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Biochar amendment did not influence the growth of two tree plantations on nutrient-depleted Ultisols in the south Ecuadorian Amazon region

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Abstract

The literature suggests that biochar increases the fertility of degraded, nutrient-poor tropical soils. We hypothesized that the addition of biochar (a) increases tree growth in two plantations on Ultisols in the south Ecuadorian Amazon region, (b) reduces litterfall during the dry season because the soil remains moister, and (c) improves the benefit–cost ratio of the plantation. We grew two tree species—the native leguminous *Schizolobium parahyba* var. *amazonicum* (Ducke) Barneby and the exotic *Gmelina arborea* Roxb—and used a full factorial split-split-plot design of all treatments for both tree species at each of two sites. The treatments included the amendment of mineral fertilizer plus lime, 3 and 6 t ha^{-1} biochar, and a control. The plots were replicated three or four times. Tree height (TH), basal diameter (BD), and diameter at breast height (DBH) were measured several times during 51 mo after planting in September 2009 and litterfall during 12 mo (March 2012–February 2013). The site and the mineral fertilizer plus lime treatment had significant effects on TH, BD, and DBH. The amendment of mineral fertilizer plus lime increased TH, BD, and DBH by 47, 43, and 58%, respectively, relative to the control. The litterfall of *G. arborea* was on average 84% higher than that of *S. parahyba*. The amendment of biochar did not significantly influence TH, BD, DBH, or litterfall. The benefit–cost ratio of wood production was >1 in the mineral fertilizer plus lime treatment and controls but <1 in the biochar treatments and decreased with increasing addition of biochar. Our results demonstrate that the assumption that biochar can be used to improve the fertility of degraded Amazon soils cannot be generalized.

1 | INTRODUCTION

From 2000 to 2005, Ecuador annually lost 1.7% of the original forest cover, which was the highest annual deforestation rate of South America during this period (FAO, 2006; Mosandl et al., 2008). Most of the current deforestation in Ecuador

Abbreviations: BD, basal diameter; BS, base saturation; CEC, cation exchange capacity; DBH, diameter at breast height; ECEC, effective cation exchange capacity; SOM, soil organic matter; TH, tree height is attributable to the conversion of secondary forests to pastures (Mosandl et al., 2008). From 1972 to 1989, the pasture area in Ecuador tripled (Wunder, 2000). In the Ecuadorian Amazon region, deforestation caused a loss of surface soil organic matter (SOM) and exchangeable cations and thus a loss in soil fertility (Mainville et al., 2006). Moreover, the common practice of pasture burning favors the ingression of bracken ferns, which further decreases the pasture value and contributes to its final abandonment at many locations (Roos et al., 2013). Reforestation is one option to recover the degraded land, counteract the high deforestation rate, and mitigate climate change through carbon sequestration (Cunningham et al., 2014; Mosandl et al., 2008). However, the site conditions of the Amazon region render reforestation a great challenge because the strongly weathered and overexploited soils show low fertility (Mainville et al., 2006), hampering the establishment of afforestations. Under these conditions, the use of biochar (i.e., pyrolyzed organic matter) to improve soil fertility has been suggested (Glaser et al., 2000, 2001, 2002; Lehmann et al., 2003; Lima et al., 2002; Major et al., 2010). The addition of biochar is thought to mimic the formation of the Terra Preta do Indio soils, which are anthropogenic soils with high organic matter concentrations partly consisting of biochar. Terra Preta do Indio soils occur in areas with strongly chemically weathered soils of the inner tropics, such as the Amazon lowland.

The application of biochar to soils can increase nutrient concentrations, particularly of bioavailable P (Biederman & Harpole, 2012; Drake et al., 2015; Viger et al., 2015). Bioavailable P frequently shows low concentrations in strongly weathered tropical soils and limits plant growth (Chadwick et al., 1999; Walker & Syers, 1976). It has also been reported that the amendment of biochar stabilized SOM, created ion-exchange sites, and improved soil biological activity (El-Naggar et al., 2018; Lawrinenko & Laird, 2015; Lehmann et al., 2011). Moreover, particularly wood biochar increased the soil pH, increased cation exchange capacity (CEC), and lowered the soil exchangeable Al concentrations (Berek & Hue, 2016; Enders et al., 2012). Many researchers have therefore suggested that biochar amendment may improve the fertility of degraded tropical soils (e.g., Jeffery et al., 2017; Lefebvre et al., 2019; Major et al., 2010). Consequently, the use of biochar as a soil amendment to improve fertility and enhance carbon sequestration has received great attention in recent years (Jeffery et al., 2017; Schneider et al., 2011; Thomas & Gale, 2015).

Biochar consists of a heterogeneous combination of pyrogenic compounds with varying physical and chemical properties and has a number of properties of particular interest from the perspective of forest restoration. (a) Biochar is recalcitrant and therefore does not rapidly decompose, guaranteeing a long-term effect after a single amendment (Criscuoli et al., 2014; Hernandez-Soriano et al., 2016); (b) biochar provides cation and anion exchange sites that improve the retention of plant nutrients (Deluca et al., 2015; El-Naggar et al., 2019); (c) biochar increases water retention in soil (Das & Sarmah, 2015); (d) biochar can adsorb potentially toxic compounds, such as Al or legacy pesticides from previous land use (Qian et al., 2013; Rizwan et al., 2016; Shi et al., 2019); and (e) biochar may be relatively easily and economically generated from available feedstocks, such as fermentation residue (Maroušek, 2014), sewage sludge (Yue et al., 2017), or the wood chips locally available in Ecuador, although the optimum biochar generation still requires more research.

Core Ideas

- Mineral fertilizer plus lime increased the growth of two tree species on Ultisols.
- Biochar amendment did not influence tree growth and litterfall.
- The economic benefit compensated the mineral fertilizer plus lime amendment.
- Biochar amendment was not economically viable.

In a meta-analysis of agricultural biochar amendment experiments, Crane-Droesch et al. (2013) reported a mean increase of 10% in crop yield when 3 t ha^{-1} of biochar were amended to the soil in the tropics and subtropics (84 studies). Similarly, the meta-analysis of Jeffrey et al. (2017) revealed significant increases in crop yield by ~25% at a median biochar application rate of 15 t ha^{-1} for tropical regions. In the same analysis, crop yield in temperate regions decreased by 5% (65 studies from the tropics and 44 from the temperate zone) (Jeffrey et al., 2017). The yield increase depended on the biochar type, the application rate, and the soil type (Igalavithana et al., 2015). Biochar effects seem to be generally positive in tropical and boreal latitudes (Thomas & Gale, 2015) and neutral or negative in temperate latitudes (e.g., Jeffery et al., 2017; Kloss et al., 2014; Schmidt et al., 2014). The amendment of biochar to soil had a greater impact on crop productivity in pot experiments than in field experiments, in acidic soils than in neutral soils, and in sandy or clayey soils than in loamy soils (Liu et al., 2013). Biochar has also been used to improve the growth of tree plantations. Thomas & Gale (2015) indicated a consistent and strong positive growth response of 36 woody plant species to biochar additions based on a meta-analysis of 17 studies (six tropical, six temperate, and five boreal sites) and reported a mean increase in diameter growth by 41% in response to biochar additions of both tropical and boreal trees.

In the humid tropics, such as the Amazon basin, strongly weathered Oxisols and Ultisols are widespread, covering ~75% of the land surface (Furley, 1990). These soils have undergone desilication under continuously high temperature and precipitation and therefore only contain quartz, Fe and

Al (oxy)hydroxides, and sometimes kaolinite, which results in a low cation exchange capacity but a high anion exchange capacity (Marques et al., 2002). If the soils are free of kaolinite, SOM in the topsoil is the only source of cation exchange sites (Zech et al., 1997). As a consequence of unsustainable land use, Oxisols and Ultisols can lose SOM and undergo compaction, the two most frequent signs of soil degradation (Alegre & Cassel, 1996; Fujisaka et al., 1998; McGrath et al., 2001). In the south Ecuadorian Amazon region (Province of Zamora-Chinchipe), more than 2,300 km^2 of soils show signs of degradation (GAD, 2015).

In the present paper, we report the effect of biochar application with and without mineral fertilization plus lime on the (a) height (TH), basal diameter (BD), and diameter at breast height (DBH) growth of the native leguminous Schizolobium tree [*Schizolobium parahyba* var. *amazonicum* (Ducke) Barneby] and on the exotic Gmelina tree (*Gmelina arborea* Roxb.); (b) litterfall and water-holding capacity; and (c) commercially valuable construction and paper wood production. We hypothesized that amendment of biochar (a) increases tree growth, particularly at a high application rate; (ii) reduces litterfall during the dry season because of its moisture-conserving effect via increased water-holding capacity; and (iii) improves the benefit–cost ratio of the plantations, which are used for the production of timber or paper wood.

2 | MATERIALS AND METHODS

2.1 | Study sites and selected tree species

The experiment was established at two sites in the Province of Zamora-Chinchipe, southern Ecuador, next to the city of Zamora (La Victoria, UTM WGS84 coordinates: 17M9552550 730470) at 949–965 m asl and the village of Panguintza (Los Zapotes, 17M95668135 741834) at 875–917 m asl. The site at La Victoria had a slope of up to 15%, and the site in Los Zapotes had a slope of up to 60%. The native vegetation at both sites was an evergreen tropical rainforest with a mean annual temperature of 22.0 ˚C, a mean annual precipitation of 1,945 mm, and mean annual relative humidity of 88% (1970–1993; National Institute of Meteorology and Hydrology, www.serviciometeorologico.gob.ec).

The parent rocks at La Victoria are leuco-granodiorite and hornblende-granodiorite of the Zamora Batholith, which intruded Triassic to Jurassic volcanic rocks, and at Los Zapotes the parent rocks are andesite and tuff breccias of the upper Jurassic Chapiza formation. The soils at both sites were Typic Kandiudults (Soil Survey Staff, 2014). Before the start of the experiment, the upper 0.25 m of the soils at La Victoria were sandy loams, with a bulk density of 1.2 ± 0.05 g cm^{-3} (mean ± SD), a C concentration of 30 ± 2.1 g kg^{-1}, and a C/N ratio of 14 ± 0.23; those at Los Zapotes were loamy silty clays, with a bulk density of 0.95 ± 0.05 g cm^{-3}, an organic C concentration of 28 ± 3.2 g kg^{-1}, and a C/N ratio of 11 ± 0.70. Because we expected that the effect of the mineral fertilizer plus lime and the biochar amendments on the pH, the effective cation exchange capacity (ECEC; i.e., sum of base cations $K^+ + Na^+ + Ca^{2+} + Mg^{2+}$, extracted with 1 M NH_4OAc at pH 7 plus exchangeable acidity, Al^{3+}+H^+, extracted with 1 M KCl), and base saturation (BS; % exchangeable base cations of ECEC) could underly possible treatments effects on tree growth, their initial and final values are shown in Table 1. The study sites were grasslands used as pastures before the establishment of the tree plantations.

We chose *S. parahyba* because it is one of the most important planted native tree species in the Amazon region, with wide use in the plywood industry (Silva, Vasconcelos, de Carvalho, & Cordeiro et al., 2011). The tree belongs to the Family Fabaceae (legumes), can fix atmospheric N_2 in symbiosis with *Rhizobium* bacteria, and is therefore fast growing and tolerates low soil fertility. *Schizolobium parahyba* has been frequently planted on degraded soils (Gazel Filho et al., 2007). The second tree species (*G. arborea*) is native to India, where it grows on soils with low fertility, high acidity, low organic matter, and low available nutrient concentrations. *Gmelina arborea* is used as timber wood, firewood, and fodder (Swamy et al., 2004).

Seedlings of *S. parahyba* and *G. arborea* were produced by a local tree nursery, which used seeds from a single mother plant, thus ensuring seed homogeneity, on a substrate consisting of a mixture of soil, compost, gravel >5 mm, and ash at a mass ratio of 1:1:1:1. Five seeds were planted within an area of 13 × 15 cm and transplanted to the field at the age of 2 mo with an average height of 35–40 cm. Sampling was started 6 mo after establishment of the plantations.

2.2 | Experimental design

We chose a full factorial split-split-plot design (main plot split into subplots for two tree species × further splits of the subplots into with or without mineral fertilizer plus lime × three levels of biochar [0, 3, 6 t ha^{-1} = 12 treatments]). The full design was implemented at both study sites. At La Victoria all plots were replicated four times; at Los Zapotes, where the available experimental area was smaller than in La Victoria, all plots were replicated three times. Each plot had an area of 144 m^2 and was planted with 16 trees, which corresponds to 1,111 trees ha^{-1}.

TABLE 1 Mean and SD of the pH value, effective cation exchange capacity (ECEC), and base saturation (BS) before the start of the experiment in March 2009 and at the end in November 2013

Site	Treatment[a]	pH		ECEC		BS	
		Mar. 2009	Nov. 2013	Mar. 2009	Nov. 2013	Mar. 2009	Nov. 2013
				mmol$_c$ kg^{-1}		%	
La Victoria	T1: Ctr.	4.6 ± 0.15a[b]	4.7 ± 0.10a	48 ± 4.3b	80 ± 8.6a	42 ± 7.4a	55 ± 5.6a
	T2: F+L	4.6 ± 0.08b	5.2 ± 0.03a	45 ± 1.7b	78 ± 3.8a	34 ± 1.6b	88 ± 3.3a
	T3: 3tBC	4.6 ± 0.11a	4.9 ± 0.07a	46 ± 2.3b	80 ± 0.30a	35 ± 3.3b	54 ± 8.6a
	T4: F+L+3tBC	4.6 ± 0.08b	5.0 ± 0.03a	42 ± 2.1b	86 ± 7.2a	33 ± 2.3b	71 ± 3.3a
	T5: 6tBC	4.6 ± 0.06b	4.9 ± 0.13a	47 ± 2.9b	80 ± 6.9a	32 ± 2.9b	60 ± 7.1a
	T6: F+L+6tBC	4.6 ± 0.02b	5.3 ± 0.11a	47 ± 3.1b	90 ± 4.4a	29 ± 6.1b	86 ± 4.2a
	T7: Ctr.	4.5 ± 0.05b	4.8 ± 0.11a	52 ± 0.90b	87 ± 7.9a	28 ± 0.70b	52 ± 6.5a
	T8: F+L	4.5 ± 0.04b	5.0 ± 0.07a	51 ± 3.1b	90 ± 7.3a	28 ± 2.9b	69 ± 4.6a
	T9: 3tBC	4.5 ± 0.07b	4.9 ± 0.05a	54 ± 2.8b	77 ± 8.6a	24 ± 0.78b	48 ± 6.4a
	T10: F+L+3tBC	4.7 ± 0.09b	5.1 ± 0.06a	49 ± 7.0b	80 ± 5.8a	38 ± 8.4b	77 ± 6.2a
	T11: 6tBC	4.5 ± 0.02b	5.0 ± 0.06a	52 ± 6.1a	72 ± 9.7a	32 ± 2.1a	53 ± 11a
	T12: F+L+6tBC	4.5 ± 0.04b	5.2 ± 0.10a	51 ± 6.7b	92 ± 16a	34 ± 4.5b	79 ± 10a
Los Zapotes	T1: Ctr.	4.9 ± 0.12a	4.7 ± 0.04a	72 ± 7.9a	86 ± 2.9a	57 ± 17.3a	48 ± 1.3a
	T2: F+L	4.7 ± 0.06a	4.9 ± 0.14a	66 ± 3.3b	95 ± 6.2a	53 ± 10.1a	71 ± 5.9a
	T3: 3tBC	4.9 ± 0.09a	4.8 ± 0.04a	79 ± 0.51a	83 ± 2.0a	68 ± 16.9a	48 ± 11a
	T4: F+L+3tBC	4.7 ± 0.07a	4.6 ± 0.13a	63 ± 6.8b	87 ± 0.90a	51 ± 3.6a	61 ± 6.0a
	T5: 6tBC	4.9 ± 0.10a	4.8 ± 0.08a	71 ± 2.9b	83 ± 4.9a	74 ± 2.5a	76 ± 7.7a
	T6: F+L+6tBC	4.8 ± 0.20a	4.9 ± 0.07a	69 ± 4.4b	93 ± 8.5a	59 ± 15a	85 ± 5.7a
	T7: Ctr.	5.2 ± 0.14a	5.0 ± 0.17a	99 ± 9.9a	99 ± 12a	81 ± 11a	70 ± 11a
	T8: F+L	4.8 ± 0.09a	4.8 ± 0.04a	70 ± 8.4b	100 ± 6.0a	53 ± 6.6a	63 ± 5.4a
	T9: 3tBC	4.9 ± 0.06a	4.8 ± 0.04a	75 ± 5.2b	96 ± 4.4a	66 ± 5.8a	67 ± 4.9a
	T10: F+L+3tBC	5.0 ± 0.26a	5.2 ± 0.25a	100 ± 29a	150 ± 16a	66 ± 16a	78 ± 18a
	T11: 6tBC	5.1 ± 0.08a	4.9 ± 0.06b	99 ± 13a	93 ± 8.4a	78 ± 13.5a	66 ± 3.4a
	T12: F+L+6tBC	5.0 ± 0.25a	4.8 ± 0.10a	100 ± 31a	10 ± 4.4a	68 ± 15.4a	67 ± 12a

[a]Treatments T1–T6 include *Schizolobium parahyba*; T7–T12 include *Gmelina arborea*. Ctr., control; F+L, amendment with mineral fertilizer plus lime; 3tBC, amendment with 3 t biochar; 6tBC, amendment with 6 t biochar.

[b]Different lowercase letters indicate significant differences between before and the end of the experiment according to a *t* test for connected data at a significance level of $p < .05$.

2.3 | Mineral fertilizer and biochar application

We added a basal mineral fertilizer application when the tree was planted and a second mineral fertilizer application after 36 mo of plant growth only to the mineral fertilizer plus lime treatments (Table 2). We added B on 23 July 2012 to all plots because we recognized visual signs of B deficiency, which was confirmed by a growth experiment with tomato (*Solanum lycopersicum* L.). We used commercial agricultural lime of 98% purity. The lime requirement was determined with the Kamprath equation (Equation 1) (Kamprath, 1970). This resulted in the amendment of 5 t ha^{-1} $CaCO_3$ at La Victoria and 3 t ha^{-1} $CaCO_3$ at Los Zapotes (Table 2).

$$CaCO_3\left[\text{mmol kg}^{-1}\right] = 1.5\times H^{+} + Al^{3+}\left[\text{mmol kg}^{-1}\right] \quad (1)$$

We bought commercially available wood-derived biochar, which was produced from tabano (*Casearia mariquitensis* Kunth., ∼80%) and a mixture of cashco (*Weinmania fagaroides* Kunth), canelo (*Nectandra laurel* Klotzsch ex Nees), and capulí (*Prunus opaca* Walp., ∼20%). The wood was milled to <0.5 cm and pyrolyzed in a traditional earthen kiln with small holes that could be opened and closed. The biochar was produced from harvested woody forest biomass that could not be sold as construction or paper wood. The biochar used in this study contained 836 g kg^{-1} C and 26.2 g kg^{-1} ash and had a pH of 8.55. The nutrient fluxes associated with the addition of 3 and 6 t ha^{-1} of biochar are summarized in Table 2.

TABLE 2 Mass of biochar, lime, and nutrient amendments to the treatments of the afforestation experiment in a split-split-plot design

			Biochar									Mineral fertilizer										
			27 July –6 Aug. 2009									27 July –6 Aug. 2009							8 Nov. 2012			
Treatment[a]	Tree species	Mass	N	P	K	Ca	Mg	S	Fe	Mn	Na	N	P	K	Mg	S	Zn	$CaCO_3$	B	N	P	K
		t ha^{-1}	kg ha^{-1}															t ha^{-1}	kg ha^{-1}			
T1/7: Ctr.	*S. parahyba or G.arborea*	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	67	–	–	–
T2/8: F+L	*S. parahyba* or *G. arborea*	0	–	–	–	–	–	–	–	–	–	200	150	200	118	229	40	V = 5, Z = 3[b]	67	100	50	50
T3/9: 3tBC	*S. parahyba* or *G. arborea*	3	10.8	1.0	15.2	14.8	5.4	1.3	1.2	1.0	1.2	–	–	–	–	–	–	–	67	–	–	–
T4/10: F+L+3tBC	*S. parahyba* or *G. arborea*	3	10.8	1.0	15.2	14.8	5.4	1.3	1.2	1.0	1.2	200	150	200	118	229	40	V = 5,Z = 3	67	100	50	50
T5/11: 6tBC	*S. parahyba* or *G. arborea*	6	21.6	2.0	30.4	29.6	10.9	2.6	2.4	1.9	2.4	–	–	–	–	–	–	–	67	–	–	–
T6/12: F+L+6tBC	*S. parahyba* or *G. arborea*	6	21.6	2.0	30.4	29.6	10.9	2.6	2.4	1.9	2.4	200	150	200	118	229	40	V = 5;Z = 3	67	100	50	50

[a]Treatments T1–T6 include *Schizolobium parahyba*; T7–T12 include *Gmelina arborea*. Ctr., control; F+L, amendment with mineral fertilizer plus lime; 3tBC, amendment with 3 t biochar; 6tBC, amendment with 6 t biochar. The composition of the used commercial mineral fertilizer was taken from the product information.

[b]V, La Victoria; Z, Los Zapotes.

In all treatments, we mixed the topsoil extracted from a cylinder-shape volume with a radius of 2 m and a depth of 0.25 m with the amendments (fertilizer plus lime and biochar) and homogenized the mixture. This mixture was put back into the hole from which the soil was taken, and each tree seedling was planted in the middle of this plant bed. We did not add mineral fertilizer outside this plant bed. We planted the trees from 3 to 7 Aug. 2009 and harvested them from 4 to 8 Nov. 2013 after 51 mo of growth.

2.4 | Measurements and statistical analyses

We started with the plant measurements in February 2010 (i.e., 6 mo after planting) and repeated the measurements 8, 10, 12, 17, 23, 43, and 51 mo after planting. At that time, >90% of the trees had survived (i.e., at least 173 trees per plot and 14 trees per split plot). Tree height was measured from stem base to top. The BD was measured at a height of 0.2 m from the soil surface. The DBH was measured at a height of 1.3 m from the soil surface after the trees had reached at least this height. Litterfall was collected biweekly from 1 Mar. 2012 to 22 Feb. 2013 as a cumulative sample of 2 wk with four 0.6 m by 0.6 m litterfall traps per plot. To reduce the edge effect, we took all growth measurements from the four central trees (of 16) on each plot, where the litter traps were located. Litterfall was dried for 1 wk in a ventilated oven at 60 ˚C and weighed.

To estimate the stem biomass of *G. arborea* and *S. parahyba*, we used the allometric equations of Swamy et al. (2004) (Equation 2) and Silva et al. (2011) (Equation 3), respectively.

$$Y = a + b\,\mathrm{DBH} + c\,\mathrm{DBH}^2 \tag{2}$$

$$Y = d\,\mathrm{DBH}^e \tag{3}$$

where Y is fresh biomass (kg), and $a = -4.152$, $b = 1.667$, $c = 0.026$, $d = 0.076$, and $e = 2.346$.

At the end of the experiment in November 2013, we determined the soil water-holding capacity as the difference between the water contents at a vacuum of 10 MPa (pF 2.5) and 1,500 MPa (pF 4.2) on all plots. The vacuum was applied to a porous plate on which we positioned a water-saturated soil core and waited until equilibrium was reached. The water content was determined gravimetrically and is expressed in mass%.

To calculate the economic value of the tree harvest, we used local market prices of US\$16.50 m^{-3} for trees with a DBH <0.2 m and US\$57.00 m^{-3} for trees with a DBH ≥0.2 m (Aguirre, 2012; Jiménez Pozo, 2016). We considered a subsidy of US\$890 ha^{-1} offered by the Ecuadorian Ministry of Agriculture, Livestock, Aquaculture and Fisheries as an incentive for afforestations (Ministry agreement No. 035; 27 Feb. 2014). We calculated the establishment and maintenance costs of each treatment according to Table 3. Equipment included shovels, diggers, and machetes. Maintenance costs were determined by the labor required for weeding the 2-m circle around the seedlings. To the costs in Table 3, we added US\$81.63 t^{-1} for lime and US\$160 t^{-1} for biochar. We disregarded discount rates.

Data were analyzed with an ANOVA for split-split-plot designs using the software R. We used the packages *nortest()* (Gross & Ligges, 2015) for tests of normality, *agricolae()* (De Mendiburu, 2010) for ANOVA, and *gplots()* (Warnes et al., 2009) and *plotrix()* (Lemon, 2006) for plotting data.

TABLE 3 Average costs of establishment and maintenance over 4 yr for four treatments, Province of Zamora Chinchipe, Ecuador

Activity	Fertilized	Not fertilized
	US\$ ha^{-1}	
Seedling	278.00	278.00
Labor	100.00	100.00
Equipment	30.00	30.00
Transplanting	20.00	20.00
Fertilization 1	699.80	
Borax	43.40	43.40
Fertilization 2	158.55	
Maintenance cost		
Year 1	120.00	120.00
Year 2	90.00	120.00
Year 3	60.00	120.00
Year 4	40.00	120.00
Total	1,639.75	951.40

3 | RESULTS AND DISCUSSION

3.1 | Climatic conditions, TH, BD, and DBH

Mean annual rainfall during the years 2009–2013 ranged from 1,960 to 2,690 mm at La Victoria and from 1,690 to 2,060 mm at Los Zapotes. There were weak dry and rainy seasons. During the dry season, monthly rainfall was <150 mm.

Our repeated measures ANOVA revealed significant effects of the study site on TH and DBH, of tree species on BD, and of the amendment of mineral fertilizer plus lime on all three measures of tree growth (TH, BD, DBH) (Table 4). The amendment of biochar did not have a significant effect on the three measures of tree growth. Expectedly, date of measurement had a significant effect on all three measures

TABLE 4 Results of a repeated measures ANOVA examining the effects of the site (La Victoria and Los Zapotes), experimental block, tree species (*Gmelina arborea* and *Schizolobium parahyba*), amendment of fertilizer + lime, and amendment of biochar (3 and 6 Mg ha^{-1}) and their interactions on tree height (TH), basal diameter (BD), and diameter at breast height (DBH)

	TH				BD				DBH			
Source	**df**	**SS**	***F***	***p* value**	**df**	**SS**	***F***	***p* value**	**df**	**SS**	***F***	***p* value**
Between: site and tree species												
Site	1	223	32	**.001**	*1*	*8.8*	0.19	.68	1	169	6.3	**.046**
Site_block	5	97	2.8	.12	5	183	0.81	.58	5	152	1.1	.44
Tree species	1	0.67	0.10	.77	1	864	19	**.005**	1	224	8.3	**.028**
Residuals	6	42			6	271			6	162		
Between: site, tree species: mineral fertilizer + lime												
Mineral fertilizer + lime	1	829	117	**<.001** ↑	1	2657	84	**<.001** ↑	1	1,331	62	**<.001** ↑
Tree species: mineral fertilizer + lime	1	64	9.1	**.011**	1	26	0.83	.38	1	62	2.9	.12
Residuals	12	85			12	379			12	256		
Between: site, trees species: mineral fertilizer + lime: biochar												
Biochar	2	5.1	0.6	.54	2	7.1	0.4	.70	2	13	0.76	.47
Tree species: biochar	2	2.0	0.2	.79	2	7.4	0.37	.69	2	0.10	0.01	1.00
Mineral fertilizer + lime:biochar	2	5.7	0.7	.50	2	13	0.65	.53	2	0.20	0.01	.99
Tree species: mineral fertilizer + lime:biochar	2	6.8	0.8	.44	2	16	0.80	.46	2	21	1.2	.32
Residuals	48	194			48	481			48	423		
Within-subject effects												
Date	7	5,915	1,036	**<.001** ↑	7	13,776	1267	**<.001** ↑	2	947	310	**<.001** ↑
Date:site	7	383	67.0	**<.001**	7	338	31	**<.001**	2	43	14	**<.001**
Date: site_block	35	86	3.0	**<.001**	35	122	2.2	**<.001**	10	16	1.1	.40
Date: tree species	7	32	5.6	**<.001**	7	1,034	95	**<.001**	2	72	23	**<.001**
Date: mineral fertilizer + lime	7	116	20	**<.001**	7	186	17	**<.001**	2	4.2	1.4	.26
Date: biochar	14	11	0.99	.47	14	27	1.2	.25	4	4.9	0.80	.53
Date: tree species:mineral fertilizer + lime	7	59	10	**<.001**	7	9.0	0.9	.54	2	0.2	0.1	.92
Date: tree species:biochar	14	14	1.2	.28	14	8.0	0.4	.98	4	3.8	0.6	.65
Date: mineral fertilizer + lime:biochar	14	2.0	0.18	1.00	14	12	0.57	.89	4	4.3	0.70	.59
Date: tree species:mineral fertilizer + lime:biochar	14	6.0	0.56	.90	14	5.0	0.24	1.00	4	4.3	0.70	.59
Residuals	462	377			462	718			132	202		

Note. Significant *p* values are in bold. Arrows indicate direction of effect (if the effect is directed).

of tree growth, reflecting the continuous growth of the trees. There was a significant effect of the interaction of tree species with the amendment of mineral fertilizer plus lime on TH. This illustrated that the TH of the two studied tree species responded differently to the amendment of fertilizer plus lime. *Schizolobium parahyba* benefited more strongly from mineral fertilizer addition than *G. arborea*, possibly because it is a legume (Figure 1). Moreover, several interactions of date with other variables had significant effects on our measures of tree growth but none including biochar. There was also no effect of biochar on the three tree growth measures on any single measurement date.

Because biochar did not have any significant effect on our tree growth measures, we simplified our design by combining all treatments that did not receive mineral fertilizer plus lime and all treatments that received mineral fertilizer plus lime, respectively (Figures 1 and 2). We did this separately for the two study sites (combination of the two tree species) and for the two tree species (combination of the two study sites, except in Figure 2b) to best illustrate our results. We then ran a new ANOVA on the simplified design and only for the data of the harvest date in November 2013 followed by a Tukey HSD post hoc text, the results of which are shown in Figures 1 and 2 with the help of different uppercase and lowercase letters. To visualize the minimal effect of biochar, we also show the results of the biochar treatments in Figures 1 and 2, which were, however, not separately included in the statistical evaluation but were lumped with the two groups with and without mineral fertilizer plus lime.

Figure 1 illustrates that Los Zapotes was inherently more fertile than La Victoria, resulting in significantly higher TH in November 2013 (i.e., the harvest date), on the plots with and without amendment of mineral fertilizer plus lime. The higher initial fertility of the soils at Los Zapotes is also reflected by the higher pH, ECEC, and BS (Table 1) and the lower C/N ratio than at La Victoria. *Gmelina arborea* showed a significantly higher BD and DBH than *S. parahyba*, both on the fertilized and unfertilized plots. The amendment of mineral fertilizer plus lime had a consistent significant positive effect on all tree growth measures at both sites and for both tree species.

The increase of the DBH of *G. arborea* by the amendment of mineral fertilizer plus lime in our experiment was 1.98 cm yr^{-1} (18% higher than on the control plots). This was lower than the range of increase in DBH of 2.02–2.76 cm yr^{-1} reported by Kojima et al. (2009) for a fertilized *G. arborea* plantation in Indonesia under similar climatic conditions. The TH and DBH of the fertilized *S. parahyba* in our experiment was ∼40% lower than in *Schizolobium amazonicum* Huber ex Ducke plantations in the Brazilian Amazonia (State of Pará), although our trees reached a similar TH of 12 m (Fernandes da Silva et al., 2011; Ruivo et al., 2010). This possibly indicates a particularly advanced degradation of our study soils prior to afforestation.

The finding that biochar did not have a significant effect on tree growth is unexpected (Table 4) because in the literature there are several reports of strong effects of biochar amendment on tree growth. In a study of Ghosh et al. (2014), the amendment of biochar to two native tree species in a tropical urban environment in Singapore increased TH by 22%. Fagbenro et al. (2013) observed a significant effect of biochar amendment on TH, DBH, dry matter yield, and root radius of *Moringa oleifera* Lam. in Nigeria. Lefebvre et al. (2019) reported that the amendment of 1.1 and 5.5 Mg ha^{-1} biochar plus fertilizer increased monthly height growth of two Amazonian tree species [*Guazuma crinita* Mart. and *Terminalia amazonia* (J.F. Gmel.) Exell.] by a factor of 2.7–3.0 compared with the control, even when the fertilizer was limited to only one application at the beginning of the study.

Many more studies of the use of biochar to improve yields have been conducted for agricultural systems than for tree plantations, for example in lettuce (*Lactuca sativa* L.) (Carter et al., 2013; Gunes et al., 2014), corn (*Zea mays* L.) (Cornelissen et al., 2013; Rogovska et al., 2016), sweet potato [*Ipomoea batatas* (L.) Lam.] (Liu et al., 2014), and tomato (*Solanum lycopersicum* L.) (Akhtar et al., 2014; Hossain et al., 2015). All of them reported positive effects when biochar was amended with or without organic or inorganic fertilizer. Spokas et al. (2012) conducted a meta-analysis of results from 45 biochar experiments in 25 countries. They found that in ∼30% of the experiments there was no significant effect of biochar on the crop yield. In ∼20% of the experiments even negative impacts on yields were observed; and positive impacts were reported only in ∼50% of the experiments. Most of the negative or neutral effects of biochar on crop yields were reported for fertile soils. A recent review concluded that biochar application to low-fertility soils is a potential best-management practice (El-Naggar et al., 2019). It can directly or indirectly contribute to the rehabilitation of low-fertility soils. However, El-Naggar et al. (2019) also indicated that the impact of biochar application on soil fertility and crop productivity strongly depends on the experimental conditions, characteristics of the biochar, and soil types. El-Naggar et al. (2019) suggested that negative effects of biochar on crop performance are mostly related with detrimental effects on the soil microbial community because of a high pH, the induction of cation antagonisms (e.g., Ca/K), and toxic volatile organic compounds.

Our finding that biochar addition alone and in combination with mineral fertilizer plus lime did not increase tree growth is in line with the results of Schmidt et al. (2015), who observed that applying only biochar to a degraded soil did not increase pumpkin (*Cucurbita maxima* L.) yield. However, the finding that there was no additional effect of biochar on tree growth if the biochar application was combined with mineral fertilizer plus lime (Table 4; Figure 1) contrasts the results of Schmidt et al. (2015). In their study, mixing the biochar with cow urine

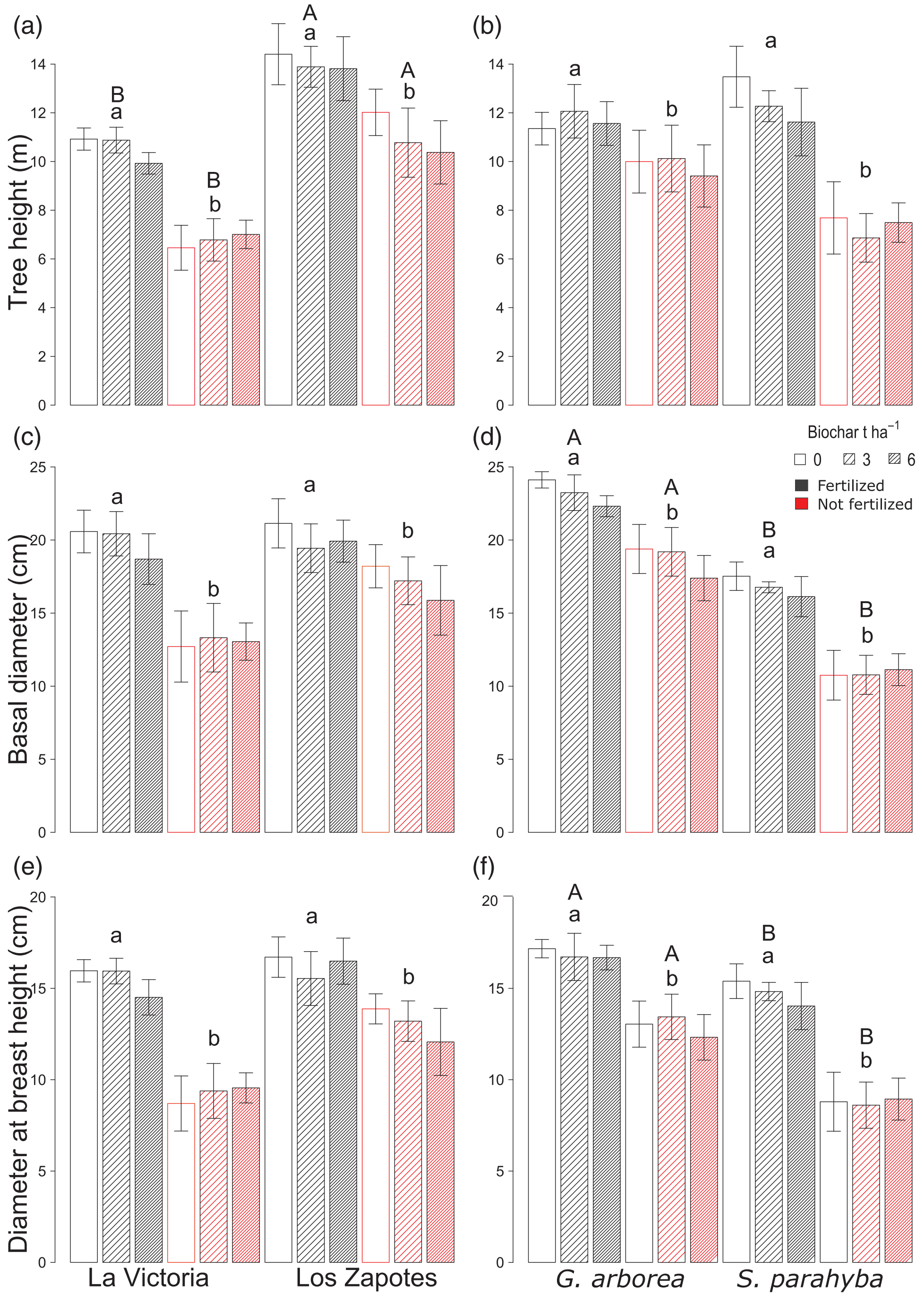

FIGURE 1 (a, b) Tree height, (c, d) basal diameter, and (e, f) diameter at breast height at La Victoria vs. Los Zapotes (a, c, e) and *Gmelina arborea* vs. *Schizolobium parahyba* (b, d, f). The data were grouped into all treatments that received mineral fertilizer plus lime (fertilized) and all treatments that did not receive mineral fertilizer plus lime (not fertilized, "simplified design"; $n = 24$ for La Victoria, $n = 18$ for Los Zapotes, $n = 21$ for each of the tree species). The ANOVA was only run on the data from November 2013. Different uppercase letters indicate significant differences between the sites (a, c, e) or tree species (b, d, f); different lowercase letters significant differences among the fertilized and not fertilized plots based on a Tukey's HSD post hoc test at a significance level of $p < .05$. To visualize the lacking effect of biochar, we show three bars for the amendments of 0, 3, and 6 t of biochar per lumped group (fertilized/not fertilized) separately. The error bars are SEs ($n = 8$ for La Victoria, $n = 6$ for Los Zapotes, $n = 7$ for *G. arborea* and *S. parahyba*)

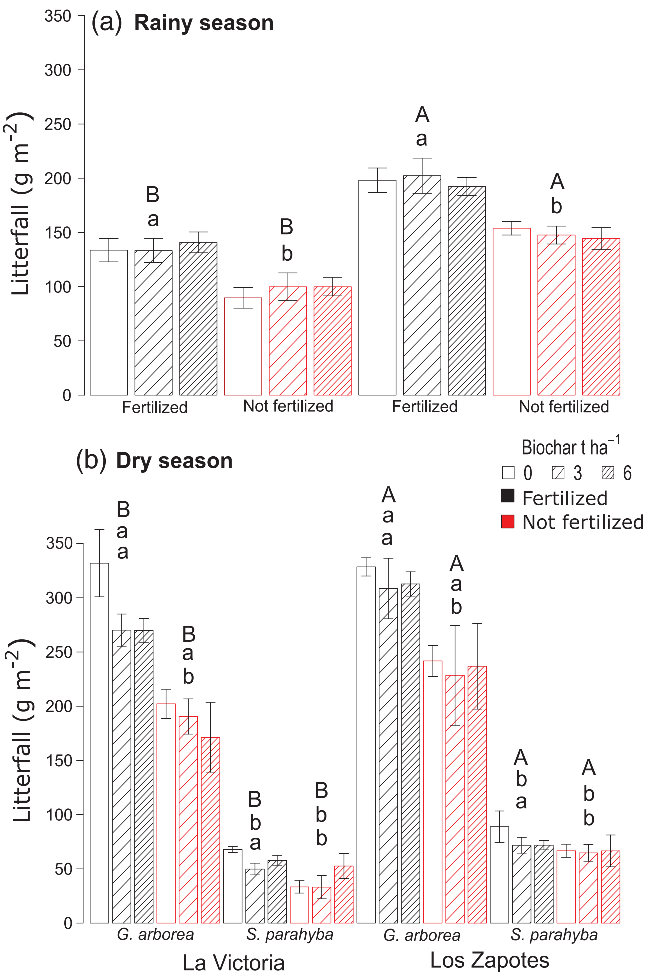

FIGURE 2 Mean cumulative litterfall during (a) one rainy season (February–August 2012) and (b) one dry season (September 2012–January 2013). Data from the rainy season were grouped into all treatments that received mineral fertilizer plus lime (fertilized) and all treatments that did not receive mineral fertilizer plus lime (not fertilized, "simplified design"; $n = 24$ for La Victoria, $n = 18$ for Los Zapotes). The data of the dry season in (b) were additionally separated according to the two tree species ($n = 12$ per species in La Victoria, $n = 9$ per species in Los Zapotes). Different uppercase letters indicate significant differences between the sites. Different lowermost lowercase letters indicate significant differences between the fertilized and nonfertilized treatments. In (b), the middle row of lowercase letters indicates significant differences between the tree species. The significance level was $p < .05$ and determined with a Tukey's HSD post hoc test. To visualize the lacking effect of biochar, we show three bars for the amendments of 0, 3, and 6 t of biochar separately. The error bars show SEs ($n = 8$ for La Victoria, $n = 6$ for Los Zapotes in a; $n = 4$ for each tree species at La Victoria, $n = 3$ at Los Zapotes in b)

and applying the urine-biochar slurry to the root zone considerably improved pumpkin yield on a tropical soil compared with treatments in which biochar was applied without urine or urine without biochar. Besides the fact that Schmidt et al. (2015) studied a crop, another major difference between our and their studies was that the soil studied by Schmidt et al. (2015) was inherently nutrient-rich.

At La Victoria, our biochar amendment increased pH, ECEC, and BS significantly in most biochar treatments (Table 1). However, the effect was generally smaller than that of the amendment of mineral fertilizer plus lime. Nevertheless, our biochar application should have reduced Al toxicity considerably, as indicated by the increase in BS and the fact that BS equals ECEC minus exchangeable acidity. We therefore suggest that at La Victoria the lack of a biochar effect is more attributable to an insufficient nutrient supply, particularly of N and P. At Los Zapotes, the amendment of biochar increased ECEC significantly in only two cases and even decreased pH in one case slightly but significantly (Table 1). Thus, at the Los Zapotes site with an a priori higher pH, ECEC, and BS, biochar had a smaller effect on these properties than at the a priori more acidic La Victoria site. Because there was a smaller risk of Al toxicity at Los Zapotes than at La Victoria, we again think that the insufficient nutrient supply is the more likely reason for the lack of biochar effect. It has to borne in mind that the lack of a biochar effect on our tree growth measures does not exclude that there was still a biochar effect on properties of the plantations that we did not measure (e.g., root development).

The significant effects of date and its interactions with site, site block, mineral fertilizer plus lime, and the combination of tree species and mineral fertilizer plus lime on at least one of TH, BD, and DBH (but frequently all three) indicated that these tree growth measures did not only change with time as expected because of the continuous growth. Instead, the tree growth measures responded differently at the two different sites and even at the site blocks and between the two tree species to the mineral fertilizer plus lime amendment (Table 4). Remarkably, neither the biochar amendment nor the interaction of the biochar amendment with the sampling date were significant, suggesting that the biochar did not develop an effect on TH, BD, and DBH during the 51 mo of our experiment.

3.2 | Litterfall

Our ANOVA revealed significant effects of the study site and the experimental block on the sites during the rainy season, the tree species during the dry season, the amendment of mineral fertilizer plus lime and its interaction with tree species during the rainy and dry seasons on litterfall (Table 5). These results illustrate that nutrient availability determined by the inherent site fertility and the amendment of mineral fertilizer plus lime drove litterfall. Moreover, the two species responded differently to nutrient availability. There was again no significant effect of the amendment of biochar and of all interac-

TABLE 5 Results of an ANOVA examining the effects of the site (La Victoria and Los Zapotes), experimental block, tree species (*Gmelina arborea* and *Schizolobium parahyba*), amendment of fertilizer + lime, and amendment of biochar (3 and 6 Mg ha^{-1}) and their interactions on litterfall in the rainy and dry seasons

	Rainy season				Dry season			
Source	**df**	**SS**	***F***	***p* value**	**df**	**SS**	***F***	***p* value**
Between: site and trees species								
Site	1	66,595	188	**<.001**	1	18,171	14	**.01**
Site_block	5	15,659	8.8	**.01**	5	11,649	1.8	.24
Tree species	1	1,834	5.2	.06	1	809,188	634	**.00**
Residuals	6	2,129			6	7,657		
Between: site, trees species: mineral fertilizer + lime								
Mineral fertilizer + lime	1	39,754	68	**<.001 ↑**	1	62,411	75	**<.001 ↑**
Tree species: mineral fertilizer + lime	1	6,231	11	**.007**	1	31,679	38	**<.001**
Residuals	12	7,031			12	9,947		
Between: site, trees species: mineral fertilizer + lime:biochar								
Biochar	2	82	0.08	.92	2	5,734	3.0	.06
Tree species: biochar	2	1,144	1.2	.32	2	3,199	1.7	.20
Mineral fertilizer + lime: biochar	2	11	0.01	.99	2	2,617	1.4	.27
Tree species: mineral fertilizer + lime: biochar	2	1,023	1.0	.36	2	288	0.15	.86
Residuals	48	23,526			48	46,603		

Note. Significant *p* values are in bold. Arrows indicate direction of effect (if the effect is directed).

tions of the amendment of biochar with other factors on litterfall. The lacking effect of biochar on litterfall is in line with our finding that the water-holding capacity at the end of our experiment in November 2013 was only significantly different between the two study sites (La Victoria: mean ± SD; 9.3 ± 1.2 mass% or 11 ± 1.4 vol%; Los Zapotes: 17 ± 1.8 mass% or 16 ± 1.7 vol%), but there was no significant effect of any treatment on the water-holding capacity. Thus, our results do not support the hypothesis that biochar increases the soil water retention.

Because the amendment of biochar did not have a significant effect, we again lumped the fertilized and unfertilized plots, respectively, together and ran an additional ANOVA on the simplified design followed by a Tukey's HSD post hoc test (see Figure 2).

At Los Zapotes, in all treatments significantly more litterfall was recorded than at La Victoria (Table 5; Figure 2). During the rainy season, *G. arborea* and *S. parahyba* produced at Los Zapotes on average 45 and 55% more litterfall than at la Victoria, respectively. During the dry season, the differences were 17 and 49% for *G. arborea* and *S. parahyba*, respectively. During the dry season, *G. arborea* produced significantly more litterfall than *S. parahyba* at both study sites (Table 5; Figure 2). The litterfall of *G. arborea* was significantly higher during the dry than the rainy season at both study sites. We attribute these findings to an interaction of the genetic differences between the two tree species and climatic conditions. The amendment of mineral fertilizer plus lime increased the annual litterfall on average by 19 and 23% for *G. arborea* and by 65 and 42% for *S. parahyba* in La Victoria and Los Zapotes, respectively.

The mean annual litterfall of our 3-to-4-yr-old *S. parahyba* stands on the plots with amendment of fertilizer plus lime was <50% of that of a 5-to-6-yr-old *S. parahyba* plantation in the Brazilian Amazonia (State of Pará; Silva et al., 2011) which produced 4.51 t ha^{-1} yr^{-1}. The mean annual litterfall of our *G. arborea* plantation was, however, higher than the range of 2.1 to 2.9 Mg ha^{-1} yr^{-1} observed for a 5-yr-old *G. arborea* plantation in Raipur, India, which was P-limited because of a strong P sequestration in Fe oxides (Swamy et al., 2004). The plantations studied by Swamy et al. (2004) were less densely planted (with tree spacing of 4 × 4 m) than ours (3 × 3 m). Mean annual litterfall of our 3-to-4-yr-old *S. parahyba* stands on the plots with amendment of mineral fertilizer plus lime reached 20–30% of the maximum litterfall reported for primary Amazon forest of 7.3–10.5 Mg ha^{-1} yr^{-1}

TABLE 6 Results of an ANOVA examining the effects of the site (La Victoria and Los Zapotes), experimental block, tree species (*Gmelina arborea* and *Schizolobium parahyba*), amendment of fertilizer + lime, and amendment of biochar (3 and 6 Mg ha^{-1}) and their interactions on the benefit–cost ratio

Source	df	SS	*F*	*p* value
Between: site and trees species				
Site	1	0.63	4.1	.09
Site_block	5	0.39	0.51	.76
Tree species	1	1.1	7.1	**.04**
Residuals	6	0.93		
Between: site, tree species: mineral fertilizer + lime				
Mineral fertilizer + lime	1	0.19	3.0	.11
Tree species: mineral fertilizer + lime	1	0.02	0.39	.55
Residuals	12	0.73		
Between: site, tree species: mineral fertilizer + lime: biochar				
Biochar	2	14	76	**<.001 ↓**
Tree species:biochar	2	0.13	0.68	.51
Mineral fertilizer + lime: biochar	2	0.07	0.40	.68
Tree species: mineral fertilizer + lime: biochar	2	0.00	0.01	.99
Residuals	48	4.5		

Note. The benefit-cost ratios were log-transformed to approximate normal distribution of the residuals. Significant *p* values are in bold. Arrows indicate direction of effect (if the effect is directed).

in the Tapajós National Forest (Nepstad et al., 2002) and 9.7–10.5 Mg ha^{-1} yr^{-1} near Manaus (Vasconcelos & Luizão, 2004).

The finding that *G. arborea* had a substantially higher litterfall during the dry than the rainy season has been reported for other seasonal tropical forests (Borchert et al., 2002; Camargo et al., 2015; Tonin et al., 2017; Wieder & Wright, 1995; Wilcke & Lilienfein, 2002). The increased litterfall during the dry season is thought to be a response to water stress because fewer leaves reduce water losses by transpiration (Borchert et al., 2002). *Schizolobium parahyba* did not show increased litterfall during the dry relative to the rainy season because it flowers and fructifies during the dry season and is almost leafless during this period (Flores Bendezu, 1998).

Akhtar et al. (2014) reported that adding biochar to a sandy loam soil under reduced irrigation saved water and enhanced the productivity and quality of tomato, because of an increased soil water content by the high adsorption capacity and porous structure of biochar. The same results were reported by Liang et al. (2014), but for calcareous soils. In the study by Akhtar et al. (2014), the bulk density of soil was reduced from 1.63 to 1.54 g cm^{-3} after the amendment of 5% (on a mass basis) of biochar. Additionally, Zheng et al. (2013) attributed the mitigation of nitrogen leaching losses following biochar addition to an increasing soil water holding capacity. Nelissen et al. (2014) found that the addition of biochar resulted in the trapping of water and nutrients which became biologically unavailable and this effect increased with increasing pyrolysis temperature. This is in line with findings that biochar produced at low pyrolysis temperatures is initially hydrophobic but can be altered in soil (Das & Sarmah, 2015). If it was generally true that biochar immobilizes soil water, the amendment of biochar could have increased litterfall because of reduced plant water availability, which was not observed.

3.3 | Benefit–cost ratio

Our ANOVA on the benefit–cost ratio for the harvested wood after 51 mo revealed significant effects of the tree species and the biochar amendment (Table 6). *Gmelina arborea* produced more wood and thus had a better benefit–cost ratio than *S. parahyba* (Figure 3). In contrast to our expectation, the benefit–cost ratios were similarly economically lucrative in the mineral fertilizer plus lime and the unfertilized treatments. Thus, the additionally created wood value because of the fertilizer effect compensated the fertilizer costs but did not improve the benefit–cost ratio. As a consequence, fertilization only served to establish the tree plantation faster with likely beneficial effects on habitat, hydrological, and erosion protection functions of the tree plantations, which were not economically quantified. Moreover, part of the benefit was attributable to the subsidy of US$890 ha^{-1}. In the mineral fertilizer plus lime treatments, the ratio of the income from selling the wood to the subsidy was >1 (1.7–2.4) except for *S. parahyba* at La Victoria (0.8). Only at the more fertile site in Los Zapotes was the income from selling the wood higher than

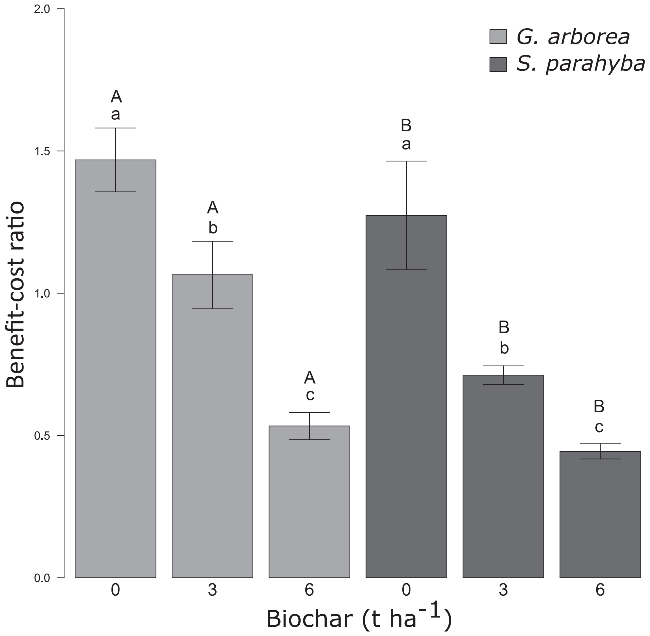

FIGURE 3 Mean benefit–cost ratios of the wood harvest after 51 mo of growth differentiated according to the amount of amended biochar irrespective of the study site and amendment of fertilizer plus lime. Error bars show SEs ($n = 14$). Different uppercase letters indicate a significant difference between the tree species; different lowercase letters indicate a significant difference among the different biochar application rates according to Tukey's HSD post hoc test at a significance level of $p < .05$. The post hoc test followed an ANOVA on a simplified design, in which all plots from both study sites that received 0, 3, and 6 Mg ha^{-1} biochar were lumped together per tree species. The benefit–cost ratio included a subsidy and did not consider discount rates

the costs; at la Victoria the benefit–cost ratio was only positive because of the subsidy. The latter is also true for the positive benefit–cost ratios of the controls. At La Victoria, the subsidy accounted for approximately two-thirds of the total income and at Los Zapotes for approximately half. If interest rates of capital had been considered, the benefit–cost ratio would have further decreased. The amendment of biochar increased the cost of the produced wood without improving the yield and therefore even had a negative effect on the benefit–cost ratio. To illustrate this, we lumped the unfertilized and fertilized treatments of both study sites per amendment rate of biochar and tree species together (Figure 3).

Our benefit–cost ratios shown in Figure 3 were at the lower end of reported values in the literature of 1.45–2.66 for *G. arborea* (Bertomeu, 2006; Coomes et al., 2008; Magcale-Macandog et al., 1999; Mali et al., 2017) but similar to the only reported benefit–cost ratio for *S. parahyba* that we found in the literature (Schwartz et al., 2017). The main reason for the comparatively low benefit–cost ratios of our plantation, particularly if the subsidy was subtracted, might be the short growth time of only 51 mo, whereas the comparison values from the literature originated from plantations were at least 8 yr old. The short growth time of our plantation resulted in a large contribution of stems with a DBH <0.2 m, which have a low commercial value.

For *G. arborea* plantations in The Philippines, Bertomeu (2006) reported a similarly low benefit–cost ratio of 1.45 as in our study in a low timber-yield scenario because of poor tree management in a corn–tree agroforestry system with separate corn and tree blocks. Magcale-Macandog et al. (1999) found a benefit–cost ratio of 2.66 when *G. arborea* was harvested after 8 yr on small-holder farms, either planted as blocks or hedgerows. A recent study in India reported a benefit–cost ratio of 1.6 for the harvest of a *G. arborea* in an agroforestry system after 12 yr of growth (Mali et al., 2017), and another study in Panama reported a benefit–cost ratio of 1.72 after 10 yr of growth (Coomes et al., 2008). For an *S. parahyba* enrichment plantation in a degraded Amazonian forest in the State of Pará, Brazil, Schwartz et al. (2017) reported a benefit–cost ratio of 1.44 for harvesting 13-yr-old *S. parahyba* trees, and Siviero et al. (2020) reported a benefit–cost ratio >1 for the harvest of trees of different species with a DBH >25 cm to which *S. parahyba* contributed ~50% of the wood volume.

It is possible that the benefit–cost ratio of our plantations would have increased if the plantations had been thinned after 5 yr of growth and if only trees with a DBH >0.25 m had been harvested after at least 8 yr of growth as recommended in the literature (Coomes et al., 2008; Jiménez Pozo, 2016; Siviero et al., 2020). However, the restrictions of our funding did not allow for these management options.

4 | CONCLUSIONS

We had to reject all three of our hypotheses. The addition of 3–6 Mg ha^{-1} biochar to degraded tropical Ultisols in Amazonia did not influence tree growth or litterfall during the dry season. Therefore, the effect of biochar addition on the benefit–cost ratio of the tree plantations was negative because the effort to amend biochar to the degraded Ultisol was associated with costs that were not returned.

We conclude that reported positive effects of the amendment of biochar to degraded tropical soils on plant growth cannot be generalized. Future research must therefore address under which conditions biochar has a positive effect on tree growth in plantations on strongly weathered, nutrient-depleted tropical soils. We suspect that similar negative effects might have remained unpublished, resulting in a positive confirmation bias of the biochar effects on plant growth on strongly weathered tropical soils.

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AUTHOR CONTRIBUTIONS

Esthela M. Gonzalez Sarango, Formal analysis, Investigation, Visualization, Writing-original draft; Carlos Valarezo Manosalvas, Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing-review & editing; Marconi Mora, Investigation, Writing-review & editing; Miguel Á. Villamagua, Investigation, Writing-review & editing; Wolfgang Wilcke, Formal analysis, Investigation, Supervision, Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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