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FROM PRACTICE

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Coffee pulp accelerates early tropical forest succession on old fields

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Abstract

1. Applying nutrient-rich agricultural by-products, such as fruit peels and pulp, to degraded land has been proposed as a strategy to overcome a number of barriers to tropical forest recovery. While such linkages between agroindustry and restoration represent win–win scenarios, practical applications remain largely unexplored. In this case study, we tested coffee pulp as an amendment to catalyze forest succession on post-agricultural land in southern Costa Rica.
2. A 0.5-m-deep layer of coffee pulp was deposited across a 35 × 40-m area and an adjacent similar-sized control plot (no coffee pulp addition) was delineated. Over 2 years, we measured changes in soil nutrients, ground cover, understory vegetation, tree establishment and canopy cover across both coffee pulp and control treatments.
3. Our results show that soil carbon, nitrogen, and phosphorous were substantially elevated in the coffee pulp compared to control treatment after 2 years. Coffee pulp addition significantly altered the ground cover characteristics, eliminating pasture grasses, facilitating establishment of herbaceous plants and increasing the percent area covered by leaf litter.
4. Early-successional trees and shrubs established quickly in the coffee pulp treatment, reaching 30-fold greater mean basal area and 20-fold greater woody stem density (>1-cm-dbh) compared to the control treatment. Structural metrics showed fourfold greater mean canopy height in the coffee pulp compared to control treatment. Canopy height >5 m was ~40% in the coffee pulp but was negligible (<3%) in the control treatment.
5. Our study highlights the significant potential for using agricultural waste, such as coffee pulp, to jump start forest succession on degraded tropical lands and encourages further research to optimize linkages between agroindustry and restoration.

KEYWORDS
agricultural by-products, agricultural waste, amendments, degraded pastures, restoration, soil, tropical forest

1 | INTRODUCTION

The use of organic waste to accelerate forest succession has received some recent attention from the restoration community (Choi et al., 2018; Treuer et al., 2018). Nutrient-rich agricultural by-products, including fruit peels, pulp and other non-market vegetable material, have been proposed as additives to ameliorate barriers to tropical forest recovery on degraded land (Choi et al., 2018; Daily & Ellison, 2002; Janzen, 2000). Given ambitious global objectives to restore large areas of forest (i.e. Bonn Challenge, UNFCCC Paris Accords), and the projected expenses of these activities, cost-effective restoration strategies that maximize multiple benefits are desirable (Brancalion et al., 2019). Linking agricultural industries to forest restoration through the use of non-market products would represent one such win–win scenario.

While agricultural by-products have been used to promote tree growth in forestry settings, actual trials in a restoration context are few. The most well-known study was carried out in northern Costa Rica in 1998 when scientists at Área de Conservación Guanacaste (ACG) reached an agreement with an orange juice company, Del Oro S.A., to dispose of several thousand tons of orange waste on ~3 ha of degraded abandoned pasture (Janzen, 2000). The results of this non-replicated study showed spectacular improvements in soil properties and aboveground woody biomass relative to the untreated control plot (Treuer et al., 2018). While the ambitious goal to restore >100 ha of degraded pasture in the ACG was upended by a well-publicized lawsuit by a rival orange juice company, ostensibly over concerns from environmental impacts of the orange waste in a national park (Escofet, 2000), the potential use of agricultural by-products in restoration settings has remained tantalizingly promising but largely untested.

Depositing a rich organic material on degraded lands such as abandoned tropical pastures has the potential to overcome multiple barriers to forest recovery. Introduced pasture grasses and ruderal vegetation that dominate pastures can effectively prevent establishment of native woody plants and arrest succession (Holl, 1999). Soils in old pastures are also often highly degraded due to compaction and loss of nutrients which can impede establishment and growth of trees (Davidson et al., 2004). Putting a thick layer of organic material on pastures is likely to eliminate grasses via asphyxiation and increase soil nutrient content, thus creating better conditions for the establishment of naturally dispersed tree seeds.

One readily available agricultural by-product in the tropics is coffee fruit pulp. Coffee is produced in over 60 countries globally (Esquivel & Jimenez, 2012; ICO, 2014). Processing of green coffee beans for market involves separation of the seed from components of the fruit, including the skin (exocarp), pulp (mesocarp) and mucilage (parenchyma). The residual coffee 'pulp', which comprises >50% by weight of the coffee harvest, is commonly treated as a waste product and heaped into storage lots where it is left to decompose (Ferrell & Cockerill, 2012; Sanchez et al., 1999). Coffee pulp is nutrient rich containing high levels of carbohydrates (35%), crude protein (10.8%) and lignin (31.5%) and has a pH ~4.25 and a C:N of ~46.3 forming a valuable compost (Janissen & Huynh, 2018; Orozco et al., 1996). While alternative uses of coffee pulp can include animal feed (Núñez et al., 2015), pharmaceutical products (Prata & Oliveira, 2007) and organic mulch and fertilizer (Rathinavelu & Graziolsi, 2005), these uses remain undeveloped in many tropical countries where the pulp is typically discarded or minimally processed *via* composting to reduce environmental and health hazards (Echeverria & Nuti, 2017; Ferrell & Cockerill, 2012). Globally, an estimated 218,400 tons of fresh pulp and mucilage must be managed at coffee processing sites for every million 60-kg bags of dried coffee produced for market (Echeverria & Nuti, 2017; Rangarajan, 2019).

In this single-site case study, we evaluated the application of unprocessed coffee pulp sourced from local coffee cooperatives to restore degraded pasture in southern Costa Rica. Based on the earlier success with orange waste to recover forest on abandoned pastures in northern Costa Rica (Treuer et al., 2018), and studies quantifying major barriers to forest regeneration in this region (Holl, 1999; Holl et al., 2020), we anticipated that application of coffee pulp would (1) eliminate introduced pasture grasses through asphyxiation; (2) improve soil conditions by creating a rich organic layer; and (3) create conditions for rapid colonization by early-successional trees.

2 | METHODS

2.1 | Study site

The study was carried out in Coto Brus county in southern Costa Rica on Reserva Biológica Sabalito (8°50′10″ N, 82°53′50″ W), a former coffee farm that is being managed for conservation. The forest in this region is classified as a tropical pre-montane rain forest (Holdridge et al., 1971) at 990 m asl and has a mean annual rainfall of 3500 mm and diurnal mean temperature range ~15–27°C. This region underwent rapid deforestation and land conversion to coffee agriculture and pasture starting in 1950 (Quesada-Roman & Diaz-Bolanos, 2019). By 2014, forest cover had been reduced to ~25% (Zahawi et al., 2015) with significant areas of agricultural land in moderate to highly degraded condition, leading to an increased interest in restoring lands to meet both local and international objectives for carbon sequestration and conservation.

Starting in February 2018, we established two adjacent treatments on a flat ~1-ha area of abandoned former agricultural land. Following guidelines from the Costa Rica Ministry of Health regarding disposal of organic waste and their approval based on site inspections, the study site was located away from streams, water sources and houses. Preliminary vegetation surveys showed that >90% of the site was dominated by introduced non-native pasture grasses, primarily *Urochloa brizantha* (Hochst. Ex. A. Rich.) R.D. Webster and *Pennisetum purpureum* Schumach with ~10% cover of ruderal shrubs including *Vernonanthura patens* (Kunth) H. Rob., *Vernonia arborescens* (L.) Sw. and *Piper umbellatum* (L.). Vegetation surrounding the study site included commercial production of *Dracaena fragrans* (L.) Ker. Gawl. and areas of early successional forest dominated by pioneer species such as *Heliocarpus appendiculatus* Turcz. and *Cecropia obtusifolia* Bertol.

2.2 | Plot establishment

The 1-ha study site was hand cleared by machete to facilitate vehicle access. Coffee pulp was sourced from a nearby coffee processing cooperative at no cost other than transportation. In March 2018, 30 dump truck loads of coffee pulp (~360 m^3 total) were deposited across a 35 × 40-m area and spread with a backhoe into a 0.4–0.5-m-deep layer. We delineated an adjacent 35 × 40-m control area (no coffee pulp addition) ~10 m away from the coffee pulp treatment. Coffee pulp and control treatment areas were divided into four 15 × 20-m sampling plots. Grass around the perimeter of the study area was clipped twice annually to allow access to the plots.

2.3 | Soil and vegetation measurements

Immediately prior to coffee pulp application and again at 2 years after treatment application (March 2020), we collected four 3-cm-diameter × 10-cm-deep soil cores in each of the four coffee pulp and control plots. For the second soil collection, the top 10 cm included the decomposed coffee pulp. All soil samples were analyzed for major nutrient elements following standard procedures at Brookside Laboratories, New Bremen, OH (see www.blinc.com/worksheet_pdf/SoilMethodologies.pdf and Gavlak et al., 2003).

Visual observations of succession were made monthly for the first 6 months and thereafter every 6 months to assess decomposition and vegetation colonization in the sampling plots. Coffee pulp depth was also measured at four randomly located points in each plot. At 1 and 2 years after treatment application, we identified species, tallied and measured the diameter at breast height (dbh, ca. 1.3 m) of all woody stems ≥1-cm dbh or larger. At the end of the second year, we also estimated percent forest ground cover (grass, herbs, coarse woody debris, leaf litter, bare ground) using a modified Braun–Blanquet cover-abundance scale in four 5 × 5-m sub plots in each sampling plot (Westhoff & Van Der Maarel, 1978). Drone flights were conducted to measure canopy cover using a DJI Mavic PRO. Flights were flown at 30 m height and a speed of 2 m/s on 12 February 2019 (1 year after establishment) and 22 February 2020 (2 years).

2.4 | Data analysis

Soil characteristics, stem density, basal area and percent ground cover types were compared between coffee pulp and control plots in each sampling year using two-sample *t*-tests ($n = 4$) or, when applicable, Mann–Whitney *U*-tests for non-parametric data. Statistical analyses were conducted using SPSS v.24 (IBM Corporation) and significance determined at $\alpha = 0.05$. Mean and standard error of the mean (±1 SE) are reported throughout.

Drone images were uploaded to Pix4D (www.pix4d.com) to generate an orthomosaic image and a Digital Surface Model (DSM) for each flight. Orthomosaics and DSMs were then imported into QGIS (https://qgis.org/; 3.4.13 Madeira) for geospatial processing. A Digital Terrain Model raster was created from waypoints collected in the field using a handheld Garmin GPS (model 64s) and plot delineation was corrected through visual assessment of both orthomosaic images. Thereafter, a Canopy Height Model (CHM) was generated using the Raster Calculator tool. Treatment plots were then extracted using the SAGA 'Clip Raster with Polygon' tool. Clipped CHMs for each year and treatment were then analyzed to generate plot structural metrics using the raster package (v.3.3-13) in R (ver. 3.62; https://www.r-project.org/).

3 | RESULTS

After 3 months, the layer of coffee pulp reduced by ~50% in depth and small herbaceous. It is plants started colonizing the surface. Excavation to ground level showed that the underlying grass had been asphyxiated and was starting to decompose. By the end of 2 years, the layer of coffee pulp resembled the underlying mineral soil and had reduced to 5–10 cm depth. Visible changes in treatments over 2 years are shown in Figure 1.

Initial soil nutrient content was uniform across the coffee pulp and control treatments ($P > 0.05$ in all cases) but after 2 years, there were significant differences. In the coffee pulp treatment, percent Carbon (C) and Nitrogen (N), as well as the amount of Sulphur (S), Phosphorus (P), Iron (Fe) and Magnesium (Mn) were significantly greater, whereas C:N, pH and Potassium (K) were significantly lower relative to the control treatment (Table 1). Ground cover also differed significantly between the coffee pulp and control treatments. Grass cover was nearly eliminated in the coffee pulp treatment, whereas >80% grass cover remained in the control treatment ($t = -23.4$, $df = 6$, $p = 0.0001$). In the coffee pulp treatment herb cover was ninefold greater ($t = 38.1$, $df = 6$, $p = 0.001$) and litter was threefold greater ($t = 3.7$, $df = 6$, $p = 0.010$) (Figure 2). The percent cover of coarse woody debris and bare ground did not differ between treatments ($p > 0.05$; Figure 2).

Vegetation measurements at the end of the first year showed a 16-fold difference in mean density of stems >1-cm dbh between coffee pulp (2873 ± 882 stems/ha) and control treatments (183.2 ± 1 stems/ha) ($U = 0.0$, $Z = -2.32$, $p = 0.029$). Mean basal area was also greater in coffee pulp (1.3 ± 0.3 m^2/ha) compared to control treatments (0.1 ± 0.0 m^2/ha) ($t = 7.0$, $df = 6$, $p = 0.001$). Colonizing woody plants were dominated by two early-successional tree species: *Heliocarpus appendiculatus* (Malvaceae) (57%) and *Cecropia obtusifolia* (Urticaceae) (38%). Finally, structural metrics based on drone imagery at the end of the first year showed greater canopy height and cover in the coffee pulp treatment compared to the control (Table 2).

At the end of the second year, the coffee pulp treatment had nearly 30-fold greater mean basal area ($t = 8.5$, $df = 6$, $p = 0.001$; Figure 3A) and >20-fold greater woody-stem density ($t = 11.8$, $df = 6$, $p = 0.001$) than the control (Figure 3B). All stems in the coffee pulp treatment

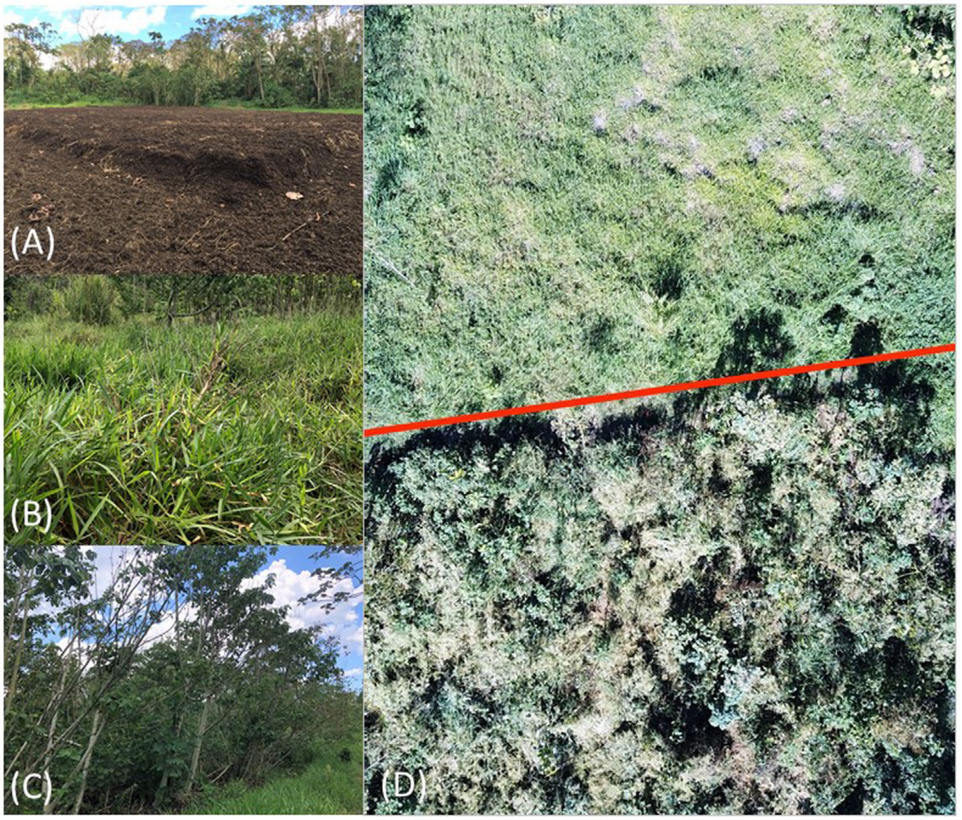

FIGURE 1 (A) Freshly added layer of coffee pulp on post-agricultural land. (B) Control treatment 2 years after initiating study. (C) Woody vegetation growing on coffee pulp treatment 2 years after initiating the study, photo credits R. Cole. (D) Aerial view of the coffee pulp treatment (bottom) and the adjacent control treatment (top) one year after initiating the study, photo credit R. Zahawi

belonged to five species including *H. appendiculatus* (55%), *C. obtusifolia* (34%), *Cestrum microcalyx* Francey (6%), *Cecropia peltata* L. (1%), and *Lippia myriocephala* Schltdl & Cham (Gomez-Laurito) (1%). In contrast, the control treatment had only one colonizing tree species, *H. appendiculatus*. Structural metrics at the end of year 2 showed a nearly four-fold difference in mean canopy height and overall cover at >2 m (shrub layer) in the coffee pulp treatment compared to the control (Table 2). Additionally, close to half the cover in the coffee pulp treatment was >5 m in height (young tree canopy layer), whereas this height class was almost absent in the control treatment.

4 | DISCUSSION

In this study, we tested an agricultural by-product, coffee pulp, as an additive to overcome barriers to forest regeneration and speed up tropical forest succession on post-agricultural lands. Within the first 2 years, there were striking differences between the coffee pulp and control treatments. First, the addition of a 0.5-m-deep layer of rich organic material substantially changed soil chemistry and increased the content of major soil nutrients. Second, the application of coffee pulp altered ground cover characteristics, eliminating pasture grasses, facilitating establishment of herbaceous plants and increasing the percent area covered by leaf litter. In the control plot, ground cover was still largely dominated by introduced pasture grasses. Finally, rapid establishment of early-successional tree species created a young forest over 4 m tall and with >80% canopy cover in the coffee pulp treatment. By comparison, tree establishment in the control treatment was more than one order of magnitude lower and mean canopy height and cover was half that found in the coffee pulp treatment.

Adding a layer of coffee pulp led to significant differences in the chemistry of the topsoil. Soil nutrients (N, P, S, K, Fe and Mn) were significantly elevated in the coffee pulp treatment 2 years after treatment application. This is a positive outcome given that tropical old fields are often highly degraded (Silver et al., 2004) and following abandonment natural succession can be delayed for decades due to reduced soil fertility (Aide et al., 1995). The increase in P is particularly noteworthy as this is likely to promote growth of tree species in tropical soils that are often P-limited (Dalling et al., 2016). Although nutrient retention over time following coffee pulp addition remains to be tested, the orange waste study in northern Costa Rica found elevated soil nutrient levels even 16 years following waste addition (Treuer et al., 2018). Other research testing coffee pulp as an amendment to degraded tropical soils showed increases in levels of exchangeable cations (Ca, Mg and K), N and plant available P, with peak concentrations occurring at ~9 months after application (Kasongo et al., 2011).

Our results also showed that adding a layer of coffee pulp rapidly changed ground cover and forest floor vegetation. The composting

TABLE 1 Soil variables are compared between Control and Coffee pulp sites 2 years after application of treatments using a two-sample *t*-test

	Treatment			
Soil variable	Control	Coffee pulp	*t*	*p*
Carbon (%)	7.2 ± 0.6	23.2 ± 6.6	3.1	**0.046**
Nitrogen (%)	0.6 ± 0	2.7 ± 0.7	3.6	**0.036**
C/N Ratio	12.5 ± 0.6	8.7 ± 0.1	−6.8	**0.001**
Total Exchange Capacity (meq/100 g)	10.6 ± 1	19.6 ± 0.7	6.9	**0.001**
pH	6.8 ± 0.1	4.8 ± 0.2	−9.1	**0.002**
Organic matter (%)	22.9 ± 0.7	47.6 ± 11	2.3	0.100
S* (ppm)	5.3 ± 0.5	23.0 ± 2.7	7.6	**0.001**
P* (mg/kg)	6 ± 1.1	35.3 ± 5	7.9	**0.001**
Bray II P (mg/kg)	4.8 ± 2	41.0 ± 19	2.1	0.120
Ca* (mg/kg)	1205.5 ± 226	1369 ± 110	0.7	0.448
Mg* (mg/kg)	211.3 ± 20.3	170.3 ± 32	−1.1	0.320
K* (mg/kg)	734.8 ± 84	141.5 ± 21	−8.5	**0.001**
Na* (mg/kg)	14 ± 1.5	13 ± 1.3	−0.5	0.632
B* (mg/kg)	0.5 ± 0	0.6 ± 0.1	0.7	0.530
Fe* (mg/kg)	38 ± 3	128.8 ± 18	5.9	**0.006**
Mn* (mg/kg)	17.3 ± 1.7	32.8 ± 2.8	5.0	**0.002**
Cu* (mg/kg)	7.0 ± 0.6	3.6 ± 1.1	−2.5	0.056
Zn* (mg/kg)	0.6 ± 0.0	2.1 ± 0.6	3.0	0.056
Al* (mg/kg)	1296.0 ± 67	602.5 ± 237	−2.5	0.083

Note: Significant differences are shown in **bold** font. Values are means ± 1 SE and *df* = 6 in all cases.

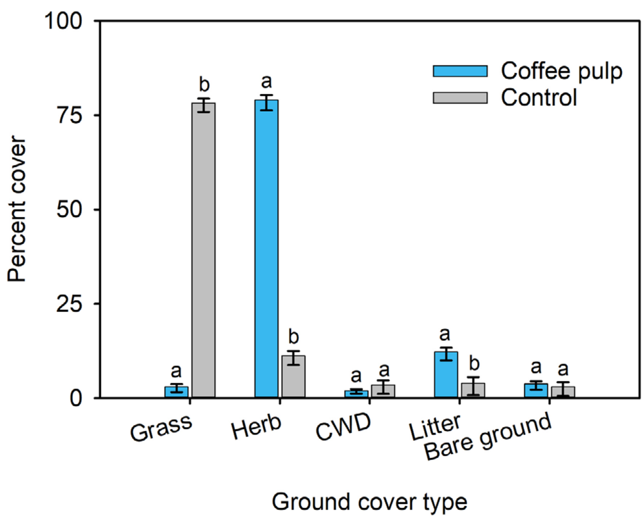

FIGURE 2 Mean percent cover of grass, herb (herbaceous plants), CWD (coarse woody debris), litter and bare ground (exposed soil) in the coffee pulp and control treatments 2 years after initiating the study. Different letters indicate significant differences between treatments ($p < 0.05$ in all cases). Error bars indicate ±1 SE

TABLE 2 Structural metrics of the Coffee pulp and Control plots in 2019 and 2020, including mean canopy height, and percent canopy cover >2 and >5 m

	Year	Canopy height (m)	% Cover >2 m	% Cover >5 m
Control	1	0.47 ± 0.34	0.15	0.04
Coffee pulp	1	2.01 ± 0.75	40.63	0.81
Control	2	1.37 ± 1.41	21.84	2.32
Coffee pulp	2	4.26 ± 2.18	82.55	39.37

coffee pulp killed the underlying grass and likely suppressed germination of grass seeds and the seeds of other plants present in the soil substrate. This is important because competition from pasture grasses is a major factor reducing establishment and growth of tropical tree seedlings in abandoned pastures (Elgar et al., 2014). While the effects of coffee pulp addition on the biochemistry and soil microbiome of restoration sites require more investigation, the effective elimination of competitive forage grasses provides an interesting alternative to the use of herbicides, which are often used to suppress grass in restoration plantings (e.g. Shoo & Catterall, 2013). The cover of early-successional herbaceous plants was also markedly greater in the coffee pulp treatment, as was the percent cover of leaf litter. The increase in litter cover is promising as litterfall is an important component of nutrient cycling (Vitousek & Sanford, 1986) and an early indicator of recovery of ecosystem processes during tropical forest succession (Powers & Marín-Spiotta, 2017).

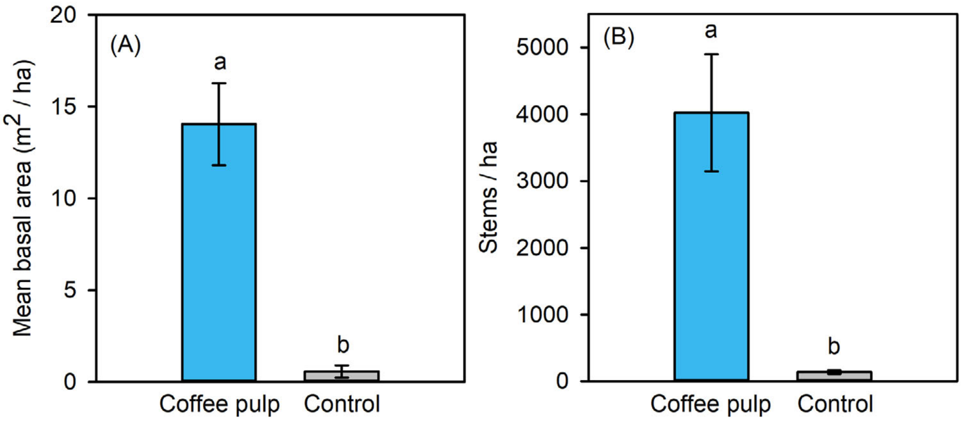

FIGURE 3 Mean basal area (A) and mean stem density (B) in the coffee pulp and control treatments 2 years after initiating the study. Different letters indicate significant differences ($p < 0.05$ in all cases). Error bars indicate ±1 SE

The coffee pulp treatment was rapidly colonized by pioneer tree species that arrived as seeds through wind and animal dispersal forming a young forest with a 4-m-tall mean canopy layer and ~40% canopy cover above 5 m in only 2 years. The difference with the control plot where tree establishment was sparse was striking; canopy cover above 5 m amounted to less than 3% of the plot. Tree establishment in the control plot was dominated by just a few commonly occurring species, all of which are small-seeded and common colonizers of restoration sites. Of these, *H. appendiculatus* and *L. myriocephala* are wind dispersed, whereas *C. obtusifolia*, *C. peltata* and *C. microcalyx* are dispersed by both birds and bats. Although all species are common, two that only colonized in the coffee pulp treatment (*C. peltata* and *C. microcalyx*) are considered later-successional species as they are also found in mature secondary forest in the area (Zahawi, unpublished data). Further, the rapid establishment of woody vegetation is promising as establishing tree cover, through planting or other means, is one of the primary ways to overcome the multiple barriers to forest regeneration by shading out pasture grasses (Holl et al., 2020), increasing arrival of bird-dispersed seeds (Cole et al., 2010), and creating safe sites for germination and establishment of seedlings (Zahawi & Augspurger, 2006). However, prior research at multiple pasture sites in Veracruz, Mexico has shown markedly different rates of recovery that are driven by both local and landscape factors (Cadavid-Florez et al., 2019). As such, it is likely that vegetation responses following coffee pulp addition will also vary with local- and landscape-level factors that were not tested in this study.

While using a nutrient-rich waste product like coffee pulp in the restoration of tropical forests is an attractive prospect, much work remains to be done to assess its viability. First, while this single-site case study points to promising outcomes for the use of an agricultural by-product to speed up forest recovery, well-replicated testing across multiple sites and over a longer period of time will be necessary to validate the restoration strategy. In turn, our study did not quantify emissions or movement of organic inputs into the surrounding area. Raw coffee pulp, like other agro-industrial wastes, contains organic pollutants and potentially agricultural pesticide residues that can have deleterious effects on watersheds and human health (Haddis & Devi, 2008; Rangarajan, 2019). In addition, there may be health concerns from insects that proliferate in the composting material. However, it is possible that natural pest control provided by animals that live in agricultural countryside landscapes (Bianchi et al., 2006) may be similarly effective to pest control measured at processing sites as was noted in the ACG orange waste project (Escofet, 2000). Addition of coffee pulp or any other rich organic waste product is also likely to be limited to areas with relatively flat topography where risk of runoff impacting watersheds can be managed and road access by heavy dump trucks is possible. In this regard, transportation will be limited to areas that are both accessible and cost-effective for agricultural industries relative to other waste disposal options. Finally, cost analyses are needed to assess the efficacy of applying agricultural waste versus other typical restoration options such as tree planting. Nonetheless, caveats notwithstanding, this study points up the significant potential for using agricultural waste to jump start forest succession on degraded tropical lands, and further research to optimize use and evaluate the method on a larger scale is encouraged.

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AUTHORS' CONTRIBUTIONS

Both the authors conceived of the study, carried out field measurements, wrote the manuscript and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.bvq83bk86 (Cole & Zahawi, 2021)

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