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# 1 **Silvicultural interventions and agroforestry systems increase the economic and**

## 2 **ecological value of *Bertholletia excelsa* plantations in the Amazon**

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### 21 **Abstract**

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

38

39 **Keywords:** Forest plantations, productive plantations, reforestation, silvicultural treatments,  
40 sustainability.

41 **Highlights:**

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

44 Planting to recover degraded areas requires fertilization to gain productivity.

45 Enrichment of secondary forests requires thinning and understory cleaning.

46 Reforestation and avoiding deforestation are complementary, not competitive processes.

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

49

50 **Introduction**

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

65 *Bertholletia excelsa* Bonpl is a large, tropical, evergreen tree in the family  
66 Lecythidaceae that can reach 60 m in height and 4 m in diameter (Mori and Prance  
67 1990). This species has adaptive plasticity to the availability of nutrients, water, and  
68 light in sites and tolerance to different types of abiotic stresses, according to several  
69 studies conducted in different phenological phases and cultivation conditions of *B.*  
70 *excelsa* (Morais et al. 2007; Ferreira et al. 2012, 2015, 2016; Schimpl et al. 2018; Lopes  
71 et al. 2019; Costa et al. 2020; da Costa et al. 2022). This tree produces an indehiscent  
72 capsule fruit with nutritious seeds, called Brazil nuts, that are sold throughout Brazil and  
73 exported to other countries (Muller et al. 1995; Scoles and Gribel 2011). Each fruit  
74 contains around 18 seeds and can weigh up to 2.5 kg (Mori and Prance 1990; Scoles and  
75 Gribel 2011). Brazil nut has a high content of calcium, phosphorus, magnesium,  
76 potassium, barium, and selenium (Gonçalves et al. 2002; Silva Junior et al. 2022).

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

87 Despite its socio-economic and ecological relevance, *B. excelsa* is vulnerable to  
88 extinction. Even though in 1994 a ban was decreed on the cutting of Brazil nut trees in  
89 native, primitive, or regenerated forests [Decree n° 1282, of October 19, 1994] (Brazil  
90 1994), the native populations of Brazil nuts continue to decrease due to the illegal  
91 logging. This fact increases the risk of extinction and compromises the availability of  
92 genetic material (IUCN 1998; Angelo et al. 2013; Homma et al. 2014; Chiriboga-  
93 Arroyo et al. 2020). The species is also vulnerable to the reduction of environmentally  
94 suitable areas caused by climate change (Evangelista-Vale et al. 2021).

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

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

## 111 1. Plantations for Recovery of degraded areas (RDA)

112 Deforestation in the Amazon basin has remained high over the years, with a  
113 record increase in the rate by about 20% of between 2020 and 2021 (Silva Junior et al.  
114 2021, INPE 2022). Deforested areas have higher irradiance and temperature and lose  
115 soil fertility (Santos Junior et al. 2006; Jaquetti et al. 2021). Through the selection and  
116 plantation of well-adapted species, biomass and ecosystem services can be recovered,  
117 restoring important biogeochemical cycles such as C and N (Nogueira et al. 2015;  
118 Jaquetti et al. 2016, 2021; Jaquetti and Gonçalves 2017). Introducing commercial  
119 species during forest restoration may help to restore unproductive areas to become  
120 productive forest systems (Lamb 2012; Homma 2017; Ferreira et al. 2016; Costa et al.  
121 2022).

122 *B. excelsa* is one of the native species with the greatest ecological aptitudes for  
123 RDA in the Amazon region, including mining areas (Ferreira and Tonini 2009; Salomão  
124 et al. 2006; Ferreira et al. 2012, 2015; Locatelli et al. 2015; Costa et al. 2022).  
125 Plantations of the species can reach absolute growth rates in diameter ( $AGR_D$ ) of 1.02  
126  $\text{cm year}^{-1}$  and height ( $AGR_H$ ) of 0.77  $\text{m year}^{-1}$  18 years after planting (Salomão et al.  
127 2006). Studies have been conducted to evaluate silvicultural treatments that favor the  
128 recovery of soil quality, increase the efficiency of resource use, and minimize stress  
129 factors during the initial establishment of seedlings, which is fundamental for  
130 conducting a productive planting (Campoe et al. 2014; Ferreira et al. 2012). Ferreira et  
131 al. (2009) demonstrated how chemical and organic fertilization treatments reduced  
132 stress responses. Compared to unfertilized plants, fertilized *B. excelsa* enhanced  
133 photosynthesis, water use-efficiency, and photochemical performance as represented by  
134 increased values of the performance index ( $PI_{ABS}$ ) and by the maximum photochemical  
135 efficiency ( $F_V/F_M$ ) values of chlorophyll *a* fluorescence (Ferreira et al. 2009, 2012,  
136 2015).

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

## 151 2. Enrichment plantations

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

159 Some studies have demonstrated that silvicultural interventions to increase light  
160 availability increase survival and the growth of the *B. excelsa* in enrichment plantations  
161 (Peña-Claros 2002). Scoles et al. (2014) compared the effect of different light  
162 environments on the performance of *B. excelsa* seedlings and observed survival rates of  
163 77% when planted in *capoeira* and of 21% when planted in the understories of native  
164 *castanhais* (sites with clusters of *B. excelsa* trees). These authors found that growth  
165 rates in *capoeira* were  $21.6 \text{ cm year}^{-1}$  for height and  $0.31 \text{ cm year}^{-1}$  for diameter in the  
166 sixth year, while in the understory the growth rates were  $4.7 \text{ cm year}^{-1}$  for height and  
167  $0.10 \text{ cm year}^{-1}$  for diameter (Scoles et al. 2014). Higher values of survival and annual  
168 growth in height and diameter in seedlings of *B. excelsa* were observed by Garate-  
169 Quispe et al. (2020) after canopy-opening interventions. A positive correlation was  
170 found between the opening of the canopy (increased irradiance) and growth rates in  
171 height and diameter (Garate-Quispe et al. 2020; Santos and Ferreira 2020). Tree  
172 mortality was higher in the forest understory (81.2 %) compared to forest gaps (25%)  
173 (Garate-Quispe et al. 2020). Due to the higher performance and high survival rate of *B.*  
174 *excelsa* seedlings in the gaps opened by falling trees, enrichment planting is  
175 recommended in gaps in natural forests and in *capoeiras* (Garate-Quispe et al. 2020).

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

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

185 treatments. Higher growth rates were found for the 6 m wide planting lines and the  
186 total-clearing treatments (Peña-Claros et al. 2002).

187 Despite *B. excelsa* being considered a shade-tolerant species with an emerging  
188 canopy in natural forests, the species has higher growth and survival when planted in  
189 high light environments. Additionally, the growth rates depend greatly on soil fertility  
190 and nutrient additions. In contrast, the use of *B. excelsa* to enrich the understory of  
191 natural forests appears to be unsuitable, as is reflected by the low growth rates and high  
192 mortality of individuals. But overall, clearing, and thinning treatments are important for  
193 enhancing productivity when used in naturally regenerating areas with the opening of  
194 25 to 50 % of the canopy as recommended by Garate-Quispe et al. (2020). Additionally,  
195 planting taller seedlings (more than 70 cm) may reduce herbivory and weed  
196 competition.

### 197 3. Pure plantations

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

208 The recommended spacing for the development of the crowns for nut production  
209 in commercial monoplantations is 10 x 10 m (Locatelli et al. 2015; Passos et al. 2018).  
210 In a monoplantation for nut production in Amazonas state, Brazil, a positive correlation  
211 was found between capsule weight and diameter at breast height (DBH) (Passos et al.  
212 2018). Among selected genetic clones from the Brazilian Agricultural Research  
213 Corporation (EMBRAPA), the Manoel Pedro, Aruanã, and Santa Fé clones had higher  
214 growth in diameter and height 31 years after plantation. With an average production of  
215 80 capsules and 12 kg tree<sup>-1</sup> of nut weight, Manoel Pedro was more productive than the  
216 other clones studied (Passos et al. 2018). Nevertheless, *B. excelsa* can take from 15 to  
217 25 years to produce nuts at a commercial scale. This can be a strong limitation for the  
218 establishment of productive monoplantations (Homma et al. 2014).

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

228 In a plantation with 12 x 12-m spacing with phosphorus fertilization and  
229 mowing, *B. excelsa* had an 86% survival rate and a relative growth rate in diameter  
230 (RGR<sub>D</sub>) of 2.15 cm year<sup>-1</sup> 28 years after planting (Locatelli et al. 2015). The species  
231 produced an average of 3.1 m<sup>3</sup> per tree totaling 269.72 m<sup>3</sup> in volume per hectare  
232 (Locatelli et al. 2015). The authors projected the technical age of harvest (TAH) at 25

233 years for the best productivity and income (Locatelli et al. 2015). Annual volume  
234 increase reached maximum values 12 years after plantation when thinning treatments  
235 were employed to avoid stagnation of diameter growth.

236 The combination of thinning, phosphorus fertilization, and liming effects on the  
237 photochemical performance of *B. excelsa* have recently been studied in plantations for  
238 wood production (Costa et al. 2020). The liming and fertilization treatments were  
239 important for maintaining photosynthesis and reducing stress after thinning. The rapid  
240 recovery responses and high efficiency of light use were reflected in the  $F_v/F_M$  and  
241  $PI_{ABS}$  values (Costa et al. 2020). Despite leaves and branches representing only 27% of  
242 total individual biomass, the higher concentration of nutrients highlights the importance  
243 of leaving the harvest residues in the planted area to maintain soil fertility (Costa et al.  
244 2015; Schroth et al. 2015). However, *B. excelsa* may export 8.0 Mg ha<sup>-1</sup> of carbon (C)  
245 in the first thinning 8 years after planting (Costa et al. 2015).

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

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

#### 260 4. Agroforestry systems

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

272 In general, agroforestry research with *B. excelsa* combines trees and annual  
273 crops to increase income during the first years of *B. excelsa* development. Livestock  
274 may also be included in these systems (Homma et al. 2014). Agroforestry can sustain  
275 soil fertility after crop rotation due to better exploitation of deeper soil layers by the  
276 roots of trees (Tapia-Coral et al. 2005, Costa et al. 2009). Moreover, the biomass  
277 production and development of the organic layer induced by *B. excelsa* favor the  
278 cycling of important nutrients and increase of C stocks in the soil (Tapia-Coral et al.  
279 2005). *B. excelsa* has been used in AFS in Tomé-Açu in Pará State, Eastern Brazilian

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

282 AFS with *B. excelsa* may also increase growth rates of the species with an  
283 average  $AGR_D$  of 2 to 3  $cm\ year^{-1}$  and  $AGR_H$  of 1 to 2  $m\ year^{-1}$  between seven and  
284 twelve years after planting (Costa et al. 2009; Ferreira and Tonini 2009; Schroth et al.  
285 2015). An  $AGR_D$  of 2.13  $cm\ year^{-1}$  was observed for *B. excelsa* when interplanted with  
286 *Theobroma grandiflorum* 28 years after planting (Locatelli et al. 2015). The great  
287 variation in the size and biomass of individuals highlights the potential for genetic  
288 improvement of the species (Schroth et al. 2015).

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

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

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

311 Markets and other factors limit the extent to which AFS can achieve recovery  
312 of the vast areas of degraded cattle pasture in Brazilian Amazonia (Fearnside 1995a,  
313 2009). This article emphasizes that the Brazil nut tree has demonstrated in both cases,  
314 plantations with silvicultural treatments applied to recover degraded areas and  
315 agroforestry, excellent results (Costa et al. 2022). In other words, these results reinforce  
316 the importance of agroforestry that includes *B. excelsa* in the Amazon as part of a  
317 circular bioeconomy that contributes to improving the environment and local  
318 livelihoods.

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

## 322 **Conclusions and future perspectives**

323 *B. excelsa* has great potential to be used in different forest plantation  
324 arrangements. Considering the time required for nut and wood products and the  
325 increased growth rates, the species is mostly recommended to be planted in agroforestry

326 systems. On the other hand, the species also demonstrates good responses in  
327 monoplantations. As a native species that produces goods and services, *B. excelsa* can  
328 be successfully planted to restore degraded environments showing satisfactory survival  
329 rates. To enrich the natural regeneration of forests the spacing and light availability  
330 mainly should be carefully considered. Additionally, leaving pruning and thinning  
331 residues in the area during harvest is recommended to sustain soil fertility.

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

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

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

344

#### 345 **Statements and Declarations**

346 The authors declare that there is no conflict of interest.

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#### 364 **Author contributions**

365 Jessica Pereira de Souza has written the manuscript with conceptual support from José  
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369 versions of the manuscript. All authors read and approved the final manuscript.

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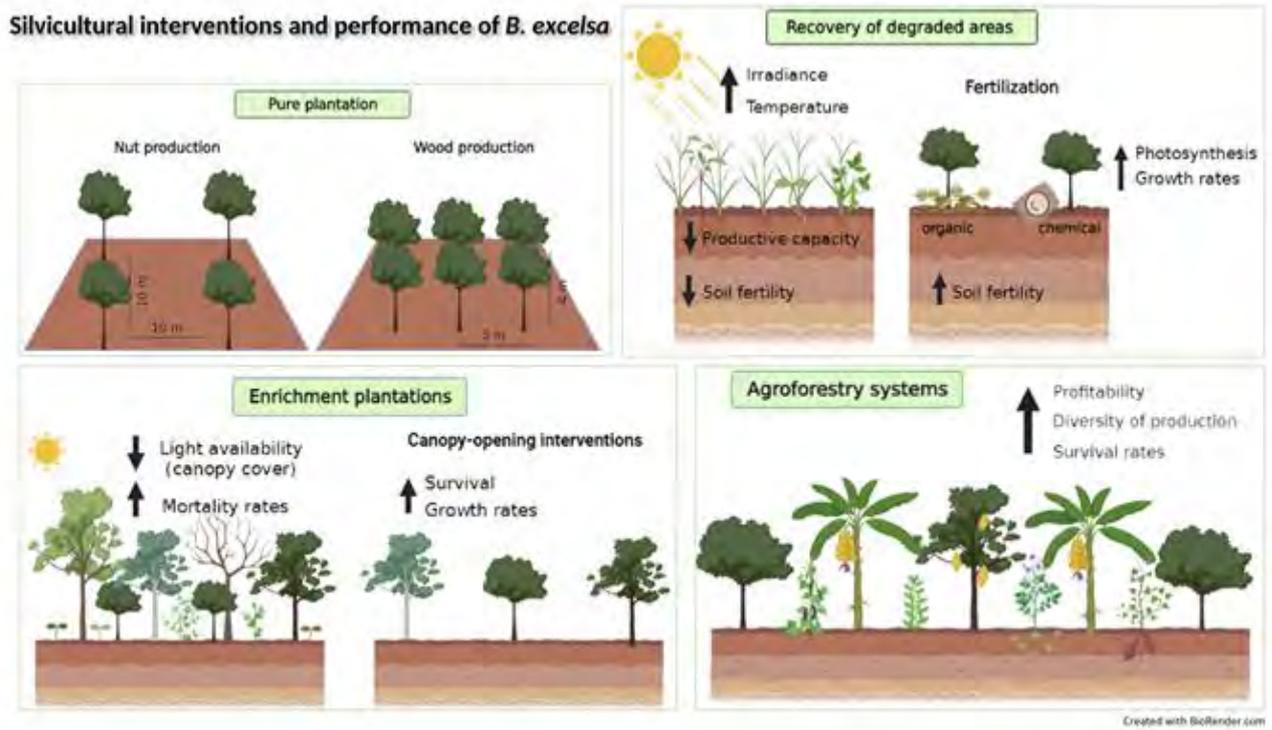
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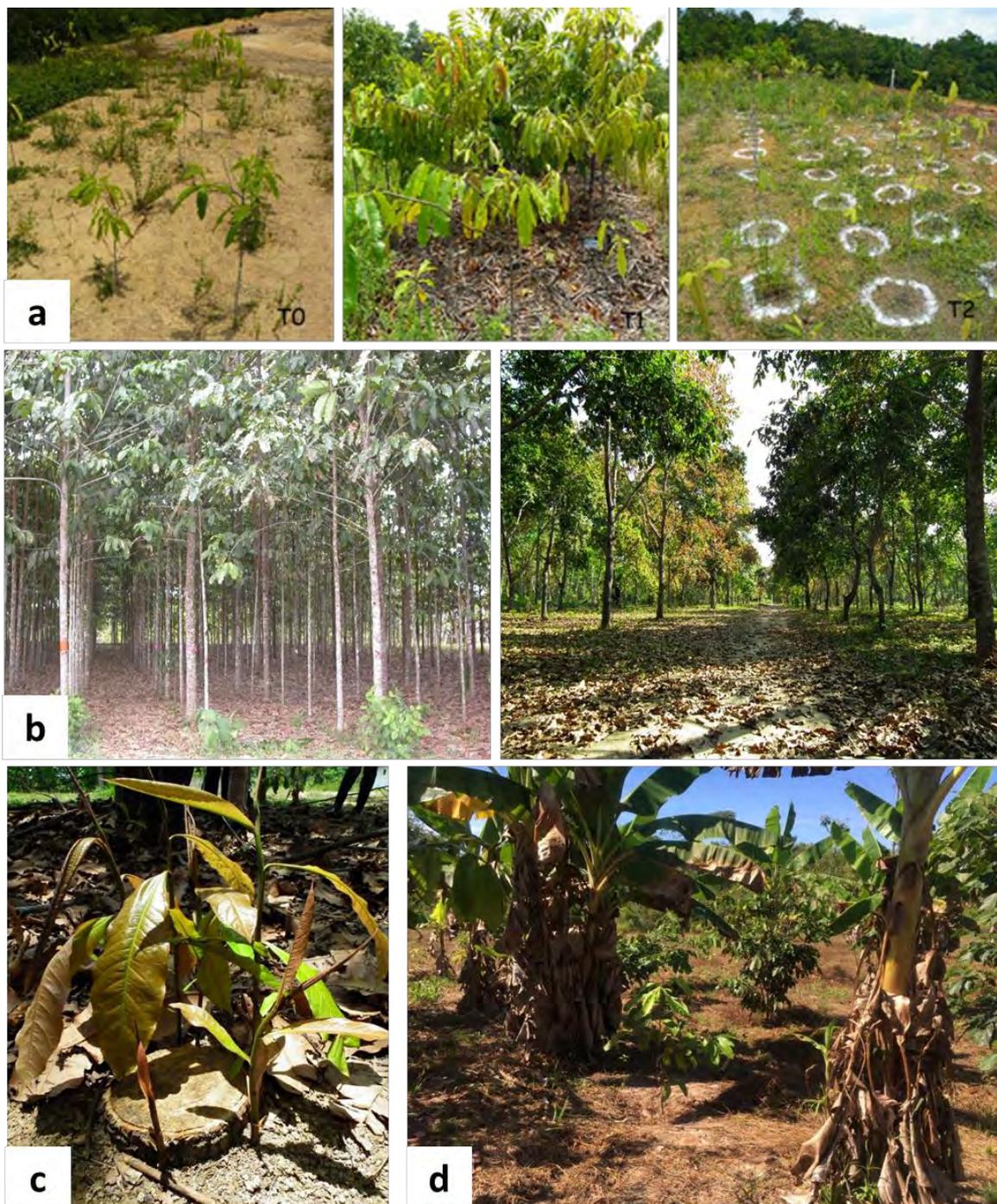
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660  
661 **Figure 1)** Illustration of the cause-and-effect relationship between silvicultural  
662 interventions of *B. excelsa* grown in different planting arrangements.



663

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