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The evolving role of *Bertholletia excelsa* in Amazonia: contributing to local livelihoods and forest conservation

O papel em evolução de Bertholletia excelsa *na Amazônia: contribuição a modos de vida locais e conservação florestal*

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ABSTRACT: In the last three decades, Brazil nut (Bertholletia excelsa) has emerged as a cornerstone species for Amazonia. This has gone hand-in-hand with the creation of extractive reserves, an alternative land use model to balance biodiversity conservation with rural development, whereby traditional forest residents are assigned legal responsibility for co-management of these reserves and their resources, including Brazil nut. The essential role of this species in conservation and local livelihoods has precipitated a shift from general exploitation to more conscious, intensive management. Drawing heavily on our more than 25 years of research in the Brazilian state of Acre and the larger body of B. excelsa research across the Amazon basin, we ask: (1) Are Brazil nut harvests sustainable in terms of fruit production patterns and resilience to nut (seed) collection? (2) In what ways might production be augmented and nut quality enhanced? We highlight that scientific evidence and local knowledge indicate that current levels of nut harvests are compatible with sustaining populations of B. excelsa and its key seed disperser, Dasyprocta spp. Rather than concentrating on the fate of most seeds produced, the more pressing risk to B. excelsa populations is survival of existing large trees. Moreover, ample knowledge indicates possible futures to increase productivity by protecting and improving conditions of these large trees. Cutting lianas from host tree crowns dramatically improves productivity over time. Additional promising ways to grow Brazil nut-rich forests include: (1) Search and map previously unharvested productive trees located beyond traditional collection trails, (2) Tend new recruits, particularly in abandoned swidden fallows, and (3) Conduct enrichment plantings to establish small-scale intensive groves. Upgraded drying, storage and processing have led to dramatic improvements in nut quality and market access over the last 30 years. The growing knowledge base and diverse management interventions examined help promote Brazil nut sustainability and maintain its critical role in conserving Amazonian forests.

Keywords: Brazil nut; extractivism; sustainable use.

RESUMO: Nas últimas décadas, a castanheira (Bertholletia excelsa) tem emergido como uma espécie chave para a Amazônia. Este reconhecimento foi acompanhado pela criação de reservas extrativistas, um modelo alternativo de uso da terra para combinar conservação da biodiversidade com desenvolvimento rural, no qual os extrativistas residentes nas florestas são responsáveis pela cogestão dessas reservas e seus recursos, incluindo a Castanha do Brasil. Baseando-se em mais de 25 anos de pesquisa no Estado do Acre e um conjunto maior de pesquisas sobre B. excelsa em toda a bacia Amazônica, perguntamos: (1) a Castanha do Brasil é sustentável em termos de padrões de produção de frutos e resiliência à coleta das sementes? (2) de que forma a produção pode ser aumentada e a qualidade da castanha melhorada? Destacamos que com base em evidências científicas e no conhecimento local, os níveis atuais de coleta são compatíveis com a manutenção das populações de castanheiras e de seu principal dispersor de sementes, Dasyprocta spp. O maior risco para as populações de B. excelsa não está no destino da maioria das sementes produzidas, e sim na sobrevivência das árvores grandes já existentes. Além disso, um amplo conhecimento indica que proteger e melhorar a condição das castanheiras grandes pode aumentar a produtividade do castanhal. O corte de cipós presentes nas copas das castanheiras melhora drasticamente a produtividade ao longo do tempo. Praticas extremamente promissoras de aumentar a densidade de castanheiras coletadas incluem: (1) Procurar e mapear novas árvores produtivas fora das trilhas tradicionais, (2) Cuidar de novos recrutas, particularmente em capoeiras abandonadas, e (3) Realizar plantios de enriquecimento para estabelecer pomares intensivos em pequena escala. Secagem, armazenamento e processamento levaram a melhorias na qualidade e acesso ao mercado da castanha nos últimos 30 anos. A crescente base de conhecimentos e diversas intervenções de manejo estudadas ajudam promover a sustentabilidade da produção de Castanha do Brasil, contribuindo para a manutenção do seu papel fundamental na conservação da floresta Amazônica.

Palavras-chave: Castanha-do-Brasil; extrativismo, uso sustentável

1. Introduction

In the last three decades, Brazil nut (*Bertholletia excelsa*) has emerged as a cornerstone species of the Amazonian extractive economy, providing food security and supporting livelihoods of thousands of Amazonian residents. This development has gone hand-in-hand with a dramatic increase in the recognized importance of *B. excelsa* in Amazonian forest conservation efforts. Brazil nuts are harvested almost solely in the wild from mature tropical forests, and this single species has been credited with protection of millions of hectares of intact forest in Brazil, Bolivia and Peru (Ortiz, 2002). Moreover, due to its massive size, Brazil nut trees contain a substantially disproportionate amount of carbon compared to other Amazonian species (Fauset *et al.*, 2015). Furthermore, the simultaneous creation of extractive reserves, the conceptually similar sustainable development reserves, and indigenous reserves throughout Amazonia has lent tremendous institutional weight to the argument that traditional and indigenous forest residents are legitimate co-managers of the reserves they inhabit and the resources therein, including Brazil nut. In Brazil alone, nearly half of all protected areas are designated for sustainable use by indigenous people and forest-based communities (SFB, 2017), most of which are in Amazonia and are an important part of the legacy left by rubber tapper leader Chico Mendes. Here, the essential role of *Bertholletia excelsa* in conservation, local livelihoods and regional economies has precipitated a shift from general exploitation of Brazil nut to more deliberate, intensive and sophisticated management of the entire value chain.

The overall aim of this paper is to contribute to the current understanding of the Brazil nut production system explicitly to assess a successful system of non-timber forest products, generating insights into factors that lead to sustainability (Ticktin, 2004). While our analysis will focus on the forest component of this transition, we will first provide a brief account of the changing socioeconomic and cultural context of Brazil nut exploitation, with emphasis on the last 30 years. We subsequently relate current knowledge of *B. excelsa* natural history and ecology. Then, drawing heavily on our more than 25 years of research in the Brazilian state of Acre and larger body of *B. excelsa* research across the Amazon basin, we ask: (1) Are Brazil nut harvests sustainable in terms of fruit production patterns and resilience to nut (seed) collection? (2) In what ways might production be augmented and nut quality enhanced given a changing yet consistently robust market demand and *B. excelsa*'s critical link with Amazonian conservation efforts? We conclude with final remarks on future opportunities and concerns centered on this keystone species.

2. A changing context

In the 100 years prior to the assassination of Chico Mendes in 1988, Brazil nut was the supportive economic and seasonal complement to rubber, the leading forest product extracted from wild *Hevea brasiliensis* trees. During that period, rubber production for international trade drove two massive migrations (Dean, 1987), the first from 1870 to 1920, and then again during World War II, defining peak rubber booms and interim years of less-intensive rubber production. Rubber production not only dominated the Amazonian extractive economy, it fundamentally changed property rights, labor (Hecht & Cockburn, 1989; Schmink & Wood, 2012) and human settlement patterns, particularly in the interior of the enormous river basin. Gradually, however, the harsh patronal relationship that left rubber tappers perpetually indebted to their rubber bosses gave way to a more autonomous production system, whereby subsistence agriculture was permitted (Allegretti, 1994; Barham & Coomes, 1996), along with Brazil nut collection and sale in the rainy season, the off-season for rubber tapping. By the late 1980s, however, the Amazonian rubber economy was in collapse. Federal rubber subsidies in Brazil had been removed, and prices were unstable (Vadjunic & Rocheleau, 2009). At this juncture, over half of the household income of rubber tappers near Xapurí (Acre) came from the sale of Brazil nuts (Schwartzman, 1989). The "complementary product" was becoming increasingly important in forest-based livelihoods, just as the proposal to establish extractive reserves was gaining momentum nationally and internationally (Allegretti, 1990). Proposed by rubber tappers and conceptualized to support sustainable extraction and conservation of renewable natural resources, these reserves also were designed to secure resident property rights, subsistence livelihoods and the economic base of reserve residents – the old-growth forest itself. In the Bolivian and Peruvian Amazon, extractive economies and development policies were also shifting, resulting in increased control of Brazil nut forests by local collectors (Cronkleton & Pacheco, 2010; Guariguata *et al*., 2017). *B. excelsa* began to play an increasingly important role in this interlinked conservation and sustainable development model.

Brazil nuts have enjoyed widespread and longstanding economic success in the international market. Commercial exploitation began historically in Eastern Amazonia in 1633 when the first exports were dispatched from Belem to Europe (de Souza, 1963). By the mid-1800s, Brazil nut had attained broad economic significance in the region at the mouth of the Amazon River, with exploitation expanding dramatically throughout Amazonia once ports were opened in Manaus in 1866 (de Souza, 1963). For the next century, Brazil nut commercialization largely remained in the hands of rubber bosses selling to a few trading companies in Belem that controlled processing, dominated the market, and exported almost all production to Europe and the U.S. (Clay, 1997).

This long-enduring scenario changed in the 1970s when the Brazilian government adopted policies that channelled deforestation into the Brazil nut-rich regions of eastern Amazonia (Coslovsky, 2014), transforming what was called the "Brazil nut polygon" into the "Brazil nut graveyard". While illegal to fell a Brazil nut tree, this moniker aptly depicted the burned *B. excelsa* snags that increasingly dotted the pastures of the deforested landscape (Homma, 2001). Simultaneously, Brazil experienced an extended period of economic stagnation, including currency overvaluation, which reduced export competitiveness and destabilized the Brazil nut industry (Coslovsky, 2014). In neighbouring Bolivia, this industry also was undergoing massive changes, but ones that led to dominance of the global export market, despite a clear Brazil nut policy framework to guide resource access and management (Cronkleton & Pacheco, 2010). The country had just built the first highway linking Amazonia to La Paz and was experiencing comparative macroeconomic stability and a competitive foreign exchange rate (Coslovsky, 2014). Coupled with the formalization of property rights by many Brazil nut collectors (Cronkleton & Pacheco, 2010), these factors enabled a growing private Brazil nut industry, borne out of ashes of the recently liquidated state-owned National Brazil Nut Company (*Empresa Nacional de la Castana*), to respond to more stringent European Union sanitary standards (limits on aflatoxin levels) applied to imported nuts in 1999 (Coslovsky, 2014). Brazil nuts are naturally contaminated by *Aspergillus* spp. fungi that produce aflatoxins, which can cause adverse health effects at very high concentrations (Freitas-Silva & Venâncio, 2011). The Bolivian government and producers were able to respond more quickly and effectively to these new export challenges than their Brazilian counterparts. By 2013, 77% of all Brazil nuts were processed and exported by Bolivia (Coslovsky, 2014). With the geographical shift from eastern to western Amazonia, Peru also bolstered its export focus as more than 1000 Brazil nut concessions were established, encompassing over almost one million hectares and benefiting approximately 25% of the population in Madre de Dios (Cossio-Solano *et al*., 2011). Additionally, all three countries pursued diverse types of product certification (i.e., organic, Fairtrade and Forest Stewardship Council-FSC) recognizedby the international market (Duchelle *et al*., 2014). In a nuanced Peruvian study, Quaedvlieg *et al.* (2014) demonstrated how participation in these certification schemes enhanced producer political empowerment (via greater social organization, representation, and self-confidence to effect change), yet economic empowerment was not as clearly achieved, given continued challenges to break existing hierarchical economic structures and dependencies on donor and NGO support. In response to this challenging export market, Brazil slowly turned its focus inward, targeting its more than 200 million consumers and eighth largest economy in the world (CIA, 2018). Almost ¾ of Brazil's 2016 nut harvests (total valued at US $30 million; IBGE, 2017) were traded on the domestic market (Imaflora, 2016). The net effect of these significant and diverse changes on Brazil nut harvesters has been largely positive; prices received in the forest have quadrupled in the last two decades (Wadt & Kainer, 2012), making it an increasingly more valuable forest commodity. The context of the Brazil nut economy was changing dramatically, and scientists and scholars were scrambling to keep pace and inform these changes.

Prior to this transformational period, most Brazil nut science focused on establishing plantations on large landholdings, resulting in significant findings on seed germination and seedling establishment by EMBRAPA's *Centro de Pesquisa Agropecuária do Tropical* Úmido, currently known as *Embrapa Amazônia Oriental*. These important works led to greater understanding of the potential to increase nut productivity, yet as noted by Clay (1992, p. 33), did not respond specifically to the rapidly growing interest in the role that *B. excelsa* could play in Amazonian conservation and sustainable livelihood development.

> "…nobody knows how long a Brazil nut tree lives. Nobody knows how they reproduce, the number of seeds that take root, or whether the seeds are planted by animals or Indians or simply drop to the ground. Nobody knows how many nuts an average Brazil nut tree will produce. Yet such information is needed to determine the impact of harvesting even the current levels of Brazil nuts, not to mention a project that would increase the size of the harvest."

Over the last 30 years, there has been a dramatic increase in Brazil nut scientific production that responds, at least partially, to the questions posed by Clay in 1992. A database search for scientific publications centrally focused on Brazil nut using Web of Science revealed an exponential increase in Brazil nut related publications in the last 30 years (Figure 1). Integrated scientific and local knowledge has greatly improved understanding of *B. excelsa* life history and ecology, and has informed the extent to which nut harvests are sustainable. It has revealed how current and future management might enhance productivity, and more broadly, the role Brazil nut can play in sustaining Amazonian forests and livelihoods.

3. **B. excelsa** ***life history and ecology***

Various characteristics of *B. excelsa* confer a level of resilience across the Amazonian landscape. Distribution is widespread, extending across the basin in *terra firme* (non-flooded) forests (Mori & Prance, 1990; Shepard & Ramirez, 2011). Throughout central and eastern Amazonia, clustered groves (>9 individuals ha^{-1}) of *B. excelsa* adults (≥ 40 cm diameter at breast height, dbh measured

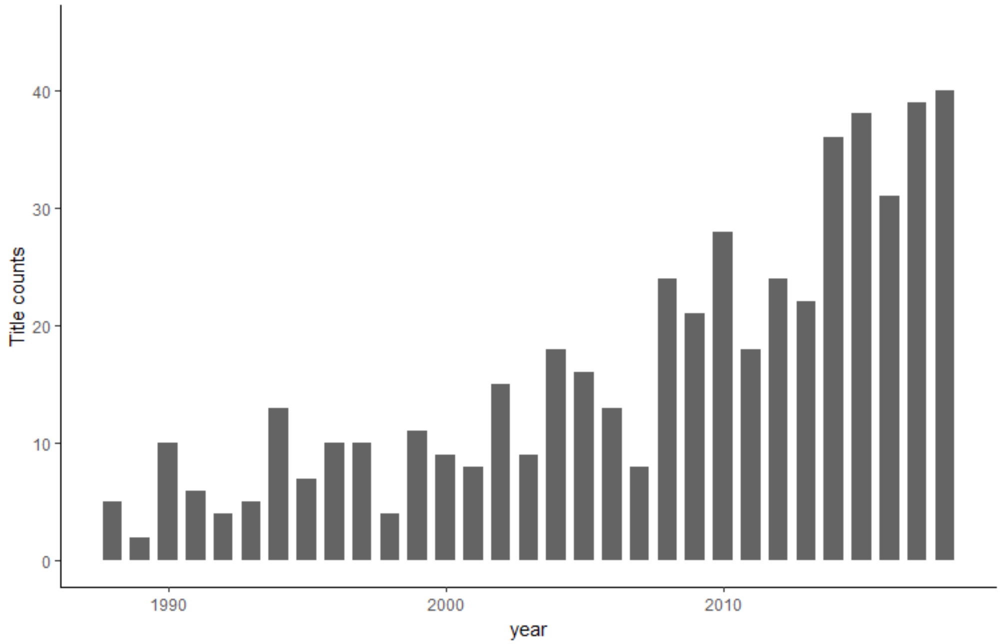

FIGURE 1 – Numbers of publications found in Web of Science searching titles containing the words “brazil nut” “Bertholletia excelsa” “B. excelsa” “Para nut” “Amazon nut” “Amazonia nut” “Amazonian nut” “brazilnut” and “castanha-do-brasil”. Abstracts were not searched in order to eliminate those papers that were not centrally focused on Brazil nut.

at 1.3 m above ground level) are reported (Scoles & Gribel, 2011), while in western Amazonia, tree distribution seems less aggregated with adult densities between 1-3 trees ha^{-1} (Zuidema & Boot, 2002; Wadt *et al*., 2005), although Rockwell *et al*. (2017) report spatial aggregations at a local scale (< 6 km^2) and lower adult densities (0.58-0.95 trees ha^{-1}) in three Peruvian sites . Brazil nut is a canopy emergent, attaining up to 50 m in height and 3 m in dbh (Zuidema, 2003). Tree-ring analyses estimate individuals of up to 400 years or older (Brienen & Zuidema, 2006; Schöngart *et al*., 2015) and radiocarbon dating suggests a maximum lifespan of over 1000 years (Vieira *et al*., 2005). While population ecology dictates that, for every large old tree that eventually dies in a forest, only one individual needs to reach reproductive maturity to replace it and maintain a stable population, this process can involve multiple release and suppression events occurring over decades (Brienen & Zuidema, 2006; Schöngart *et al*., 2015). For two populations in Acre, this process was estimated to take 167 and 83 years, respectively, with the 25-75 percentile intervals ranging between 126-200 and 64-112 years, respectively. (Bertwell *et al*., 2018). Yet in full sun, planted seedlings can initiate production within 10 years, and grafted seedlings within 3.5 years (Homma *et al*., 2014).

To better understand these Brazil nut establishment and maturation processes in forest settings, one study followed 190 trees in a *B. excelsa* population in Acre over different life stages. Staudhammer *et al.* (2013) explored the role of light, water and other factors in explaining the tradeoffs between growth and production in the species from the juvenile phase through tree senescence. Trees showed a long period of pre-reproductive height growth followed by radial growth (Figure 2). Position of trees in the canopy revealed that access to light was critical at this stage. Very few of these juvenile trees (5 cm ≤ dbh < 50 cm) produced fruits, and those that did demonstrated reduced growth, as did larger (50-100 cm dbh) reproductively mature trees. Upon reaching the canopy and attaining 100-150 cm dbh, however, fruit production peaked and these large trees with robust girth and tall stems that rose above most others seemed to have the structural support to both produce and grow well. No tradeoffs between radial growth and fruit production were observed, meaning that at this stage, growth and fruit production seem to be independently influenced by other abiotic (i.e., rainfall, nutrient availability) and biotic (e.g. genetic makeup, lianas) factors (Figure 3). As trees matured and senescence set in, fruit production was not as high in trees larger than 150 cm dbh, despite greater girth.

Brazil nuts (botanically seeds) are protected from most predators within a heavy globose woody fruit that averages ~700 g, but can vary between ~500 to 1500 g (Fernandes, 2007; Camargo *et al.*, 2010; Sujii *et al.,* 2013). These fruits are indehiscent and have a small opercular opening, causing the 10-25 sizeable seeds to remain inside the fruit when it falls from the tall trees. Fruitfall is fairly synchronized across the basin [although see Tonini (2011) results from Roraima] over an

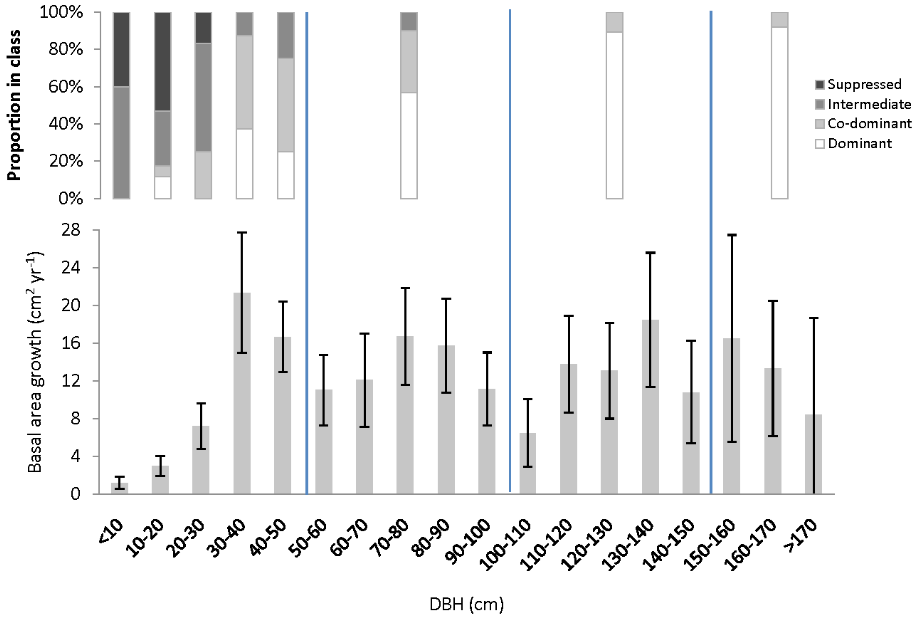

FIGURE 2 – Annual basal area growth rates (mean ± standard error; SE) of *B. excelsa* trees (n = 190) by diameter class and corresponding proportion of individuals in each class in four categories of canopy position. DBH Diameter at breast height.

SOURCE: Staudhammer *et al.* (2013), Figure 1.

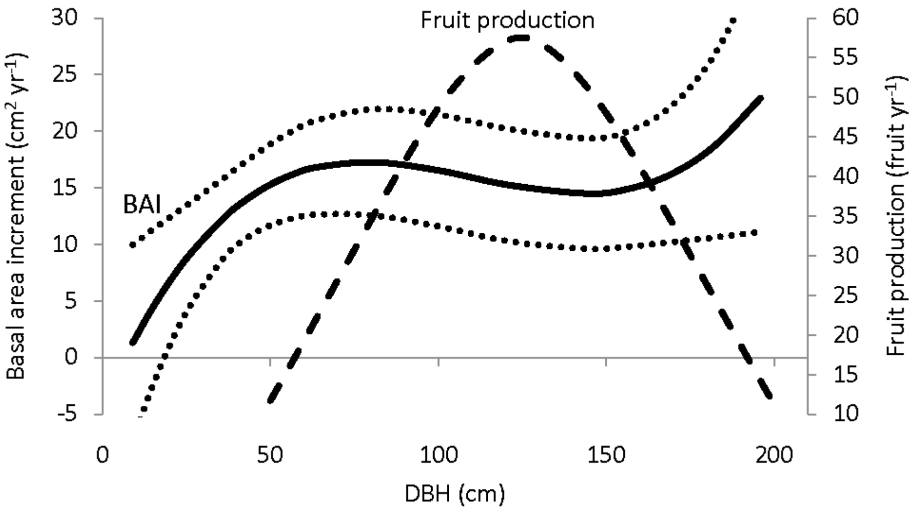

FIGURE 3 – Model of basal area increment (BAI; continuous line with 95 % confidence intervals) and annual fruit production (dashed line) of *B. excelsa* trees (n = 190) by tree diameter. DBH=Diameter at breast height.

SOURCE: Staudhammer *et al.* (2013), Figure 3.

approximate 3- to 4-month period during the rainy season (Campos *et al.*, 2013; Wadt *et al.*, 2018). The agouti (*Dascyprocta* spp.) is the key Brazil nut seed disperser (Peres & Baider, 1997), with much speculation about the role of dispersal by pre-Columbian indigenous populations in shaping current Brazil nut population distributions (Thomas *et al.*, 2015). Life history characteristics and behavioural patterns of the scatterhoarding *Dasyprocta* spp. greatly facilitate *B. excelsa* recruitment, and make this medium-sized rodent adaptable and resistant to ongoing anthropogenic activities. Scatterhoarders store seeds in spatially-scattered caches (Vander Wall, 1990), which serve to move seeds away from the parent tree with which it could potentially compete (Janzen, 1970). In addition to consuming the nutrient-rich Brazil nut seeds, *Dasyprocta* spp. habitually bury them below the soil surface, which can minimize robbery from food competitors (Galvez *et al.*, 2009) and importantly, greatly facilitates germination of forgotten seeds (Forget, 1990). *Dasyprocta* spp. can also move Brazil nut fruits well beyond individual trees, preferentially to areas of tangled vegetation (Haugaasen *et al.*, 2012), where they can remain relatively hidden while gnawing fruits. The dense regenerating vegetation formed when patches of forest are cut and burned for shifting cultivation also provides agouti cover. Indeed, in forest fallows formed by shifting cultivation in Acre, Cotta *et al.* (2008) observed that densities were two and four times greater for Brazil nut seedlings (<1.5 m height) and saplings (1.5 m height and < 10 cm dbh) respectively, than in mature forest. Although less dramatic, greater sapling densities were also observed in fallows in the Cajarí Extractive Reserve in Amapá (Guedes *et al.*, 2014).

Brazil nut harvesters report that agoutis preferentially bury Brazil nut seeds and even whole fruits in young fallows to avoid predator detection and due to the ease with which these rodents can work on the already loosened soil. *Dasyprocta* spp. not only seem well-adapted to use both forest and fallow habitats, they are, like all rodents, fast-reproducing (Naughton-Treves *et al*., 2003), permitting perhaps greater persistence in areas such as sustainable use reserves where hunting and anthropogenic disturbance are important components of the landscape. Nonetheless, *Dasyprocta* spp and humans compete intensively for Brazil nut fruits/seeds, causing concern regarding effects of this competition on *B. excelsa* recruitment and population persistence, as well as agouti behaviour and survival.

4. Are Brazil nut harvests sustainable?

This critical question has been posed for decades. Whether harvesters leave enough *B. excelsa* seeds in the forest to germinate and develop into adults is difficult to answer definitively. Outcomes depend on reproductive output of adult trees, frequency and intensity of harvest, and whether *Dasyprocta* spp. are actively facilitating seedling recruitment. Moreover, multiple interacting factors drive these three key proximate variables, including rainfall patterns, anthropogenic activities such as hunting and agriculture, and Brazil nut market prices.

How many fruits, and with what consistency, do Brazil nut trees produce? At the landscape and perhaps basin level, a more or less consistent supply of Brazil nuts over years and decades has certainly contributed to the high commercial success of this forest product. At the population level, however, research in Bolivia (Zuidema, 2003), Peru (Rockwell *et al*., 2015), Acre (Kainer *et al*., 2007; Kainer *et al*., 2014) and Roraima, Brazil (Tonini & Pedroso, 2014) clearly demonstrate that fruit production varies by year. At the individual tree level, the number of fruits produced each year can also vary, and dramatically (Zuidema, 2003; Kainer *et al*., 2014), suggesting that data from multiple years is necessary when studies intend to capture the effects of variables or experimental treatments on individual tree production. For example, production data from 2002-2012 revealed that individual trees had an average production range of 164 fruits per year (Kainer *et al*., 2014), and in any given year approximately 27% of trees produced 75% of the total population production. More recent data, however, comparing two populations ~30 km distant revealed differences between the two regarding variation in individual fruiting levels, variability at the population level, and differences in the degree to which individual levels of fruiting are synchronous across the population (unpublished data). Identified drivers of fruit production variation include total and timing of annual rainfall and tree diameters (Zuidema, 2003; Kainer *et al*., 2007), soil variables and liana loads in the crowns of producing trees (Kainer *et al*., 2007), as well as elevation (Zeidemann *et al*., 2014). Crown variables (e.g., better crown position and form) are also positively associated with higher fruit production (Zuidema, 2003; Kainer *et al*., 2007; Tonini *et al*., 2008; Kainer *et al*., 2014; Rockwell *et al*., 2015). Indeed, the prominence of crown size in fruit production was quantified by holding diameter fairly constant (by isolating those trees in the most productive 100-150 cm dbh class) and examining 60 trees over seven years in Acre (Staudhammer *et al*., 2013). Trees that produced very high numbers of fruits (>300 fruits tree^{-1} year^{-1}) had enormous crowns that were almost twice as expansive as those that produced very low numbers (<5 fruits tree^{-1} year^{-1}), presumably because crown size influences photosynthetic capacity, potential carbohydrate production and structural support for fruit production. Finally, that reduced and delayed rainfall results in lower *B. excelsa* productivity is disquieting, given that increased moisture stress is a dominant feature of models predicting future Amazonian climate scenarios (Cox *et al*., 2008).

The concern that humans are removing nuts (the very seeds that sustain a population) from the forest is valid. Indeed, this oft-articulated worry is amplified because Brazil nut seedlings are naturally at low densities in mature forests, and even veteran Brazil nut collectors often have difficulty in accurate *B. excelsa* seedling identification. The matter on whether or not nut harvests have been too intense has been keenly debated, and answers have been pursued scientifically. At a basin-wide scale, a meta-analysis by Peres *et al*. (2003) that drew on data collected by diverse research groups using diverse methods and sample sizes, reported that history of seed harvest was most highly correlated with population structure. Because persistently and intensively harvested populations were characterized by larger trees (> 60 cm dhb) and few to no 10-60 cm trees, suggesting population decline, restrictions on nut harvests were recommended to avoid 'demographic collapse'. Other studies focused on smaller size classes to link recruitment to harvest intensities. When focusing on seedling (<1.5 m height) and sapling (1.5 m height and < 10 cm dbh) counts in three Acre sites where an estimated 45 to 71% of seeds were harvested, Wadt *et al.* (2008) reported 3.2-5.8 and 0.9-1.8 individuals ha^{-1}, respectively, concluding that regeneration was sufficient for population persistence in all three sites. A study of three sites in Peru reported low average densities of trees 10-40 cm dbh (0.10-0.19 individuals ha^{-1}) (Rockwell *et al*., 2017) as did 25 sites in northern Pará, Brazil (0.5 ± 0.8 individuals ha^{-1} – average ± standard error), but the latter found no relation between these low pre-reproductive levels and harvest intensity (Scoles & Gribel, 2012). When comparing 20 Brazil nut groves in southern Pará that underwent varying harvesting intensities (including unharvested groves), Ribeiro *et al*. (2014) reported *higher* seedling (0.3-1.5 m height) densities with persistent low-intensity nut harvesting by Kayapó Indigenous. Applying matrix models to a 2-year demographic study of two sites in Bolivia, Zuidema & Boot (2002) concluded that even with collection rates of 93%, *B. excelsa* populations were stable. Another matrix modelling effort based on 14 years of research in two sites in Acre came to similar conclusions under 39 and 81% collection rates (Bertwell *et al*., 2018).

Brazil nut population stability also depends on agouti behavior. While primary dispersal is gravity-induced with fruits fairly synchronously falling from the tall parent tree during the rainy season (Faustino *et al.*, 2014), secondary dispersal by animals is instrumental in *B. excelsa* recruitment. In addition to humans who also disperse seeds intentionally (and unintentionally) along harvest trails (Ribeiro *et al*., 2014), several mammalian species open *B. excelsa* fruits. Brown capuchin monkeys (*Sapajus apella*) open older fruits whose shell has begun to decompose (Haugaasen *et al*., 2010; Peres & Baider, 1997). Giant Amazonian squirrels (*Sciurus* spp.) also have been reported to gnaw open fruits and removing seeds (Peres &

Baider, 1997), but only acouchy (*Myoprocta* spp.) and *Dasyprocta* spp. open the hard fruits, access the seeds, and habitually bury them intact (Forget, 1990; Peres & Baider, 1997; Smythe, 1978). The smaller *Myoprocta* spp. can slowly gnaw through the *B. excelsa* capsule and eventually access the seeds, but the larger *Dasyprocta* spp. completes these tasks much more efficiently. Several studies of *B. excelsa* seed dispersal have been conducted, tracking seeds experimentally placed on the forest floor (Peres & Baider, 1997; Haugaasen *et al*., 2010), revealing dispersal distances of < 20 m. A follow up study by Haugaasen *et al*. (2012) revealed that whole (albeit manipulated) fruits were carried up to 60 m from their original location, demonstrating that *Dasyprocta* spp. movement of whole fruits results in much more efficient seed dispersal and at greater distances than previously assumed.

Tracking 6855 fruits from 20 trees as they fell over approximately three months, Wadt *et al*. (2018) observed that scatterhoarders removed 4.1% to outside the projection of the tree crown and opened another ~ 0.5% under mother trees. Moreover, continuous quantification of disperser activity revealed that prior to the start of human nut harvests, *Dasyprocta* spp. had weeks of unlimited seed access, consuming or dispersing 197 fruits (or 3351 seeds assuming an average of 17 seeds per fruit) (Wadt *et al*., 2018). It is unknown whether this is enough to sustain agouti populations, while providing sufficient Brazil nut seed dispersal and burial. Safety concerns, however, dictate that most nut harvesters delay their collection efforts until after the majority of fruits have fallen, although timing and intensity of nut harvests vary across the Amazon basin (Duchelle *et al*., 2011).

Considering all data and our cumulative understanding of *Bertholletia*-*Dasyprocta*-*Homo sapien* interactions – from reproductive output of adult trees to intensity of harvests to *Dasyprocta* spp. behavior – we come to similar conclusions as Scoles & Gribel (2011) and Ribeiro *et al*. (2014). Scientific evidence and local knowledge indicate that restrictions on current levels of nut harvests are not necessary to sustain *B. excelsa* and *Dasyprocta* spp. populations. Instead of concentrating on the fate of most of the seeds that are produced, the more pressing risk to *B. excelsa* populations is the survival of existing trees, particularly those nearing reproductive size and those that are already producing (Bertwell *et al*., 2018). The extent to which climatic changes might modify current *B. excelsa* mortality and productivity scenarios remains uncertain. Bertwell *et al*. (2018) found no evidence that confirms that isolated years of low rainfall were a threat to population stability. Their limited sample size in both individual tree numbers and years monitored, however, were insufficient to capture robust relationships between rainfall and survival, and the probability of tree mortality increases after multiple years of low rainfall (Brienen *et al*., 2015). Still, of the 18 large tree mortality cases identified with certainty over a 14-year period, Bertwell *et al*. (2018) reported that none appeared to be due to factors related to water availability.

5. *Increasing productivity*

In 2015, Brazil nut exports (both fresh and dried) from Brazil, Bolivia and Peru were valued at US $268 million (UN Statistics Division, 2017). Local people living in or near old growth forests collect an estimated 98% of these commercial harvests (Homma *et al*., 2014). For these families, this one product provides between 17 and 74% of forest-derived incomes (Guariguata *et al*., 2017), and up to 44% of total household income (Duchelle *et al*., 2011; Soriano *et al.*, 2017). How might these smallholders increase production?

5.1. Protecting and improving conditions of large trees

Focusing on large reproductive trees that already exist in the forest is a strategic way to increase productivity quickly. Two harmful practices that can cause mortality even in large trees have been increasingly abandoned by harvesters: 1) the use of fire to clear forest debris around adult trees to facilitate fruit collection and avoid snake encounters (Kainer, 1997), and 2) "bleeding" adult trees - cutting the inner bark to release the naturally red *B. excelsa* resin. This wounding, typically done with a machete and practiced by almost 1/3 of interviewed harvesters in Bolivia and Brazil (Duchelle *et al.*, 2014), can stimulate fruit production in the short term, but creates invasive routes for pathogens, negatively impacting tree health over time (Kramer & Kozlowski, 1979). That no interviewed Peruvian producers bled trees was attributed to the "no bleeding" message delivered by FSC certification promoters (Duchelle *et al*., 2014). Both clearing around trees via fire and bleeding trees should be avoided.

Lianas (or woody vines) commonly find support in the crowns of long-lived canopy dominants like *B. excelsa*, causing tree crown damage particularly in trees with heavy liana loads (>75% crown coverage), and negatively affecting fruit production (Kainer *et al*., 2006). Nut harvesters relate this phenomenon, and Duchelle *et al*. (2014) documented that cutting lianas was the most commonplace Brazil nut management practice conducted in the tri-country border region of Bolivia, Peru and Brazil, while Zeidemann *et al*. (2014) reported highly variable liana cutting across different regions of *Riozinho do Anfrísio* Extractive Reserve in Pará state. A 10-year controlled experiment on reproductively mature *B. excelsa* revealed that treated trees were significantly better producers 3 ½ years after liana cutting, and these differences increased dramatically in subsequent years (Kainer *et al*., 2014). Their findings suggested that liana cutting reduces above- and below-ground liana competition with Brazil nut host trees and allows damaged crowns to recover over time. Nine to 10 years after liana cutting, trees that received the liana cutting treatment produced on average three times as many fruits as those that did not (Kainer *et al*., 2014). Furthermore, the actual cutting of lianas (and repeated treatments as necessary when liana resprouting occurs) takes only a few minutes, which means that the time invested in this best management practice is minimal when incorporated into routine annual fruit harvests (Kainer *et al*., 2014).

The number of community-based timber projects has increased in Brazil nut rich forests across the Amazon basin, in both sustainable use protected areas such as Brazil's extractive reserves (IFT, 2016), in Peru's Brazil nut concessions (Rockwell *et al*., 2015; Rockwell *et al*., 2017), and in Bolivia's private timber concessions (Guariguata *et al*., 2009) and community forests (Soriano *et al*., 2012; Soriano *et al*., 2017). When asked to evaluate opportunities and limitations related to logging in Brazil nut-

-rich forests, communities in both Bolivia and Peru prioritized their concern that logging would damage Brazil nut stands (Duchelle *et al*., 2012). Perhaps this is why Rockwell *et al.* (2015) reported that in overlapping Brazil nut-logging concessions in Peru, ~80% of the almost 500 reproductively mature Brazil nut trees they inventoried were at least 100 m from logged stumps. On the other hand, in Acre, Brazil, neither communities nor any other diverse Brazil nut-related actors considered logging damage to be a relevant threat to Brazil nut trees, particularly given its legal status and economic value (Duchelle *et al*., 2012). Additionally, a field-based study that quantified logging damage to Brazil trees suggested that under the right conditions, logging may not harm adult *B. excelsa* trees. In three FSC-certified timber concessions where Brazil nuts were annually harvested, Guariguata *et al*. (2009) determined that when following reduced-impact logging guidelines and harvesting timber at low intensities (~0.5 trees per ha), selective logging resulted in low damage (~ 1 tree per 10 ha) to Brazil nut trees ≥ 10 cm dbh. Still, even under reduced-impact and low-intensity logging, it is difficult to assess unequivocally all potential impacts to the ecological system that supports Brazil nut production (e.g. pollinator or wind impacts). For example, it is unclear whether even relatively small logging gaps present a significantly greater wind risk to large Brazil nut trees. Bertwell *et al*. (2018) reported that a localized storm blew down four large reproductively mature trees, and wind likely contributed to the mortality of 10 others.

Finally, mindful searching and mapping of *B. excelsa* individuals outside traditional Brazil nut harvest trails could increase overall productivity. Research transects in unharvested areas of one reserve identified significant numbers of reproductively mature trees (Zeidemann *et al*., 2015) that could be brought into the annual harvest fold. A systematic mapping effort in a 145-ha Brazil nut-rich forest in Chico Mendes Extractive Reserve in Acre identified 32 new trees of reproductive size, revealing that when using his traditional trails, the harvester collected only from ~70% of all adult trees (Munaretti, 2016). Less than half and a quarter of Brazil nut harvesters in Bolivia and Acre respectively mapped their stands, while 79% of those in Peru did, as promoted by FSC Brazil nut certification (Duchelle *et al*., 2014). Rightfully, harvesters do not visit or harvest from trees already identified as negligible producers. Because trees outside the well-honed traditional harvest trails continuously grow into reproductive maturity, however, easily accessible mapping technologies could potentially increase productivity simply by including more extant trees into collection routes (Munaretti, 2016).

5.2. Tending new recruits and enrichment plantings

Protecting and tending new recruits and future Brazil nut crop trees could increase overall nut productivity across the landscape. Over 60% of harvesters across the tri-border region (Brazil, Bolivia and Peru) reported protecting seedlings encountered in abandoned fallows that arose from subsistence agricultural disturbances (Duchelle *et al*., 2014). *B. excelsa* seedlings and saplings are not only found in relative abundance in fallows (12.7 and 5.2 individuals ha^{-1}, respectively), diameter growth tends to be better due to elevated light levels than in forest settings (Cotta *et al*., 2008). Tending, or even simply abandoning these fallows to grow into Brazil nut-rich forests could significantly increase resident incomes and contribute to Brazil nut population sustainability. *B. excelsa* seedling recruitment also has been examined in the various types of disturbances created by selective logging (felling gaps, skid trails, access roads and log landings). Recruitment was significantly greater in larger disturbance sites (i.e., log landings versus skid trails) two to five years after logging, but overall, regeneration densities were no different between logged and unlogged sites (Soriano *et al*., 2012).

Planting Brazil nut seedlings is another intervention with potential for economic enrichment and ecosystem restoration. Kainer *et al*. (1998) compared the success of establishing Brazil nut seedlings in forest gaps, pastures and shifting cultivation plots encountered across the landscape of sustainable use reserves. Although forest gaps were appropriate planting sites from a socioeconomic perspective (e.g., low labor inputs), light availability was low and both nutrients and water appeared to be very limiting, such that gap seedlings demonstrated slow growth. Planting Brazil nut seedlings concurrently with cultivation of subsistence crops was the most highly advantageous of the three options studied. This enrichment option ensured timely weeding of the seedlings, that all resources needed for growth were abundant, and by the time subsistence crops were harvested and plots were abandoned, that seedlings had a clear competitive edge over successional vegetation. Pasture sites were also ecologically suitable for plantings (i.e., light, water and nutrients were available), but seedling establishment and maintenance required high labor inputs (e.g., fencing and weeding), particularly if grazing animals were part of the system. Nonetheless, in these sites, because resources to promote growth were present, small-scale intensive plantings of Brazil nut seedlings could be a way to enhance nut productivity and restore the hectares of degraded pasture in sustainable use reserves and other previously forested landscapes. Indeed, motivated by the 2012 Brazilian Forest Code that requires landowners in Amazonia to maintain 80% of their property in native forest, at least one property owner had established small-scale groves of Brazil nut trees that seemed to be highly productive (LHW and KAK: personal observation). In contrast, large-scale plantations of Brazil nut trees have not proven successful. This may be due to the absence of genetic variation in the planting stock, given that *B. excelsa* is largely self-incompatible (O'Malley *et al*., 1988), and/or due to the limited presence of effective pollinators (Calvacante *et al.,* 2012). *B. excelsa* is pollinated by carpenter and bumble bees of the Apidae and Anthophoridae families (Maues, 2002). These large-bodied bees are capable of lifting the hood of the zygomorphic flower (Prance, 1976), but only one species to date has been successfully reared in boxes (Calvacante *et al*., 2012). Upon examination of foraging behavior of pollinators in the largest Brazil nut plantation in the world located in Amazonas state, Calvacante *et al*. (2012) went on to argue that proximate natural forests are essential to provide Brazil nut pollinators with food, nesting and other needed resources.

6. Improving nut quality

A diversity of in-forest harvest and post-harvest activities can improve Brazil nut quality, meaning a clean and dry product free from aflatoxins. This is a challenging task given that fruits fall and nuts are collected almost exclusively during the rainy season. Best management practices promoted includes collecting fruits as soon as possible after falling (Faustino *et al*., 2014) and keeping fruit placental tissues and damaged (cut or rotten) nuts out of collection bags (Duchelle *et al.*, 2014). Based on their fruit tracking research and in recognizing tradeoffs, Faustino *et al*. (2014) recommended a first gathering and transporting of fruits eight weeks after the start of fruitfall, a period when most fruits are safely on the ground and have spent minimal time on the moist forest floor. Duchelle *et al*. (2011), however, reported that the threat of nut theft in neighboring Bolivia motivated the more dangerous practice of adhering to a much earlier start date. The threat of theft prompted harvesters to gather, open and transport nuts to a secure location – all on the same day, a routine that is relatively inefficient given that this process needs to be continuously repeated over the entire harvest season (Duchelle *et al*., 2011). These authors attributed the relative freedom to harvest fruits during a safer period in Brazil to the real and perceived greater level of resource security, a hard-won achievement afforded residents of extractive reserves and other sustainable use reserves in Brazil. Drying nuts in elevated and covered storage units away from contaminants such as batteries, domestic animals and petroleum-based fuels is another recommended practice. Evidence suggests that these harvest and post-harvest best management practices promoted by the worldwide umbrella organization for organic certification have been adopted by the majority of harvesters, at least in the tri-border region of Peru, Bolivia and Brazil (Duchelle *et al.*, 2014).

7. Conclusions

Over the last 30 years, *B. excelsa* has become increasingly linked with greater local control over Brazil nut-rich forests, including indigenous and sustainable use reserves in their various forms. Research indicates that community-controlled forests in general (Porter-Bolland *et al.*, 2012), and these types of reserves in particular (Nepstad *et al.*, 2006; Nolte *et al*., 2013), help stem deforestation, conserving the Brazil nut-rich forests within. Furthermore, as nut quality has improved, so has the Brazil nut market, and this product has multiple elements that render it poised to further reach conventional and niche markets. The Brazil nut system represents tremendous conservation values that simultaneously promote smallholder livelihoods, and given that almost all are collected from old-growth forests, virtually all Brazil nuts are naturally organically produced.

The biggest threat to Brazil nut sustainability is conversion of mature forests (where *B. excelsa* thrives) to other uses, such as the market crops and cattle production that have crept into some resident livelihoods in Brazil (Salisbury & Schmink, 2007; Vadjunec & Rocheleau, 2009). Scientific evidence suggests that nut harvest levels are sustainable, and ample scientific and local knowledge indicates possible pathways to increase productivity, enrich, and even grow back the forested landscape. We concur with others who call to fortify the property rights of local collectors, to promote equitable development of the Brazil nut sector, and to increase the knowledge base and local capacity to manage and navigate the broader and ever-changing resource system (Cronkleton & Pacheco, 2010; Soriano *et* *al.*, 2017). Such interventions tailored to the local context (Guariguata *et al.*, 2017) can better promote the sustainability of Brazil nut and continue its critical role in conserving forests throughout the Amazon Basin.

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