DOI: 10.1007/s10457-022-00798-9

ISSN: 1572-9680

Silvicultural interventions and agroforestry systems increase the economic and ecological value of *Bertholletia excelsa* plantations in the Amazon

Jéssica Pereira de Souza[a], José Francisco de Carvalho Gonçalves[a*], Roberto Kirmayr Jaquetti[a], Karen Cristina Pires da Costa[b], Roberval Monteiro Bezerra de Lima[c], Philip Martin Fearnside[d], Adamir da Rocha Nina Junior[e]

a. National Institute for Amazonian Research – INPA - MCTI, Laboratory of Plant Physiology and Biochemistry - Manaus, AM, Brazil.
jess_psouza@hotmail.com (ORCID 0000-0003-4340-0779); jaquettiroberto@gmail.com (ORCID 0000-0002-9450-2209); jfc@inpa.gov.br (*corresponding author – ORCID 0000-0001-9197-4617)
b. Federal University of South and Southeast of Pará – UNIFESSPA, Faculty of Agronomy, Institute of Studies in Agrarian and Regional Development – IEDAR - Marabá, PA, Brazil.
karencosta@unifesspa.edu.br (ORCID 0000-0002-9295-4412)
c. Embrapa Amazônia Ocidental - Manaus, AM, Brazil. roberval.lima@embrapa.br (ORCID 0000-0003-1260-447X)
d. National Institute for Amazonian Research – INPA - MCTI, Coordination of Research in Environmental Dynamics - Manaus, AM, Brazil. pmfearn@inpa.gov.br (ORCID 0000-0003-3672-9082)
e. Federal Institute of Education, Science and Technology of Amazonas (IFAM)–Campus Humaitá, BR230 Highway, KM 07, Humaitá-AM 69.800-000, Brazil. il. adamir.nina@ifam.edu.br (ORCID 0000-0003-4999-0335)

Abstract

Bertholletia excelsa is a native tree of the Amazon that has great economic importance e in producing multiple products (wood, nuts, and oil). It has an important role in the carbon cycle in the Amazon basin. Its ecophysiological characteristics indicate that it can be part of various tree-planting systems. We have compiled important information on *B. excelsa* growing in forest restoration, forest enrichment plantations, homogeneous plantations, and agroforestry systems to assess how the species responds to silvicultural interventions. Plantation studies on *B. excelsa* are relevant in implementing sustainable forestry systems in the Amazon region. Silvicultural interventions are crucial tools to ensure greater productivity, increase production capacity, and reduce cost and return time. *Bertholletia excelsa* is usually recommended for planting in agroforestry systems because of their physiological plasticity, maturation time for nuts, and substantial wood production, providing employment and income with a significant social impact in the field. *B. excelsa* can be successfully planted to restore degraded environments with satisfactory survival rates linked to physiological strategies, which allow for responses to spacing, fertilization, and thinning treatments demonstrating the potential for increasing both biomass production and yields of nuts.

Keywords: Forest plantations, productive plantations, reforestation, silvicultural treatments, sustainability.

Highlights:

Optimal practices for nut and wood production of planted *B. excelsa* have been identified.

Planting to recover degraded areas requires fertilization to gain productivity.

Enrichment of secondary forests requires thinning and understory cleaning.

Reforestation and avoiding deforestation are complementary, not competitive processes.

Planting *Bertholletia excelsa* in agroforestry systems provides income and sustainability.

Introduction

Tree planting is a means of recovering of forest cover in deforested areas and is one of the possibilities for carbon neutralization (Koch and Kaplan 2022). If the potential benefits of tree planting are to be obtained, forest plantation projects must include the local community and have efficient forestry and cultivation systems. Otherwise, the enterprise could become ecologically and economically unsustainable, as in the case of large unmonitored, and underdeveloped restoration projects (Holl and Brancalion 2020). In the Amazon region, ecosystem degradation drives this important biome toward an ecological collapse (Lovejoy and Nobre 2018). The southeastern portion of the forest has already changed from a carbon sink to a carbon source (Gatti et al. 2021). Deforestation continues to increase in the Brazilian Amazon, with the annual total reaching 13,235 km^2 in 2021, a record for the decade (INPE 2022). This forest loss must be halted as a first priority, and degraded areas must then be restored. Restoring degraded areas requires species selection that interacts with local fauna, enriches the food chain, and ensures ecosystem services (Giannini et al. 2016).

Bertholletia excelsa Bonpl is a large, tropical, evergreen tree in the family Lecythidaceae that can reach 60 m in height and 4 m in diameter (Mori and Prance 1990). This species has adaptive plasticity to the availability of nutrients, water, and light in sites and tolerance to different types of abiotic stresses, according to several studies conducted in different phenological phases and cultivation conditions of *B. excelsa* (Morais et al. 2007; Ferreira et al. 2012, 2015, 2016; Schimpl et al. 2018; Lopes et al. 2019; Costa et al. 2020; da Costa et al. 2022). This tree produces an indehiscent capsule fruit with nutritious seeds, called Brazil nuts, that are sold throughout Brazil and exported to other countries (Muller et al. 1995; Scoles and Gribel 2011). Each fruit contains around 18 seeds and can weigh up to 2.5 kg (Mori and Prance 1990; Scoles and Gribel 2011). Brazil nut has a high content of calcium, phosphorus, magnesium, potassium, barium, and selenium (Gonçalves et al. 2002; Silva Junior et al. 2022).

Brazil nut is produced in all countries that comprise Pan-Amazonia. This activity represents 2.8% of the production value (Production multiplied by the unit price) of non-timber forest products (NTFPs) extracted in 2020 in Brazil, this being the NTFP with the third-highest production in the Brazilian Amazon (IBGE 2021). In 2021, Brazil produced 33,406 tons of nut, generating 142,367 million reais (approximately 50 million US dollars). Studies indicate a strong connection between *B. excelsa* to human livelihood strategies in the Amazon region rural areas (Scoles and Gribel 2011; Caetano Andrade et al. 2019) and this species has great relevance to the carbon cycle in the Amazon basin, this being the species with the third greatest cumulative stock of biomass (Fauset et al. 2015; Selaya et al. 2017; Thomas et al. 2018).

Despite its socio-economic and ecological relevance, *B. excelsa* is vulnerable to extinction. Even though in 1994 a ban was decreed on the cutting of Brazil nut trees in native, primitive, or regenerated forests [Decree nº 1282, of October 19, 1994] (Brazil 1994), the native populations of Brazil nuts continue to decrease due to the illegal logging. This fact increases the risk of extinction and compromises the availability of genetic material (IUCN 1998; Angelo et al. 2013; Homma et al. 2014; Chiriboga-Arroyo et al. 2020). The species is also vulnerable to the reduction of environmentally suitable areas caused by climate change (Evangelista-Vale et al. 2021).

The establishment of *B. excelsa* plantations should be considered as an alternative to these scenarios (Homma et al. 2014). In addition, silvicultural interventions can improve the yield and quality of forest products, thus reducing competition for primary resources and the incidence of pests and diseases (Forrester et al. 2013). Recent studies demonstrate how intensive silviculture influences the morphophysiological responses of forest species, such as increasing growth rates, above-ground biomass, leaf area, specific photosynthetic rate, leaf nutrients, and photosynthetic pigments (Costa et al. 2020; Turchetto et al. 2020; da Costa et al. 2022).

Considering the potential gaps in the plantation systems of *B. excelsa,* in this review, we compiled information related to silvicultural interventions potentially required in four different planting arrangements (1. Pure plantations; 2. Plantations for recovery of degraded areas; 3. Enrichment plantations; and 4. Agroforestry) (Figure 1) to provide information to help producers and that these insights can lead to the best decision-making. This new practical knowledge can help to leverage the productive capacity of *B. excelsa* plantations, to enhance tropical silviculture, and to contribute to the prominent role of production and export of Brazil nuts.

1. Plantations for Recovery of degraded areas (RDA)

Deforestation in the Amazon basin has remained high over the years, with a record increase in the rate by about 20% of between 2020 and 2021 (Silva Junior et al. 2021, INPE 2022). Deforested areas have higher irradiance and temperature and lose soil fertility (Santos Junior et al. 2006; Jaquetti et al. 2021). Through the selection and plantation of well-adapted species, biomass and ecosystem services can be recovered, restoring important biogeochemical cycles such as C and N (Nogueira et al. 2015; Jaquetti et al. 2016, 2021; Jaquetti and Gonçalves 2017). Introducing commercial species during forest restoration may help to restore unproductive areas to become productive forest systems (Lamb 2012; Homma 2017; Ferreira et al. 2016; Costa et al. 2022).

B. excelsa is one of the native species with the greatest ecological aptitudes for RDA in the Amazon region, including mining areas (Ferreira and Tonini 2009; Salomão et al. 2006; Ferreira et al. 2012, 2015; Locatelli et al. 2015; Costa et al. 2022). Plantations of the species can reach absolute growth rates in diameter (AGR_D) of 1.02 cm year^{-1} and height (AGR_H) of 0.77 m year^{-1} 18 years after planting (Salomão et al. 2006). Studies have been conducted to evaluate silvicultural treatments that favor the recovery of soil quality, increase the efficiency of resource use, and minimize stress factors during the initial establishment of seedlings, which is fundamental for conducting a productive planting (Campoe et al. 2014; Ferreira et al. 2012). Ferreira et al. (2009) demonstrated how chemical and organic fertilization treatments reduced stress responses. Compared to unfertilized plants, fertilized *B. excelsa* enhanced photosynthesis, water use-efficiency, and photochemical performance as represented by increased values of the performance index (PI_{ABS}) and by the maximum photochemical efficiency (F_V/F_M) values of chlorophyll *a* fluorescence (Ferreira et al. 2009. 2012, 2015).

Organic fertilization can recover the quality of degraded soils, since it favors positive changes in the biological, physical, and chemical characteristics of the soil (Ferreira et al. 2015; Bhattacharya et al. 2016) and results in performance gains in *B. excelsa* (Ferreira et al. 2009, 2015). Moreover, the organic fertilization of the regenerating vegetation with leaves and branches increased the AGR_D (2.4 mm month^{-1}) and AGR_H (10.4 cm month^{-1}) compared to the unfertilized and chemical fertilization treatments (Ferreira et al. 2012). Under organic fertilization, specific leaf area (SLA) values are lower and the photosynthetic rates, transpiration rates, and water use efficiencies are higher. This increases the physiological and photosynthetic performance of these individuals and makes them more resilient in the face of environmental changes, such as water deficit (Ferreira et al. 2009, 2012). These data provide information about physiological plasticity and the mechanisms for escaping from stress, demonstrating that, if fertilized, plantations of *B. excelsa* in degraded areas can be more efficient and productive than other native species.

2. **Enrichment plantations**

Enrichment planting in "*capoeiras",* an Amazonian popular name for secondary forest, is an important form of economic production and is combined with ecological gains, contributing to an increase in the density of species of interest in underutilized areas (Fantini et al. 2019; Santos et al. 2020). When we relate silvicultural interventions to planting in areas of secondary vegetation, we prioritize is practices that alter the availability of light and reduce the competition between *B. excelsa* seedlings and already-established species.

Some studies have demonstrated that silvicultural interventions to increase light availability increase survival and the growth of the *B. excelsa* in enrichment plantations (Penã-Claros 2002). Scoles et al. (2014) compared the effect of different light environments on the performance of *B. excelsa* seedlings and observed survival rates of 77% when planted in *capoeira* and of 21% when planted in the understories of native *castanhais* (sites with clusters of *B. excelsa* trees). These authors found that growth rates in *capoeira* were 21.6 cm year^{-1} for height and 0.31 cm year^{-1} for diameter in the sixth year, while in the understory the growth rates were 4.7 cm year^{-1} for height and 0.10 cm year^{-1} for diameter (Scoles et al. 2014). Higher values of survival and annual growth in height and diameter in seedlings of *B. excelsa* were observed by Garate-Quispe et al. (2020) after canopy-opening interventions. A positive correlation was found between the opening of the canopy (increased irradiance) and growth rates in height and diameter (Garate-Quispe et al. 2020; Santos and Ferreira 2020). Tree mortality was higher in the forest understory (81.2 %) compared to forest gaps (25%) (Garate-Quispe et al. 2020). Due to the higher performance and high survival rate of *B. excelsa* seedlings in the gaps opened by falling trees, enrichment planting is recommended in gaps in natural forests and in *capoeiras* (Garate-Quispe et al. 2020).

Studies have begun to assess the impact of thinning on enrichment plantations. Growth rates of *B. excelsa* were enhanced after thinning and understory clearing of natural regeneration in Central Amazonia (Santos and Ferreira 2020). Santos and Ferreira (2020) and Scoles and Gribel (2021) also found *B. excelsa* to have higher mortality in treatments with low irradiance.

Opening planting lines also enhanced the survival and growth of *B. excelsa* compared to the treatment without the removal of vegetation (Peña-Claros et al. 2002). The 6 m wide opening line was found to be the best treatment 4 years after planting due to increased irradiance. However, only small differences were found between width treatments. Higher growth rates were found for the 6 m wide planting lines and the total-clearing treatments (Peña-Claros et al. 2002).

Despite *B. excelsa* being considered a shade-tolerant species with an emerging canopy in natural forests, the species has higher growth and survival when planted in high light environments. Additionally, the growth rates depend greatly on soil fertility and nutrient additions. In contrast, the use of *B. excelsa* to enrich the understory of natural forests appears to be unsuitable, as is reflected by the low growth rates and high mortality of individuals. But overall, clearing, and thinning treatments are important for enhancing productivity when used in naturally regenerating areas with the opening of 25 to 50 % of the canopy as recommended by Garate-Quispe et al. (2020). Additionally, planting taller seedlings (more than 70 cm) may reduce herbivory and weed competition.

3. **Pure plantations**

Monoplantations of *B. excelsa* have been established for nut and wood production. Due to the Brazilian legislation mentioned in the introduction, *B. Excelsa* wood can only be legally extracted from planted individuals and not from native forests. The effects of thinning, fertilization, spacing, and coppice regrowth have been studied to increase productivity and biomass growth. The species has desirable silvicultural characteristics, with single stems and high-quality wood (Costa et al. 2009; Ferreira and Tonini 2009; Scoles et al. 2011; Machado et al. 2017). Monoplantation goals should be considered when choosing silvicultural practices, including spacing. Pruning, thinning, and mowing are important to reduce weed competition and increase the availability of light and nutrients (Schroth et al. 2015, Machado et al. 2017).

The recommended spacing for the development of the crowns for nut production in commercial monoplantations is 10 x 10 m (Locatelli et al. 2015; Passos et al. 2018). In a monoplantation for nut production in Amazonas state, Brazil, a positive correlation was found between capsule weight and diameter at breast height (DBH) (Passos et al. 2018). Among selected genetic clones from the Brazilian Agricultural Research Corporation (EMBRAPA), the Manoel Pedro, Aruanã, and Santa Fé clones had higher growth in diameter and height 31 years after plantation. With an average production of 80 capsules and 12 kg tree^{-1} of nut weight, Manoel Pedro was more productive than the other clones studied (Passos et al. 2018). Nevertheless, *B. excelsa* can take from 15 to 25 years to produce nuts at a commercial scale. This can be a strong limitation for the establishment of productive monoplantations (Homma et al. 2014).

Studies on pruning and thinning silvicultural treatments to produce straight, knot-free trunks have been conducted on reduced spacing (Homma et al. 2014). The spacing of 3 × 4 m and 5 × 5 m area indicates for spacing increases wood quality, growth in height, and volumetric production (Lima and Souza 2014; Oliveira 2021). In addition, the spacing of the plantation seems not to influence the survival of *B. excelsa* seedlings in the first years of the plantation (Oliveira 2021). In a 27-year-old pure plantation in the state of Amazonas, Central Brazilian Amazon, with a spacing of 3 x 3 m, *B. excelsa* had an average height increase equal to 0.47 m year^{-1} in diameter of 0.81 cm year^{-1} and in a volume of 8.77 m^3 ha^{-1} year^{-1} (Machado et al. 2017).

In a plantation with 12 x 12-m spacing with phosphorus fertilization and mowing, *B. excelsa* had an 86% survival rate and a relative growth rate in diameter (RGR_D) of 2.15 cm year^{-1} 28 years after planting (Locatelli et al. 2015). The species produced an average of 3.1 m^3 per tree totaling 269.72 m^3 in volume per hectare (Locatelli et al. 2015). The authors projected the technical age of harvest (TAH) at 25 years for the best productivity and income (Locatelli et al. 2015). Annual volume increase reached maximum values 12 years after plantation when thinning treatments were employed to avoid stagnation of diameter growth.

The combination of thinning, phosphorus fertilization, and liming effects on the photochemical performance of *B. excelsa* have recently been studied in plantations for wood production (Costa et al. 2020). The liming and fertilization treatments were important for maintaining photosynthesis and reducing stress after thinning. The rapid recovery responses and high efficiency of light use were reflected in the F_V/F_M and PI_{ABS} values (Costa et al. 2020). Despite leaves and branches representing only 27% of total individual biomass, the higher concentration of nutrients highlights the importance of leaving the harvest residues in the planted area to maintain soil fertility (Costa et al. 2015; Schroth et al. 2015). However, *B. excelsa* may export 8.0 Mg ha^{-1} of carbon (C) in the first thinning 8 years after planting (Costa et al. 2015).

The growth of *B. excelsa* sprouts has been studied in coppice systems in commercial monoplantations. These systems may reduce implementation costs and time to first harvest and increase the C stocks in the soil (Paiva et al. 2011; Scoles 2011; Homma et al. 2014; Fortes 2016; Germon et al. 2019; Johann 2021). Additionally, due to the root system already being developed, coppiced trees may access deeper water and nutrient reservoirs, increasing their tolerance to dry periods (Paiva et al. 2011; Germon et al. 2019).

Despite its good silvicultural and physiological characteristics, basic information on the species in commercial plantations is still lacking. The economic viability of plantation establishment is limited by the relatively long time before large-scale production of nuts or wood begins. Additionally, poor logistics in the region may limit the use *B. excelsa* in many parts of the Amazon region. Therefore, studies to reduce the harvest time are needed. The importance of choosing the right silvicultural treatments is also clear.

4. Agroforestry systems

As regards referring to the topic of Agroforestry systems (AFS), we choose to take into consideration the conceptions described by Gómez et al (2022) about Traditional agroforestry systems (TAS) and agroforestry research. Agroforestry is a land-use alternative with many advantages over other options for already-deforested areas. Its generation of employment and appropriateness for implementation by small farmers are advantages over monocultural plantations, including those of *B. excelsa*. They clearly have greater environmental benefits and sustainability as compared to the cattle pastures that dominate deforested landscapes in Brazilian Amazonia. Agroforestry is a sustainable and economic alternative to be implemented in protected areas such as the legal reserves that Brazilian law requires in private properties (Homma et al. 2014; Souza et al. 2017).

In general, agroforestry research with *B. excelsa* combines trees and annual crops to increase income during the first years of *B. excelsa* development. Livestock may also be included in these systems (Homma et al. 2014). Agroforestry can sustain soil fertility after crop rotation due to better exploitation of deeper soil layers by the roots of trees (Tapia-Coral et al. 2005, Costa et al. 2009). Moreover, the biomass production and development of the organic layer induced by *B. excelsa* favor the cycling of important nutrients and increase of C stocks in the soil (Tapia-Coral et al. 2005). *B. excelsa* has been used in AFS in Tomé-Açu in Pará State, Eastern Brazilian

Amazon, since 1970 to increase the diversity of production and to increase the income of local communities (Schroth et al. 2015; Homma et al. 2014).

AFS with *B. excelsa* may also increase growth rates of the species with an average AGR_D of 2 to 3 cm year^{-1} and AGR_H of 1 to 2 m year^{-1} between seven and twelve years after planting (Costa et al. 2009; Ferreira and Tonini 2009; Schroth et al. 2015). An AGR_D of 2.13 cm year^{-1} was observed for *B. excelsa* when interplanted with *Theobroma grandiflorum* 28 years after planting (Locatelli et al. 2015). The great variation in the size and biomass of individuals highlights the potential for genetic improvement of the species (Schroth et al. 2015).

Survival rates between 78 and 98.6% have been found in AFS plantations with *B. excelsa* (Schroth et al. 2015; Ferreira and Tonini 2009; Costa et al. 2009; Locatelli et al. 2015). The positive effects on growth rates and nutrient stocks with combined chemical fertilization and liming treatments have been reported in agroforestry plantations with *B. excelsa*. The species appears to be highly demanding of Mg and Ca (Schroth et al. 2015). Increased organic matter and phosphorus, specifically, in the soil may enhance the performance of *B. excelsa* (Costa et al. 2009).

The most-common spacing in AFS with *B. excelsa* is 10 x 10 m for nut production (Costa et al. 2009; Schroth et al. 2015; Locatelli et al. 2015). However, increasing spacing along with pruning and thinning treatments may reduce the risk of fungal disease spreading (Forrester et al. 2013; Santos et al. 2020). Increased nut production has been reported under 12 x 12-m spacing due to better crown development (Costa et al. 2009). Choosing the right spacing may reduce interspecific and weed competition, thereby increasing growth and allocation of nutrients to aboveground biomass (Schroth et al. 2015). Compared to monoplantations, the nut production of the species may start earlier in AFS, around 8 to 10 years after planting (Costa et al. 2009; Homma et al. 2014; Ferreira and Tonini 2009).

Adopting a spacing that induces natural pruning may increase wood quality (Schroth et al. 2015). As observed by Ferreira and Tonini (2009), 81.16% of individuals had excellent straight trunks with no defects, while 28.8% had no bifurcations. Therefore, reduced spacing may influence the growth patterns that increase height growth and the quality of wood production.

Markets and other factors limit the extent to which AFS can achieve recovery of the vast areas of degraded cattle pasture in Brazilian Amazonia (Fearnside 1995a, 2009). This article emphasizes that the Brazil nut tree has demonstrated in both cases, plantations with silvicultural treatments applied to recover degraded areas and agroforestry, excellent results (Costa et al. 2022). In other words, these results reinforce the importance of agroforestry that includes *B. excelsa* in the Amazon as part of a circular bioeconomy that contributes to improving the environment and local livelihoods.

All in all, we can confirm that *B. excelsa's* responses to spacing, fertilization, and thinning treatments demonstrate the potential for increasing both biomass production and yields of nuts (Figure 2).

Conclusions and future perspectives

B. excelsa has great potential to be used in different forest plantation arrangements. Considering the time required for nut and wood products and the increased growth rates, the species is mostly recommended to be planted in agroforestry systems. On the other hand, the species also demonstrates good responses in monoplantations. As a native species that produces goods and services, *B. excelsa* can be successfully planted to restore degraded environments showing satisfactory survival rates. To enrich the natural regeneration of forests the spacing and light availability mainly should be carefully considered. Additionally, leaving pruning and thinning residues in the area during harvest is recommended to sustain soil fertility.

The species shows great physiological plasticity under different levels of resource availability. Because of the prominence of the species in sequestering and storing carbon, it is relevant to evaluate the opportunities to add value to plantations through the carbon market and other initiatives for payment for environmental services.

Thus, *B. excelsa* can be used as key species for stocking carbon in reforestation programs and climate change mitigation.

Despite the ecological and economic relevance of *B. excelsa* limitations on basic research with the species may be a factor that reduces the implementation of commercial plantations in the Amazon region. Therefore, studies are needed on the effects of silvicultural treatments to increase productivity and reduce the rotation time in agroforestry systems and in monoplantations, covering different scales of forestry production.

Statements and Declarations

The authors declare that there is no conflict of interest.

Acknowledgments

The authors are grateful to the Laboratory of Plant Physiology and Biochemistry of INPA (INPA-LFBV) for the use of their equipment and infrastructure for our analyses. We would also like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES, project Pro-Amazonia: Biodiversity and Sustainability - 042/2012) and the National Council for Scientific and Technological Development (CNPq) for financial support. José F. C. Gonçalves and Philip M. Fearnside acknowledge the fellowship provided by CNPq. and the Brazilian Research Network on Global Climate Change (FINEP/Rede Clima 01.13.0353-00).

Funding

This study was financially supported by the Coordination for the Improvement of Higher-Level Personnel (CAPES, Brazil, Project Pro-Amazonia AUXPE 3390/2013 and CAPES - Finance Code 001), the Amazonas State Research Support Foundation (FAPEAM, Brazil, N° 024/2014) and the National Council for Scientific and Technological Development (CNPq, Brazil, 480233/2011-0; 311103/2015-4) and the Brazilian Research Network on Global Climate Change FINEP/Rede Clima (01.13.0353-00).

Author contributions

Jessica Pereira de Souza has written the manuscript with conceptual support from José Francisco de Carvalho Gonçalves. The literature search and data analysis were performed by Jéssica Pereira de Souza. The first draft of the manuscript was written by Jéssica Pereira de Souza and all authors commented on and critically revised the versions of the manuscript. All authors read and approved the final manuscript.

References

Albuquerque FC (1960) Mancha parda das folhas da castanheira-do-Pará causada por uma nova espécie de fungo. Boletim Técnico, Instituto Agronômico do Norte, Belém, Pará. 28 pp.

Angelo H, Almeida NA, Calderon RA, Pompermayer RS, Souza NA (2013) Determinantes do preço da castanha-do-Brasil (*Bertholletia excelsa*) no mercado interno brasileiro. Sci. For. 41: 195-203.

Azevedo GFC (2013) Photosynthetic parameters and growth in seedlings of *Bertholletia excelsa* and *Carapa guianensis* in response to pre-acclimation to full sunlight and mild water stress. Acta Amazonica 44: 67–77.

Bhattacharya SS, Kim KH, Das S, Uchimiya M, Jeon BH, Kwon E, Szulejko E (2016) A review on the role of organic inputs in maintaining the soil carbon pool of the terrestrial ecosystem. J. Environ. Manag. 167: 214-227.

Brancalion, P.H.S., de Almeida, D.R.A., Vidal, E., Molin, P.G., Sontag, V.E., Souza, S.E.X.F., Schulze, M.D. (2018) Fake legal logging in the Brazilian Amazon. Science Advances, 4, art. eaat1192. https://doi.org/10.1126/sciadv.aat1192

Brazil Decreto Nº 1.282, de 19 de outubro de 1994. Regulamenta os arts. 15, 19, 20 e 21, da Lei nº. 4.771, de 15 de setembro de 1965, e dá outras providências.

Caetano Andrade VL, Flores BM, Levis C, Clement CR, Roberts P, Schöngart J (2019) Growth rings of Brazil nut trees (*Bertholletia excelsa*) as a living record of historical human disturbance in Central Amazonia. PLoS ONE 14: 1-18.

Campoe O, Iannelli C, Stape J, Cook R, Mendes J, Vivian R (2014) Atlantic Forest tree species responses to silvicultural practices in a degraded pasture restoration plantation: From leaf physiology to survival and initial growth. Forest Ecology and Management 313: 233-242.

Chiriboga-Arroyo F, Jansen M, Bardales-Lozano R, Ismail SA, Thomas E, García M, Gomringer RC, Kettle CJ (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: 194-210. doi:10.1002/ppp3.10166

Cook-Patton SC, Drever CR, Griscom BW, Hamrick K, Hardman H, Kroeger T, Pacheco P, Raghav S, Stevenson M, Webb C, Yeo S, Ellis, PW (2021). Protect, manage and then restore lands for climate mitigation. Nature Climate Change 11(12): 1027-1034. doi:10.1038/s41558-021-01198-0

Costa JR, Castro ABC, Wandelli EV, Coral SCT, Souza SAG (2009) Aspectos silviculturais da castanha-do-brasil (*Bertholletia excelsa*) em sistemas agroflorestais na Amazônia Central. Acta Amazonica 39(4): 843-850.

Costa KCP, Ferreira MJ, Linhares ACC, Guedes AA (2015) Biomassa e nutrientes removidos no primeiro desbaste em plantio de *Bertholletia excelsa* Bonpl. Sci. For. 43(107): 591-600.

Costa KCP, Jaquetti RK, Goncalves JFC (2020) Special issue in honour of Prof. Reto J. Strasser. Chlorophyll a fluorescence of *Bertholletia excelsa* Bonpl. plantations under thinning, liming, and phosphorus fertilization. Photosynthetica 58: 138-145.

Costa MG, Tonini H, Mendes Filho P (2017) Atributos do solo relacionados com a produção da castanheira-do-Brasil (*Bertholletia excelsa*). Floresta e Ambiente 24: e20150042.

Dasgupta, S (2021) Hold the tree planting: Protect ecosystems first for maximum carbon storage, study says. Mongabay, 7 December 2021. https://bit.ly/3ie3nya

Diniz TDAS, Bastos TX (1974) Contribuição ao conhecimento do clima típico da castanha-do-Brasil. Boletim Técnico IPEAN, 64: 59-71.

Duarte MLR (1999) Doenças de plantas no trópico úmido brasileiro. I. Plantas Industriais. Belém: Embrapa Amazônia Oriental.

Evangelista-Vale JC, Weihs M, José-Silva L, Arruda R, Sander NL, Gomides SC, Machado TM, Pires-Oliveira JC et al (2021) Climate change may affect the future of extractivism in the Brazilian Amazon. Biological Conservation 257: 109093, doi:10.1016/j.biocon.2021.109093.

Fantini AC, Schuch C, Siminski A, Siddique I (2019) Small-scale management of secondary forests in the Brazilian Atlantic Forest. Floresta Ambiente 26(4).

Fauset S, Johnson MO, Baker TR, Monteagudo A, Brienen RJW et al. (2015) Hyperdominance in Amazonian Forest carbon cycling. Nature Communications 6: 6857.

Fearnside PM (1995a) Agroforestry in Brazil's Amazonian development policy: The role and limits of a potential use for degraded lands. pp. 125-148 In: Clüsener-Godt M, Sachs I (Eds) Brazilian Perspectives on Sustainable Development of the Amazon Region. UNESCO, Paris, and Parthenon Publishing Group, Carnforth, U.K. 311 pp. https://bit.ly/3p2w6g2

Fearnside PM (1995b) Global warming response options in Brazil's forest sector: Comparison of project-level costs and benefits. Biomass and Bioenergy 8(5): 309-322. doi:10.1016/0961-9534(95)00024-0

Fearnside PM (1998) Plantation forestry in Brazil: Projections to 2050. Biomass and Bioenergy 15(6): 437-450. doi:10.1016/S0961-9534(98)00061-0

Fearnside PM (2002) Time preference in global warming calculations: A proposal for a unified index. Ecological Economics 41(1): 21-31. doi:10.1016/S0921-8009(02)00004-6

Fearnside PM (2003) Conservation policy in Brazilian Amazonia: Understanding the dilemmas. World Development, 31(5): 757-779. doi:10.1016/S0305-750X(03)00011-1

Fearnside PM (2009) Degradação dos recursos naturais na Amazônia brasileira: Implicações para o uso de sistemas agroflorestais. pp. 161-170 In: R. Porro (ed.) Alternativa Agroflorestal na Amazônia em Transformação. World Agroforestry Centre (ICRAF) & EMBRAPA Amazônia Oriental, Belém, Pará, Brazil. 825 pp. https://bit.ly/3nQtR05

Fearnside PM (2012) The theoretical battlefield: Accounting for the climate benefits of maintaining Brazil's Amazon Forest. Carbon Management 3(2): 145-148. doi:10.4155/CMT.12.9

Ferreira MJ, Gonçalves JFC, Ferraz JBS (2009) Photosynthetic parameters of young Brazil nut (*Bertholletia excelsa* H. B.) plants subjected to fertilization in a degraded area in Central Amazonia. Photosynthetica 47: 616-662.

Ferreira MJ, Gonçalves JFC, Ferraz JBS (2012) Crescimento e eficiência do uso da água de plantas jovens de Castanheira-da-Amazônia em área degradada e submetidas à adubação. Ciência Florestal 22: 393-401.

Ferreira MJ, Goncalves JFC, Ferraz JBS, Correa VM (2015) Nutritional traits of young *Bertholletia excelsa* Bonpl. plants under fertilization treatments in a degraded area in Amazonia. Scientia Forestalis 43:863-872.

Ferreira MJ, Gonçalves JFC, Ferraz JBS, Júnior U, Rennenberg H (2016) Clonal variation in photosynthesis, foliar nutrient concentrations, and photosynthetic nutrient use efficiency in a Brazil nut (*Bertholletia excelsa*) plantation. Forest Science 62:323-332.

Ferreira LMM, Tonini H (2009) Comportamento da castanha-do-brasil (*Bertholletia excelsa*) e da cupiúba (*Goupia glabra*) em sistema agrosilvicultural na região da Confiança, Cantá – Roraima. Acta Amaz. 39(4).

Forrester DI, Collopy JJ, Beadle CL, Baker TG (2013) Effect of thinning, pruning and nitrogen fertiliser application on light interception and light-use efficiency in a young *Eucalyptus nitens* plantation. Forest Ecology and Management 288: 21-30.

Fortes SLK (2016) Ecofisiologia de rebrotas de *Bertholletia excelsa* bonpl. em plantio florestal submetido ao desbaste. Dissertation, Instituto Nacional de Pesquisas da Amazônia.

Garate-Quispe JS, Roca MRG, Aguirre GA (2020) Survival and growth of brazil-nut seedlings in tree-fall gaps and forest understory. Floresta e Ambiente 27(3): e20171168.

Gatti, L.V., Basso, L.S., Miller, J.B. et al. (2021) Amazonia as a carbon source linked to deforestation and climate change. Nature 595, 388–393.

Germon A, Jourdan C, Bordron B, Robin A, Nouvellon Y, Chapuis-Lardy L, Gonçalves JLM, Pradier C, Guerrini IA, Laclau J-P (2019) Consequences of clear-cutting and drought on fin e root dynamics down to 17 m in coppice-managed eucalypt plantations. Forest Ecology and Management 445: 48-59.

Giannini TC, Giulietti AM, Harley RM, Viana PL, Jaffe R, Alves R, Pinto CE, Mota FO,Caldera CF, Imperatriz-Fonseca VL, Furtini AE, Siquiera JE (2016) Selecting plant species for practical restoration of degraded lands using a multiple-trait approach. Austral Ecology 42(5):510-521. doi: https://doi.org/10.1111/aec.12470

Herraiz AD, Fearnside PM, Graça PMLA (2017) Amazonian flood impacts on managed Brazilnut stands in natural forests along Brazil's Madeira River: A sustainable economy threatened by climate change. Forest Ecology and Management 406: 46-52. doi:10.1016/j.foreco.2017.09.053

Holl BN, Brancalion PH (2020) Tree planting is not a simple solution. Science 368: 580–582. doi:10.1126/science.aba8232.

Homma, AKO. (1994) Plant extraction in the Amazon: Limitations and possibilities. pp. 34-57 In: M. Clüsner-Godt & I. Sachs (eds.) Extractivism in the Brazilian Amazon: Perspectives in Regional Development. MAB Digest 18. United Nations Educational and Scientific Organization (UNESCO), Paris, France. 88 pp. https://bit.ly/3l397Ar

Homma AKO; Carvalho R de A; Ferreira CAP; Nascimento Júnior J de DB (2000) A destruição de recursos naturais: o caso da castanha-do-pará no sudeste paraense. Belém: Embrapa Amazônia Oriental, 74p. Documentos, 32. ISSN 1517-2201

Homma AKO (2013) Amazônia: prioridade para as florestas ou para as áreas desmatadas? Revista Conexões 6: 7-41.

Homma, AKO (2017) A Terceira Natureza da Amazônia. Revista Paranaense de Desenvolvimento 38(132): 27-42.

Homma AKO, Menezes AJEA, Maués MM (2014) Castanheira-do-Pará: os desafios do extrativismo para plantios agrícolas. Bol. Mus. Para. Emílio Goeldi. Cienc. Nat. 9(2): 293-306.

IBGE (2021) Contas de ecossistemas: produtos florestais não madeireiros: 2006/2016/ IBGE, Coordenação de Recursos Naturais e Estudos Ambientais, Coordenação de Contas Nacionais. Rio de Janeiro: IBGE. https://biblioteca.ibge.gov.br/index.php/biblioteca-catalogo?view=detalhes&id=2101796. Accessed 17 January 2022.

INPE (National Institute for Space Research) (2022) Projeto Prodes: Monitoramento de Floresta Amazônica Brasileira por satélite. INPE (http://www.obt.inpe.br/prodes/index.php). Access September 2022.

Insam H, Gómez-Brandón M, Ascher-Jenull J (2018) Recycling of organic wastes to soil and its effect on soil organic carbon status. In: Garcia, C; Nannipieri, P; Hernandez, T The Future of Soil Carbon: Its Conservation and Formation. Academic Press, EU, pp 195-214.

IUCN (International Union for the Conservation of Nature) (1998) The IUCN Red List of Threatened Species. *Bertholletia excelsa* 1998: e.T32986A9741363. doi:10.2305/IUCN.UK.1998.RLTS.T32986A9741363.en. Accessed 6 May 2021.

Jaquetti RK, Gonçalves JFC (2017) Carbon and nutrient stocks of three Fabaceae trees used for forest restoration and subjected to fertilization in Amazonia. Anais da Academia Brasileira de Ciências 89: 1761-1771.

Jaquetti RK, Gonçalves JFC, Ferraz JBS, Ferreira MJ, Santos Junior UM, Lacerda CF (2014) Green Fertilization Enhances the Photosynthetic Performance and the Growth of Leguminous Trees for Restoration Plantation in Central Amazon. American Journal of Plant Sciences 5: 2497–2508.

Jaquetti RK, Gonçalves JFC, Ferraz JBS, Ferreira MJ, Santos Junior UM (2016) Ecofunctional traits and biomass production in leguminous tree species under fertilization treatments during forest restoration in Amazonia. Forests 7(76): 1-16.

Jaquetti RK, Gonçalves JFC, Nascimento HEM, Costa KCP, Maia JMF, Schimpl FC (2021) Fertilization and seasonality influence on the photochemical performance of tree legumes in forest plantation for area recovery in the Amazon. Plos one 16(5): e0243118.

Johann E (2021) Coppice forests in Austria: The re-introduction of traditional management systems in coppice forests in response to the decline of species and landscape and under the aspect of climate change. Forest Ecology and Management 490: 119129.

Kainer KA, Wadt LHO, Staudhammer CL (2007) Explaining variation in Brazil nut fruit production. Forest Ecology and Management 250: 244-255.

Koch, A., Kaplan, J.O. Tropical forest restoration under future climate change. Nature Climate Change 12, 279–283 (2022). https://doi.org/10.1038/s41558-022-01289-6

Lamb D (2012) Forest Restoration - The Third Big Silvicultural Challenge. Journal of Tropical Forest Science 24(3): 295-299.

Lima RMB, Souza CRS (2014) Recomendação de espaçamento para produção de madeira de castanha-do-brasil (*Bertholletia excelsa* Humb. et Bonpl.) para plantios em áreas alteradas no Amazonas. Embrapa Amazônia Ocidental. Comunicado Técnico 110.

Locatelli M, Marcante PH, Cipriani HN, Martins EP, Vieira AH (2015) Avaliação do crescimento da castanha-do-brasil (*Bertholletia excelsa* bonpl.) em um plantio no munícipio de Machadinho do Oeste – Rondônia Enciclopédia Biosfera, Centro Científico Conhecer 11(22): 457.

Louman B, David Q, Margarita N (2001) Silvicultura de Bosques Latifiliados Húmidos com ênfases em América Central. CATIE, Turrialba, Costa Rica. 265 pp.

Lovejoy T.E., Nobre, C. (2018) Amazon tipping point. Science Advances 4: art. eaat2340, doi:10.1126/sciadv.aat2340

Luize BG, Magalhães JLL, Queiroz H, Lopes MA, Venticinque EM, Leão de Moraes Novo EM, et al. (2018) The tree species pool of Amazonian wetland forests: Which species can assemble in periodically waterlogged habitats? PLoS ONE 13(5): e0198130. https://doi.org/10.1371/journal.pone.0198130

Machado KS, Maltoni KL, Santos CM, Cassiolato AMR (2014) Resíduos orgânicos e fósforo como condicionantes de solo degradado e efeitos sobre o crescimento inicial de *Dipteryx Alata* Vog. Ciência Florestal 24(3): 541-552.

Machado MR, Souza RC, Sampaio PTB, Ferraz JBS (2017) Aspectos silviculturais da castanha-do-brasil (*Bertholletia excelsa* Humb. e Bonpl.). Biota Amazônia 7(3): 41-44.

Mori SA, Prance GT (1990) Taxonomy, ecology and economic botany of the Brazil nut (*Bertholletia excelsa* Humb. and Bonpl.: Lecythidaceae). Advances in Economic Botany 8: 241-251.

Müller CH, Figueiredo FJC, Kato AK, Carvalho JEU, Stein RL, Silva AB (1995) A cultura da castanha-do-brasil. Belém, PA: EMBRAPA-CPATU, Coleção plantar 23, 65 pp.

Nogueira WLP, Ferreira MJ, Martins NOA (2015) Estabelecimento inicial de espécies florestais em plantio para a recuperação de área alterada no Amazonas. Revista de Ciências Agrárias / Amazonian Jornal of Agricultural and Environmental Sciences 58: 365-371.

Oliveira RG, Souza AS, Santos VAHF, Bezerra RM, Ferreira MJ (2021) Long-term effects of plant spacing on the growth and morphometry of *Bertholletia* excelsa. Acta Amaz. 51 (3). DOI: 10.1590/1809-4392202003611

Paiva PM, Guedes MC, Funi C (2011) Brazil nut conservation through shifting cultivation. Forest Ecology and Management 261(3): 508-514.

Passos RMO, Azevedo CP, Lima RMB, Souza CR (2018) Características biométricas e produção de frutos de castanha-da-amazônia em plantios clonais na Amazônia Central – Documentos 140, EMBRAPA, 40 pp.

Peña-Claros M, Boot RGA, Dorado-Lora J, Zonta A (2002) Enrichment planting of *Bertholletia excelsa* in secondary forest in the Bolivian Amazon: Effect of cutting line width on survival, growth and crown traits. Forest Ecology and Management 161: 159-168.

Pimentel LD, Wagner Júnior A, Santos CEM, Bruckner CH (2007) Estimativa de viabilidade econômica no cultivo da castanha-do-brasil. Informações Econômicas 37(6): 26-36.

Quisen RC, Souza VF, Castilla C (1996) Teste de sistemas agroflorestais para solos de baixa fertilidade. Avaliação da biomassa de liteira sobre o solo. IV Simpósio Internacional Sobre Ecossistemas Florestais pp. 347-348.

Salomão RP, Matos AH, Rosa NA (2002) Dinâmica de reflorestamentos visando a restauração da paisagem florestal em áreas de mineração na Amazônia. Bol. Mus. Para. Emílio Goeldi, Sér. Bot., Belém 18(1):1 57-194.

Salomão RP, Rosa NA, Castilho A, Morais KAC (2006) Castanheira-do-brasil recuperando áreas degradadas e provendo alimento e renda para comunidades da Amazônia Setentrional. Boletim do Museu Paraense Emílio Goeldi de Ciências Naturais 1: 65-78.

Santelli, A. (2021) 1,7 milhão de tartarugas são consumidas por ano no Amazonas. É possível um manejo sustentável? National Geographic Brasil, 11 May 2021. https://bit.ly/3DVeUiI

Santos VAHF, Ferreira MJ (2020) Initial establishment of commercial tree species under enrichment planting in a central amazon secondary forest: effects of silvicultural treatments. Forest Ecology and Management 460: 117822.

Santos Junior UM, Gonçalves JFC, Feldpausch TR (2006) Growth, leaf nutrient concentration and photosynthetic nutrient use efficiency in tropical tree species planted in degraded areas in central Amazonia. Forest Ecology and Management 226: 299-309.

Santos VAHF, Modolo GS, Ferreira MJ (2020) How do silvicultural treatments alter the microclimate in a Central Amazon secondary forest? A focus on light changes. Journal of Environmental Management 254: 109816.

Selaya NG, Zuidema PA, Baraloto C, Vos VA, Brienen RJW, Pitman N, Brown F, Duchelle AE, Araujo-Murakami A, Carilloo LAO, Chupinagua GH, Nay HF, Perz S (2017) Economically important species dominate aboveground carbon storage in forests of southwestern Amazonia. Ecology and Society 22(2):40.

Schroth G, Mota M, Elias MEA (2015) Growth and nutrient accumulation of Brazil nut trees (*Bertholletia excelsa*) in agroforestry at different fertilizer levels. Journal of Forestry Research 26: 347-353.

Scoles R (2011) Do rio Madeira ao rio Trombetas: novas evidências ecológicas e históricas da origem antrópica dos castanhais amazônicos. Novos Cadernos NAEA 14(2): 265-282.

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

Scoles R, Klein GN, Gribel R (2014) Crescimento e sobrevivência de castanheira (*Bertholletia excelsa* Bonpl., Lecythidaceae) plantada em diferentes condições de luminosidade após seis anos de plantio na região do rio Trombetas, Oriximiná, Pará. Bol. Mus. Para. Emílio Goeldi. Cienc. Nat. 9(2): 321-336.

Scoles R, Gribel R (2021) Growth and survival over ten years of Brazil-nut trees planted in three anthropogenic habitats in northern Amazonia. Agronomy and Forestry, Acta Amaz. 51 (1). https://doi.org/10.1590/1809-4392202001462

Souza C, Santos VA, Ferreira MJ, Gonçalves JFC (2017) Biomassa, crescimento e respostas ecofisiológicas de plantas jovens de *Bertholletia excelsa* Bonpl. submetidas a diferentes níveis de irradiância. Ciência Florestal 27:557-569.

Tapia-Coral SC, Luizão FJ, Wandelli E, Fernandes ECM (2005) Carbon and nutrient stocks in the litter layer of agroforestry systems in central Amazonia, Brazil. Agroforestry Systems 65: 33-42.

Thomas E, Atkinson R, Kettle C (2018) Fine-scale processes shape ecosystem service provision by an Amazonian hyperdominant tree species. Scientific Reports 8: 11690.

Thomas E, Valdivia J, Alcázar Caicedo C, Quaedvlieg J, Wadt LHO, Corvera R (2017) NTFP harvesters as citizen scientists: Validating traditional and crowdsourced knowledge on seed production of Brazil nut trees in the Peruvian Amazon. PLoS 12:e0183743.

Tonini H, Costa P, Kaminski PE (2008) Estrutura e produção de duas populações nativas de castanheira-do-Brasil (*Bertholletia excelsa* O. Berg) em Roraima. Floresta 38(3): 445-457.

Tourne DCM, Ballester MVR, James PMA, Martorano LG, Guedes MC, Thomas E (2019) Strategies to optimize modeling habitat suitability of Bertholletia excelsa in the Pan-Amazonia. Ecol Evol. 9:12623–38.

Turchetto F, Araujo MM, Tabaldi LA, Griebeler AM, Rorato DG, Berghetti ALP, Barbosa FM, Lima MS, Costella C, Sasso VM (2020) Intensive silvicultural practices drive the forest restoration in southern Brazil. Forest Ecology and Management 473: 118325.

Vilhena MR (2004) Ciência, tecnologia e desenvolvimento na economia da castanha-do-brasil - A transformação industrial da castanha-do-brasil na COMARU - Região Sul do Amapá. Dissertation, Universidade Estadual de Campinas.

Walker, R.T. (2021) Collision course: Development pushes Amazonia toward its tipping point. Environment: Science and Policy for Sustainable Development 63(1): 15-25. doi:10.1080/00139157.2021.1842711

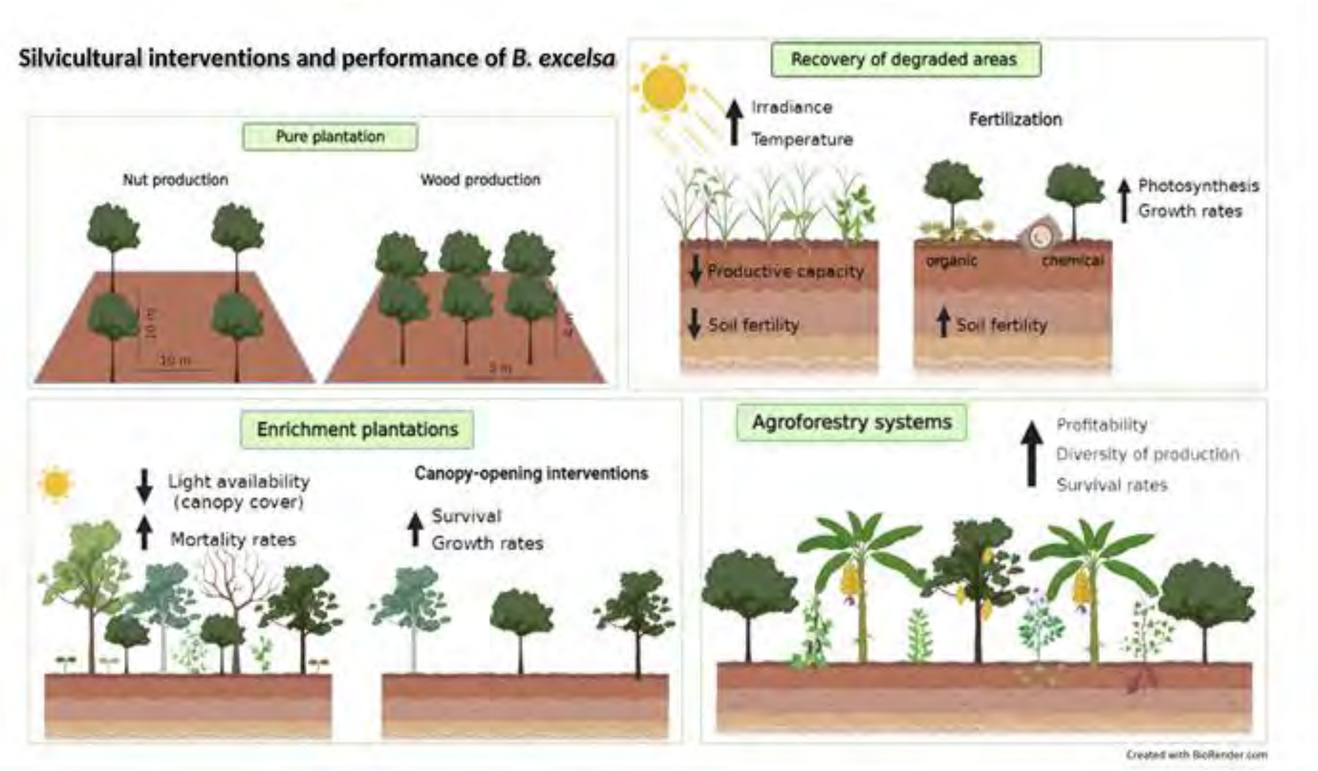

Figure 1) Illustration of the cause-and-effect relationship between silvicultural interventions of *B. excelsa* grown in different planting arrangements.

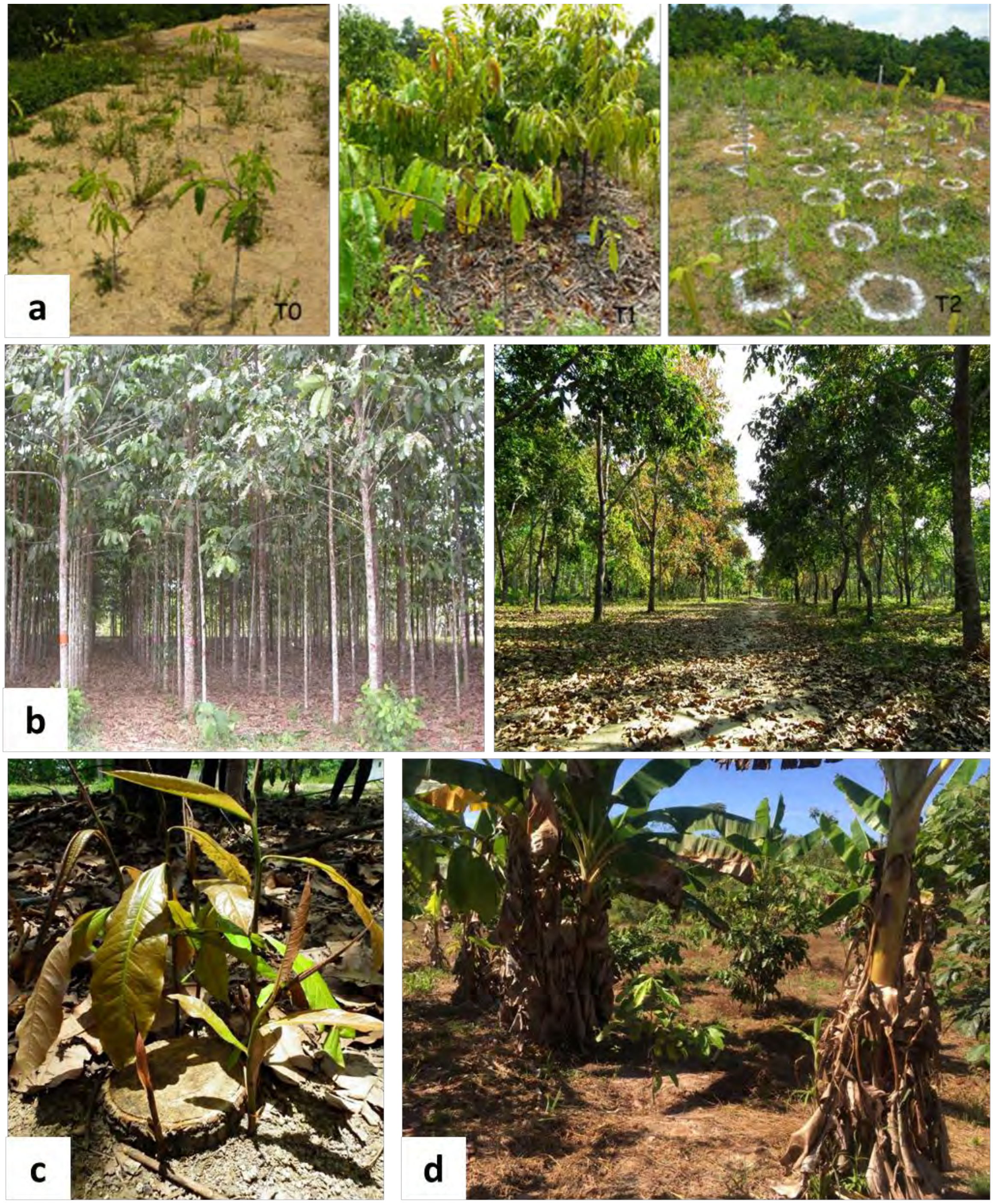

Figure 2) Brazil nut plantations on degraded areas (Fig 1a) without fertilization (T0), organic fertilization (T1) and mineral fertilization (T2). Manaus, Amazonas – Brazil; (Fig 1b) Brazil nut plantations for timber and nuts production, Fazenda Aruanã Itacoatiara, AM, Brazil.; (Fig 1c) Growth of Brazil nut sprouts after thinning. Fazenda Aruanã, Itacoatiara, AM, Brazil. Fonte: Laboratório de Fisiologia e Bioquímica Vegetal – LBFV/INPA; (Fig 1d) Brazil nut in AFS in a degraded area, Marabá, Pará, Brazil. Fonte: Laboratório de Agrobiodiversidade de Carajás – Unifesspa.