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Research Article

Brazil Nut (*Bertholletia excelsa*, Lecythidaceae) Regeneration in Logging Gaps in the Peruvian Amazon

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Brazil nut (*Bertholletia excelsa* Bonpl.) extraction serves as an important economic resource in the Madre de Dios region of Peru simultaneously promoting forest conservation, yet, under current management, it cannot compete with other land uses. This study investigated the effects of logging gaps on Brazil nut natural regeneration. A total of 48 paired logging gap-understory sites were visited in Brazil nut concessions in the Tambopata province of Madre de Dios, Peru. At each site, the number of Brazil nut recruits was counted and canopy openness and gap area were measured. Significantly higher levels of recruit density were found in logging gaps than in understory sites. Additionally, recruit density was positively correlated with canopy openness. Further, in experimental plantings in paired gap and understory sites, canopy openness, height, total leaf area, and number were recorded from August 2011 to February 2012. Height, total leaf area, and leaf number were significantly higher for tree-fall gap grown seedlings, lending further evidence to improved recruitment success of Brazil nuts in forest gaps. These results suggest that multiple-use forest management could be considered as an alternative for the sustainable extraction of Brazil nuts but also highlight that further studies are required.

1. Introduction

Brazil nut (*Bertholletia excelsa*, Bonpl) is a gap-dependent canopy emergent tree requiring high light levels to reach maturity [1, 2] and that relies on scatter-hoarding agoutis (*Dasyprocta* sp.) to release seeds from the woody pericarp fruit [3]. The long-term demographic viability of Brazil nut populations currently relies on purely natural regeneration. The existing density of mature *B. excelsa* trees, largely responsible for determining natural regeneration rates, is lower in Madre de Dios, Peru (0.5–1.5 individuals ha^{-1}) [4] than in neighboring Acre, Brazil (1.5–2.5 ind. ha^{-1}) [5] and Pando, Bolivia (2.5–3.0 individuals ha^{-1}) [1].

Commercially, the seeds of *B. excelsa* (commonly referred to as Brazil nuts) are an economically important nontimber forest product (NTFP) contributing an estimated $8 million USD to Peru's GDP annually [6], $73 million in Bolivia [7], and $30 million in Brazil [8]. Within Madre de Dios, as much as 22% of the local residents rely directly or indirectly on Brazil nut harvest for their economic livelihoods [9]. The ecological sustainability of Brazil nut extraction is disputed with some researchers alluding to an imminent demographic collapse [10], while others suggest stable populations with current extraction rates [11–13].

Brazil nut has been celebrated as having the potential to reconcile forest conservation and development objectives [14]. Yet, doubts have been raised surrounding the success of Brazil nut harvesting as a means to reduce forest degradation [9], as it is not economically competitive with other land uses [12, 15]. Selective logging has the potential to allow both commercial timber extraction simultaneous to extraction of nontimber forest products [16]. Since 2004, selective logging has been permitted within Brazil nut concessions in Madre de Dios as a complementary income source. However, the potential effects of selective logging on natural regeneration have been poorly studied so far. Soriano et al. [17] found

that in Pando, Bolivia, levels of Brazil nut regeneration in selectively logged forests suggested compatibility with timber harvesting.

To our knowledge, the current study is the first to investigate the effect of logging gaps on *B. excelsa* natural regeneration in the Peruvian Amazon. Specifically, we studied Brazil nut recruit density (seedlings, saplings, and juveniles) in logging gaps paired with understory plots in active Brazil nut concessions in Madre de Dios, Peru. We investigated the importance of (a) logging gaps or understory sites; (b) canopy openness; and (c) distance to the nearest reproductively mature tree, on recruitment. Our hypothesis was that higher light availability would favor *B. excelsa* regeneration in logging gaps. These data were complimented by a comparative seedling growth experiment investigating the importance of canopy openness on height, total leaf area, and leaf number in tree-fall gaps and understory environment, with the aim to provide further understanding of Brazil nut recruitment success.

2. Materials and Methods

2.1. Study Site. We selected 16 active Brazil nut concessions as study sites in Tambopata Province, Department of Madre de Dios, Peru (12°04′19″–12°17′52″S and 69°00′52″–69°16′41″W, approximate elevation 190 masl). Fieldwork was conducted during the 2011 dry season (June–August, 2011). The area receives 2500–3500 mm of rain per year and has stable average temperatures around 24°C [18]. The Brazil nut concession system was established in the year 2000 by the Peruvian government, which granted 40-year leases exclusively for Brazil nut extraction in Madre de Dios. Since 2004, mechanized timber extraction in Brazil nut concessions has been allowed on a selective basis. Currently, Brazil nut concessions in Madre de Dios cover an area of 1 million ha [19].

Brazil nut concessionaires were previously interviewed to understand Brazil nut management within these units. These 16 concessions (ranging in area from 125 to 1000 ha; Table 2) were selected based on concessionaires knowledge of the locations of 1–5-year-old logging gaps arising from selective logging of timber species other than Brazil nut. In each concession, three logging gaps, each paired with an area of understory forest located at least 50 m away in a random direction, were sampled for a total of 48 paired plots. Individual logging gaps were identified either with the assistance of concession owners or by following skid trails based on their instructions. Gap sizes ranged from 120 to 290 m^2 with a mean ± std. deviation of 218 ± 34 m^2.

2.2. Measurement of Recruit Density. Plot length was measured from the center of the stump to the first bifurcation at the base of the crown of the felled tree (Supplementary materials A in Supplementary Material available online at http://dx.doi.org/10.1155/2014/420764), with a width of 10 m (roughly the width cleared during postlogging timber processing) (12–29 m, mean = 21.8 m). The corresponding paired understory plot was established with the same length and width. The length measurement often excluded a large portion of the logging gap where the canopy lay. Whereas the measured area was cleared for sawing planks, the excluded canopy areas were characterized by large amounts of branches and debris. In each plot, all size classes of *B. excelsa* were sampled and had their height recorded. Size classes were seedlings (<1.3 m), saplings (1.3 m ≥ 10 cm dbh), and juveniles (>10 cm dbh). Four canopy openness measurements were taken using a convex canopy densiometer [20, 21] held at 1.5 m height at each of the three points within the gap: the stump, center of the gap, and base of the crown. These were averaged together for a single canopy openness estimate for each plot. Canopy openness was measured at corresponding points in the paired understory plot. To assess whether distance to the closest reproductively mature tree affected regeneration density, the nearest mature Brazil nut tree (minimum 40 cm diameter at breast height (dbh); Zuidema and Boot [11] reported that 98% of trees were reproductive when ≥40 cm dbh) was identified by an experienced field assistant and its distance from the center of the gap was measured up to 100 m (modified from Kainer et al. [22]).

As the distribution of *B. excelsa* recruits deviated from a normal distribution, a nonparametric Wilcoxon sign-rank test was used to compare *B. excelsa* recruitment between gap and understory (defined as the aggregate density of seedlings ≤1.3 m tall, saplings between 1.3 m tall and 10 cm dbh, and juveniles >10 cm dbh) in stems ha^{-1}. Further, Poisson distribution generalized linear models of recruit density by canopy openness and recruit density by distance to the nearest mature tree were used to investigate the effects of these two variables in more detail, with the Poisson parameter estimated using maximum likelihood. Using the observed recruit density and canopy openness in each study plot in our sample, we derived a maximum likelihood estimate for the changing probability of encountering a recruit. The same was repeated for recruit density and distance to the nearest mature tree. All statistical analyses were conducted in JMP Software (JMP 9.0.1, SAS), or in R v.2.9.2 (R Development Core Team, 2009).

2.3. Comparative Seedling Growth Experiment. In August 2011, 64 Brazil nut seedlings were planted in 5 paired natural tree-fall gaps and understory sites in the experimental forest plot of the Universidad Nacional Amazónica de Madre de Dios (UNAMAD, 12.4702°S, 69.1426°W), with 32 seedlings in each growth environment. The forest plot is characterized by *terra firme* forest, which is representative for the area, with approximately 68 woody species ha^{-1} (see Table 1).

Brazil nutseedlings were 9 months of age, ranged from 8 to 20 cm in height, and had between 3 and 17 leaves at planting. All had been grown under homogenous conditions of partial shade netting at the UNAMAD nursery located at the same site as the experimental forest plot. Seedlings were chosen randomly for planting across growth environments to avoid bias in their initial distribution. The following measurements were taken on a monthly basis between August 2011 and February 2012 for each seedling: height above the ground (cm), length and width of each leaf, leaf number, and

Table 1: The common name, scientific name, and family for the ten most frequent woody species in the UNAMAD experimental forest and Brazil nut (M. Usca, personal communication), ranked by Importance Value index (IVi) and calculated as the sum of relative density, relative frequency, and basal area. This data was collected in five 20 × 100 m transects, equaling 1 ha.

Common name	Scientific name	Family	IVi	Count
Tamamuri	*Brosimum lactescens*	Moraceae	49	21
Chimicua	*Pseudolmedia laevis*	Moraceae	37	33
Cumala	*Virola sp.*	Myristicaceae	35	17
Almendrillo	*Laetia procera*	Flacuortiaceae	33	13
Meliosma	*Meliosma sp.*	Sabiaceae	33	16
Huasai	*Euterpe precatoria*	Arecaceae	27	31
Copal	*Protium amazonicum*	Burseraceae	25	28
Cumala colorada	*Iryanthera juruensis*	Myristicaceae	23	25
Shimbillo	*Inga sp.*	Fabaceae	20	17
Moena	*Ocotea sp.*	Lauraceae	18	15
Castaña	*Bertholletia excelsa*	Lecythidaceae	1	1

canopy openness directly above the seedling using a canopy densiometer. The equation for total leaf area is as follows:

$$\mathrm{LA}_T = 0.622\,(L * W) + 2.36, \quad (1)$$

where LA_T = total leaf area (cm^2), L = leaf length (cm), and W = leaf width (cm), which was calibrated by regressing LA_T for ten different sized leaves (measured using ImageJ64) against their $L * W$ ($P < 0.0001$; Adj-$R^2 > 0.99$; $n = 10$). For each monthly measurement, mean height, LA_T, leaf number, and canopy openness were compared between seedlings grown in tree-fall gaps and understory sites using Bonferroni corrected t-tests, and linear regressions were then run between openness and height, total leaf area, and leaf number separately for felling gap and understory habitats.

3. Results

3.1. Recruit Density. Brazil nut concessions ranged from 125 to 1083 ha with a mean ± SD of 569±338 ha (Table 2). Sampled paired gap-understory sites ranged from 120 to 290 m^2 with a mean ± SD of 216 ± 34 m^2. Mean canopy openness in gap sites was 19.7 ± 6.4%, and it was 7.6 ± 1.3% in understory sites (Table 3). A total of 16 recruits, including seedlings, saplings, and juveniles, were found in the 48 paired sites, with 12 occurring in logging gaps and 4 in understory sites (Figure 1). As gaps ages ranged from 1 to 5 years, only seedlings could have been established postlogging. To meet statistical assumptions, one outlier was omitted from all analyses where nine seedlings were germinating from a single fruit found in a logging gap; thus, the statistics were conservative as inclusion of the outlier would have enhanced the observed higher recruit density in gaps. While these results included many plots without any recruits, these data were still valuable in establishing a relation between growth environment and presence of recruits. In addition, logging gaps contained an array of early pioneer species, which are generally taller than any Brazil nut recruits present, whereas understory sites were characterized by much lower stem counts and more shade tolerant species (J. Moll-Rocek, personal observation).

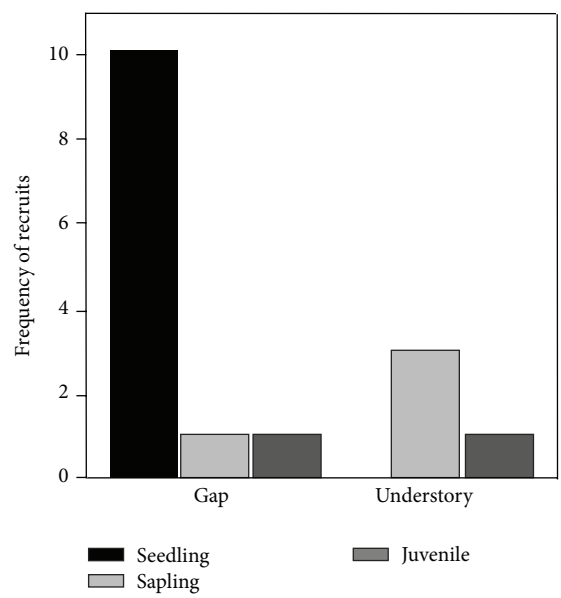

Figure 1: Histogram of recruit frequency by height and diameter at breast height (dbh) in gap and understory Sites. Size classes were seedlings (<1.3 m), saplings (1.3 m ≥ 10 cm dbh), and juveniles (>10 cm dbh). A total of four recruits were found in understory sites and 12 recruits in logging gaps sites (Wilcoxon sign-rank, $P = 0.02$, $n = 47$).

We found a significantly higher recruit density in logging gaps (11.5 ind. ha^{-1}) than in understory sites (3.8 ind. ha^{-1}), using a Wilcoxon sign-rank test ($P = 0.02$, $n = 47$, excludes outlier). Further, the Poisson distribution model yielded an increasing probability of encountering a recruit as canopy openness increased ($P = 0.001$, $n = 97$) supporting the idea that recruit success is related to high light environments. Recruit density showed no significant relationship to distance of nearest mature tree ($P = 0.4$, $n = 97$).

3.2. Seedling Growth. All measures of growth, including height, LA_T, and leaf number were found to be significantly

Table 2: The Brazil nut concession ID, total area (ha) and number and density of Brazil nut trees, and the area (m^2) and location (decimal degree) of the logging gaps (3 per concession) are included in this study. Paired understory sites were located a minimum of 50 m from the logging gap, but never more than 200 m.

Brazil nut concession		Productive Brazil nut trees		Unshelled Brazil nut	Gap 1			Gap 2			Gap 3		
ID	Area (Ha)	#	Density	harvest (kg yr^{-1})*	Area (m^2)	Lat. (S)	Long (W)	Area (m^2)	Lat. (S)	Long (W)	Area (m^2)	Lat. (S)	Long (W)
1	290.6	174	0.528	6659.8	246	12.142	69.142	223	12.152	69.134	224	12.153	69.136
2	801.5	405	0.505	15525.3	240	12.120	69.151	198	12.119	69.151	200	12.111	69.149
3	932.7	275	0.513	18540.2	201	12.074	69.094	235	12.075	69.094	219	12.072	69.093
4	1083.0	—	—	19617.5	178	12.089	69.048	120	12.092	69.051	160	12.094	69.044
5	749.1	—	—	19110.0	213	12.138	69.081	252	12.138	69.079	227	12.140	69.082
6	765.4	—	—	23085.3	196	12.120	69.014	203	12.119	69.016	182	12.118	69.015
7	279.1	—	—	7289.8	190	12.265	69.036	290	12.265	69.036	182	12.268	69.039
8	1076.4	—	—	31509.1	243	12.234	69.037	220	12.235	69.036	175	12.236	69.036
9	277.5	300	0.995	12194.7	220	12.268	69.043	160	12.268	69.043	201	12.268	69.040
10	715.4	—	—	11909.1	165	12.224	69.047	284	12.233	69.037	175	12.223	69.047
11	191.3	186	0.972	8325.1	221	12.259	69.131	246	12.260	69.132	223	12.260	69.131
12	152.3	256	1.694	—	263	12.268	69.132	250	12.269	69.133	213	12.269	69.134
13	125.8	95	0.752	4454.8	268	12.278	69.128	213	12.278	69.129	230	12.278	69.130
14	654.5	331	0.506	17290.0	244	12.276	69.171	229	12.278	69.171	220	12.273	69.174
15	242.9	119	0.582	4904.9	255	12.297	69.129	244	12.298	69.130	204	12.296	69.129
16	771.4	318	0.412	11760.0	219	12.164	69.273	268	12.162	69.275	225	12.160	69.278

*As reported to the POA for the 2010-2011 harvest season.

Table 3: Mean area, canopy openness, and recruit density compared between logging gap and understory environments. Additionally, Soriano et al.'s results [17] on recruit density are included. Soriano et al. [17] collected logging gap data for both informal and formal logging types, while all logging gaps in our study were due to informal logging.

	Mean area ± SD (m^2)	Canopy openness ± SD (%)	Recruit density (ind · ha^{-1})	Soriano et al. 2012 [17] Recruit density (ind · ha^{-1})	
Logging gap	216.6 ± 34	19.7 ± 6.4	11.5	Informal: 7.6*	Formal: 5.8*
Understory	216.6 ± 34	7.6 ± 1.3	3.8	3.9*	

higher in tree-fall gaps than in understory sites from the fourth month onward (Figure 2). The average height in tree-fall gap seedlings increased by 18.4 cm over the course of the six months compared to an increase of 1.5 cm for understory seedlings. Average LA_T in tree-fall gap seedlings increased by 344.5 cm^2 but decreased by 24.3 cm^2 in understory seedlings over the course of the six months. As expected, canopy openness was significantly higher in tree-fall gaps throughout all 6 months of measurement. Within understory sites, openness was significantly correlated with total leaf area ($P < 0.0001$; Adj-$R^2 = 0.09$; $n = 180$) and leaf number ($P = 0.0026$; Adj-$R^2 = 0.044$; $n = 180$). Seedling height was not significantly correlated with openness in either understory or gap sites ($P > 0.05$, $n = 180$).

4. Discussion

An improved understanding of the impacts of selective logging on Brazil nut recruitment is crucial to the long-term sustainability of Brazil nut extraction in multiple use forests. Higher recruit density in logging gaps, a positive correlation between recruit density and canopy openness, and increased growth rates in tree-fall gaps support the earlier classification of *B. excelsa* as a gap-dependent species [1, 2, 5]. Further, higher seedling growth rates in logging gaps and fallows [5, 23], which lead to improved recruitment success, were positively correlated with higher light environments. Together, these results and the literature suggest the possibility that selective logging could foster natural *B. excelsa* regeneration, both through enhanced establishment and growth rates, but further studies more explicitly comparing regeneration in natural forest gaps and unlogged forest understory environments are needed.

In a study of selective logging effects on natural regeneration of *B. excelsa* in Bolivia, Soriano et al. [17] found no significant difference in recruitment between logged and understory sites (Table 3). The difference between these findings and those in our study may be due to how Soriano et al. [17] defined logged sites, which included skid trails, access roads, and log landings in addition to logging gaps. Our study defined logged sites as logging gaps only. Thus, smaller disturbed areas, such as skid trails or access roads, may have lowered the average recruit density across all logged areas. Additionally, skid trails or access roads have only marginal differences in canopy openness compared with understory forest. This is consistent with Soriano et al.'s [17] finding of a positive correlation between recruit density and canopy openness, as well as logging disturbance size. The threefold lower densities of productive trees in Madre de Dios compared to the rest of the Western Amazon region may also explain the low levels of natural regeneration across the 16 concessions studied here. We found only saplings in understory sites, with no seedlings present. These findings contrast with those of Myers et al. [1] in Bolivia who only observed seedlings and no saplings in understory forest. The lower density of mature trees noted in Peru may explain the relative infrequency of individuals encountered in the present study, and thus the difference in recruit size class. However, the presence of some saplings in the understory would suggest that recruits can reach a height above 1.3 m in this growth environment.

Interestingly, recruit density showed no significant relationship with distance to the nearest mature tree. A negative relationship was expected as dispersal by agoutis, the primary dispersal agent for the heavy Brazil nut, would likely have a limited range [3, 24, 25]. Instead, seedlings were noted at distances greater than 50 m from the nearest mature tree.

Recruit success is a function of establishment, survival, and growth of seedlings [5], which are influenced by a number of factors including dispersal, predation and herbivory, and local ecophysiological conditions. In the growth experiment, higher seedling growth rates in tree-fall gaps as compared to mature forest confirm Cotta et al.'s [5] and Kainer et al.'s [23] findings that growth rate (height, total leaf area, and leaf number) are positively correlated with increasing light availability. Seedlings in gap environments had significantly higher growth rates than those in understory environments, yet interestingly, openness was not correlated with growth rate within gaps (though there was a positive relationship). Within understory environments, where average canopy openness reached a maximum of 11%, there was a significant positive correlation between openness and growth, implying that at very low openness levels, growth is primarily limited by light availability, whereas in gap environments other factors may be more important in determining growth rate. Recruit success, then, was improved in gaps: both in higher recruit densities in logging gaps and in higher seedling growth rates in natural tree-fall gaps. This suggests that selective logging may improve conditions for Brazil nut recruitment success, by affecting establishment and subsequent growth.

Multiple-use forest management (MFM) for diverse products including timber, NTFPs, and ecosystem services has the potential to contribute to sustainable development while meeting forest conservation goals [16, 26]. Recommended (i.e., low impact) selective logging practices aim to reduce forest disturbance [27], which can be compatible with NTFP extraction, particularly for light-demanding NTFP

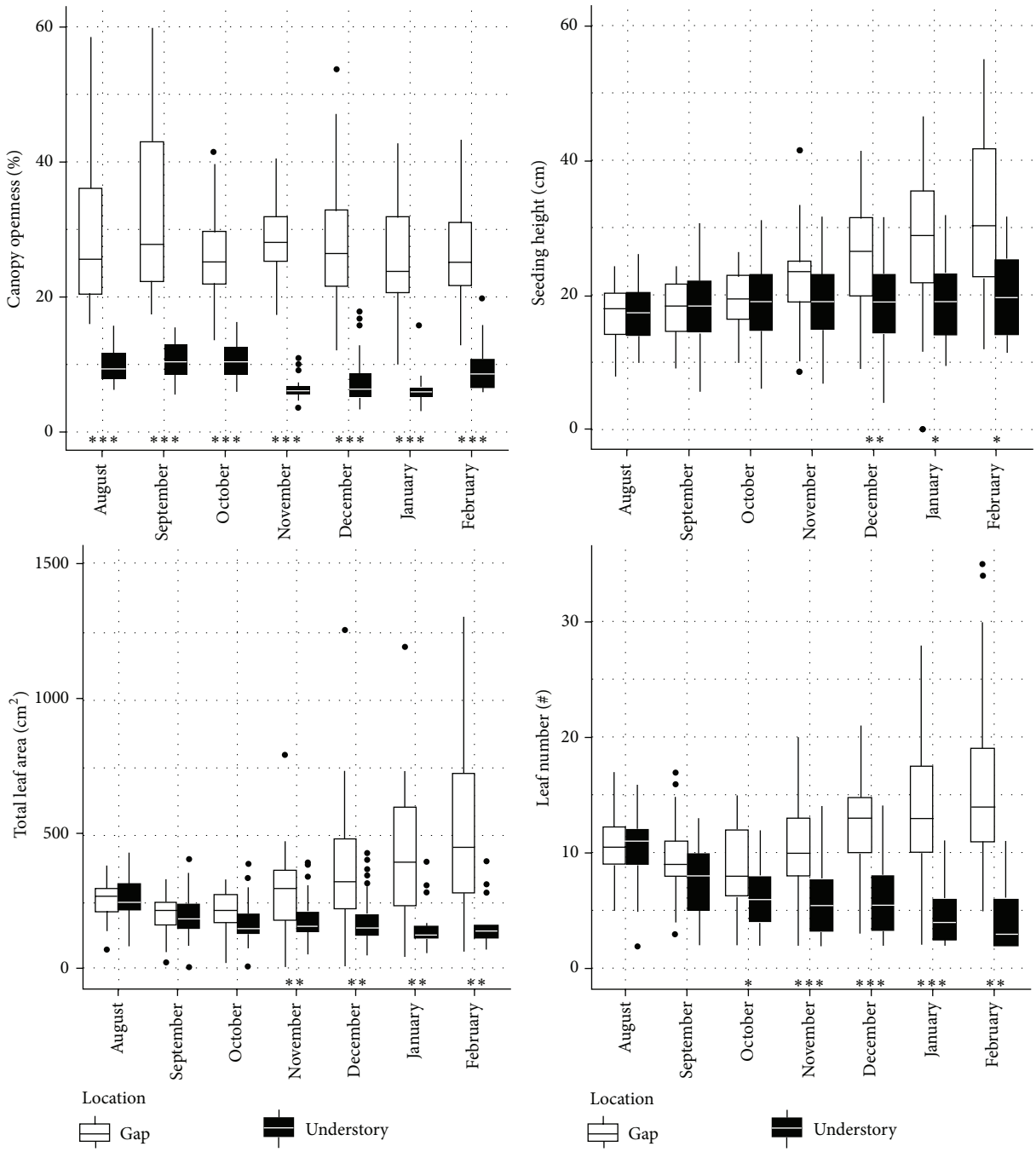

Figure 2: Boxplots showing: openness in tree-fall and understory plots; seedling height in cm from ground; total leaf area in cm^2; and leaf number versus measurement month (years 2011-2012). Black boxes represent seedlings in understory sites; white boxes represent seedlings in tree-fall gaps. Significance of difference is provided as P value * =< 0.05, ** =< 0.01, and *** =< 0.001.

species [28–30] including Brazil nut [31]. Furthermore, selective logging and Brazil nut extraction have a high potential for integration including cooccurrence, high economic value, temporal segregation in harvest seasons, Brazil nut's legal protection from logging, and shared use of forest inventories [14, 31]. In a review of the barriers to MFM, Guariguata et al. [32] identified the need to refine the scientific basis for assessing tradeoffs between extraction activities. This study contributes evidence to the ecological compatibility of the two activities.

However, the potentially critical role of logging intensity in determining sustainability of MFM remains murky. Although we were not able to measure logging intensity, our observations across the 16 Brazil nut concessions studied suggest that intensities did not exceed one timber tree per ha (4-5 m^3/ha), which is consistent with reported logging

intensities in this region [19]. At higher intensities, one would expect Brazil nut recruitment densities to increase as light availability increased [1, 5] provided that logging practices avoid excessive damage to mature Brazil nut trees [33]. Further investigation is required to understand the interaction of different logging intensities and Brazil nut demographics to guide policy design of MFM.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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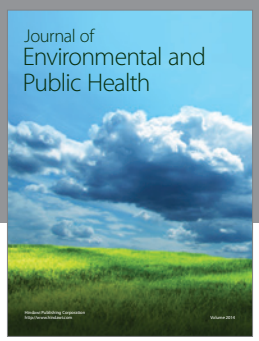

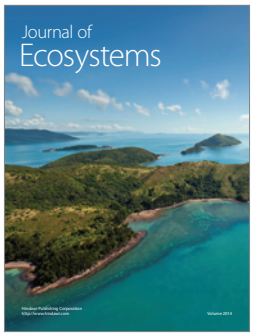

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