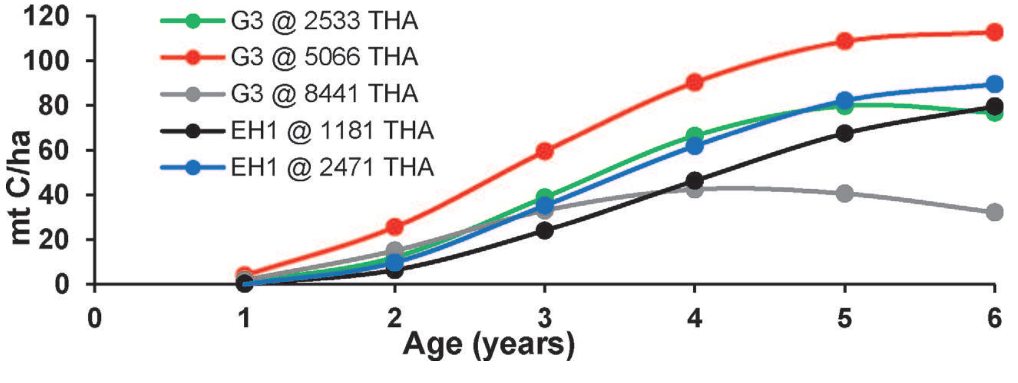

Figure 1.
Cumulative total (stem + crown + roots) carbon sequestration (C, mt/ha) for each genotype × planting density (trees/ha, THA) scenario by age (without BC application).

4. Biochar production systems

BC production needs to be considered in the context of charcoal production. Charcoal has been produced for millennia for various applications from art to soil amendments creating terra preta soils in the Amazon to metallurgical and other industrial applications. What differentiates high-quality BC from lower-quality BC or simple charcoal is the production system, i.e., the ability to control the process and operating conditions and ultimately BC's physical and chemical properties.

BC is produced via pyrolysis, which is the process of heating wood in a low oxygen environment (ideally close to zero oxygen) with the objective of removing all moisture and volatiles in the wood, maximizing carbon content, and minimizing ash content all while trying to increase porosity (pore structure) and maximize surface area.

BC from trees may be produced in systems ranging from small, simple kilns (e.g., mound and brick kilns) to large centralized, custom designed facilities (e.g., retort technologies). As with all production technologies, there are tradeoffs which impact cost, efficiency, quality, emissions, and product applications. BC production techniques are no different, and as the market and applications advance, these differences will become even more relevant.

Batch systems require less technical expertise, are easy to set up, and have low or very low capital requirements. Consequently, there are numerous batch production technologies used around the world and available for purchase. At the other end of the spectrum are continuous production technologies that are typically custom designed, require greater technical expertise, and require significant capital investment. However, the quality and consistency of the BC as well as the economies of scale are significantly enhanced, and a well-designed continuous process captures all components of the value-chain. As more sustainable and environmentally friendly production is sought, these issues will become increasingly important.

For perspective, we specifically review seven batch technologies (Pit, mound, and brick kilns, Metal kiln, Missouri-type kiln, Kon-Tiki kiln, and Rotary kiln), three mobile BC production units (Carbonator 6050, FireBoxes, and "cooker"), and two continuous production technologies (Polchar and GCS).

4.1 Pit, mound and brick kilns

Simple kilns—pit, mound and brick—are still widely used worldwide, and all operate as a batch process (**Figure 2**: 1–3). The earliest kilns were temporary in nature—either pits or mounds. They are low cost, simple, and are still widely used in developing countries. While there is value in simple and low-cost production, this simple "pyrolysis" technique has low yield with inconsistent quality and very limited ability to control the process.

Pit kilns (**Figure 2**: 1) are the lowest-tech "pyrolysis" technique. At their simplest, pit kilns are open pits with more advanced pits being covered with leaves and earth or mud to create a partially closed carbonization environment. An open pit is dug, wood is added to the pit and set alight with the goal of combusting the volatile material inherent in the wood without fully burning the wood to ash, in essence making charcoal. Control over oxygen in the carbonization process is limited. Pits require significant oversight, quality is poor, and BC yields (kilogram of BC produced per kilogram of wood) are low. Yields are independent of the size of the pit, but larger pits increase labor efficiency.

The mound kiln (**Figure 2**: 2) is an aboveground version of the pit kiln. Wood is stacked vertically into a mound with a built-in wood chimney in the center of the mound, and the mound is covered with twigs and leaves and then earth. This

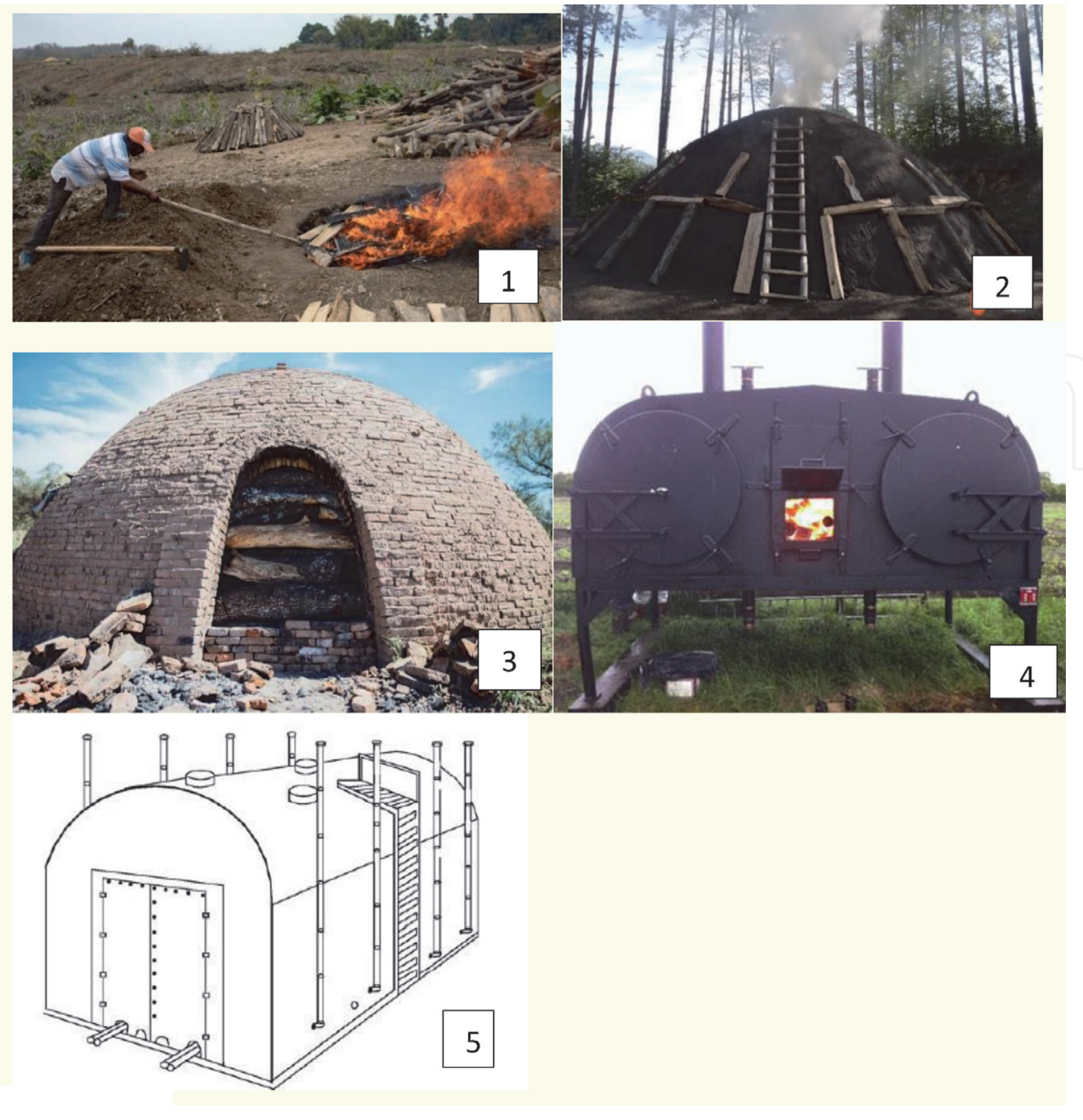

Figure 2.
Representative kilns: (1) Open pit (source—Pacific biochar), (2) mound (courtesy register of the intangible cultural heritage, Slovenia), (3) brick (courtesy Kamado Joe Europe BV, Netherlands), (4) metal kiln (courtesy four seasons fuel ltd., UK), (5) Missouri-type kiln (courtesy the biomass project).

technique allows BC producers to better control heat and air during carbonization of the wood. Mound kilns are typically 4–5 m wide, 1.5–2.0 m high with a number of vents at the bottom of the mound to control air flow into the kiln.

The brick kiln (**Figure 2**: 3) is a step up from pit and mound kilns. With a relatively low capital cost, creates a better carbonization "chamber," produces better quality BC and generates better BC yields. Since the entire kiln is constructed from bricks it works similarly to a brick refractory by providing better heat insulation. Brick kilns are typically larger than mound kilns with diameters up to 7 m. However, production time is still relatively lengthy with carbonization and cooling taking up to 10 days.

4.2 Metal kilns

Advancement in kiln technology led to metal kilns a little over a century ago. Metal kilns (**Figure 2**: 4) have many benefits over brick and mound kilns; (1) they require less oversight and attention, (2) process wood faster (reduced residence time), and (3) have improved airflow all of which lead to improved yield and better-quality BC. With the reduced residence time, BC can be produced in as little at 3 days but as with all kilns, there is no control of air pollution/emissions.

4.3 Missouri-style kiln

In the quest to improve quality, combustion dynamics, and economies of scale, the Missouri Kiln (**Figure 2**: 5) was developed in the early 1900s. A rectangular kiln, with concrete or concrete block walls to improve thermal insulation and mechanized loading and unloading, allows producers to increase volume resulting in better economies of scale. Missouri-type kilns have approximately three times the capacity of a brick kiln and with the ability to modify and add chimneys, yields are better than metal kilns, and quality is improved.

While Missouri-type kilns can be designed to have reduced emissions compared to other kilns—chimneys can be connected to afterburners to reduce CO and volatile organic emissions—the batch production makes this difficult since there is no continuous process and no steady state.

4.4 Kon-Tiki kiln

Kon-Tiki kiln (**Figure 3**: 1, 2) was developed in Switzerland [19]. As opposed to high volume BC production, Kon-Tiki focused on the democratization of BC by developing a simple but ingenious invention that produces reasonably high-quality BC. Unlike earthen or brick kilns, steel walls reflect the pyrolysis and combustion heat back into the kiln, resulting in improved combustion dynamics and more uniform temperature distribution, thus ensuring more homogeneous charring conditions.

A steep cone shape is used. Air is drawn in over the hot outer wall of the kiln and swirls above the fuel bed creating a vortex that ensures good mixing of pyrolysis and combustion air. Once the kiln reaches its working temperature of 650–700°C, hardly any smoke is visible. The combustion air rolls in over the metal edge of the outer wall and into the kiln. But at the same time, the burning gases must escape upwards and so, a counter-rotating vortex is established in the center of the kiln. The wood gas, which is heavier than air, is kept in the vortex until it is burned. The garden scale Kon-Tiki kiln in **Figure 3**: 2 allows anyone to carbonize biomass quickly and cleanly. In approximately 2 hours, 0.2 m^3 of BC can be produced.

4.5 Rotary kiln

Rotary kiln technologies can be applied to powders, granules, or sized feedstock. A rotary kiln (**Figure 4**) consists of a cylindrical, rotating tube mounted between stationary material feed and outlet housings. The rotating tube mixes the material,

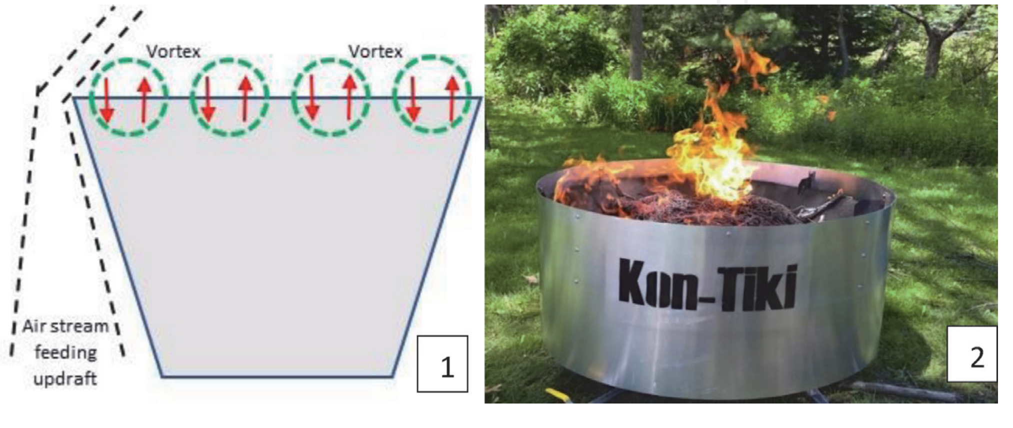

Figure 3.
Kon-Tiki kiln schematics (1, courtesy the democratization of biochar) and in operation (2, courtesy garden scale Kon-Tiki, Finger Lakes biochar, New York).

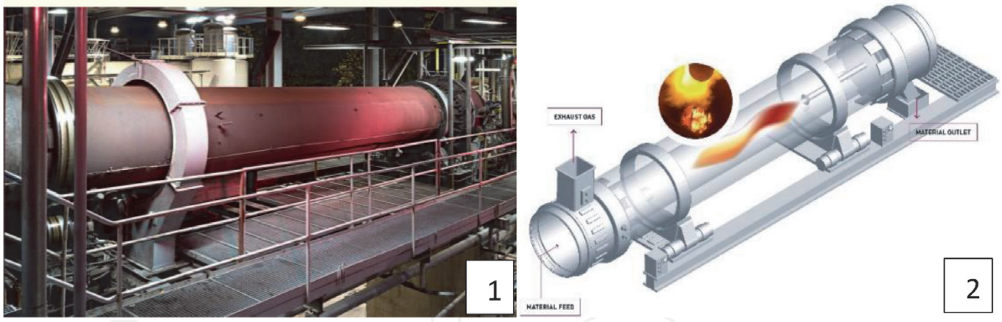

Figure 4.
Rotary kiln (1) and its schematics (2, courtesy IBU-tec AG, Germany).

ensuring that it is processed homogeneously. Rotary kilns can be heated either directly (inside the kiln) or indirectly (from outside).

In a direct-fired rotary kiln, the burner is situated inside the kiln body, that is, inside the reaction chamber. The material is heated directly by the burner flame and the stream of hot gas produced by the burner. These kilns are usually lined with a refractory (heat-resistant) material so that they can be operated at higher temperatures, as high as 1500° C. Directly fired kilns are generally robust and scalable.

4.6 Mobile biochar production

Tigercat's Carbonator 6050 (**Figure 5**: 1) is a mobile, carbon negative BC production system designed to cost effectively reduce logging, land clearing, etc., residues by 90% [20]. The single operator, remotely controlled, continuously running Carbonator 6050 converts low value, bulky woody biomass without chipping or grinding into high quality, variable sized BC (e.g., 71% recalcitrant carbon, 91% void space, 8% ash) that can be used on-site or easily transported.

Air Burners' FireBoxes (**Figure 5**: 2, airburners.com/products/) are cost-effective, self-contained, above ground air curtain burners (ACB) with thermal ceramic refractory walls designed to eliminate wood and vegetative waste by up to 98% with the lowest environmental impact, while producing clean carbon ash and BC. Burn rates are from 1 to 13+ tons/hour. Only Air Burners' Fireboxes have been tested by the U.S. EPA and other international government environmental agencies and proven to meet and exceed U.S. EPA regulations for ACBs.

A batch retort BC cooker (**Figure 5**: 3) built by Passive Remediation Systems Ltd. (www.prsi.ca) illustrates a cost effective small scale BC production system. Assembled from a 3785 l propane tank, a small propane fuel tank, a boat trailer, and upcycled pipes and valves, this 0.14 m^3 machine makes BC from any dried biomass. After sealing the bolted oven door with water-based caulking, pallets supply startup heat and spark to initiate pyrolysis. A thermocouple indicates internal conditions for BC production and facilitates the testing of biomass materials for improving organic

Figure 5.
Representative mobile BC production systems: (1) carbonator 6050, (2) air burner fireboxes, and (3) cooker.

farm growing operations and sequestering carbon. It has produced high quality hemp BC (82% pure, A&L Canada Laboratories, London, Ontario). With minimal operating impact, it can also produce valuable volatile organic compounds collectively called wood vinegar, which is rich in chemicals used for natural health products, fertilizer, insecticides, industrial chemicals, and manufacturing feedstocks [21].

4.7 Continuous production technologies

There are few “off-the-shelf” continuous production technologies. As a result, most continuous processes are custom designed around a specific pyrolysis technology. The benefit of a custom design continuous-process is that quality and consistency of the BC as well as economies of scale are significantly enhanced. One continuous production technology is vertical retort pyrolysis. Retorts may have a high capital cost, but the labor cost per unit of production is low.

GCS’ sister company, Polchar (polchar.p) in Poland, is a large facility (**Figure 6**: 1) that specializes in pyrolysis and carbonization of different feedstocks using horizontal moving grate and vertical retort pyrolysis technologies. GCS and Polchar have developed a custom retort BC production process that is fully integrated.

Wood feedstock is cut to size, pre-dried and processed in a vertical, gravity-fed retort process. Pyrolysis temperatures can be modified to run the process hotter or cooler with typical temperatures between 600 and 700°C. With control over the process, high quality BCs are produced, and the volatiles emitted in the pyrolysis process are either fully combusted in a combustion chamber and the associated heat used in other applications, including the pyrolysis process, or the volatiles can be condensed into wood vinegars and bio-oils for further refinement. With the ability to control temperature and residence time, the retort technology allows production of a high quality BC in volume. For example, GCS’ general BC specs are: fixed carbon: 93–95% DW, volatiles: 3–4% DW, ash: 2–3% DW, and surface area: 585–630 m^2/g.

High-end BCs can offer specs not achievable with most production techniques, including custom sizing and moisture content, enhanced pore structure—micro, meso, and macro pores, high surface area, and high-carbon content with low-ash.

GCS runs its process 24 hours a day, 7 days a week. The process quickly achieves steady state which allows GCS to control product quality, capture all components of the value-chain including excess heat produced from the pyrolysis process, condense vaporized volatiles into bio-oils and wood vinegars, and significantly reduce

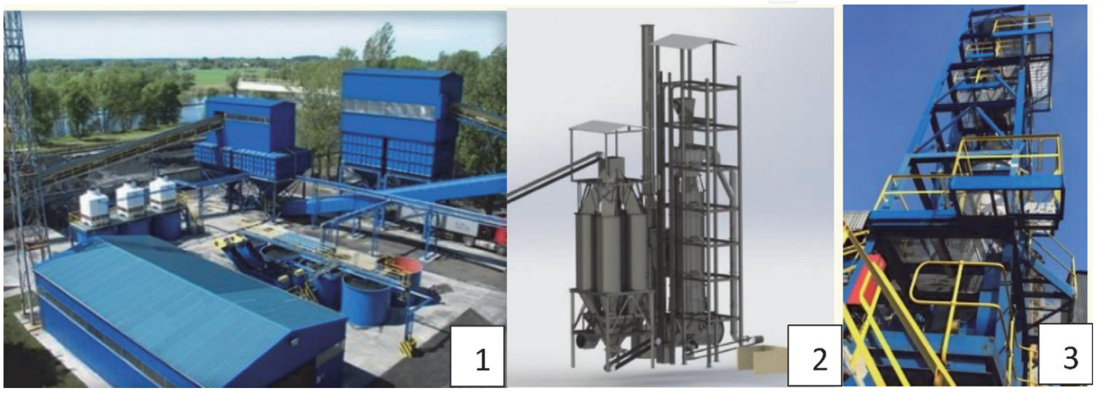

Figure 6.
Representative continuous BC production systems: (1) Polchar production facility, GCS’s (2) vertical retort process and (3) vertical retort.

Technology	Technology cost	Technical expertise	Quality and consistency	Emission control
Pit (open and closed)	Very low	Very low	Low	None
Mound kiln	Very low	Low	Low	None
Brick kiln	Low	Low	Low/moderate	None
Metal kiln	Low	Modest	Moderate	None
Missouri-type kiln	Moderate	Modest	Moderate	Limited
Rotary kiln	Large/high	High	High	High
Kon-Tiki	Low	Low	Moderate	Low
Advanced mobile	Moderate	Modest	Moderate	None/modest
Custom continuous	Very high	High	High	Very high

Table 3.
Comparison of BC production technologies for cost, technical expertise, BC quality and consistency, and ability to control emissions.

the environmental footprint by reducing carbon monoxide and volatile organic emissions.

The BC production technologies reviewed, while varying in cost, expertise, consistency, and emissions (**Table 3**), can all process different wood feedstocks. The combination of varying feedstocks and production technologies results in significant variation of BC specs. *Eucalyptus* biomass components also influence BC properties such as grindability, slagging, and ash content [22]. GCS' new BC production facility in southern Florida will likely use eucalypts grown in nearby plantations.

5. Biochar applications

While interest in and demand for BC are growing [2], BC's multiple applications range widely in potential market size, timing, competitiveness, and pricing compared to alternative products, all of which influence the value of wood grown for BC (**Table 4**).

Historically BC has been viewed through the lens of a soil amendment to help build modern-day terra preta type soils, a type of very dark, fertile artificial (anthropogenic) soil found in the Amazon Basin. But with improved and more sophisticated BC production techniques, there is a vastly expanded market for BC. With the need to replace the substantial loss of soil carbon due to modern agricultural practices [23] and considering the emerging carbon cascades (utilizing BC for one application before it is used for a second) [24], the applications and future potential markets become quite large (**Table 4**).

Focusing on the soil amendment applications, there are growing opportunities to utilize BC to increase nutrient and water retention. However, more than this, many soils have been compromised with heavy metal buildup and other environmental toxicity. BC is now being utilized to help remediate these soils and similarly remediate contaminated water.

In general industrial markets, there are emerging BC applications in many large markets including concrete where BC is starting to be used as a partial substitute for sand and cement. While there are a number of benefits to including BC in concrete, some include reducing weight and increasing strength since BC's water retention

Application	Market size	Timing	Competition	Pricing
Soil carbon	Large	Current	Low	Low
Soil nutrients	Limited	Emerging	High	Low
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 4.
Comparison of market size, timing, competition, and pricing for nine BC applications.

capacity improves the curing process. Other industrial applications include the metallurgical industry and as a filler in asphalt. With 1.8 billion tons of asphalt poured every year, if only 0.5% BC were added this would result in demand for 8 million tons of BC a year; increase the BC component and this market could be very large.

BC applications for specialty industrial markets are growing quickly too. There are opportunities in applications such as acoustic and thermal insulation in walls, ceilings and floors. There are also applications for BC in carbon fiber and polymer space where BCs increase strength, reduce weight, and improve thermal properties. Other emerging specialty industrial applications include protecting against electrosmog, filtration media, heavy metal adsorption, and as partial filler in car and truck tires. Growing trends in developing sustainable supply chains and reducing societal carbon footprint will help accelerate growth of many of these markets.

6. Biochar research

Based on results elsewhere, forest and agronomic crops in Florida USA are likely to respond to organic soil amendments such as BC. Applying BC improves soil physicochemical properties, including bulk density, porosity, cation exchange capacity, and pH. BC also increases soil water and nutrient retention and consequently influences crop production while reducing leaching [25]. Productivity of many crops significantly increased after soils were amended with BC [26, 27]. Sandy soils are more responsive to BC than clayey soils [28] due to their low water and nutrient holding capacities [29]. Most soils in Florida are sandy (>90% of soil particles) and have low nutrient and moisture holding capacities. Fertilizers necessary for crop yield and quality are readily leached, causing environmental pollution. The following recent and ongoing studies in Florida illustrate the response of a few crops to organic soil amendments with and without wood BC.

Green Edge (GE), an organic, slow-release fertilizer (6-4-0), and planting density both influenced the productivity of cultivar EH1 in a study at the IRREC near Ft Pierce, FL ([4], **Table 5**). While the differences among five fertilizers [GE equivalent to 0, 112, 224, and 336 kg N/ha and diammonium phosphate (DAP) at 336 kg N/ha] initially favored the higher GE rates, subsequent differences were inconsistent. The highest planting density had the smallest tree DBH through harvesting at 47 months.

Treatment	Trt. level	Tree DBH at age			Coppice trait		
		36	41	47	Ht	DBH	No.
Planting density (trees/ha)	3588	9.3 b*	10.3 b	11.4 b	2.4	2.6	3.9
	1794	10.9 ab	12.3 ab	13.5 ab	2.2	3.2	3.4
	1196	13.2 ab	14.2 a	15.4 a	2.3	3.3	4.3
Fertilizer (kg N/ha)	0	11.8	13.7 a	14.9 a	2.3	3.4	3.9
	GE 112	10.7	11.2 b	12.4 b	2.3	3.1	3.8
	GE 224	12.6	13.2 ab	14.5 a	2.3	3.0	3.7
	GE 336	11.3	12.6 ab	14.1 ab	2.3	3.0	4.3
	DAP 336	11.2	12.0 ab	13.3 ab	2.2	3.1	3.8

Table 5.
Effects of three planting densities and five fertilizers on EH1 tree (DBH in cm at 36-, 41-, and 47-months of age) and coppice [height (Ht) at 3 months and DBH and number of stems at 8 months of age] traits.

Early coppice responses to planting density and fertilization were nonsignificant, although some earlier trends remained (**Table 5**). The lower planting densities had somewhat larger coppice stem DBHs. The early fertilizer effects were no longer evident.

In a BC-GE study at the IRREC, BC at 11.2 tons/ha enhanced the soil nutrients and tree leaf nutrient levels [4]. GE at 336 kg/ha generally increased available soil nitrogen, and GE + BC further increased NH_4-N. Soil available P significantly increased for GE + BC 5 months after amendment. However, both available N and P in the soil decreased 11 months after amendment, likely due to uptake by the trees. At 11 months, soil NH_4-N was significantly higher with GE and GE + BC. BC also generally enhanced tree leaf nutrient levels, with GE increasing leaf concentrations of Ca, K, Mg, P, Fe, and Mn, and GE + BC significantly increasing 5-month Zn. GE + BC further improved tree leaf Ca, Mg, Zn and Mn, and such improvement was also observed 11 months after amendment. However, a general decrease in leaf Ca, K, Mg, P, and Zn occurred over time, likely due to decreased availability in the soil and dilution by rapidly increased tree biomass.

Further, GE and GE + BC gradually enhanced tree growth [4]. Six months after treatment applications, the cultivars receiving GE only and GE + BC had doubled in height, approximately twice the increase with no treatment. Eleven months after application, cultivars receiving GE + BC were bigger than those receiving GE only and no GE.

Longer term, GE and GE + BC further enhanced tree growth (**Table 6**). At 16 months, the cultivars receiving GE only and GE + BC had nearly tripled tree DBH with no GE and BC. Subsequently, cultivars receiving GE + BC continued to surpass

Age	Treatment*		
	Control	GE	GE + BC
16	2.0 b	5.1 ab	6.5 a
27	2.6	6.3	8.6
31	3.9	8.3	11.2

*Treatment means not sharing the same letter in a trait differ at the 5% level.

Table 6.
Tree DBH (cm) at ages 16-, 27-, and 31- (11, 22, and 26 months after treatment applications) months of E. grandis *cultivar G5 receiving three treatments: Control, GE, GE + BC.*

those receiving GE only and no GE. BC plus fertilizer greatly improved reforestation performance of two tropical species [30].

The fertilizer and planting density differences observed in the IRREC fertilizer × planting density and BC-GE studies are consistent with previously observed influences of fertilizer and planting density on eucalypt productivity in Florida [31–34] and worldwide [35–38]. While inorganic fertilizers have been necessary for rapid growth of eucalypts on Florida's infertile sandy soils, the observed response here to the slow release organic GE, and its apparently beneficial coupling with BC, is encouraging for sustainable eucalypt management. Planting density effects were evident early, with, for example, the 3588 trees/ha in the fertilizer × planting density having the tallest trees at 9 months and the largest stand basal area but smallest tree DBH at subsequent ages. Similar effects of planting density have been noted for *E. dunnii* seedlings and clones [39].

BC enhanced the soil properties of infertile sandy Florida soils as well as the nutrient status of *E. grandis*, especially when applied together with GE and/or chemical fertilizers. BC's large cation exchange capacity facilitates retention of nutrients, particularly Ca, Mg, K, Fe and Mn against leaching. BC's large water holding capacity improves water availability, which is especially important during the dry season. Due to high temperature and humidity, decomposition of organic materials in sandy soils is very rapid, leading to low organic matter contents. BC is a good organic amendment for sandy soils because it stays in soil much longer than other organic materials.

Outside Florida, BC applications on forest trees have given mostly positive results. When broadcast on temperate hardwoods, the major short-term BC impact was an increase in limiting soil P and Ca [40]. BC application in forest ecosystems generally improved soil physical, chemical, and microbial properties [41]. BC from *E. marginata* decreased soil microbial carbon in a coarse soil [42], and BC added to a sandy desert soil did not significantly change soil physical properties [43]. Two BC types had different impacts on growth of young *Pinus elliottii* in subtropical China [44]. Varying doses of macadamia BC combined with two fertilizer rates had contrasting results on soil nutrients and ambiguous trends in the growth of young *E. nitens* [45]. BC did not enhance *Eucalyptus* hybrid survival or growth on degraded soils in southern Amazonia [46]. Compost and BC-compost mixes did not improve the performance of poplar, willow, and alder [47]. BC made from forest thinnings, when applied to temperate managed forests, had no detrimental effects, suggesting that BC can be used for carbon sequestration [48]. A meta-analysis of wood-based BCs indicates a large potential for early tree growth responses to soil amendment in reforestation of boreal and tropical systems [49]. An increase in carbon accumulation in planted loblolly pine due to fertilization [50] suggests that eucalypt plantations receiving BC with fertilizer will also experience an increase in soil carbon.

In Florida, BC has also been recently tested on agronomic crops. Oak-derived BC combined with standard fertilizers enhanced lettuce (*Lactuca sativa*) productivity. Superphosphate (SP) derived from dolomite phosphate rock (DPR) alone generally resulted in less biomass compared to DAP, likely due to lower P availability (**Table 7**). However, lettuce growth was significantly enhanced by P fertilizer plus BC, as indicated by a significant increase in lettuce height and leaf chlorophyll content (by 19.3–138%). Lettuce dry biomass on average is increased by 61.7–76.8%. The maximum biomass yield occurred with DAP and BC combined.

BC application increased soil pH by 1.2–1.7, which was significantly higher than the treatments without BC ($P < 0.05$). As compared with DAP fertilizer, SP application increased soil electrical conductivity (EC) ($P < 0.05$), but this effect was mitigated with BC ($P > 0.05$).

Treatment	Biomass yield	Height	LeafC	Soil pH	Soil EC
	g/pot	cm	SPAD	—	μS/cm
CK	1.1 ± 0.5 a*	7.7 ± 1.5 a	15.2 ± 1.5 a	5.65 ±0.04 b	1215 ±288 b
DAP	24.6 ± 2.3 c	24.3 ± 0.8 cd	28.1 ± 0.5 d	4.94 ± 0.08 a	833 ± 41 ab
SP1	2.6 ± 0.9 a	10.7 ±2.2 a	26.7 ± 1.5 cd	5.06 ± 0.08 a	2526 ±57 cd
SP5	11.4 ± 6.7 ab	17.7 ± 4.9 b	29.7 ± 0.9 d	5.07 ± 0.01 a	1950 ± 291 c
SP7	2.7 ± 1.2 a	8.4 ± 1.8 a	29.5 ± 0.7 d	5.05 ± 0.07 a	2643 ± 298 d
BC-DAP	39.8 ± 4.5 d	29.0 ± 0.7 d	22.0 ± 1.5 b	6.60 ± 0.07 d	410 ± 107 a
BC-SP1	22.4 ± 4.1 bc	22.6 ±1.5 bc	23.5 ± 1.4 bc	6.34 ± 0.05 c	2148 ± 300 cd
BC-SP5	26.1 ± 8.4 c	23.7 ± 3.2 bcd	23.4 ± 1.7 bc	6.44 ± 0.04 c	901 ± 44 cd
BC-SP7	17.4 ± 5.9 bc	19.9 ± 1.9 bc	26.6 ± 2.2 cd	6.28 ± 0.09 c	1964 ± 314 c

**The same trait means not sharing the same letter differ at the 5% level.*

Table 7.
Effects of P fertilizer and BC treatments (CK, control; DAP; SP1, SP2 and SP3: Superphosphate derived from DPR1, DPR2 and DPR3; and BC at 1% application rate) on lettuce biomass yield, height, leaf chlorophyll (LeafC), and soil properties.

Other recent agronomic BC studies are summarized in **Table 8**. As suggested most by the cauliflower response in Gainesville, notable soil and plant responses to BC may take up to 2 years, although BC immediately increased soil organic matter

Location—Crop	BC treatments	Notable responses
Gainesville—Cauliflower	(1) 11.2 mt/ha in 3/2018, (2) 11.2 mt/ha in 9/2018, (3) 0 mt/ha; 1961 kg/ha of 10-10-10 in 10/2019, 78 kg/ha of liquid 5–1-1 every 3 weeks	In 1/2020, (1), (2), (3)—Soil NO3-N: 3.44, 2.19, 2.45 ppm Leaf N: 5.29, 4.70, 4.68%
Gainesville—Perennial peanut	(1) 11.2 mt/ha in 1/2020, (2) 0 mt/ha in 1/2020, (3) 112 kg/ha of N as GE in 2/2020	In 1/2020, (1), (2)—OM: 1.93, 1.42% In 2/2020, (1), (3)—pH: 5.5, 5.2
Old Town—Vegetables	(1) 16.8 mt/ha in 1/2019, (2) 11.2 mt/ha, (3) 5.6 mt/ha, (4) 0 mt/ha; 672 kg/ha of DAP, 448 kg/ha of potassium sulfate, and 15.7 mt/ha of lime in 5/2019	In 5/2019, (1), (2), (3), (4)—No evident trends
Old Town—Sorghum	(1) 22.4 mt/ha in 1/2019, (2) 16.8 mt/ha, (3) 11.2 mt/ha, (4) 5.6 mt/ha, (5) 0 mt/ha	In 5/2019, (1), (2), (3), (4)—Soil NO3-N: 2.25, 2.05, 2.16, 3.69, 1.47 kg/ha Soil Ca: 3525, 3255, 3670, 3094, 3015 kg/ha Soil CEC: 8.8, 8.2, 9.0, 8.0, 7.6 meq/100 g
Old Town—Bahiagrass	(1) 11.2 mt/ha in 1/2019, (2) 0 mt/ha	In 2/2020, (1), (2)—Soil K: 166, 21 kg/ha Soil OM: 1.3, 0.8% Soil CEC: 9.1, 5.0 meq/100 g

Table 8.
Summary of notable results from recent wood BC agronomic studies in Florida.

in a new perennial peanut-based study in Gainesville. The studies near Old Town had varied responses after several BC rates were applied.

Outside Florida, BC from forest trees has benefited agronomic crops. Soil incorporation of BC produced from *E. camaldulensis* increased critical soil properties and the yield of groundnut in south Senegal [51]. BC-blended compost significantly improved quantity and quality of four crops in Europe [52].

7. Carbon sequestration potential of *Eucalyptus* plantations

Given eucalypts high productivity and their use for traditional forest products and because economic feasibility is one of several conditions for a sustainable BC system [53], our financial analysis goal here is to estimate the cost of potential carbon sequestration by *Eucalyptus* plantations using BC as a soil amendment. The following scenario for growing cultivar EH1 on sandy former citrus beds assumed original and two coppice rotations of 5.5 and 4.7 years for 1187 and 2471 trees/ha, respectively, with the first and second coppice growing at 90 and 80% of the original planting. The application of 2.5 tons/ha of BC priced at $750 and $1000/ton assumed a 7% growth increase per ton of BC.

The price of adding BC to the soil was approximately $3 and $5/ton for BC priced at $750 and $1000/ton, respectively, across two planting densities and three discount rates (**Table 9**). Increasing planting density from 1181 to 2471 trees/ha typically increased BC price by $2 per ton. Given the at least 91.5% C content of GCS's BC, the resulting cost for sequestering C in plantation soils ranges from $3.30–5.49/ton added to the soil. This cost is considerably less than the $30–50/ton estimated in 2005 for US forestry sequestering up to 500 million tons of C/year [54]. In 2015, the California Air Resources Board listed C sequestration credits at $12–13/ton [55]. BC produced from hardwoods has a soil residence time in excess of 1000 years [56].

Besides economic feasibility, other conditions of a sustainable BC system include producing/deploying BC safely and not competing with other wood uses; initiatives are necessary in research, policies, and implementation to meet these standards [53]. BC application to soil in Poland is viewed as an important component of the region's circular economy and means of counteracting climate change [57]. In South Africa, carbon storage by *Eucalyptus* and pine plantations and by their long-lived

Planting density (trees/ha)	**Discount rate (%)**		
	4	**6**	**8**
No BC added to soil			
1181	5.6	6.7	7.9
2471	7.7	9.0	10.4
2.5 mt/ha of BC added to soil at $750/mt			
1181	8.5	10.2	12.0
2471	10.3	12.0	13.9
2.5 mt/ha of BC added to soil at $1000/mt			
1181	9.6	11.5	13.6
2471	11.3	13.2	15.3

Table 9.
Effects of planting density, discount rate, and BC price on carbon price ($/mt) for E. urophylla × E. grandis *cultivar EH1 grown on former citrus land.*

Metabolite	*Eucalyptus* genotype					
	G2	G3	G4	G5	5408	EH1
α-Pinene	32.2	28.7	59.3	12.2	38.3	11.6
1,8-Cineole	41.8	47.2	0.1	1.5	1.0	32.5
g-Terpinene	0.1	0.2	0.1	0.6	9.9	17.6
15.81195238	0	0	0	27.9	0.1	5.9
Squalene	5.9	5.7	16.3	9.9	10.4	2.1
Vitamin E	7.6	5.9	7.3	4.0	11.4	1.3

Table 10.
Percent of total hexane extractable metabolites in the crown biomass of six Eucalyptus *genotypes.*

forest products may equally contribute to offsetting almost a total of 4% of the country's carbon emissions [17]. However, because soil C may decrease as *Eucalyptus* plantations mature [15], BC incorporation into plantation soil can be beneficial.

Other bioproducts may also enhance *Eucalyptus* value [4]. Classified as naturally occurring, generated by biochemical processes, or by thermochemical processes [8, 58], many bioproducts have higher value than or could augment traditional wood products, thereby reducing the cost of carbon sequestration by planted eucalypts. However, genetic variation in *Eucalyptus* influences which genotype is best for a particular bioproduct. For example, Florida eucalypts that have been evaluated as jet fuel feedstocks vary widely in percentage of six important metabolites (**Table 10**), with cultivar EH1 not only having a relatively high proportion of 1,8-cineole, but also a much higher absolute amount of this important chemical.

8. Conclusions

While planted eucalypts are very productive worldwide, their above- and below-ground carbon sequestration depends on plantation management options such as cultural intensity, planting density, and rotation length. In Florida USA, *E. grandis* × *E. urophylla* cultivar EH1 planted on former citrus beds and managed at relatively low intensity could sequester over ∼20 mt of C/ha/year at a cost of $30–40/mt. BC production systems ranging from small mobile units to large centralized facilities influence the quality and price of the BC produced, and high-quality feedstocks are critical to producing consistently high-quality BC with uniform quality and specifications for many promising applications. Research in Florida USA and elsewhere addresses responses of forest and agronomic crops to wood BC soil amendments with and without other fertilizers. While BC from wood has many applications, its use as a soil amendment in forest plantations is appealing as a long-term sequestration strategy. In combination with the carbon sequestered in trees, cost estimates of sequestration in *Eucalyptus* plantations by using wood BC as a soil amendment for those plantations are around $5 per mt of BC added per ha.

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Conflict of interest

The authors declare no conflicts of interest.

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References

[1] Hussein H, Farooq M, Nawaz A, Al-Sadi AM, Solaiman ZM, Alghamdi SS, et al. Biochar for crop production: Potential benefits and risks. Journal of Soils and Sediments. 2017;**17**(3):685-716

[2] Grand View Research. Global Biochar Market Estimates and Forecast, 2012–2025; Report issued April 2017

[3] Business Wire. Global Biochar Market Outlook Report, 2019-2024; 30 January, 2020

[4] Rockwood D, Ellis M, Liu R, Zhao F, Ji P, Zhu Z, et al. Short rotation eucalypts: Opportunities for biochar. Forests. 2019;**10**:314. Available from: https://www.mdpi.com/1999-4907/10/4/314/html

[5] CIRAD - FRA, IUFRO - AUT, MUSE - FRA. Eucalyptus 2018: Managing Eucalyptus Plantation under Global Changes. Montpellier, France; 17 September 2018/21. DOI: 10.19182/agritrop/00023

[6] Carle J, Homgren P. Wood from planted forests: A global outlook 2005-2030. Forest Products Journal. 2008;**58**(12):6-18

[7] Sims REH, Hastings A, Schlamadinger B, Taylor G, Smith P. Energy crops: Current status and future prospects. Global Change Biology. 2006; **12**(11):2054-2076

[8] Rockwood DL, Rudie AW, Ralph SA, Zhu J, Winandy JE. Energy product options for *Eucalyptus* species grown as short rotation woody crops. International Journal of Molecular Sciences. 2008;**9**:1361-1378. Available from: http://www.mdpi.org/ijms/papers/i9081361.pdf

[9] Rockwood DL. History and status of Eucalyptus improvement in Florida. International Journal of Forest Research. 2012;**2012**:607879. 10 pages. Available from: http://www.hindawi.com/journals/ijfr/2012/607879/

[10] Rockwood DL, Peter GF. Eucalyptus and Corymbia species for mulchwood, pulpwood, energywood, bioproducts, windbreaks, and/or phytoremediation. In: Florida Cooperative Extension Service Circular 1194. Gainesville, FL: Institute of Food and Agricultural Sciences; 2018. p. 6. Available from: http://edis.ifas.ufl.edu/FR013

[11] Singh B, Singh BP, Cowie AL. Characterisation and evaluation of biochars for their application as a soil amendment. Australian Journal of Soil Research. 2010;**48**(7):516-525. DOI: 10.1071/SR10058

[12] Kloss S, Zehetner F, Dellantonio A, Hamid R, Ottner F, Liedtke V, et al. Characterization of slow pyrolysis biochars: Effects of feedstocks and pyrolysis temperature on biochar properties. Journal of Environmental Quality. 2012;**41**:990-1000

[13] Fabbro KW, Rockwood DL. Optimal management and productivity of *Eucalyptus grandis* on former phosphate mined and citrus lands in central and southern Florida: Influence of genetics and spacing. In: Proceedings 18th Biennial Southern Silvicultural Research Conference, March 2–5, 2015, Knoxville, TN. *e-Gen. Tech. Rpt. SRS-212*. 2016. pp. 510-517. Available from: http://www.srs.fs.usda.gov/pubs/gtr/gtr_srs212.pdf

[14] Campoe OC, Stape JL, Laclau JP, Marsden C, Nouvellon Y. Stand-level patterns of carbon fluxes and partitioning in a *Eucalyptus grandis* plantation across a gradient of productivity, in Sao Paulo State, Brazil. Tree Physiology. 2012;**32**:696-706. DOI: 10.1093/treephys/tps038

[15] Du H, Zeng F, Peng W, Wang K, Zhang H, Liu L, et al. Carbon storage in a *Eucalyptus* plantation chronosequence in southern China. Forests. 2015;**6**: 1763-1778. DOI: 10.3390/f6061763

[16] Zhang H, Guan D, Song M. Biomass and carbon storage of *Eucalyptus* and *Acacia* plantations in the Pearl River Delta, South China. Forest Ecology and Management. 2012;**277**:90-97. DOI: 10.1016/j.foreco.2012.04.016

[17] Christie S, Scholes R. Carbon storage in Eucalyptus and pine plantations in South Africa. Environmental Monitoring and Assessment. 1995;**38**:231-241

[18] Ulman Y, Avudainayagam S. Carbon storage potential of *Eucalyptus tereticornis* plantations. Indian Forester. 2014;**140**(1):53-58

[19] Schmidt HP, Taylor P, Eglise A, Arbaz C. Kon-Tiki - the democratization of biochar production. Biochar Journal. 2014;**1**:14-24

[20] Tigercat. 2020. Available from: www.tigercat.com/product/6050-carbonator/

[21] Murch S. Report for Passive Remediation Systems Biochar Project; 2016. Unpublished. Contact david.derbowka@prsi.ca

[22] Abdullah H, Mediaswanti K, Wu H. Biochar as a fuel: 2. Significant differences in fuel quality and ash properties of biochars from various biomass components of Mallee trees. Energy & Fuels. 2010;**24**(3):1972-1979. DOI: 10.1021/ef901435f

[23] Montgomery D. Growing a Revolution; Bringing our Soil Back to Life. New York: W Norton and Company; 2017

[24] Bales A, Draper K. BURN, Using Fire to Cool the Earth. London: Chelsea Green Publishing; 2018

[25] Ahmed A, Kurian J, Raghavan V. Biochar influences on agricultural soils, crop production, and the environment: A review. Environmental Reviews. 2016;**24**(4):495-502

[26] Jeffery S, Abalos D, Prodana M, Bastos AC, van Groenigen JW, Hungate BA, et al. Biochar boosts tropical but not temperate crop yields. Environmental Research Letters. 2017;**12**:5

[27] Ahmed F, Arthur E, Plauborg F, Razzaghi F, Korup K, Andersen MN. Biochar amendment of fluvio-glacial temperate sandy subsoil: Effects on maize water uptake, growth and physiology. Journal of Agronomy and Crop Science. 2018;**204**(2):123-136

[28] Blanco-Canqui H. Biochar and soil physical properties. Soil Science Society of America Journal. 2017;**81**(4):687-711

[29] Bruun EW, Petersen CT, Hansen E, Holm JK, Hauggaard-Nielsen H. Biochar amendment to coarse sandy subsoil improves root growth and increases water retention. Soil Use and Management. 2014;**30**(1):109-118

[30] Lefebvre D, Román-Dañobeytia F, Soete J, Cabanillas F, Corvera R, Ascorra C, et al. Biochar effects on two tropical tree species and its potential as a tool for reforestation. Forests. 2019;**10**: 678

[31] Langholtz M, Carter DR, Rockwood DL. Assessing the economic feasibility of short-rotation woody crops in Florida. In: Florida Cooperative Extension Service Circular 1516. Gainesville, FL: Institute of Food and Agricultural Sciences; 2007. p. 5. Available from: http://edis.ifas.ufl.edu/FR169

[32] Rockwood DL, Dippon DR, Lesney MS. Woody species for biomass production in Florida. In: Final Report 1983-1988. Oak Ridge National

Laboratory; 1988. p. 153. ORNL/Sub/81-9050/7. Available from: http://web.ornl.gov/info/reports/1988/3445602753456.pdf

[33] Rockwood DL, Carter DR, Stricker JA. Commercial tree crops on phosphate mined lands. Florida Institute of Phosphate Research. FIPR Publication#03-141-225; 2008. p. 123. Available from: http://fipr.state.fl.us/wp-content/uploads/2014/12/03-141-225Final.pdf

[34] Zalesny RS Jr, Cunningham MW, Hall RB, Mirck J, Rockwood DL, Stanturf JA, et al. Chapter 2. Woody biomass from short rotation energy crops. In: In ACS Symposium Book: Sustainable Production of Fuels, Chemicals, and Fibers from Forest Biomass (Zhu J et al.). 2011. pp. 27-63. Available from: http://pubs.acs.org/doi/abs/10.1021/bk-2011-1067.ch002

[35] Perez-Cruzado C, Merino A, Rodriguez-Soalleiro R. A management tool for estimating bioenergy production and carbon sequestration in *Eucalyptus globulus* and *Eucalyptus nitens* grown as short rotation woody crops in north-west Spain. Biomass and Bioenergy. 2011;**35**:2839-2851

[36] Morales M, Aroca G, Rubilar R, Acuna E, Mola-Yudego B, Gonzalez-Garcia S. Cradle-to-gate life cycle assessment of *Eucalyptus globulus* short rotation plantations in Chile. Journal of Cleaner Production. 2015;**99**:239-249

[37] Hinchee M, Rottman W, Mullinax L, Zhang C, Chang S, Cunningham M, et al. Short-rotation woody crops for bioenergy and biofuels applications. In Vitro Cellular & Developmental Biology: Plant. 2009;**45**:619-629

[38] Harper RJ, Sochacki SJ, Smettem RJ, Robinson N. Bioenergy feedstock potential from short-rotation woody crops in a dryland environment. Energy & Fuels. 2010;**24**:225-231

[39] Stape JL, Binkley D. Insights from full-rotation Nelder spacing trials with *Eucalyptus* in Sao Paulo, Brazil. Southern Forests: A Journal of Forest Science. 2010;**72**:91-98

[40] Sackett TE, Basiliko N, Noyce GL, Winsborough C, Schurman J, Ikeda C, et al. Soil and greenhouse gas responses to biochar additions in a temperate hardwood forest. GCB Bioenergy. 2015;**7**:1062-1074. DOI: 10.1111/gcbb.12211

[41] Li Y, Hu S, Chen J, Muller K, Li Y, Fu W, et al. Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: A review. Journal of Soils and Sediments. 2018;**18**:546. DOI: 10.1007/s11368-017-1906-y

[42] Dempster D, Gleeson D, Solaiman Z, Jones D, Murphy D. Decreased soil microbial biomass and nitrogen mineralisation with *Eucalyptus* biochar addition to a coarse textured soil. Plant and Soil. 2012;**354**:311-324

[43] Mertens J, Germer J, de Araújo Filho JC, Sauerborn J. Effect of biochar, clay substrate and manure application on water availability and tree-seedling performance in a sandy soil. Archives of Agronomy and Soil Science. 2017;**63**:969-983

[44] Lin ZB, Liu Q, Liu G, Cowie AL, Bei QC, Liu BJ, et al. Effects of different biochars on *Pinus elliottii* growth, N use efficiency, soil N_2O and CH_4 emissions and C storage in a subtropical area of China. Pedosphere. 2017;**27**:248-261

[45] Wrobel-Tobiszewska A, Boersma M, Adams P, Singh B, Franks S, Sargison JE. Biochar for eucalyptus forestry plantations. Acta Horticulturae. 2016;**1108**:55-62

[46] de Farias J, Marimon BS, de Carvalho Ramos Silva L, Petter FA, Andrade FR, Morandi PS, et al. Survival and growth of native *Tachigali vulgaris*

and exotic *Eucalyptus urophylla* × *Eucalyptus grandis* trees in degraded soils with biochar amendment in southern Amazonia. Forest Ecology and Manage ment. 2016;**368**:173-182

[47] Glisczynski FV, Pude R, Amelung W, Sandhage-Hofmann A. Biochar-compost substrates in short-rotation coppice: Effects on soil and trees in a three-year field experiment. Journal of Plant Nutrition and Soil Science. 2016;**179**:574-583

[48] Sarauer J, Page-Dumroese D, Coleman M. Soil greenhouse gas, carbon content, and tree growth response to biochar amendment in western United States forests. GCB Bioenergy. 2019;**11**: 660-671

[49] Thomas S, Gale N. Biochar and forest restoration: A review and meta-analysis of tree growth responses. New Forests. 2015;**46**:931-946. DOI: 10.1007/s11056-015-9491-7

[50] Bracho R, Vogel J, Will R, Noormets A, Samuelson L, Jokela E, et al. Carbon accumulation in loblolly pine plantations is increased by fertilization across a soil moisture availability gradient. Forest Ecology and Management. 2019;**424**:39-52

[51] Goudiaby A, Diedhiou S, Diatta Y, Adiane A, Diouf P, Fall S, et al. Soil properties and groundnut (*Arachis hypogea* L.) responses to intercropping with *Eucalyptus camaldulensis* Dehn and amendment with its biochar. Journal of Materials and Environmental Science. 2020;**11**(2):220-230

[52] Sánchez-Monedero M, Cayuela M, Sánchez-García M, Vandecasteele B, D'Hose T, López G, et al. Agronomic evaluation of biochar, compost and biochar-blended compost across different cropping systems: Perspective from the European project FERTIPLUS. Agronomy. 2019;**9**:225. DOI: 10.3390/agronomy9050225

[53] Shackley S, Sohi S, Ibarrola R, Hammond J, Masek O, Brownsort P, et al. Biochar, tool for climate change mitigation and soil management. In: Meyers RA, editor. Encyclopedia of Sustainability Science and Technology. New York, NY: Springer; 2012. DOI: 10.1007/978-1-4419-0851-3

[54] Stavins RN, Richards KR. The cost of U.S. forest-based carbon sequestration. In: Pew Center on Global Climate Change. 2005. Available from: https://www.c2es.org/document/the-cost-of-u-s-forest-based-carbon-sequestration/

[55] California Air Resources Board. Compliance Offset Protocol U.S. Forest Offset Projects. 2015. Available from: arb.ca.gov/cc/capandtrade/protocols/usforest/usforestprojects_2015.htm

[56] Lehman J, Joseph S. Biochar for Environmental Management. New York: Earth Scan; 2006. pp. 188-200

[57] Bis Z, Kobyłecki R, Ścisłowska M, Zarzycki R. Biochar – Potential tool to combat climate change and drought. Ec ohydrology & Hydrobiology. 2018; **18**(4):441-453

[58] Gardiner ES, Ghezehei SB, Headlee WL, Richardson J, Soolanayakanahally RY, Stanton BJ, et al. The 2018 Woody Crops International Conference, Rhinelander, Wisconsin, USA, 22–27 July 2018. Forests. 2018;**9**:693. Available from: https://www.mdpi.com/1999-4907/9/11/693