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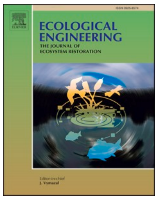

Survival and early growth of 51 tropical tree species in areas degraded by artisanal gold mining in the Peruvian Amazon

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ABSTRACT

Artisanal gold mining in Amazon forests and rivers has been reported in all Amazonian countries. Amazon mining has a wide range of negative effects and severe environmental and social consequences. Given that the activity in the region is mostly illegal, there are few studies published in the scientific literature on recovery of areas degraded by gold mining. This study conducts an experimental reforestation project aimed to evaluate soil degradation and explore the seedling survivorship and early growth of 51 tropical tree species in gold mined areas at 5 study sites distributed across the Madre de Dios region, in the Peruvian Amazon. The study evaluates the effect of biochar amendments on the survivorship and growth of 51 tropical species. The study also analyzes the influence of species wood density on seedling performance one year after planting. In order to inform further restoration plantation strategies, species were chosen with the end goals of timber production, biodiversity enhancement, and soil restoration. Site degradation, soil properties and mercury levels were analyzed in degraded areas and paired reference forest patches. Soils after gold mining are found to be highly degraded, with soil C being nearly absent, cation content greatly decreased, and loss of fine sediment. Soil mercury levels were found below national and international environmental quality standards. A positive correlation and a statistically significant relationship were found between survivorship and wood density. This reveals that the higher the wood density of the species, the higher the survival percentage. Growth and overall performance of mid, and especially low wood density species were significantly increased by biochar additions, while no effect was recorded on high wood density species growth. The study provides guidance on the post-ASGM restoration potential for 51 common and useful tree species and gives practitioners recommendations for combinations of species and fertilization treatments to optimize restoration designs.

1. Introduction

The Amazon has great potential for mineral production, particularly copper, tin, nickel, bauxite, manganese, iron ore, and gold (Sonter et al., 2017). As a result, governments are providing incentives in order to boost mineral resource development. As extractive technologies improve and the prices of commodities remain high due to uncertainty in global markets, it is likely that the scale of Amazon mining will increase, particularly illegal and poorly regulated artisanal and small-scale gold mining (ASGM) (Alvarez-Berríos and Aide, 2015). While illegal mining has always been present in the region, current levels are unprecedented. A recent analysis reported 2312 illegal gold mining sites

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with more than 500,000 informal gold miners active across six South American countries – Venezuela, Brazil, Bolivia, Colombia, Ecuador and Peru (RAISG, 2018).

Artisanal and small-scale gold mining is responsible for the largest fraction of forest loss and disturbance in the Amazonian region of Madre de Dios, in Peru (Caballero et al., 2018). ASGM is unique compared to other drivers of deforestation because of the severity of its impacts, leaving a highly altered landscape (Peterson and Heemskerk, 2001; Asner and Tupayachi, 2017) and threatening local communities, including indigenous people, by affecting the quality of the food supply (Diringer et al., 2015). Mining causes the destruction of natural ecosystems through removal of soil and vegetation, and contamination with heavy metals beneath waste disposal sites (Cooke and Johnson, 2002).

Previous studies on abandoned mining sites in the Neotropics suggests that forest recovery following ASGM is slow and qualitatively inferior compared to regeneration following other land uses (Parrota & Knowles, 2001; Peterson and Heemskerk, 2001; Rodrigues et al., 2009). It has the lowest residual forest carbon of any other land use, and leads to loss of ecosystem services, removal of fine sediments, defaunation, severely impaired water quality, and mercury contamination of soil, water, and air (Román-Dañobeytia et al., 2015; Wyatt et al., 2017). Compared to normal soils, mining substrates can present extreme challenges to plant colonization and the formation of any kind of self-sustaining ecosystem (Bradshaw, 1997; Ilunga et al., 2015; Buch et al., 2017).

Most reforestation projects centered on mining recovery in the tropics fail due to inappropriate knowledge on species choice, their growth and survival rates under different site conditions, as well as their fertilization needs in areas degraded by gold mining (Cooke and Johnson, 2002). Species selection based on functional traits is also of vital importance for the success of restoration or rehabilitation plantations (Baraloto et al., 2010). Wood density has been shown to be a key functional trait in tropical forest communities (Chave et al., 2009) and is being used to predict performance of tree species in degraded areas (Charles et al., 2017). Despite the evidence of a survival–growth trade-off in tropical trees (Wright et al., 2010), early successional species with low wood densities are often selected for restoration projects under the assumption that restoration plantings follow the same recovery trajectory as naturally regenerating forests (Berenguer et al., 2018). However, there is growing evidence that planting high wood dense species with slower growth rates may also help to maximize mid-term restoration success (Cardinale et al., 2007; Ostertag et al., 2015).

Successful restoration following mining usually depends on transplanting seedlings and applying soil amendments such as fertilizer, lime, and organic manure, on severely degraded sites as a means of catalyzing forest succession (Ni et al., 2015). Biochar, or charcoal intended for use as a soil amendment, has received great attention in recent years because of its recalcitrance (at least 100–200 years and up to 1000s) and potential for enhancing carbon sequestration and soil properties (Thomas and Gale, 2015; Purakayastha et al., 2019). Also, some studies have documented reduced bioavailability of heavy metals and sulfates in the presence of biochar incorporated in contaminated soils (Beesley et al., 2010; Borchard et al., 2012). Though promising, biochar's potential for land remediation and for improving plant growth in areas degraded by gold mining has not been explored so far (Wang et al., 2012; Lefebvre et al., 2019).

In Madre de Dios, government and community views on post-mining land use have resulted in regulations and programs emphasizing the reestablishment of native ecosystems inside protected areas that were illegally mined (SERNANP, 2017), as well as the establishment of tree plantations and improved agroforestry systems near indigenous or mestizo communities. In both of the cases, the species most suitable for restoration goals in soils altered by ASGM, soil amendments, and position on the landscape that offer greatest success, are still unknown (https://www.nature.com/articles/d41586-020-00119-z).

Here we report the results of a large-scale restoration experiment distributed across the Peruvian department of Madre de Dios to develop strategies for the recovery of ASGM mined lands. The main objectives of the study were to (1) test 51 species with potential for ecological restoration and/or forest rehabilitation; (2) assess the potential for biochar amendments for use in reforestation efforts; and (3) explore species performance regarding their contrasting wood density traits. To enhance our understanding of the functional response of planted species, we used wood density, a key plant functional trait, as a predictor of species seedling performance. Due to the fact that fast growing early successional species starts the regeneration process and later successional species move in to replace them (Whitmore, 1989), we predicted a negative relationship between seedling performance and species wood density. We also hypothesized that biochar and fertilizer amendments will improve seedling performance, especially of lower wood density species (Huante et al., 1995; Lefebvre et al., 2019).

2. Materials and methods

2.1. Study area

The study was conducted in five gold mining sites totaling 7.6 ha in the southeastern Peruvian Amazonian region of Madre de Dios, province of Tambopata, districts of Laberinto and Inambari (see Table 1 for specific locations and site characteristics). The study sites were located between 220 and 360 m and had a seasonal tropical climate (MAT 25 °C) with a mean annual rainfall of 2200–2400 mm concentrated in a ~ 8 month wet season (Malhi et al., 2002). The forest types of the region are representative of seasonal tropical moist forests in southwestern Amazonia and are recognized worldwide for their exceptionally high biological diversity (Gentry, 1988; Asner et al., 2017).

2.2. Characterization of degraded areas

The study was focused on ASGM areas mined with water cannons and suction pumps, which is the most widely used method of gold mining in Madre de Dios and much of the wet tropics (Grimaldi et al., 2015; RAISG, 2018). In a recent previous study, a total of 100,000 ha have been reported as deforested by ASGM in Madre de Dios, of which 61,000 ha correspond to minimally mechanized pump-based mining and 31,000 ha to gold mining with heavy machinery (Caballero et al., 2018). Unmanned Aerial Vehicles (UAVs) were used to generate high resolution mosaics (~3 cm/pixel) in order to calculate site areas, characterize site level variations on topography and soil fertility, and to plan the experiment. Most of the study sites were covered by sandy areas with no vegetation cover and gravel/cobble mounds, some of them partially shaded with natural regenerated tree cover, and others with no vegetation or regeneration (Table 1, Fig. 1). Natural regeneration on shaded gravel mounds was mainly 3 to 6 m height stands of the pioneer woody species *Cecropia membranacea*, *Ochroma pyramidale*, *Tessaria integrifolia*, and *Trema micrantha* (Garate, 2011).

A total of 43 soil cores at a depth of 0–20 cm were collected for soil characterization across sites in a randomly stratified sampling design; 17 cores were taken on open sandy areas, 16 on gravel/cobble mounds partially shaded, and 10 on open gravel/cobble mounds. For comparison, a total of 30 soil cores were taken in the nearest old growth forest stands of the 5 study sites. Soil properties varied within mined areas, with the gravel mounds (vegetated and unvegetated) having lower acidity (higher pH), higher cation exchange capacity (CEC), and lower sand content than the open sandy areas, and closer to reference forest. Open sandy areas were nearly devoid of soil organic matter (SOM) and fine sediment, and were radically different than reference soils and gravel mounds. Even though soil mercury (Hg) was higher in the paired reference forest than in the degraded areas, all levels were found below the national and international environmental quality standards (UNEP, 2013). Soils across mined areas in our study sites are characterized by low pH (4.90–5.49), low SOM (0.22–1.92%) and low CEC (6.39–12.38

Table 1

Location and characteristics of the area covered by the experiment in five ASGM study sites.

Sites	Coordinates (UTM)	Time since abandonment (years)	Number of plots	Total area (ha)	Area covered (%)		
					Open sandy areas	Shaded gravel mounds	Open gravel mounds
1	432990 (E) 85977872 (N)	2	3	1.6	56	25	19
2	431682 (E) 8598050 (N)	3	3	0.8	50	13	37
3	432085 (E) 8598131 (N)	2	6	3.1	68	29	3
4	423803 (E) 8595627 (N)	4	3	1.0	10	80	10
5	353600 (E) 8565750 (N)	4	3	1.1	18	73	9
All Sites			18	7.6	49	39	12

Fig. 1. Aerial view of a typically ASGM area mined with water cannons and suction pumps (A), including gravel/cobble mounds partially shaded with natural regenerated plant cover (B) and with no vegetation or regeneration (C), and open sandy areas with no vegetation cover (D).

Cmol/kg), compared to the reference forest soil (Table 2).

2.3. Species studied

Selection of tree species was based on reviews of relevant literature regarding their end uses and potential for restoration, as well as on personal field observations, discussions with local landholders, and seed availability in the planting year. All species were native save for *Acacia mangium*, *Averrhoa carambola*, *Flemingia macrophylla*, *Theobroma grandiflorum*, and *Tithonia diversifolia*. Of those, all are commonly found in the Americas in agroforestry systems. The exotic *Acacia mangium*, was included due to its use in rehabilitation of mined areas in Colombia and the Guyanas (Reyes et al., 2018) (Table 3). In this study, species were grouped into three wood density categories; 12 species were considered as low wood density species ($< 0.4\ \mathrm{g/cm^3}$), 29 as mid wood density species ($0.4–0.7\ \mathrm{g/cm^3}$), and 10 species as high wood density species ($> 0.7\ \mathrm{g/cm^3}$) (Table 3).

2.4. Experimental design

The experiment was established at the end of the rainy season in March 2017. A total of 8325 seedlings from 51 species were row planted randomly in 5 study sites covering a total area of 7.6 ha (1111 seedlings/ha). Seedlings were produced in partnership with local public and private nurseries and were grown in shade houses for the first 2 months, then in full sun for 4 months, and were approximately 35–60 cm tall and 0.3–0.9 cm diameter at the stem base when planted.

Following a split-plot design, the experiment was comprised of 18 plots ranging from 0.3 to 0.5 ha each. At least 33 seedlings per species per site (11 seedlings per species per plot/treatment) were planted randomly across three biochar amendment treatments: i) pure biochar, at a rate of 1.1 t/ha; ii) enriched biochar, consisting of biochar at a rate of 1.1 t/ha added with a one-time application of granulated NPK 20–20-20 at a rate of 100 kg/ha; and iii) a control treatment without any soil amendment or fertilization. Biochar for soil amendments was produced using local agroforestry waste Brazil nut (*Bertholletia excelsa*) husks using 6 top-lit up-draft reactors made with 55-gal drums run in parallel.

Table 2
Soil properties and mercury content across reference forest and degradation classes in soils from ASGM areas.

	Reference forest ($n = 30$)*	Shaded gravel mounds ($n = 10$)*	Open gravel mounds ($n = 16$)*	Open sandy areas ($n = 17$)*
pH	4.8 ± 0.4	4.9 ± 0.6	5.3 ± 0.5	5.5 ± 0.6
SOM (%)	3.0 ± 1.9	1.9 ± 1.3	1.3 ± 1.1	0.2 ± 0.2
CEC (Cmol /kg)	17.4 ± 5.2	12.4 ± 4.8	10.7 ± 3.9	6.4 ± 2.5
Sand (%)	60.0 ± 16.7	64.7 ± 23.5	65.4 ± 17.8	87.1 ± 12.3
Clay (%)	13.6 ± 6.4	10.9 ± 5.3	13.8 ± 6.5	7.5 ± 8.2
Silt (%)	26.5 ± 13.9	24.4 ± 20.3	20.8 ± 12.3	5.3 ± 5.1
Hg (mg/ kg)	0.10 ± 0.05	0.04 ± 0.02	0.03 ± 0.02	0.02 ± 0.01

* Samples were air dried and passed through a 2.0 mm sieve to further determine particle size distribution (sand, clay, and silt percentages), soil acidity or pH (1:1 H2O method), soil organic matter or SOM (Walkley & Black method), and cation exchange capacity or CEC (ammonium acetate pH = 7 method) (Binkley and Fisher, 2013). For mercury (Hg) analysis, samples were freezed and dehydrated previous to determination of mercury content (EPA method 473).

The biochar produced was certified as "Premium Quality Grade" according to the European Biochar Certificate standard (Lefebvre et al., 2019).

2.5. *Measurements and statistical analysis*

The number of live individuals, seedling height (cm), and basal stem diameter (cm) were assessed at 7–14 days and 12 months after planting (binary response, 1 = living, 0 = dead). Diameter was measured with calipers at the stem base and plant height was taken with a measuring tape. Species survivorship was calculated in a plot basis, as the percentage of initially planted seedlings still alive 12 months after planting. Diameter and height relative growth rates (RGR) were calculated for all surviving individuals as follows: $\mathrm{RGR}_{\mathrm{height}} = [\ln\ (\text{final height}) - \ln\ (\text{initial height})]/12$ months. For $\mathrm{RGR}_{\mathrm{diameter}}$ (cm/mo) basal diameter was substituted in the formula used to calculate $\mathrm{RGR}_{\mathrm{height}}$ (Hoffmann and Poorter, 2002). An integrated response index (IRI) was calculated for the surviving seedlings as a means for comparing species performance. IRI was calculated as follows: IRI = survival percentage × $\mathrm{RGR}_{\mathrm{height}} \times \mathrm{RGR}_{\mathrm{diameter}}$ (De Steven, 1991).

The effect of biochar amendment treatments on species survivorship was examined using the non-parametric Kruskal-Wallis test for independent samples, followed by the Bonferroni pairwise comparison procedure (Scheiner and Gurevictch, 2001). Univariate analysis of variance (ANOVA) followed by Tukey's least significant difference ($p < 0.05$) were used to detect differences in $\mathrm{RGR}_{\mathrm{height}}$, $\mathrm{RGR}_{\mathrm{diameter}}$, and IRI, by the effect of biochar amendment treatments on low, mid, and high wood density species. Assumptions of ANOVA were met through a test for normality of variables (Kolmogorov-Smirnov test) and homogeneity of group variances (Levene's test) (Fry, 1993). Bivariated correlations (Spearman) were used to evaluate the relationship of seedling survival and growth rates with species wood density. All statistical analyses and graphs were made using IBM SPSS Statistics v.23.

3. Results

3.1. *Survivorship and growth among species*

One year after plantation establishment, mean seedling survival percentage across sites and treatments ranged from 41% to 66%. Survivorship was >75% only for 4 of 51 species tested, two of those being high wood density species (*Syzigium* and *Flemingia*) and the other two

Table 3
Scientific name, species code, wood density, and selection criteria for 51 tropical species used in the reforestation experiment.

Species code*	Species	Family	Wood density (g/cm^3)**	Main selection criteria***
ACLO	*Acacia loretensis*	Fabaceae	0.67	v
ACMA	*Acacia mangium*	Fabaceae	0.52	v
AMCE	*Amburana cearensis*	Fabaceae	0.52	i
ANOC	*Anacardium occidentale*	Anacardiaceae	0.43	ii
ANSP	*Aniba sp.*	Lauraceae	0.67	i
ANMU	*Annona muricata*	Annonaceae	0.32	ii
APTI	*Apeiba tibourbou*	Malvaceae	0.20	iii
AVCA	*Averrhoa carambola*	Oxalidaceae	0.52	ii
BASP	*Batocarpus sp.*	Moraceae	0.53	iv
BEEX	*Bertholletia excelsa*	Lecythidaceae	0.64	ii
BIOR	*Bixa orellana*	Bixaceae	0.32	ii
CAAN	*Calliandra angustifolia*	Fabaceae	0.84	v
CASP	*Calycophyllum spruceanum*	Rubiaceae	0.72	i
CEOD	*Cedrela odorata*	Meliaceae	0.46	i
CEPE	*Ceiba pentandra*	Malvaceae	0.35	i
CESA	*Ceiba samauma*	Malvaceae	0.57	i
CLRA	*Clarisia racemosa*	Moraceae	0.59	i
COOF	*Copaifera officinalis*	Fabaceae	0.63	i
COAL	*Cordia alliodora*	Boraginaceae	0.52	i
COGU	*Couroupita guianensis*	Lecythidaceae	0.43	iv
CRLE	*Croton lechleri*	Euphorbiaceae	0.46	ii
DIMI	*Dipteryx micrantha*	Fabaceae	0.87	i
ERUL	*Erythrina ulei*	Fabaceae	0.11	ii
EUOL	*Euterpe oleracea*	Arecaceae	0.41	ii
FLMA	*Flemingia macrophylla*	Fabaceae	0.71	iii
FIIN	*Ficus insipida*	Moraceae	0.38	iv
GUCR	*Guazuma crinita*	Malvaceae	0.41	iii
HASE	*Handroanthus serratifolius*	Bignoniaceae	0.92	i
HISU	*Himatanthus sucuuba*	Apocynaceae	0.46	ii
HUCR	*Hura crepitans*	Euphorbiaceae	0.37	i
HYCO	*Hymenaea courbaril*	Fabaceae	0.81	i
INED	*Inga edulis*	Fabaceae	0.59	ii
INSP	*Inga sp.*	Fabaceae	0.58	ii
MAFE	*Mauritia flexuosa*	Arecaceae	0.46	ii
MONI	*Morus nigra*	Moraceae	0.55	ii
MYBA	*Myroxylon balsamum*	Fabaceae	0.78	i
MYDU	*Myrciaria dubia*	Myrtaceae	0.71	ii
OCPY	*Ochroma pyramidale*	Malvaceae	0.14	iii
PAMU	*Parkia multijuga*	Fabaceae	0.40	v
POGU	*Pourouma guianensis*	Urticaceae	0.38	iv
POCA	*Pouteria caimito*	Sapotaceae	0.80	ii
QUCO	*Quararibea cordata*	Malvaceae	0.37	ii
SAHU	*Salix humboldtiana*	Salicaceae	0.40	iii
SCPA	*Schizolobium parahyba*	Fabaceae	0.35	iii
SIAM	*Simarouba amara*	Simaroubaceae	0.38	i
SWMA	*Swietenia macrophylla*	Meliaceae	0.53	i
SYMA	*Syzygium malaccense*	Myrtaceae	0.71	iv
THCA	*Theobroma cacao*	Malvaceae	0.42	ii
THGR	*Theobroma grandiflorum*	Malvaceae	0.53	ii
THSP	*Theobroma speciosum*	Malvaceae	0.63	iv
TIDI	*Tithonia diversifolia*	Asteraceae	0.59	iii

* Species code will be used for graphs, and genera will be used through the text in the results and discussion sections.

** Source: Chave et al., 2009 and Zanne et al. (2009).

*** (i) timber production; (ii) silvopastoral/agroforestry use; (iii) high growth rates in natural regeneration light gaps; (iv) wildlife attraction; (v) soil rehabilitation through nitrogen fixation and other processes.

mid wood density species (*Copaifera* and *Tithonia*). Survivorship was 50–75% for 22 species, including 5 high wood density species (i.e. *Dipteryx*, *Calliandra*, *Hymenaea*), 13 mid wood density species (i.e. *Inga*, *Acacia*, *Amburana*), and 4 low wood density species (i.e. *Bixa*, *Erythrina*, *Ceiba*). Survivorship was found 25–50% for 20 species, including 3 high wood density species (i.e. *Myroxylon*, *Pouteria*, *Handroanthus*), 10 mid wood density species (i.e. *Euterpe*, *Swietenia*, *Bertholletia*), and 7 low wood density species (i.e. *Pourouma*, *Ochroma*, *Simarouba*). Finally, survivorship was recorded <25% for 5 species, including 4 mid wood density species (i.e. *Clarisia*, *Croton*) and 1 low wood density species (*Apeiba*); no high wood density species were registered in this last group (Fig. 2).

One year after planting, the low wood density species with the highest height and diameter RGR's were *Erythrina*, *Hura*, *Ceiba*, and *Ochroma*; while *Inga*, *Acacia*, and *Tithonia* were the mid wood density species with the highest height and diameter RGR's; and *Calliandra*, *Syzygium*, *Handroanthus*, *Calycophyllum*, and *Dipteryx* were the high wood density species with the highest height and diameter RGR's (Fig. 3).

However, considering not only growth but also survivorship, excellent overall performance was recorded for 6 species which showed the highest IRI values (> 3.0), including 2 high, 3 mid, and 1 low wood density species. Good performance IRI values (2.0–3.0) were registered for 9 species, of which 5 were low, 3 were mid, and 1 was high wood density species. Acceptable performance IRI values (1.0–2.0) were registered for 12 species, of which 10 were mid, and 2 were high wood density species. Poor performance was registered for 24 species, corresponding to 6 low, 5 mid, and 13 mid wood density species (Fig. 4).

3.2. *Effect of biochar amendments on species performance*

Seedling survivorship, relative growth rates in height and diameter, and the overall integrated response index (IRI), varied significantly by the effect of biochar amendment treatments (Fig. 5; Table S1). Pure and enriched biochar improved survivorship for both low, mid, and high wood density species, respectively (Fig. 5-A). Enriched biochar improved significantly diameter and height growth rates for low and mid wood density species, while no effect was recorded for high wood density species (Figs. 5-B, 5-C). Regarding IRI, low wood density species increased significantly their performance by the effect of pure or enriched biochar, while mid wood density species only responded positively to the enriched biochar treatment. High wood density species showed no significant effects by any addition of biochar respect to the control (Fig. 5-D). Although low and mid wood density species showed significant differences, clearly the greatest gain in performance by the addition of biochar was recorded for low wood density species (Fig. 5; Table S1).

A positive correlation and a statistically significant relationship were found between survivorship and height RGR with wood density, while a negative correlation was found between diameter RGR and IRI with respect to species wood density. This reveals that the higher the wood density of the species, the higher the seedling survival percentage and height RGR's; and as higher the diameter growth rates and IRI, the lower wood density of the species. Despite the low correlation coefficients, due to the great number of species and their differences in performance values across treatments, most of the relationships were statistically significant (Table 4).

4. Discussion

In our study, at least 27 of 51 species (53%) recorded acceptable

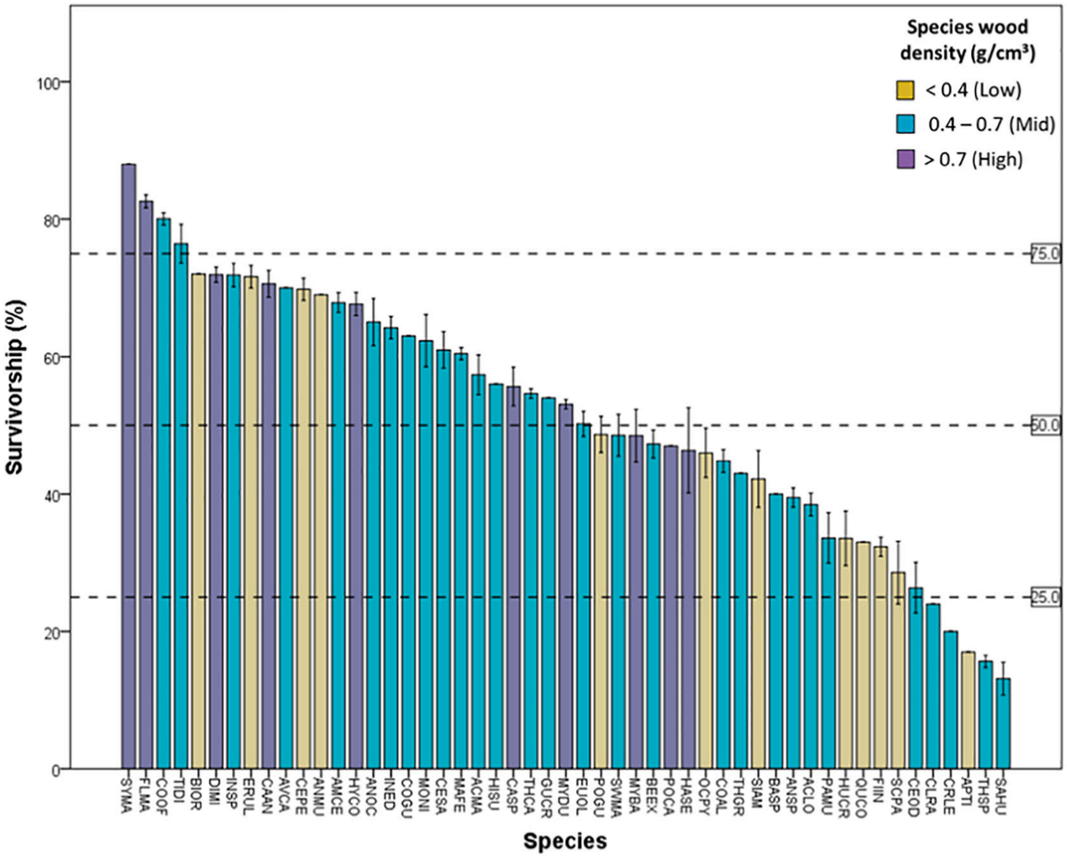

Fig. 2. Survivorship of 51 tropical species differing in wood density one year after planting in five ASGM areas. Error bars represent 95% confidence interval.

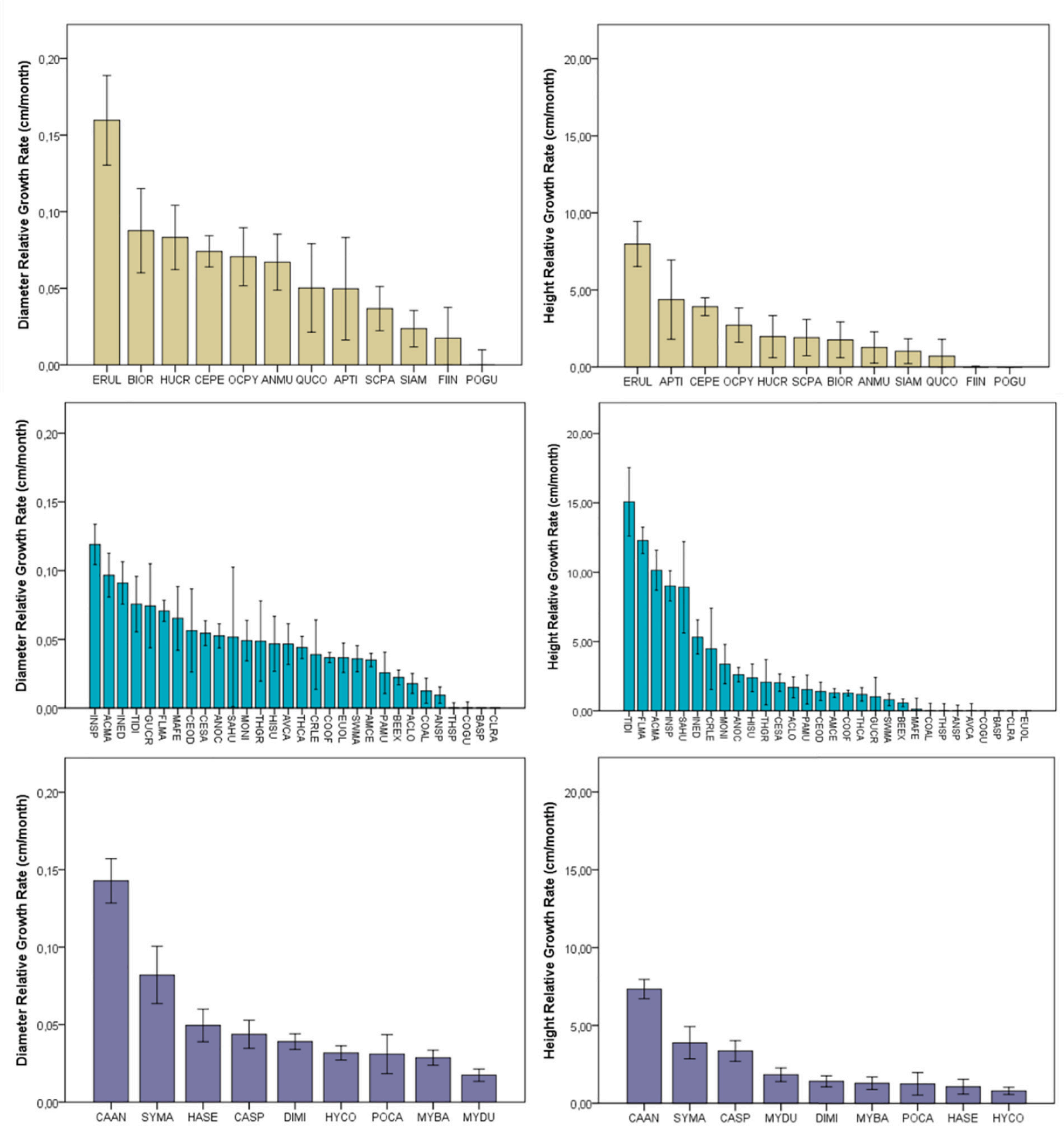

Fig. 3. Diameter and height relative growth rates across low, mid, and high wood density species (yellow, green, and purple, respectively) one year after planting in 5 ASGM areas. Error bars represent 95% confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

performance standards in ASGM areas one year after planting. Species from the leguminous family, both low, mid and high wood density species (i.e. *Erythrina*, *Inga*, and *Dipteryx*, respectively) were ranked with the highest diameter and height growth rates, revealing the great potential of this family for soil rehabilitation in areas degraded by gold mining. The inclusion of different N2-fixing tree species with different life history traits in restoration plantings, can have a central role in nitrogen cycling during tropical forest stand development, with potentially important implications for the ability of tropical forests to sequester CO2, and to support ecosystem functional diversity across the forest age sequence (Batterman et al., 2013). Other fruiting trees from the low, mid and high wood density species groups (i.e. *Bixa*, *Inga*, and *Syzygium*, respectively), rapid ground coverage species (i.e. *Ochroma*, *Tithonia*, and *Calliandra*, respectively), as well as high valued timber tree species (i.e. *Hura*, *Calycophyllum*, and *Handroanthus*, respectively) recorded in this study high performance rates, showing the potential for designing rehabilitation or restoration plantations in ASGM areas (Rodrigues et al., 2009; Strassburg et al., 2018).

4.1. *Influence of species wood density on seedling performance*

In our study, seedling performance was correlated to species wood density. High wood density species showed higher survivorship than lower wood density species typically used in rainforest restoration plantings (Baraloto et al., 2010). This result is consistent with seedling survival–growth trade-offs identified in other tropical rainforest species, with higher wood density species displaying higher survival rates than species with lower wood densities, at the expense of slower growth (King

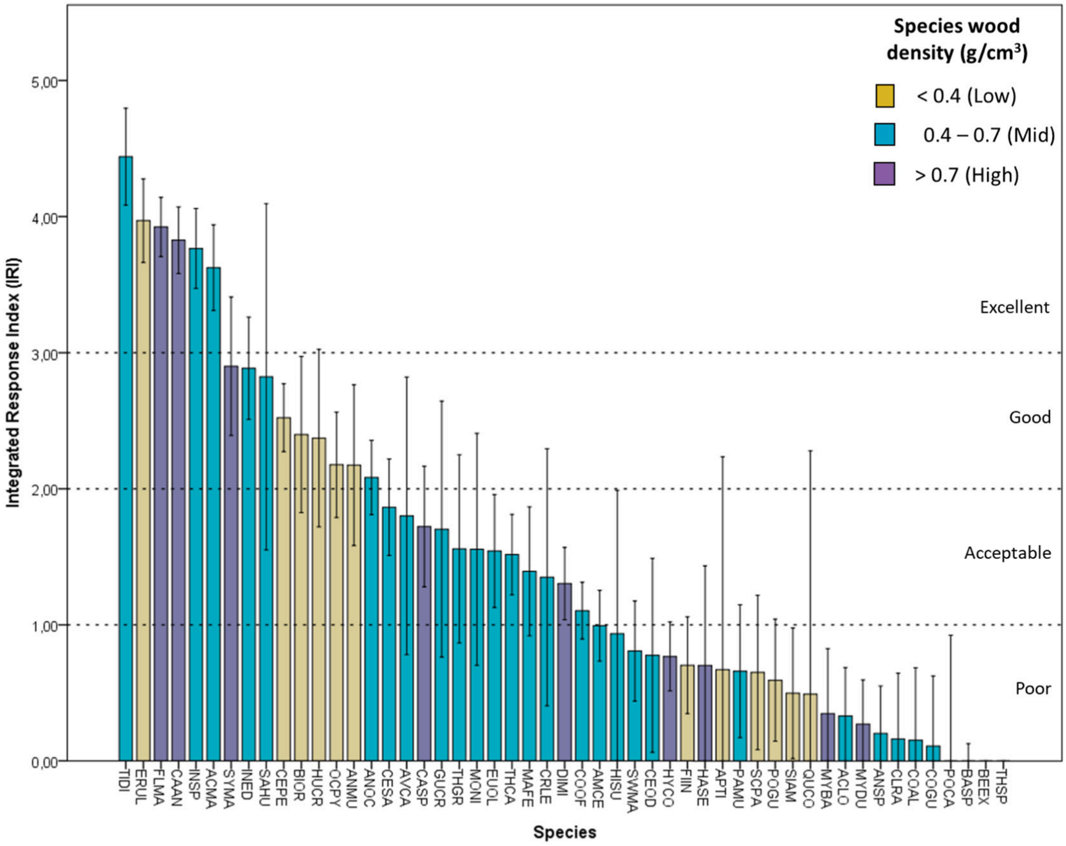

Fig. 4. Integrated response index (IRI) of 51 tropical species differing in wood density after one year of planting in five ASGM areas. Error bars represent 95% confidence interval.

et al., 2005; Chave et al., 2009). Improved survival can be attributed to greater stress resistance of hardwood species given its physiological attributes compared to that of present in light wood species (Grossnickle, 2012; Krause et al., 2012). The very high levels of light and heat exposure typically experienced in open ASGM areas, may also favor species with higher wood densities that typically have reduced risk of xylem implosion under water stress than low wood density species (Kraft et al., 2010; Charles et al., 2017).

This result supports the complementary use of species with more conservative growth strategies when limited funds are available for follow-up plantings. This is consistent with other studies suggesting the inclusion of carefully selected mid- and high wood density species and not only pioneer and light wood fast-growing species in restoration plantings (Charles et al., 2017). The inclusion of this type of species from the beginning of the restoration process is particularly important when the distance to the forest edge is large and the probability of these species to be naturally dispersed to the restoration areas is low (Wyatt and Silman, 2004; Martínez-Garza et al., 2013). It is known that floristic enrichment of mined areas through natural regeneration of colonizing tree species is largely dependent on seed-dispersing wildlife, the conservation status of the surrounding old-growth forest and its proximity to degraded areas (Gorchov et al., 1993; Parrotta and Knowles, 2001; Rozendaal et al., 2019). This is specially the case in some areas of Madre de Dios, such as the buffer zone of the Tambopata National Reserve, where the massive presence of illegal miners destroyed vast areas of primary rainforest (Asner and Tupayachi, 2017), leaving some sites several kilometers from surrounding forests (Caballero et al., 2018). This fact clearly limits the potential for natural regeneration of many species, especially animal-dispersed species (Poorter and Markesteijn, 2007). Designing appropriate species mixtures in plantations, foresters and restorationists could ensure the sustainability of the restoration efforts by promoting the diversity of functional traits, the complementarity on the use of resources between species, the diversity of end uses, and the different life spans of the species (Rodrigues et al., 2009; Chechina and Hamann, 2015; Van der Peer et al., 2016).

4.2. *Effect of biochar amendments*

In our study, biochar improved species performance. Survivorship of low wood density species was enhanced by pure and enriched biochar, while growth of low and mid wood density species was improved by enriched biochar. Systematic reviews have shown a consistent and strong overall pattern of positive growth responses to biochar additions among woody plants, corresponding to a ~ 40% increase in biomass (Crane-Droesch et al., 2013). However, there appears to be high heterogeneity in responses among tree species and ecological systems, as well as among properties of chars and soils (Thomas and Gale, 2015). A recent study found that biochar plus fertilizer had synergistic and positive effects on seedling growth, but slightly lowers early seedling survival in an early and late successional tropical tree species nursery experiment (Lefebvre et al., 2019). Biochars generally have very low N content and through sorption of ammonium may so strongly bind available N that it makes it less available, an effect expected to be offset by additions of fertilizers or composts with high N content. There are thus compelling reasons to expect that biochar use in forest restoration practice would be as a component of a mixture of soil amendments, especially on mined lands with high levels of soil degradation (Woolf et al., 2010; Oshowski et al., 2018).

It was also expected that enriched biochar would have a greater effect on the growth of low and mid wood density species as compared to high wood density species (King et al., 2006; Hérault et al., 2011). In the literature, the large responses to biochar additions observed in tropical

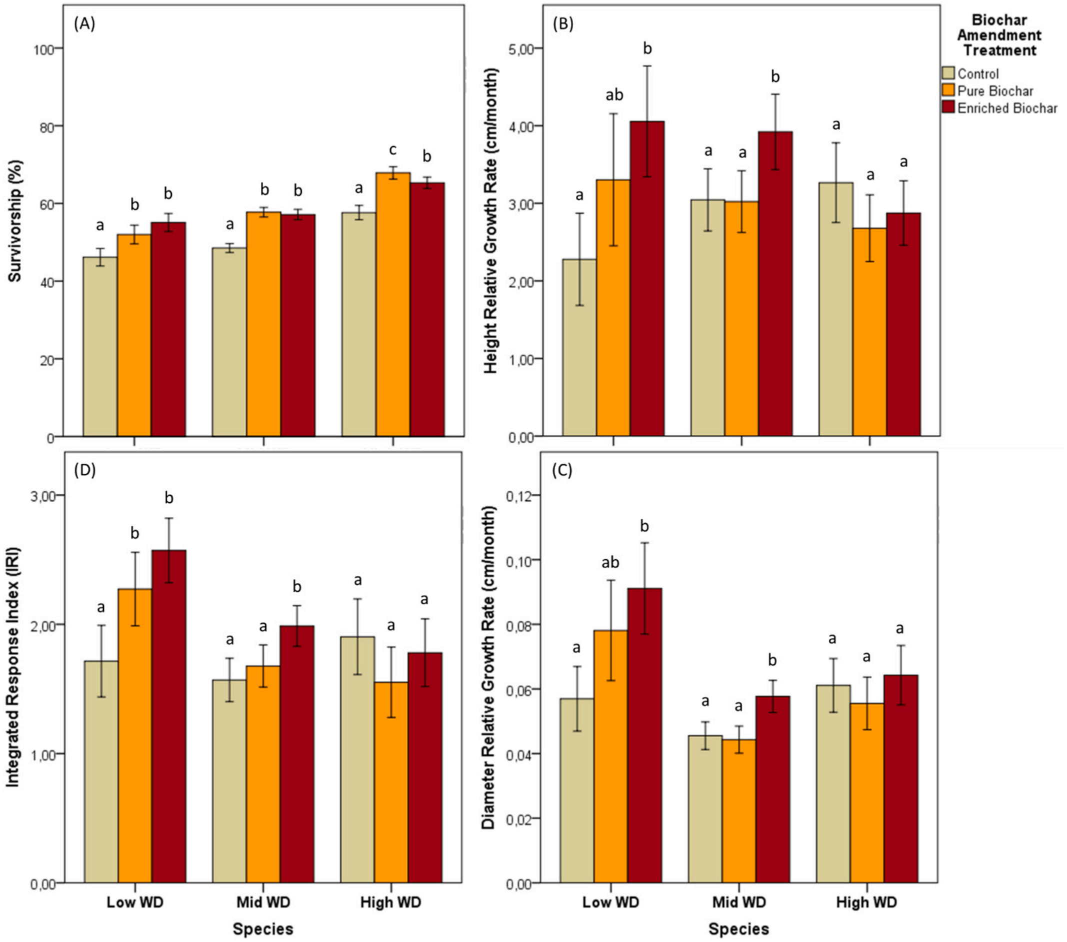

Fig. 5. Effect of biochar amendment treatments on seedling survivorship (A), relative growth rates (RGR) in height (B) and diameter (C), and integrated response index (D) across low, mid, and high wood density (WD) species after one year of planting in five ASGM areas. Different letters above error bars represent statistically significant differences both for survivorship (Kruskal-Wallis and Bonferroni pairwise comparison procedures, $p < 0.05$), and RGR's and IRI (ANOVA, Tukey test, $p < 0,05$). Error bars represent 95% confidence interval.

Table 4

Correlation (Spearman r values) between seedling performance variables and species wood density, across biochar amendment treatments.

	Control treatment	Pure biochar	Enriched biochar	All treatments
Survivorship	0.202**	0.203**	0.163**	0.189**
Height RGR	0.153**	0.101**	0.061*	0.102**
Diameter RGR	−0.002	−0.037	−0.097**	−0.047**
Integrated Response Index	0.037	−0.070*	−0.065*	−0.038*

[*] Significance at 0.05.

[**] Significance at 0.001 (ANOVA).

species are consistent with a pervasive pattern of strong phosphorous (P) limitation in tropical forests (Vitousek, 1984), in conjunction with both high soluble P in chars and a capacity for chars to retain phosphate ions by sorption (Crane-Droesch et al., 2013). Morphological and physiological adaptations in low and mid wood density species for fast growth can provide a competitive advantage for rapid exploitation of resources when they are relatively abundant, as observed in our enriched biochar treatment. In this study the species were chosen to be functionally dissimilar to each other, according to physiological and morphological traits driving ecosystem properties and responses to biotic and abiotic conditions. This understanding is required to design effectively mixed species plantations and predict restoration trajectories of species' abundances and community composition, as well as of carbon and biodiversity recovery (Rodrigues et al., 2009; Hulvey and Aigner, 2014; Van der Peer et al., 2016).

5. Conclusions

Species survivorship and growth in ASGM substrates were strongly influenced by species wood density, and in many cases greatly modified by soils amendments with pure and enriched biochar. High wood density species showed higher survival rates than lower wood density species. Growth and overall performance of mid, and especially low wood density species was significantly increased by biochar additions. Therefore, planning of restoration plantings in areas degraded by gold mining, would include carefully selected species mixtures of low, mid and high wood density species to maximize survival and growth during the crucial early stages of establishment and to support long-term ecosystem functions.

CRediT authorship contribution statement

Francisco Román-Dañobeytia: Conceptualization, Data curation, Formal analysis, Investigation. **France Cabanillas**: Investigation, Methodology, Supervision. **David Lefebvre**: Methodology. **Jhon Farfan**: Methodology. **Jesús Alferez**: Methodology. **Fredy Polo-Villanueva**: Methodology. **Juana Llacsahuanga**: Methodology. **Claudia M. Vega**: Methodology. **Manuel Velasquez**: Methodology. **Ronald Corvera**: Supervision. **Edith Condori**: Supervision. **Cesar Ascorra**: Project administration, Supervision. **Luis E. Fernandez**: Conceptualization, Funding acquisition, Investigation. **Miles R. Silman** Conceptualization, Formal analysis, Funding acquisition, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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