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Population Demography and Spatial Distribution Pattern of Brazil Nut Trees in a Peruvian Concession

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Abstract

Bertholletia excelsa, commonly known as Brazil nut, is a keystone species in Amazonia due to its irreplaceable role in local ecosystems and economic potential for local Brazil nut harvesters. A literature review yields inconclusive research on the impacts of Brazil nut harvesting and the sustainability status of its population. In light of conservation concerns, this study analyzes the population demography and spatial distribution pattern of *Bertholletia excelsa* in an extensively harvested Brazil nut concession in the Peruvian Madre de Dios region. After identification training, a consistent methodology was employed using transects along pre-existing paths to collect tree size and coordinates for Brazil nut trees of all sizes (ranging from seedlings to mature individuals) within 5 meters from either side of the trail. The study raises concerns about the sustainability of the observed population due to the dominance of mature trees, the absence of juveniles, and low seedling density. The spatial analysis indicates the existence of hierarchical clustering, which may be influenced by both biophysical and anthropogenic factors and is typical of Brazil nut populations. Agouti behavior, the only seed dispersal agent for the species, did not align with the observed distribution of small trees, suggesting possible human influence on tree dispersal. Further research is needed to explore the impact of harvesting practices, environmental factors, and human interventions on Brazil nut population dynamics. Long-term monitoring and studies in larger areas could provide more comprehensive insights into demographic trends, seedling recruitment, and the sustainability of Brazil nut populations which is crucial for implementing effective conservation strategies for Brazil nut concessions.

Introduction

Study Species

The Brazil nut tree, *Bertholletia excelsa*, known as *'castaña'* in Peru, towers over the forest canopy in the South American Amazon Region in non-flooded (Terra Firme) areas. With an average height of 50 meters and a life span of up to 500 years, these giants make up a large percentage of the forest basal area (Zuidema, 2003). They grow in clusters throughout the rainforest, called stands, where 75-100 trees are commonly found together (Rockwell et al., 2017). These areas are interspersed with forest that might only contain 1 tree per 6 ha (Scoles and Gribel, 2012). Most demographic studies found that intermediate Brazil nut trees between 80 and 160 cm DBH dominate the population (Zuidema and Boot, 2002; Peres et al., 2003; Wadt et al., 2008, Scoles & Gribel, 2011). *Castañas* are also known to be stress tolerant and developmentally plastic; they have the ability to adjust photosynthetic rates, leaf morphology, and resource use depending on the availability of light, water, and nutrients (da Costa et al., 2022).

Brazil Nut Reproduction

The trees produce large flowers with an inward bent hood that can only be pollinated by medium to large bees strong enough to pry open the hood (Maués, 2002). After fertilization, the tree produces 10-25 large Brazil nut seeds within a “coco” - a woody fruit resembling a coconut in appearance and strength (Zuidema, 2003; Scoles and Gribel, 2012). After falling to the ground, fruits are collected by Brazil nut harvesters who remove the outer shell with a machete and dry and shell the seeds before taking them to market. If not gathered by harvesters, the agouti (*Dasyprocta spp.*), a rodent with the ability to drill holes into the cocos without damaging the seeds, scatter-hoards the Brazil nuts (Tuck Haugaasen et al., 2012). On average, agoutis open and bury ¼ of the fruit 5 days after it falls (Wadt et al., 2018) and typically carry seeds 30 meters (some fruits are carried up to 60 m) from their original position, though most of this distance occurs while seeds are still within cocos (Tuck Haugaasen et al., 2012). Agoutis retrieve over 99% of the seeds they disperse, causing concern that intensive harvest could lead to more predation than seed burial and negatively impact Brazil nut regeneration (Tuck Haugaasen et al., 2012). Other research disagrees stating that animals have enough time to locate seeds prior to harvesting (Wadt et al., 2018), and humans unknowingly assist in dispersal by dropping nuts when opening cocos and walking along trails (Scoles and Gribel, 2015). After they are planted, seeds take 12 to 18 months to germinate (Müller, 1981, cited in Tuck Haugaasen et al., 2012) and require a forest gap to develop into saplings, though seedlings are common regardless of shade (Myers et al., 2000). Brazil nut trees are relatively shade tolerant after establishment but since they are light gap specialists, grow rapidly when exposed to adequate light (Schöngart et al., 2015).

Spatial Distribution Pattern of the Brazil Nut Tree

Many tree species exhibit negative density dependence in tree recruitment. This is thought to be due to increased attraction of herbivores, and host-specific pathogens. Another reason for which this can occur is to reduce rates of inbreeding. Negative density dependence of conspecifics ensures that genetically similar individuals are less able to interbreed (Johnson et al., 2012). Studies have also shown that this effect is present in more mature trees, beyond the sapling stage, due to an increase in competition for limited resources (Zambrano et al., 2017), in addition to numerous other factors. If we consider the action of these effects, we should expect to see negative density dependence exhibited in the distribution of Brazil Nut Trees. However, in reality, this is not the case. As covered earlier in this report, we observe that mature Brazil Nut trees tend to occur in clusters of 75-100 trees called stands, potentially indicating positive density dependence. One reason for this observed distribution may be the large bees that pollinate the species, and their capability to fly for large distances. This long-range pollination ensures that gene flow between individuals is not limited to the nearest neighbours, thus minimising the accumulation of interbreeding within populations (Thomas, Atkinson and Kettle, 2018). Another possible explanation for this observed pattern of distribution is the nurse-plant effect. Nurse plants can facilitate the growth and recruitment of juvenile plants. This facilitation usually arises due to the shelter provided by the nurse plant’s canopy. The shade beneath the canopy can create microhabitats and provide shelter that increases the chances of seed germination (Ren, Yang and Liu, 2008). In addition to these spatial pressures, the mode of seed dispersal of the tree also contributes to the observed distribution patterns. The agouti (*Dasyprocta spp.*), a rodent with the ability to drill holes into the seeds, is the only non-human animal responsible for dispersing Brazil nuts without damaging the seeds (Haugaasen et al., 2010).

Current Conservation Efforts

One of the main strategies employed by the Peruvian Government to assist in the conservation of the Brazil Nut tree is the use of Brazil Nut concessions. The system started in the year 2000 and involves a specific type of agreement between the Peruvian Government and a family or small local community. This agreement entails a 40-year contract of responsibility for land that contains a higher density of harvestable Brazil Nut trees. In return for the right to harvest the nuts, the contracted individuals, known as *castañeros*, would have to agree to a variety of conditions (Chavez and Cossio, 2014). This two-way agreement provides economic incentive for the preservation of primary rainforest within these concessions and aims to promote sustainable harvesting practices (Willem, Ingram and Guariguata, 2019).

How Conservation Efforts can be Guided by the Study of Spatial Distribution Patterns

Understanding the existing spatial distribution pattern of a plant species can be an extremely useful tool to refine the targeting of conservation efforts to improve their efficiency. Changes in a species' distribution pattern can give us valuable insights into a population's viability and performance, which can help to identify regions of high priority at earlier stages (Olive et al., 2002). Therefore, the greater our knowledge of a species' varying distribution patterns becomes, the easier it becomes to target conservation efforts more effectively (Alados et al., 2003). The analysis of spatial distribution patterns can give us key information as to how positive/negative density dependence and nurse-plant effects are acting upon the species. These insights can help to guide reforestation efforts, allowing for the planting of seeds in areas that are most conducive for their germination and continued survival (Lim et al., 2008). An understanding of smaller plants' distribution in relation to mature trees can aid in the understanding of microsites of suitable conditions, perhaps created by nurse-plant relationships with fully grown trees. If we combine spatial distribution studies with knowledge of abiotic factors, we can gain an increased understanding of the biotic and abiotic factors crucial for the plant's survival (Cristina et al., 2022). Spatial distribution studies such as this one alongside envelopes of abiotic factors can give us insight into the optimal conditions for a species' growth and development.

Environmental Importance of the Brazil Nut Tree

Brazil nut trees are considered a keystone species in Amazonia and provide various environmental benefits and ecosystem services. As one of the largest trees in the rainforest, they support biodiversity by supplying habitat and a nutritious food source for many populations (Rainforest Alliance, 2012). Brazil nuts also contribute to the extensive Amazon rainforest hydrological cycle; transpiration from Amazonian trees influences rainfall across South America and up to the midwestern United States (Amazon Aid, 2023). In addition to uptaking water from the ground, the trees' large roots help stabilize the soil and prevent erosion (da Costa et al., 2022; Rainforest Alliance, 2012). Since large trees represent high percentages of mature forest biomass, they are believed to have important roles in carbon cycling at the local and global levels, especially with the prevalence of climate change (Lutz et al., 2018). Castañas in particular sequester the most carbon of all species important to the Amazonian economy and rank third for biomass accumulation out of 3,458 evaluated rainforest species (Fauset et al., 2015).

Economic Significance

Since Brazil nuts have low mortality and long lifespans, the trees produce high volumes of nuts for hundreds of years (Zuidema and Boot, 2002). Starting in the rainy season, Brazil nuts are harvested from the wild and provide an important source of income to local forest-based communities (Mori, 1992; Scoles and Gribel, 2012). The vast majority of nuts are consumed raw since they are high in protein, fat, vitamins, and minerals, but humans also utilize oil from nuts as an ingredient in natural beauty products (Rainforest Alliance, 2012; Mast Producing Trees, 2022). The designation of Brazil nut concessions prevented the destruction of Brazil nut forests and allowed nut collection to become an important financial activity for many locals, particularly in areas with high enough tree density to ensure economic harvests. One such location is Madre de Dios, where 30,000 people are involved in the Brazil nut industry and depend on it for 67% of their annual income. (Flores 2002 and Campos 2006, cited in Nunes et al., 2012). Madre de Dios houses 2.5 million ha of Brazil nut forests (Escobal and Aldana 2003), permitting Peru's global title as the second largest exporter of Brazil nuts (Guariguata et al. 2017). Overall, Brazil nuts are one of the most important non timber forest products (NTFP) in the area. They have the potential to be a sustainable and economic endeavor - even outcompeting other land use that degrades the environment (Willem et al., 2019). Research shows that if harvesters upgrade methods to certified-shelled production, they could generate profit that matched or exceeded money made from traditional agriculture and cattle ranching in Madre de Dios, especially when paired with sustainable logging and eco-tourism (Nunes et al., 2012). Ensuring the profitability of Brazil nut concessions means that more land stays forested and *castañeros* have less incentive to turn to environmentally degrading economic prospects like logging, cattle ranching, and gold mining (Nicolau et al, 2019).

Issues for Concessions

Although Brazil nut concession can be a sustainable model, they are currently plagued with many issues that threaten their sustainability and ability to preserve Brazil nut trees. In Madre de Dios, the Brazil nut economy is fragile and market prices are volatile, which leads to the majority of Peruvian Brazil nut harvesters living below the poverty level (Kalliola, and Flores, 2011). Since the concession managers are unable to rise from poverty and the nut collecting season only lasts for a few months, they supplement their income with other activities that are environmentally degrading, such as agriculture, logging, fishing, hunting, and sometimes paid work. The poorest nut gatherers participated in agriculture, even though it was very low profit, whereas the richer gatherers preferred timber extraction which brought in as much income as Brazil nut collection (Escobal and Aldana, 2003). Hunting during Brazil nut harvesting contributes to the endangerment of the red deer (*Mazama americana*) and collared peccary (*Tayassu tajacu*). Concessions outside of protected reserves, which comprise the majority in Madre de Dios, experience rampant, illegal logging due to regulation problems, ineffective monitoring, and overlapping tenure types and property rights (Willem et al., 2019). In addition to logging, illegal gold mining is another main driver of ecosystem conversion; in 2014, this activity increased by 239% in Madre de Dios (Scullion et al. 2014). Although Brazil nut trees are protected by the government, they are also at risk since land degradation negatively impacts gene-flow in tree populations. Depending on the amount of forest degradation, seedlings have lower genetic diversity and higher inbreeding than adults (Chiriboga-Arroyo et al., 2021). This impacts the trees' ability to react to environmental change, which is especially important with the prevalence of climate change. In addition, the changing climate is predicted to reduce the co-occurrence potential of Brazil nut trees and their pollinators by 80% (Sales et al., 2021). The combination of these issues has resulted in a major decline in Brazil nut-rich forests and consequently a national decrease in nut production (Coslovsky 2014, cited in Guariguata et al. 2017), and in the future this could translate into concessions becoming unprofitable and consequently replaced by environmentally degrading practices.

Nut Harvest Sustainability

There is, however, contrasting information on whether or not the actual act of harvesting Brazil nuts is sustainable, particularly in regard to Brazil nut tree regeneration. Peres et al., 2003 - a study that received widespread attention in scientific and common media - analyzed 23 populations with varying harvest intensities throughout the Amazon basin and found that juvenile trees were only discovered in areas with a history of light or recent exploitation. They warned that populations with long-term intensive harvesting will likely experience a demographic collapse. L.H.O. Wadt et al. (2008) found that populations could sufficiently regenerate when 29-55% of fruit was left, however, most harvesters remove up to 93% of the fruits from Brazil nut stands (Zuidema and Boot, 2002). Another source said extensive harvesting could negatively impact Brazil nut populations, but there were greater concerns to the species like land use change (Bertwell et al., 2018). Other sources provide extensive research suggesting harvesting intensity is not responsible for low recruitment rates and levels of non-reproductive trees in Brazil nut stands (Wadt et al., 2018; Scoles and Gribel, 2011, 2012 and 2015; Zuidema and Boot, 2002; Guariguata et al., 2017; Zuidema, 2001). Scoles and Gribel (2015) even found that there were higher levels of regeneration in areas with more extensive harvesting practices compared to land with lower rates of extraction.

Project Aims

To better understand Brazil nut population demography in the Peruvian Madre de Dios region, this study provides data from an extensively harvested Brazil nut concession to analyze the sustainability and spatial distribution of the local tree population. Initially, it seems that extensively harvesting nuts from a species with highly specific reproductive practices, distribution relying on one animal, and long germination times would result in a population bottleneck. However, this idea has been challenged by recent research and this study aims to further the debate.

Methods

Study Site

This study was conducted during a six-week period on a Brazil nut concession managed by José Callo that borders land owned by the Finca las Piedras research station. The land, which is largely primary forest (only primary forest was surveyed during this study), is located at

12°13'31.67"S latitude and 69° 6'7.36"W longitude, placing it within the Madre de Dios Region. The elevation is 250 m above sea level and the area has an average temperature of 24.9°C and 2,459 mm of rainfall every year (en.climate-data.org, n.d.). The ~350-hectare plot has been extensively harvested for decades and contains trails leading to known reproductive Brazil nut trees. The pre-existing paths were used as transects for this study, and although it was not a randomized method, it was assumed that these paths would likely provide access to more *castañas* due to the known presence of mature individuals.

Identification Training

Two individuals participated in the surveying process, one for the entire six weeks and the other for the last week of the data collection period, though the surveying process was always done individually. The main surveyor had two separate identification sessions with two resident naturalists based at Alliance for a Sustainable Amazon (ASA), the first in a planted secondary forest identifying Brazil nut trees at different growth stages, and the second searching for trees in primary forest and studying and identifying photos of similar plants. The individual also spent time observing mature Brazil nuts at Finca las Piedras and seedlings grown in an ASA plant nursery. The second surveyor was trained by the initial individual and given a very similar identification training experience. Photos of signifying characteristics (leaf shape and arrangement, petioles, branching pattern, etc.) were taken during these experiences and referenced by both people during surveying. The later addition of another surveyor is not believed to impact the results of this study, as evidenced by the successful identification of young Brazil nuts in the field by the second surveyor.

Surveying Methodology

To be consistent and thorough, a surveyor walked 10 large paces (estimated to be 10 meters) then stopped and, while remaining in the same place unless examining a tree, scanned the forest in a 360° circle an estimated 5 meters from the trail (See Figure 1). Binoculars were used to aid in the identification process when plant material was beyond the reach of the individual.

Figure 1: Illustration of surveying method. A solo surveyor walked 10 paces and scanned a 5m distance 360° while standing in place.

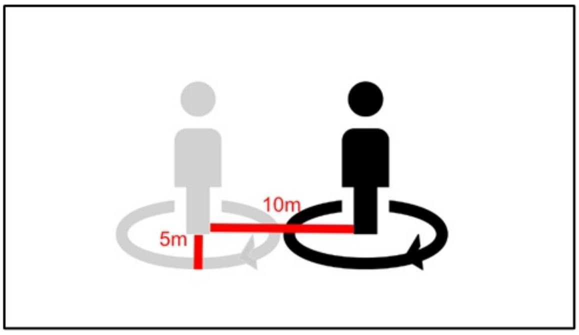
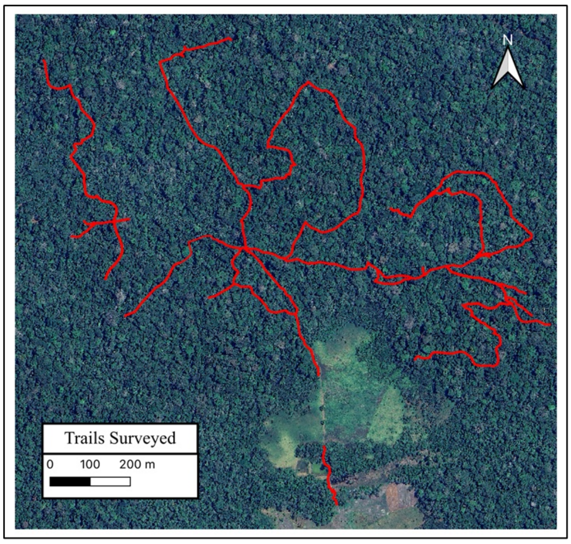


Figure 2: Map of the trails surveyed. This is not representative of the total area surveyed since 5m on each side of the trails was also analyzed. Note the gap in the southern part of the map which was excluded to only survey primary forest.



Data Collection

Tree size and coordinates were recorded for all Brazil nut trees within the 5-meter radius, ranging from seedlings to mature trees. It is unknown exactly what size trees in this species become reproductive and is estimated to be somewhere between 40-60 cm DBH; some studies recognize mature individuals as at least 40 cm (Zuidema and Boot, 2002; Scoles and Gribel 2012), while others consider larger trees (60 cm DBH) to be reproductive (Peres et al., 2003; Wadt et al., 2008). To find a middle ground, this study will consider Brazil nut trees with a DBH of at least 50 cm reproductively viable. Juveniles are trees with a DBH between 10 and 50 cm, saplings are trees less than 10 cm DBH but taller than 1.5 meters, and seedlings are Brazil nuts less than 1.5 m tall. During the survey, seedling height in meters was recorded and a diameter tape was used to measure the DBH for all other trees. Coordinates and trail data were recorded in the mobile app GPS Tracks and later uploaded to Google Earth and QGIS. The total distance surveyed was calculated using the ruler tool in Google Earth and multiplying the sum of all trail lengths by 10 m since 5 m on each side of the trail was analyzed. The remaining triangle in between scanning circles was included in this calculation as the small space was easy to cover while scanning. Latitude, longitude, and either DBH or height for every tree found were entered into an Excel spreadsheet and used for graphics and data analysis.

Population Demography Analysis

Similar to Zuidema and Boot, 2002, trees were categorized by size to compare the frequency of individuals among all classes, regardless of whether height or DBH was recorded (Table 1). The specific categories were selected to best represent the distribution of the population and better understand tree sizes within broader size classes. Statistics were calculated to determine density, population percentages, averages, standard deviation, etc.

Nearest Neighbor Analysis

Labeled tree point coordinates were uploaded to Google Earth and the measuring tool was utilized to obtain the distance (m) between trees of different size classes. For every small tree (including both seedlings and saplings to increase sample size), the distance to the nearest mature tree (>50cm) was recorded to analyze the location of small Brazil nuts in relation to reproductive individuals. Data was also compiled to determine if small trees were typically located by mature trees of a certain size. One sapling was excluded from this calculation because its nearest mature neighbor was located on Finca las Piedras land rather than the concession where surveying took place. However, the mature individual (labeled tree 80 in Figure 13 in Appendix) was included in the general nearest neighbor analysis to avoid skewing results.

Spatial Distribution Pattern Analysis by Ripley's K(t)-function

Ripley's K function is a fundamental tool in spatial distribution pattern analysis, providing valuable insights into the arrangement and clustering patterns of points within a given window. Ripley's K function offers a comprehensive framework to characterize completely mapped spatial point data. By quantifying the expected number of neighboring points within varying distances from each individual occurrence, Ripley's K function distinguishes between whether point patterns exhibit clustering, or complete spatial randomness. Ripley's K-function differs from other spatial analyses in that it preserves the individual distances between points within its output, allowing the examination of the clustering pattern's variation with scale (Wehenkel et al., 2015).

Ripley's Univariate K-function was used to determine at what scales the distribution of Brazil nut trees was clustered. The function was used to describe the spatial relationships between all classes of tree, mature trees only, and seedlings and saplings only, separately. The univariate Ripley's K function can be estimated as:

$$K_{\cup}(r) = \frac{A}{n^2}\sum\sum W_{ij}(r)\delta(d_{ij} < r)$$

where A is the area of the study region, n is the number of observed points, $w_{ij}(r)$ is an edge effect correction factor, $\delta(r)$ is an indicator function and d_{ij} is the distance between the i-th and j-th points.

Monte Carlo Hypothesis Testing

Monte Carlo hypothesis testing is a statistical method used to estimate the significance of observed data. The method involves the simulation of datasets under the assumption of the null hypothesis. We can compare the observed and simulated datasets in order to estimate if they are significantly different. By comparing the two datasets, we can quantify how likely it is that we observe our data under the null hypothesis.

In this case, our null hypothesis was that trees of all size classes were distributed under the conditions of complete spatial randomness (CSR). Using the specified study area as the background, 500 simulations placed our 80 trees in completely random locations to create multiple point distribution patterns for each size class under CSR conditions. Subsequently, the Ripley's univariate K-function was applied to each simulated dataset, and these values were stored for comparison. P-values were calculated based on the proportion of the observed data K-functions that were greater than the simulated K-functions for each distance-pair. The P-value for each distance-pair can be written as:

$$p\_val = \frac{1}{N}\sum_{i=1}^{N}\gamma(K_{sim}^{i} \geq K_{obs})$$

where N is the number of simulated K-values, K_{sim}^{i} represents the i-th simulated K-value, K_{obs} is the observed K-value, and $\gamma(K_{sim}^{i} \geq K_{obs})$ is an indicator function that equals 1 if the inequality is satisfied and 0 otherwise. The set of P-values obtained can then be plotted against their relative distance-pair.

Significance Envelope

The 'envelope' function from within the "spatstat" package in R allows us to create a significance envelope around our CSR simulations. This envelope can allow us to visually gauge the significance of our data by observing the overlaps between the plot and the significance band. Any data that lies outside of the envelope can be considered statistically significant, and outside the range of uncertainty. In order to create this envelope, 100 point simulations under CSR were created. The K-functions of these point simulations were plotted, yielding K-function curves reflecting the range of expected outcomes under randomness. Confidence bands were then synthesised from the averages of these function curves. The envelope represents the area where 95% of the K-functions lies, under CSR conditions. The envelope function can be estimated as:

$$envelope(r) = \bar{K}_{sim}(r) \pm \sigma(r)$$

where $\acute{K}_{sim}(r)$ is the average of the simulated K-functions at distance (r) and *σ(r)* is the standard deviations of the simulated K-functions at distance (r). It is important to note that this mathematical equation is an over-simplification of the actual envelope function.

Bootstrap Confidence Intervals

Bootstrap resampling to generate confidence intervals allows us to quantify the uncertainty associated with our observed K-function values and provides a means of measuring the viability of our data in relation to the sample size. This approach involves resampling the original data 100 times to create simulated datasets of the same size. The K-functions are calculated allowing for the generation of percentile-based confidence intervals at the 95% confidence level. This signifies the range in which the true K-values are likely to fall regardless of sample size. This analysis further aids in informing our identification of statistically significant deviations from CSR. The incorporation of these intervals enhances the reliability of our findings. The quantiles created by this analysis can be represented as:

$$\left(K^{1}_{resample}, \frac{\alpha}{2}\right), and\ \left(K^{B}_{resample}, 1-\frac{\alpha}{2}\right)$$

where B is the number of resampled K-values, and α is the significance level. For each observed K-values, these quantiles are calculated based on the resampled K-values.

Results

Population Structure of the Study Group

In the surveyed 7.16 ha of forest, a total of 79 trees were identified, 61 of which were potentially reproductive mature trees (DBH>50cm), 8 were saplings (>1.5m tall and DBH<10cm), and 10 were seedlings (<1.5m tall). No juvenile individuals (DBH>10<50) were found in the sample area, so descriptive statistics will not be presented since the values are 0. The overall density of trees in the sample size was 11.03 trees per ha. Mature tree density was 8.52 trees/ha, sapling density was 1.12 trees/ha, and seedling density was 1.40 trees/ha. The average DBH (measured in cm) of all trees (excluding seedlings) was 126.2 ± 54.0; trees in the mature class had an average DBH of 142.2 ± 33.1 cm, saplings had an average DBH of 3.97 ± 2.3 cm, and seedlings had an average height of 0.6 ± 0.3 m (note that the measurement for seedlings is in height since DBH was not recorded for this group). The largest Brazil nut found during the study measured 216.4 cm DBH, while the smallest sapling measured 0.5 cm DBH. Due to the lack of a juvenile population in the study, the data does not follow a normal distribution. The population was dominated by mature trees (77%), and of this percentage, 30% were considered old mature trees (DBH >160cm). Saplings and seedlings comprised 10 and 13% of the entire population, respectively. The largest specific size class was category 16, with 19% of the population represented by trees between 140-160 cm DBH.

More information on the structure of the study group can be found in Table 1. The spatial distribution of the study group is represented in Figure 3.

Nearest Neighbor Analysis

Small trees, which includes seedlings and saplings (n=18) were on average 52.3±27.7 m away from the nearest mature individual. This data was highly variable; the minimum distance was 2.44 m and the maximum distance was 110 m. Of 17 small trees (one sapling was excluded, see *Nearest Neighbor Analysis* in Methodology) 41% were closest to a mature tree between 140-160 cm DBH.

Figure 3: Map of all trees surveyed in a Peruvian Brazil nut concession separated by size. The juvenile category is absent since no trees 10-50 cm DBH were located.

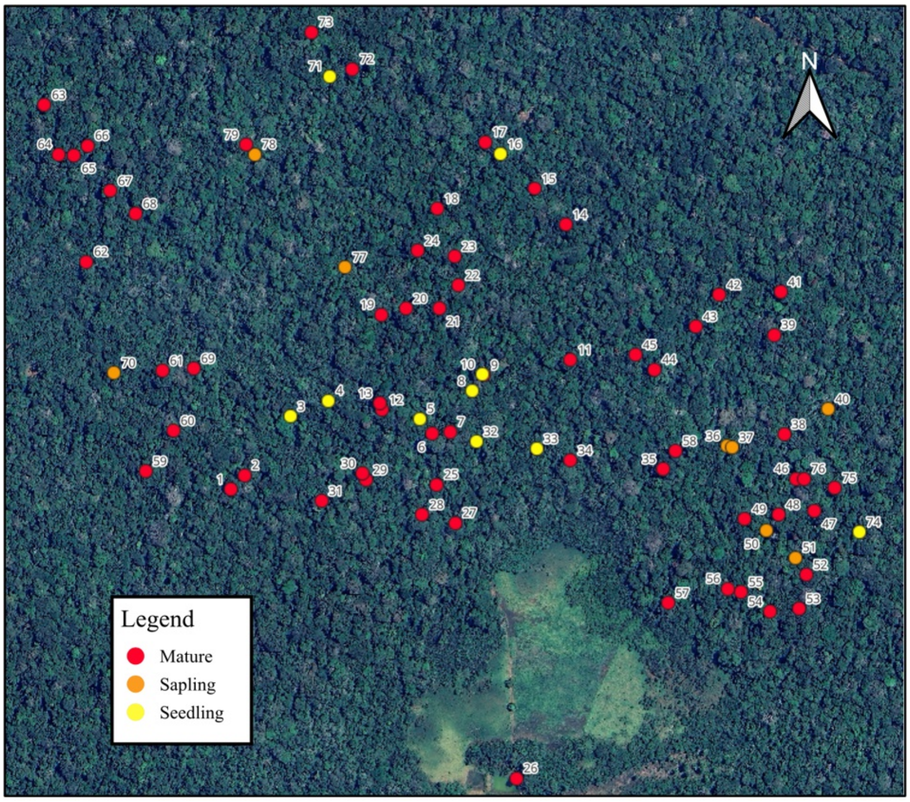


Table 1: Number of individuals and percentage of the entire population separated by categories based on either height or DBH. Categories 1-3 represent the seedling population; 4-6 represent saplings; 7-10 represent juveniles, and 11-19 represent mature trees.

Category	DBH (cm)	Height (m)	No. Individuals	% of Pop
1		<0.35	5	6%
2		0.35–0.7	2	3%
3		0.7–1.5	3	4%
4	0.5-1		2	3%
5	1-5		2	3%
6	5-10		4	5%
7	10-20		0	0%
8	20-30		0	0%
9	30-40		0	0%
10	40-50		0	0%
11	50-60		0	0%
12	60-80		3	4%
13	80-100		3	4%
14	100-120		10	13%
15	120-140		12	15%
16	140-160		15	19%
17	160-180		8	10%
18	180-200		8	10%
19	>200		2	3%

Figure 4: Population distribution of trees located during the study as represented by categories specified in Table 1, n=79.

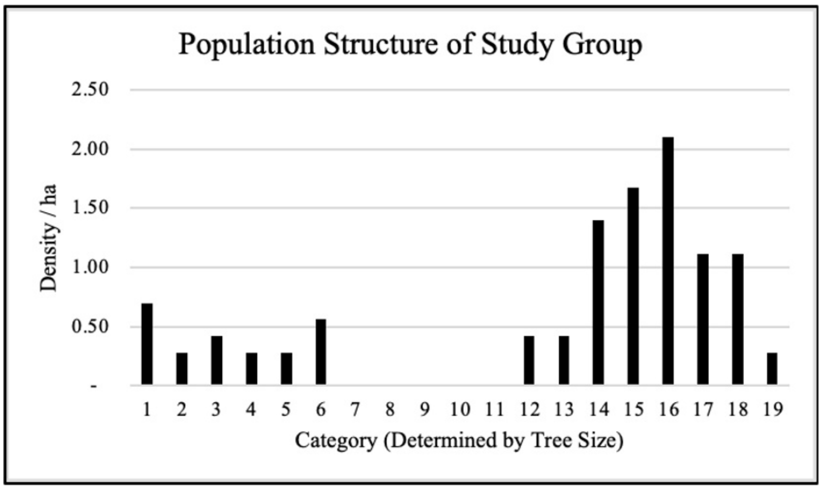
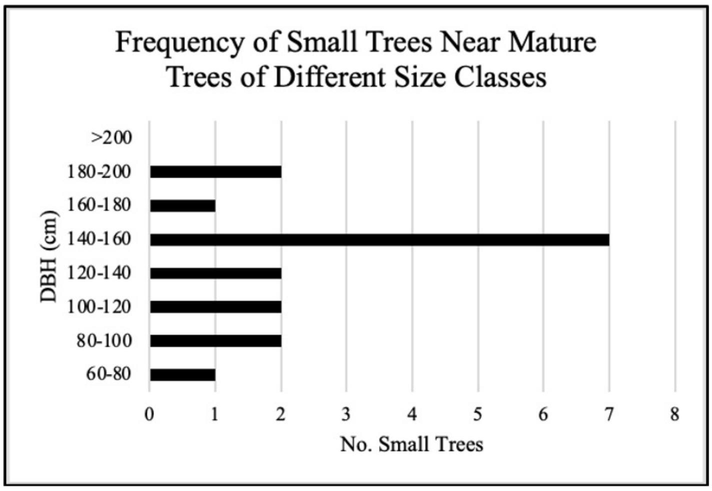


Figure 5: The number of small trees (defined as seedlings and saplings together), n=17 found near reproductive trees of differing DBH. One sapling was excluded from the dataset because its nearest neighbor was located outside of the surveyed area (see *Nearest Neighbor Analysis* in Methodology for more information).



Spatial Distribution Pattern Analysis

The results of the spatial distribution pattern analysis by using Ripley's K-function on each of the datasets is shown in Figure 6. In all cases all observed K-function plots are equal with or above the expected K-functions of the data points that follow Poisson distribution under the conditions of CSR. This means that all plots indicate that the observed distribution of trees is more clustered than would be expected under conditions of CSR. The results of the Monte Carlo hypothesis test are shown in Figure 7.

We can see that the data becomes more significant as the distance increases. The significance envelope plots for each of the datasets created from CSR simulations are shown in Figure 8. The plot for mature trees only, and the plot for all trees both indicate that at least some of the K-function plot exists outside the bounds of the significance envelope. In the middle plot for seedlings and saplings only, we can see that the black K_{obs} line does not leave the grey band as the band is much larger.

Figure 6: Ripley's K-function plot for all trees, mature trees only, and seedlings and saplings only. In all plots, the light blue dotted-line K_{pois} is the K-function calculated for data points that follow a Poisson distribution under the assumption of complete spatial randomness (CSR). K_{iso}, K_{trans}, and K_{bord} are all calculated K-functions for the observed data, each with a different edge-effect correction applied.

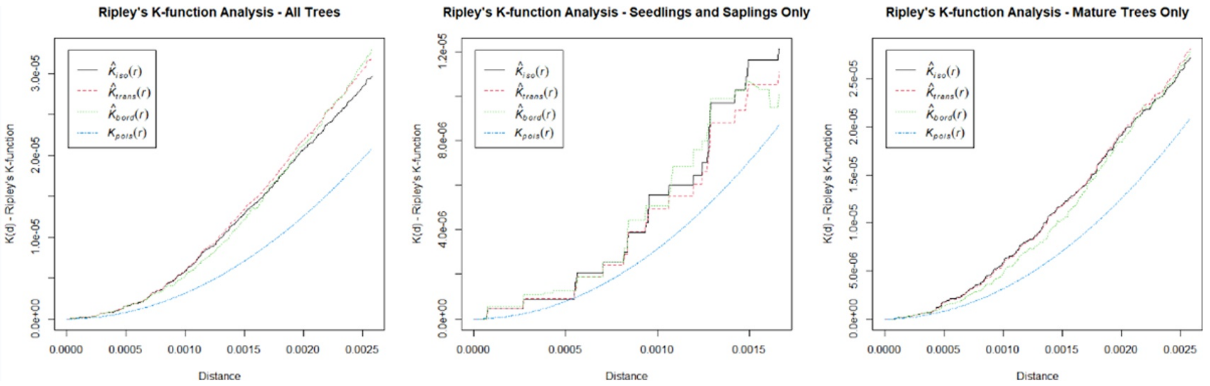


Figure 7: A plot of the calculated P-values for each of the distance-pairs (r) within the datasets for all trees, and seedlings and saplings only.

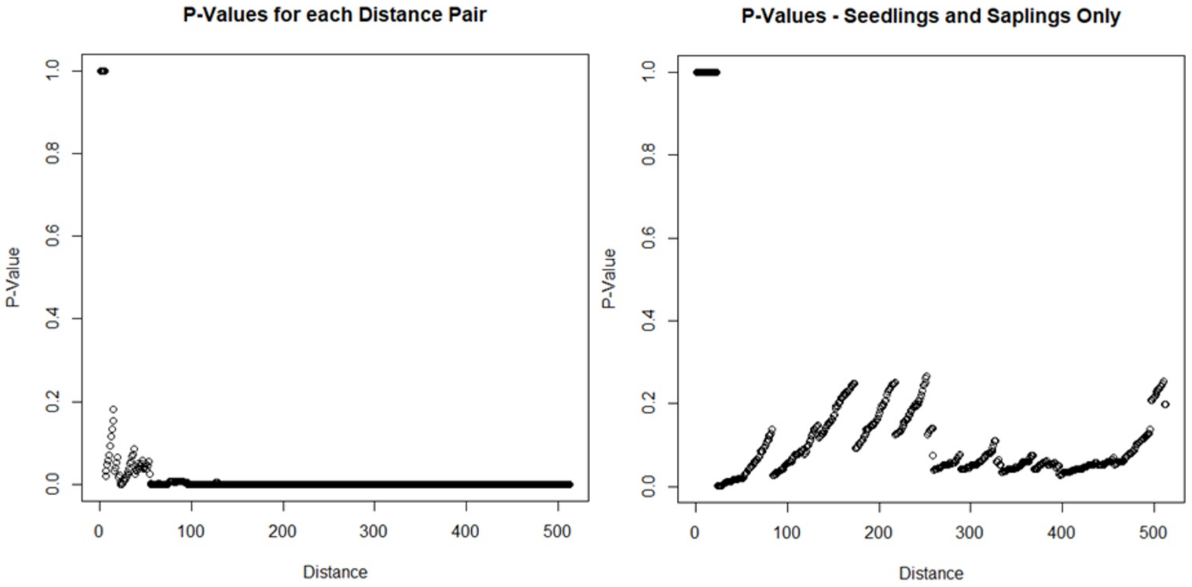


Figure 8: A plot of the K-functions for each of the observed datasets. In each plot, the grey band signifies the significance envelope generated from the CSR simulations, and the solid-black line is K_{obs} which is the average K-function of that dataset for each distance-pair (r). There are no edge-correcting calculations applied to this data. The red-dotted line represents K_{theo}, calculated for data that follows a Poisson distribution under the assumption of CSR.

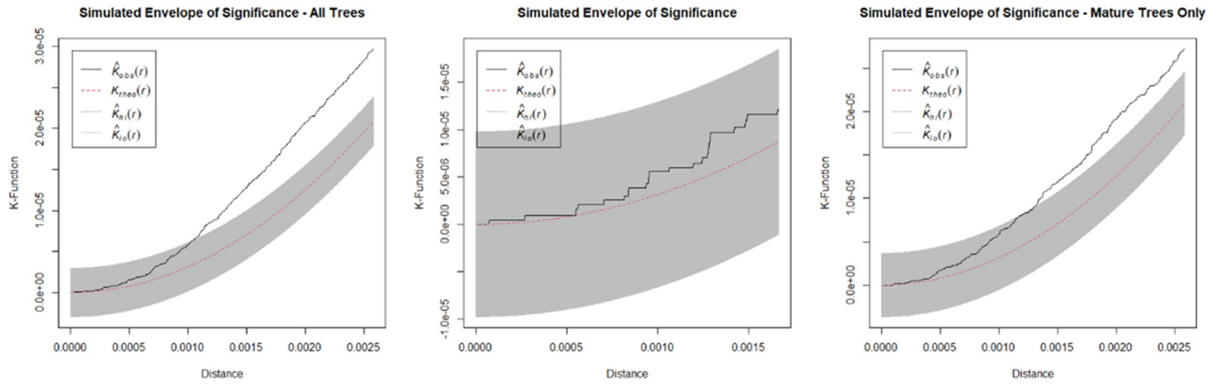
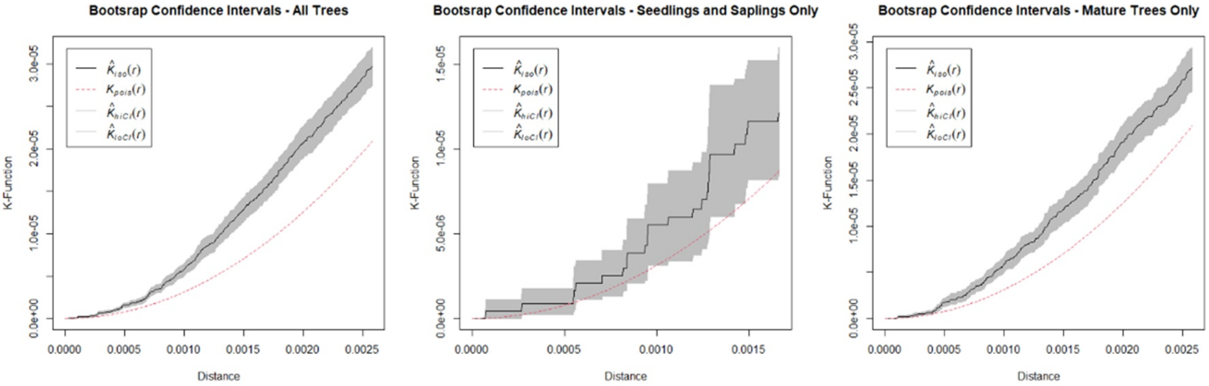


Figure 9: A plot of the K-functions for each of the observed datasets. In each plot, the grey band signifies the bootstrap confidence intervals calculated by the repeated resampling of the data. The solid-black line K_{iso} represents the K-function calculated for the observed data with an edge-effect corrector applied. The red-dotted line K_{pois} represents the K-function calculated from data that follows a Poisson distribution under the assumption of CSR.



The bootstrap confidence interval plots generated from the CSR simulations for all the datasets are shown in Figure 9. The mature trees and all trees' plots are very similar with only a slightly wider grey band in the mature trees plot separating them visually. Both plots indicate that the true values for the K-function lie significantly above the K_{pois} line. The seedlings and saplings plot indicates that the true K-function values for this dataset may lie on or below the K_{pois} line at selected distance pairs.

Discussion

The Brazil nut tree is a keystone species in Amazonia, due to its expansive environmental and economic importance to Peru and the broader society. Their colossal size and long lifespan ensure the species' role in biodiversity, carbon sequestration, and other invaluable ecosystem services (Rainforest Alliance, 2012). In addition, it is known as one of the most important NTFPs in the Amazonian economy, and since the establishment of the Peruvian concession system, has played an important role in rainforest conservation (Chavez and Cossio, 2014). Unfortunately, concessions are susceptible to a variety of environmental and economic issues, such as volatile market prices (Kalliola, and Flores, 2011), overlapping property rights (Willem et al., 2019), loss of genetic biodiversity (Chiriboga-Arroyo et al., 2021), climate change (Sales et al., 2021), and harvesters utilizing negative practices like agriculture, logging, and mining to supplement income outside of the harvesting season (Escobal and Aldana, 2003; Scullion et al. 2014). The combined effect of these problems threatens the sustainability of Brazil nut trees and the concessions that preserve the most biodiverse land on the planet.

Although the species has been highly researched, there are many debated and unknown topics that this study hopes to provide data for. Recent literature suggests that intensive Brazil nut harvesting does not negatively impact recruitment rates and the overall population structure, which is contradictory to a well-cited study by Peres et al., 2003 which argued that harvesting results in a population bottleneck. Anthropogenic influences are not largely understood in the context of the Brazil nut population structure, though there are some studies that suggest humans can positively impact recruitment and regeneration (see *Nut Harvest Sustainability* in Introduction).

The conflicting literature and lack of knowledge of the Brazil nut concession neighboring Finca las Piedras, land owned by the NGO Alliance for a Sustainable Amazon, influenced the decision to research this topic. This study aimed to understand the population demographics of a heavily harvested Brazil nut concession near Monterey, Peru, determine the sustainability of said population, understand the spatial distribution pattern of the trees, and compare the collected data to recent research.

Sustainability Status of the Observed Population

The population structure of the study is dominated by larger trees, has a low density of seedlings, and contains no juvenile trees. This varies greatly from that of a healthy Brazil nut population, where size class distribution roughly follows a reverse-J curve and has a large representation of small trees (Wadt et al., 2008). In addition, this study found a high percentage (23%) of old trees (>160 cm DBH), presenting a sustainability concern for the population. In a study that compared juveniles and mature trees of different sizes, trees >120 cm DBH were the most likely to die. When looking at trees in this category, 57% of the observed population was found to be >120 cm DBH and therefore at a heightened risk of mortality due to wind, storm, fire, and liana infestation (Bertwell et al., 2018). Seedlings in their first year of growth are also highly susceptible due to endosperm predation by mammals (Zuidema and Boot, 2002). This is also problematic for the study group since seedlings comprise a small portion of the data collected (10% of the population and 1.4 trees/ha) and have much lower rates than any other published literature on Brazil nuts to these authors' knowledge (See Table 1 in Appendix). In the long term, low seedling recruitment can be an indicator of a negatively affected population, whereas population stability can be determined by the survival of adults and saplings. Since Brazil nut trees require between 73 and 100+ years (variance is due to differing measurement methods) to reach maturity, the conservation of pre-reproductive and mature trees should be prioritized in the sampled concession to promote sustainable forest use (Zuidema and Boot, 2002; Bertwell 2018). However, since the total sample size was 7.16 ha, this might not be a large enough area to determine if the juvenile population is inadequate; only 1 juvenile individual per ha is expected in Brazil nut populations (Rockwell et al., 2017). Regardless, there was still a low density of seedlings and a large percentage of old mature trees which suggests the analyzed population is at risk of a demographic crash.

Spatial Distribution Pattern

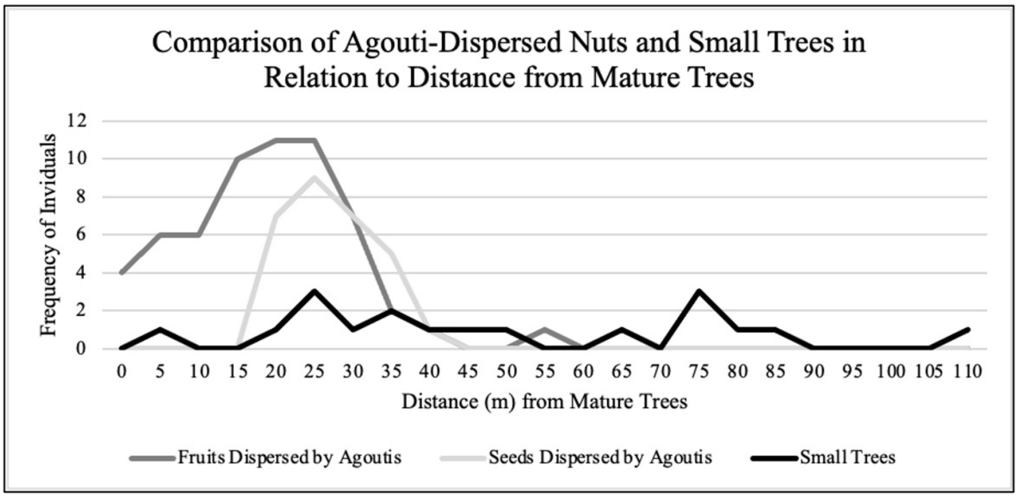
For the spatial analyses of this study, we examined the clustering patterns for each observed dataset of Brazil nut (*Bertholletia excelsa*) trees in a concession in the Madre de Dios region of Peru. The current consensus on the spatial distribution pattern of the species is centered around the occurrence of mature trees in stands or groves (Rockwell et al., 2017). In this study we set out to confirm and corroborate these findings. Whilst the occurrence patterns of these trees are well documented, the reasons for these observed groves are not completely clear. Currently, it is thought that this distribution is due to a complicated mixture of both biophysical and anthropogenic factors (Scoles and Gribel, 2011). A better understanding of the distribution of these trees, especially in over-harvested land such as concessions, could be instrumental in the improvement of our knowledge of the interplay between these complex factors. As shown in Figure 6, we can see that for each of the groups of trees, the observed K-function is consistently larger than what would be expected of data that follows a Poisson distribution under the assumption of CSR. This is indicative of a greater degree of clustering than would be expected by chance. From our Monte Carlo hypothesis testing, in Figure 7, we can see that the observed p-value for each distance pair becomes increasingly significant as the distance between points (r) increases, for all trees. In fact, we can see that the top 95% of p-values are below 0.05 and therefore statistically significant. This pattern can also be observed in all of our K-function plots. The distance between the observed K-function line and the K_{pois} line increases as distance (r) also increases. This pattern implies that the clustering is not uniform across all distances. Specifically, it suggests the presence of long-distance clusters that exist over larger scales, which is indicative of hierarchical clustering. This phenomenon usually stems from smaller clusters that aggregate into large ones and is typical of the Brazil nut tree distribution (Mori and Prance, 1990). However, in Figure 7 we can also see that the p-values for seedlings and saplings only do not exhibit the same pattern.

In Figure 8 we can see the calculated envelopes of significance for our simulated data points. The envelope signifies the range in which 95% of the simulated tree populations' K-functions lie, meaning that any observed data out of this range can be considered statistically significant. For all trees, and mature trees only, we can see that much of the observed data lies outside of the significance envelope. This falls in line with the observed p-values that we calculated from the Monte Carlo simulations and agrees that the data points are significantly clustered. We can see in the middle plot for seedlings and saplings only that the K-functions lie within the significance envelope due to the larger area of the grey-band. This larger band is likely due to the smaller sample size of the dataset with only 18 seedlings and saplings found compared to the 80 trees found overall. This small sample size means that we can't make any statistically significant conclusions about the clustering of the smaller trees. In Figure 9 we can see the calculated confidence intervals for our data. The confidence intervals represent the area in which we can be 95% certain that our K-functions lie, considering the sample size. In our data we can see that, again, for all trees and mature trees only, the grey bands do not overlap with any other lines. This means that we can be sure that our observed K-values lie above the K_{pois} line, and our clustering is significant.

Comparing Agouti Behavior to Small Tree Nearest Neighbor Data

The distance from each small tree to the closest mature tree was compared to a study that analyzed agouti dispersal distance for fruits and seeds that traveled inside and outside the fruit. The distance of nuts carried by agoutis was normally distributed and averaged 30 m from the original position (Tuck Haugaasen et al., 2012). It was expected that small trees would follow a similar distribution but this was not the case. Data for small trees was evenly spread out, ranging from 5 m to 110 m from the nearest reproductive tree. Not only does the data lack a distribution that aligns with agouti behavior, but 39% of the small trees' distance from the nearest big tree was greater than the farthest agouti dispersed distance. This data suggests that agoutis are not responsible for the observed location of seedlings and saplings in the 7.2 ha area sampled. Similar to the results in

Figure 10: The number of agouti-dispersed fruits and seeds ('seeds' includes the distance the seed traveled inside and outside the fruit) and their corresponding distance from mature trees compared with data from this study on the number of small trees and the distance to their nearest mature neighbor. Agouti dispersal data obtained from Tuck Haugaasen et al., 2012.



this study, Porcher et al., 2018 found that recruits in high forest were 51.7 ± 31.8 m from the closest mature Brazil nut tree and believed it unlikely that agouti behavior could explain the evenly distributed data. One possible explanation for the observed patterns is human influence on the dispersal and recruitment of Brazil nut trees. One study observed indigenous Brazil nut collectors during harvesting and found they dropped a total of 34 seeds on 16% of the days they were followed (Ribeiro et al., 2014). This idea of dispersal by harvesters could explain how seeds traveled so far outside the agouti's dispersal range.

Conclusion

The observed population structure raises sustainability concerns, showing dominance of larger trees, low seedling density, and absence of juvenile trees. High percentages of old trees (>160 cm DBH) pose risks, as they are more susceptible to mortality. The causes of these results are unknown since they do not align with patterns in earlier Brazil nut studies, nor do they support current hypotheses related to nut harvesting and recruitment. Limited study size could have impacted on the results, so the study should be repeated across a larger area in Madre de Dios for more definitive results. The spatial distribution analysis indicates significant clustering, particularly hierarchical clustering, which is typical of Brazil nut tree distribution.

Comparing agouti behavior to small tree nearest neighbor data reveals that small trees' distribution does not align with agouti dispersal patterns. Instead, human influence on dispersal and recruitment is suggested, with the possibility that harvesters play a role in seed dispersal over longer distances. This finding is unique to current literature, so the relationship between Brazil nut trees, agoutis, and human harvesters should be explored in future studies.

Though there is no overarching consensus of *Bertholletia excelsa* sustainability, this study advises concession managers to analyze their Brazil nut tree population and implement conservation strategies accordingly. For the Brazil nut concession bordering Finca Las Piedras, planting and protecting immature trees should be prioritized. Additionally, further research on Brazil nut tree population demography, nut harvesting, other human-species interactions, and the role of agouti dispersal is required to best advise future conservation efforts. A comprehensive understanding of these topics will hopefully allow this keystone species to continue to protect the most biodiverse land on the planet and those that depend on it.

Works Cited

Amazon Aid Foundation (2023). *The Hydrological Cycle* [online]. Available at: https://amazonaid.org/resources/about-the-amazon/the-hydrological-cycle/.

Bertwell, T.D., Kainer, K.A., Cropper Jr, W.P., Staudhammer, C.L. and de Oliveira Wadt, L.H. (2018). Are Brazil nut populations threatened by fruit harvest?. *Biotropica*, 50(1), pp.50-59.

Chavez, A.B. and Cossio, R.E. (2014). Linking national forestry reform through forest concession policy and land cover change. *Small-scale forestry*, 13(3), pp.349-366.

Chiriboga-Arroyo, F., Jansen, M., Bardales-Lozano, R., Ismail, S.A., Thomas, E., García, M., Corvera Gomringer, R. and Kettle, C.J. (2021). Genetic threats to the Forest Giants of the Amazon: Habitat degradation effects on the socio-economically important Brazil nut tree (*Bertholletia excelsa*). *Plants, People, Planet,* 3(2), pp.194-210.

Da Costa, K.C.P., de Carvalho Gonçalves, J.F., Gonçalves, A.L., da Rocha Nina Junior, A., Jaquetti, R.K., de Souza, V.F., de Carvalho, J.C., Fernandes, A.V., Rodrigues, J.K., de Oliveira Nascimento, G. and de O. Wadt, L.H. (2022). Advances in Brazil nut tree ecophysiology: Linking abiotic factors to tree growth and fruit production. *Current Forestry Reports*, 8(1), pp.90-110.

De Oliveira Wadt, L.H., Faustino, C.L., Staudhammer, C.L., Kainer, K.A. and Evangelista, J.S. (2018). Primary and secondary dispersal of *Bertholletia excelsa*: Implications for sustainable harvests. *Forest Ecology and Management*, 415, pp.98-105.

en.climate-data.org. (n.d.). Puerto Maldonado climate: Temperature Puerto Maldonado & Weather By Month [online]. Available at: https://en.climate-data.org/south-america/peru/madre-de-dios/puerto-maldonado-27856/#google_vignette [Accessed 23 Aug. 2023].

Escobal, J. and Aldana, U. (2003). Are nontimber forest products the antidote to rainforest degradation? Brazil nut extraction in Madre De Dios, Peru. *World Development*, 31(11), pp.1873-1887.

Fauset, S., Johnson, M.O., Gloor, M., Baker, T.R., Monteagudo M, A., Brienen, R.J., Feldpausch, T.R., Lopez-Gonzalez, G., Malhi, Y., Ter Steege, H. and Pitman, N.C. (2015). Hyperdominance in Amazonian forest carbon cycling. *Nature communications*, 6(1), pp.1-9.

Guariguata, M.R., Cronkleton, P., Duchelle, A.E. and Zuidema, P.A. (2017). Revisiting the 'cornerstone of Amazonian conservation': a socioecological assessment of Brazil nut exploitation. *Biodiversity and Conservation*, 26, pp.2007-2027.

Kalliola, R. and Flores, P., (2011). Brazil nut harvesting in Peruvian Amazonia from the perspective of ecosystem services. *Fennia-International Journal of Geography*, 189(2), pp.1-13.

Lutz, J.A., Furniss, T.J., Johnson, D.J., Davies, S.J., Allen, D., Alonso, A., Anderson-Teixeira, K.J., Andrade, A., Baltzer, J., Becker, K.M. and Blomdahl, E.M. (2018). Global importance of large-diameter trees. *Global Ecology and Biogeography,* 27(7), pp.849-864.

Maués, M.M. (2002). Reproductive phenology and pollination of the Brazil nut tree (*Bertholletia excelsa Humb. & Bonp*l. *Lecythidaceae*) in Eastern Amazonia. *Pollinating bees: the conservation link between agriculture and nature*, 245.

Nicolau, A.P., Herndon, K., Flores-Anderson, A. and Griffin, R. (2019). A spatial pattern analysis of forest loss in the Madre de Dios region, Peru. *Environmental Research Letters,* 14(12), p.124045.

Nunes, F., Soares-Filho, B., Giudice, R., Rodrigues, H., Bowman, M., Silvestrini, R. and Mendoza, E. (2012). Economic benefits of forest conservation: assessing the potential rents from Brazil nut concessions in Madre de Dios, Peru, to channel REDD+ investments. *Environmental Conservation,* 39(2), pp.132-143.

Peres, C.A., Baider, C., Zuidema, P.A., Wadt, L.H., Kainer, K.A., Gomes-Silva, D.A., Salomão, R.P., Simões, L.L., Franciosi, E.R., Cornejo Valverde, F. and Gribel, R. (2003). Demographic threats to the sustainability of Brazil nut exploitation. *Science*, 302(5653), pp.2112-2114.

Porcher, V., Thomas, E., Gomringer, R.C. and Lozano, R.B. (2018). Fire-and distance-dependent recruitment of the Brazil nut in the Peruvian Amazon. *Forest Ecology and Management,* 427, pp.52-59.

Rockwell, C.A., Guariguata, M.R., Menton, M., Quispe, E.A., Quaedvlieg, J., Warren-Thomas, E., Silva, H.F., Rojas, E.E.J., Arrunátegui, J.A.H.K., Vega, L.A.M. and Hancco, R.Q. (2017). Spatial distribution of *Bertholletia excelsa* in selectively logged forests of the Peruvian Amazon. *Journal of Tropical Ecology,* 33(2), pp.114-127.

Ribeiro, M.B.N., Jerozolimski, A., de Robert, P., Salles, N.V., Kayapó, B., Pimentel, T.P. and Magnusson, W.E. (2014). Anthropogenic landscape in southeastern Amazonia: contemporary impacts of low-intensity harvesting and dispersal of Brazil nuts by the Kayapó Indigenous people. *PloS one*, 9(7), p.e102187.

Sales, L.P., Rodrigues, L. and Masiero, R. (2021). Climate change drives spatial mismatch and threatens the biotic interactions of the Brazil nut. *Global Ecology and Biogeography*, 30(1), pp.117-127.

Schöngart, J., Gribel, R., Ferreira da Fonseca-Junior, S. and Haugaasen, T. (2015). Age and growth patterns of Brazil nut trees *(Bertholletia excelsa Bonpl.*) in Amazonia, Brazil. *Biotropica*, 47(5), pp.550-558.

Scoles, R. and Gribel, R. (2011). Population structure of Brazil nut (*Bertholletia excelsa, Lecythidaceae*) stands in two areas with different occupation histories in the Brazilian Amazon. *Human Ecology,* 39, pp.455-464.

Scoles, R. and Gribel, R. (2012). The regeneration of Brazil nut trees in relation to nut harvest intensity in the Trombetas River valley of Northern Amazonia, Brazil. *Forest Ecology and Management,* 265, pp.71-81.

Scoles, R. and Gribel, R. (2015). Human

Influence on the Regeneration of the Brazil Nut Tree (*Bertholletia excelsa Bonpl., Lecythidaceae*) at Capanã Grande Lake, Manicoré, Amazonas, Brazil. *Human Ecology,* 43, pp.843-854.

Scullion, J.J., Vogt, K.A., Sienkiewicz, A., Gmur, S.J. and Trujillo, C. (2014). Assessing the influence of land-cover change and conflicting land-use authorizations on ecosystem conversion on the forest frontier of Madre de Dios, Peru. *Biological Conservation*, 171, pp.247-258.

Silvertown, J. (2004). Sustainability in a nutshell. *Trends in Ecology & Evolution*, 19(6), pp.276-278.

Tuck Haugaasen, J.M., Haugaasen, T., Peres, C.A., Gribel, R. and Wegge, P.. (2012). Fruit removal and natural seed dispersal of the Brazil nut tree (*Bertholletia excelsa*) in Central Amazonia, Brazil. *Biotropica*, 44(2), pp.205-210.

Wadt, L.D.O., Kainer, K.A., Staudhammer, C.L. and Serrano, R.O.P. (2008). Sustainable forest use in Brazilian extractive reserves: natural regeneration of Brazil nut in exploited populations. *Biological Conservation*, 141(1), pp.332-346.

Willem, H.V., Ingram, V.J. and Guariguata, M.R. (2019). Brazil nut forest concessions in the Peruvian Amazon: success or failure?. *International Forestry Review,* 21(2), pp.254-265.

Zuidema, P.A. and Boot, R.G. (2002). Demography of the Brazil nut tree (*Bertholletia excelsa*) in the Bolivian Amazon: impact of seed extraction on recruitment and population dynamics. *Journal of Tropical Ecology,* 18(1), pp.1-31.

Zuidema, P.A. (2003). Ecology and management of the Brazil nut tree (*Bertholletia excelsa*). *Promab*.

Appendix

Figure 11: Number of Brazil nut trees per general size class in the observed population.

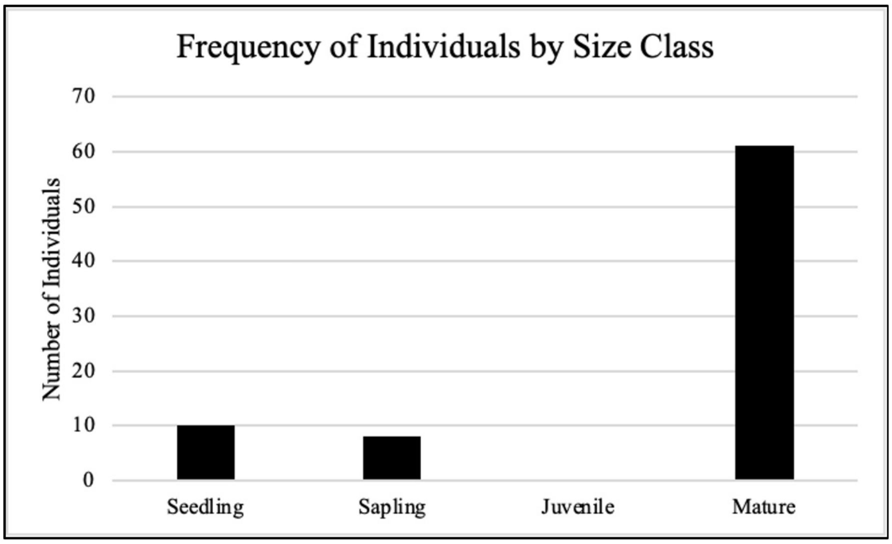


Figure 12: Number of individuals per category as described in Table 1 under *Population Structure of the Study Group*.

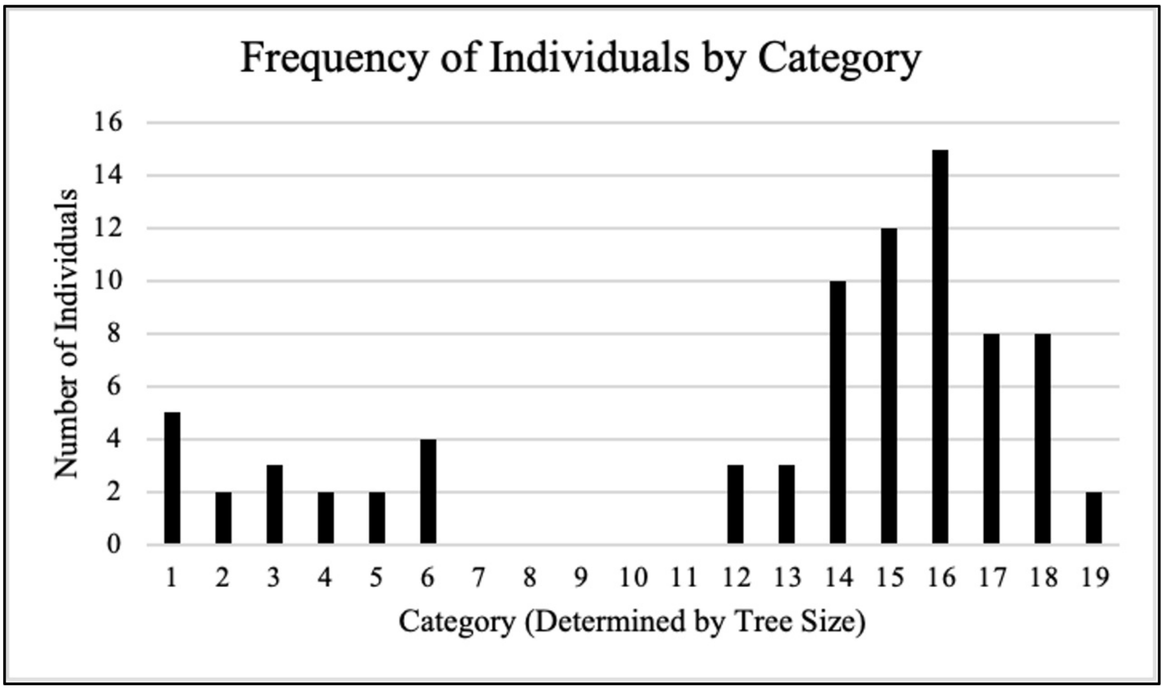


Figure 13: Small trees (saplings represented by red pins, seedlings represented by yellow pins) with lines to the nearest three mature trees. Tree 80 (white pin) is located on Finca Las Piedras land and was not surveyed but was included in the nearest neighbor analysis to avoid skewing results.

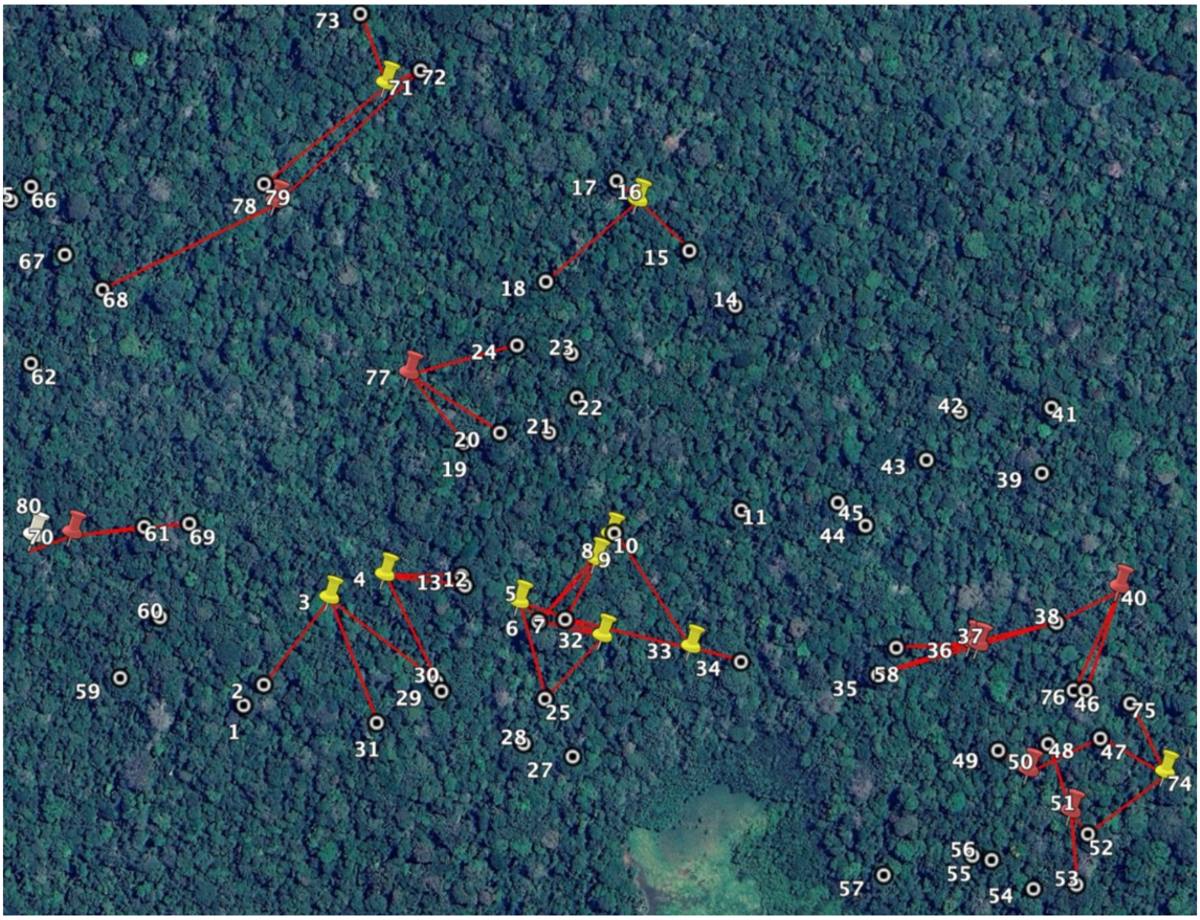
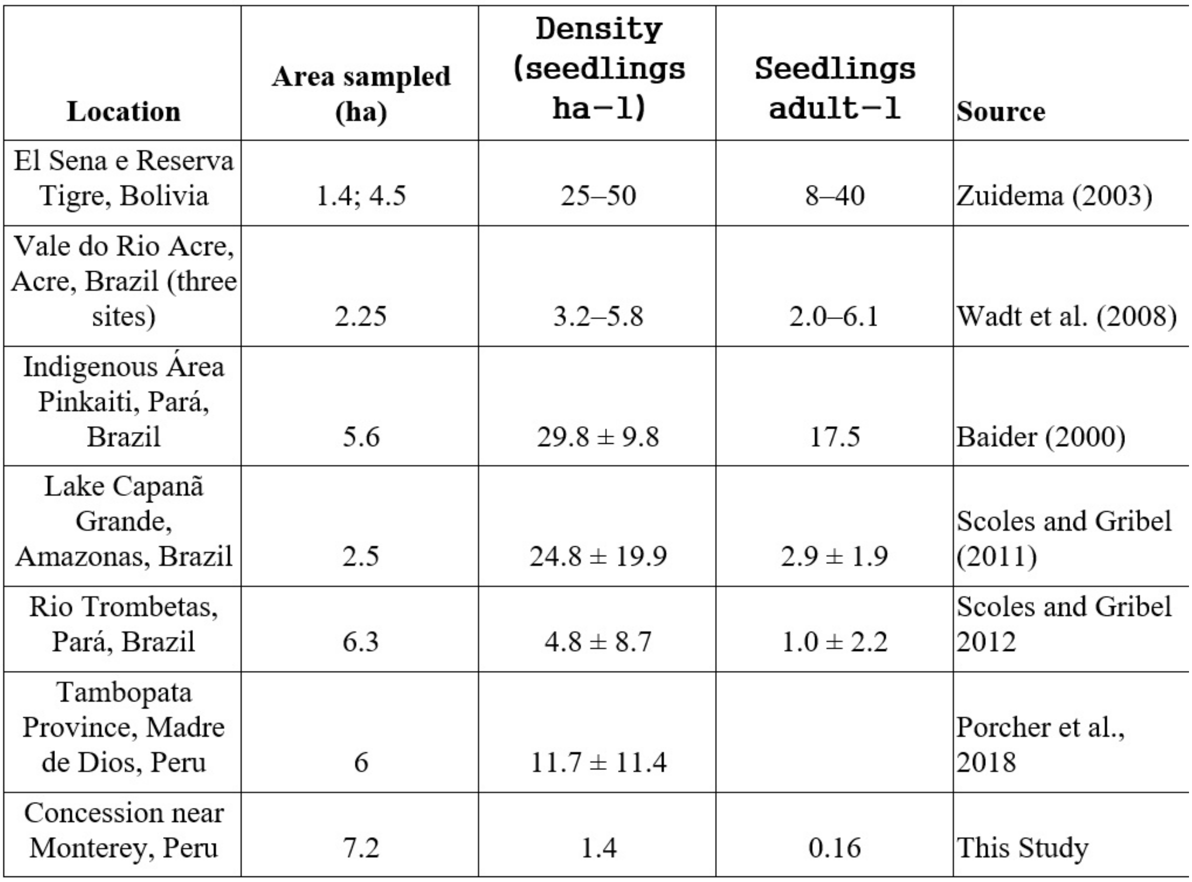


Table 2: Seedling density and number of seedlings per adult tree. Data obtained from Scoles and Gribel 2015.



Location	Area sampled (ha)	Density (seedlings ha−1)	Seedlings adult−1	Source
El Sena e Reserva Tigre, Bolivia	1.4; 4.5	25–50	8–40	Zuidema (2003)
Vale do Rio Acre, Acre, Brazil (three sites)	2.25	3.2–5.8	2.0–6.1	Wadt et al. (2008)
Indigenous Área Pinkaiti, Pará, Brazil	5.6	29.8 ± 9.8	17.5	Baider (2000)
Lake Capanã Grande, Amazonas, Brazil	2.5	24.8 ± 19.9	2.9 ± 1.9	Scoles and Gribel (2011)
Rio Trombetas, Pará, Brazil	6.3	4.8 ± 8.7	1.0 ± 2.2	Scoles and Gribel 2012
Tambopata Province, Madre de Dios, Peru	6	11.7 ± 11.4		Porcher et al., 2018
Concession near Monterey, Peru	7.2	1.4	0.16	This Study

Table 3: Comparison of the number of trees >10 cm DBH and the percentage of juveniles for the population. Data obtained from Scoles and Gribel 2015.

Location	Area (ha)	No. trees (DBH > 10 cm)	% Juveniles	Source
Flona Saracá-Taquera, Pará, Brazil	769	815	0.7	Salomão (2009)
Resex Cajari, Amapá, Brazil	22.6	276	1.5	Baider (2000)
Forest Reserve El Tigre, Beni, Bolivia	12	152	5.9	Zuidema and Boot (2002)
River Trombetas Region, Pará, Brazil	125	850	7.4	Scoles and Gribel 2012
El Sena, Pando, Bolivia	6	161	13.1	Zuidema and Boot (2002)
Marabá, Pará, Brazil	9	38	23.7	Salomão (1991)
Resex Chico Mendes, Acre, Brazil	420	568	25.5	Wadt et al. (2005)<50
Resex Lake Capanã Grande, Amazonas, Brazil	49	609	18	Scoles and Gribel (2011)
Valley River Acre, Acre, Brazil	108	224	31.3	Wadt et al. (2005)<50
Nova Esperança, Acre, Brazil	51	161	40	Viana et al. (1998)
Indigenous Area Pinkaiti, Pará, Brazil	60	224	43.3	Baider (2000)<60
Between Puerto Maldonado and Alerta (three sites)	1414.2	1153	17.00	Rockwell et al., 2017
Concession near Monterey, Peru	7.2	61	0	This Study

Table 4: Comparison of density for trees >10 cm DBH. Data obtained from Scoles and Gribel 2015.

Location	Area (ha)	Tree Density (DBH > 10 cm)	% Juveniles
Forest Reserve El Tigre, Beni, Bolívia	12	1.7	Zuidema and Boot (2002)
Indigenous Area Pinkaiti, Pará State, Brazil	28.5	4.8	Peres and Baider (1997)
Saracá-Taquera Forest, Pará State, Brazil	203.7	5.6	Salomão (2009)
River Trombetas Region, Pará State, Brazil	125	6.8	Scoles and Gribel 2011
Cajari, Amapá State, Brazil	22.6	12.2	Baider (2000)
Lake Capanã Grande, Amazonas State, Brazil	49	12.5	Scoles and Gribel 2011
Concession near Monterey, Peru	7.2	8.52	This Study

Table 5: Tree Coordinate Data

Tree Name	Type	Longitude	Latitude
1	Mature	-69.10574	-12.22703
2	Mature	-69.10555	-12.22684
3	Seedling	-69.10492	-12.22602
4	Seedling	-69.1044	-12.22581
5	Seedling	-69.10314	-12.22606
6	Mature	-69.10297	-12.22626
7	Mature	-69.10272	-12.22624
8	Seedling	-69.10242	-12.22567
9	Mature	-69.10226	-12.22545
10	Seedling	-69.10228	-12.22544
11	Mature	-69.10107	-12.22524
12	Mature	-69.10366	-12.22593
13	Mature	-69.10369	-12.22584
14	Mature	-69.10113	-12.22337
15	Mature	-69.10156	-12.22287
16	Seedling	-69.10203	-12.22239
17	Mature	-69.10224	-12.22223

18	Mature	-69.10290	-12.22315
19	Mature	-69.10367	-12.22462
20	Mature	-69.10333	-12.22453
21	Mature	-69.10287	-12.22453
22	Mature	-69.10261	-12.22421
23	Mature	-69.10266	-12.22381
24	Mature	-69.10317	-12.22373
25	Mature	-69.10291	-12.22697
26	Mature	-69.10181	-12.23103
27	Mature	-69.10265	-12.22750
28	Mature	-69.10311	-12.22738
29	Mature	-69.10388	-12.22690
30	Mature	-69.10393	-12.22681
31	Mature	-69.10449	-12.22719
32	Seedling	-69.10236	-12.22637
33	Seedling	-69.10153	-12.22647
34	Mature	-69.10107	-12.22663
35	Mature	-69.09979	-12.22675
36	Sapling	-69.09891	-12.22643
37	Sapling	-69.09884	-12.22645
38	Mature	-69.09812	-12.22627
39	Mature	-69.09826	-12.22490
40	Sapling	-69.09752	-12.22592
41	Mature	-69.09817	-12.22430
42	Mature	-69.09902	-12.22434
43	Mature	-69.09934	-12.22478
44	Mature	-69.09991	-12.22538
45	Mature	-69.10017	-12.22517
46	Mature	-69.09796	-12.22689
47	Mature	-69.09771	-12.22733
48	Mature	-69.09820	-12.22738
49	Mature	-69.09867	-12.22744
50	Sapling	-69.09837	-12.22760
51	Sapling	-69.09797	-12.22798
52	Mature	-69.09782	-12.22821
53	Mature	-69.09792	-12.22868

54	Mature	-69.09832	-12.22872
55	Mature	-69.09872	-12.22845
56	Mature	-69.09890	-12.22841
57	Mature	-69.09972	-12.22860
58	Mature	-69.09962	-12.22650
59	Mature	-69.10691	-12.22678
60	Mature	-69.10653	-12.22622
61	Mature	-69.10668	-12.22539
62	Mature	-69.10773	-12.22389
63	Mature	-69.10831	-12.22171
64	Mature	-69.10811	-12.22240
65	Mature	-69.10790	-12.22241
66	Mature	-69.10771	-12.22228
67	Mature	-69.10740	-12.22290
68	Mature	-69.10705	-12.22322
69	Mature	-69.10625	-12.22536
70	Sapling	-69.10735	-12.22542
71	Seedling	-69.10438	-12.22132
72	Mature	-69.10407	-12.22122
73	Mature	-69.10463	-12.22071
74	Seedling	-69.09709	-12.22762
75	Mature	-69.09743	-12.22701
76	Mature	-69.09785	-12.22689
77	Sapling	-69.10417	-12.22396
78	Sapling	-69.10541	-12.2224
79	Mature	-69.10553	-12.22226