

Chapter

Threats and Sustainability of Brazil Nut (*Bertholletia excelsa* Bonpl.) Pre-Industrialization in the Amazon Region

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Abstract

Brazil nut (*Bertholletia excelsa*) is an important species in the Amazon, but the relationships between seed production and climate change are still poorly understood. Seed production data were obtained for the entire Brazilian Amazon, while data on precipitation, relative humidity, vapor pressure deficit, and temperature (mean and maximum) were collected to test their relationship with seed production in the Baixo Amazonas. Annual seed production in the Baixo Amazonas varied between 2156 and 10,235 tons per year from 1990 to 2021, with an average of 5192 tons per year. Linear regression analyses did not identify significant relationships between seed production and climatic variables during the same year ($p > 0.05$). However, significant relationships were found between the volume of seeds in the base year and climatic variables from 1 year before seed collection ($p < 0.05$), except for total precipitation ($p = 0.15$). Temperature was the main climatic variable affecting Brazil nut production, indicating that each 1°C increase in temperature is associated with an average decrease in seed volume ranging from 2595 to 2673 tons. Temperature measures explain between 38% and 42% of the variability in seed volume in the Baixo Amazonas. Therefore, it is crucial to mitigate global warming, invest in technological processes to add value to the remaining seeds, and adopt *B. excelsa* varieties more adapted to climate change.

Keywords: Brazilian Amazon, climate change, climatic variability, El Niño, industrialization, non-timber forest product, relative humidity, temperature, vapor pressure deficit

1. Introduction

Brazil nut (*Bertholletia excelsa* Bonpl.) holds a key role in socio-bioeconomies [1, 2] providing vital economic inputs to local, national, and global markets during different seasons and bringing benefits to tens of thousands of small-scale producers [3] who live under a diversified economic portfolio [4]. It is also a source of food consumed in various forms, including fresh, roasted, or pressed for milk-like extract [5] within the Amazon, and outside (e.g., USA, China). Brazil is one of the leading

producers of Brazil nut harvesting 33,406 metric tons in 2021 [6]. *B. excelsa* is a monotypic genus of Lecythidaceae, a pantropical botanic family. These trees can reach heights of up to 60 meters and diameters of 5 meters, often occupying upland moist forest (non-flooded) and transitional zones between Amazon forests and Cerrado savannas, with some trees reaching up to 1000 years old [1, 5].

Human influences have contributed to shaping the geographic distribution and abundance of Brazil nuts in the Amazon, following the movement of Indigenous peoples across the Amazon for thousands of years by mean of area expansion and shifting cultivation activities [5, 7, 8]. Today the Brazil Nut is one of the 20 super-dominant trees of the Amazon contributing beyond food security to the carbon cycle of the forest [9, 10]. The economy of the Brazil Nut in the Amazon is a forest-based extractive activity [6]. Brazil Nut trees form biodiverse forests gathered and traded by traditional communities, including extractivists, Indigenous groups, and African descendants (quilombola) [11–13]. This dynamic collaboration yields most of the Brazil nuts, creating a dual impact of income generation and biodiversity conservation [13, 14], impacting positively local people's livelihoods [15]. Brazil nut management may account for >40% of the annual extractivist family income [12].

The flowering phase is most pronounced during the driest months corresponding to the period of longer photoperiods. The mutualistic interactions between Brazil nut and their pollinators have significant implications for fruit production [16]. Fruiting occurs during the early rainy season (e.g., SON). The maturation process that lasts about 14 months indicates that the environmental conditions and biological interactions that occurred in the previous year can impact Brazil nut productivity in the following year [17]. Research conducted by Maués in 2002 revealed that precipitation, temperature, relative humidity, and photoperiod play a role in shaping the phenology of *B. excelsa* [17]. Pastana et al. showed that in a forest-savanna transition in the eastern Brazilian Amazon, the 2015/2016 El Niño phenomenon, when temperatures of the ocean increased more than 2°C during the dry season, fruit production decreased by up to 97% in 2017 [18]. The temporal variability in Brazil nut productivity influenced by climate oscillations pose major social and economic impacts on such forest-based extractivist communities in the Amazon, in some cases increasing by a quarter the prices of nut production unit (from USD 10 in 2016 to USD 38 in 2017) [18].

While Brazil nuts have gained significant economic importance in terms of both form and production volume, deforestation and climate changes are major threats to forest resilience impacting mainly large trees, subjected to drier and warmer climate, such as the Brazil nut tree [19, 20]. However, because the reproductive success of Brazil nut is intrinsically linked to the interaction of climatic conditions, pollination dynamics and human activities, the limits of resilience to the increasing changes in forest climate are not fully understood. Recent study, for instance, indicates that climate change could impact positively *B. excelsa* but only when seedlings are irrigated pointing to the fact that water restriction in the dry season in the Amazon is a key limiting factor [21].

To observe how seed productivity of Brazil nut varies across time and assess the potential impact of climate on its productivity, we compared temporal patterns of nut production between 1990 and 2021 in the Brazilian Amazon and in different socioecological Amazon sub-regions. To assess the influence of the climate variability on seed productivity we took the mesoregion Baixo Amazonas, one of the regions of the Amazon with the highest historical productivity and socioeconomic importance for the Brazil nut national market. Understanding the influence of climate variability in productivity provides an indicator of ecosystem stability and resilience, guiding sustainability of forest management systems [12].

2. Material and methods

2.1 Study area

The Amazon Forest is located in South America (**Figure 1A**). The forest region covers 6.3 million square kilometers, spanning Brazil, Bolivia, Colombia, Ecuador, French Guiana, Guyana, Peru, Suriname, and Venezuela. The human population in the region is estimated at 38 million inhabitants [26], with indications of 6 million

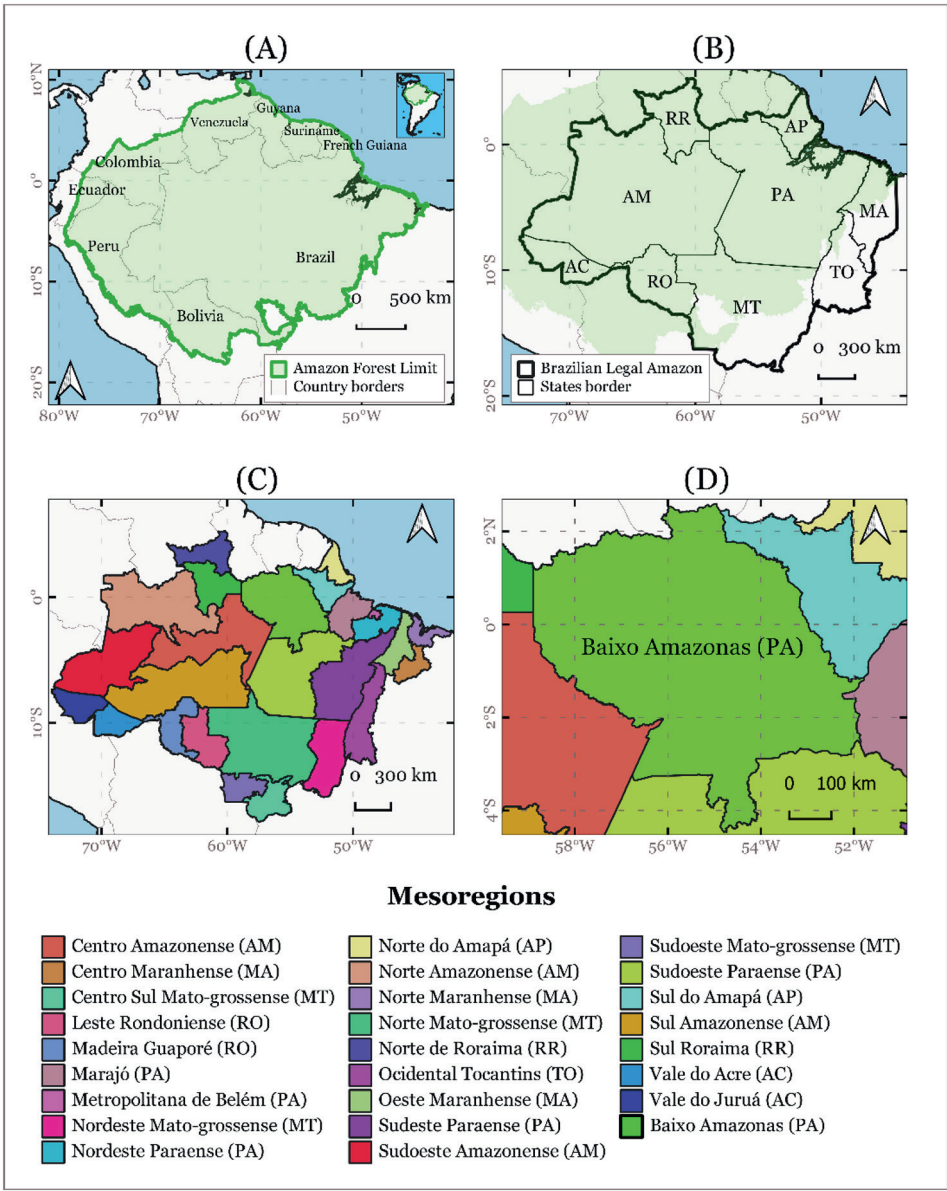


Figure 1.
 Study area. Data source: INPE [22], QGIS [23], IBGE [24, 25].

people directly dependent on the forest for subsistence in the Brazilian Amazon [27]. The study area is located in Brazil (**Figure 1B**), occupying approximately 4.2 million square kilometers [24].

The study area was subdivided into mesoregions, which were analyzed in terms of Brazil nut production volume (**Figure 1C**). As defined by Brazilian Institute of Geography and Statistics [25], a mesoregion is a geographical delineation within a Federal Unit, shaped by the dimensions of social processes as a determining factor, natural conditions as a conditioning factor, and the network of communication and places as elements of spatial articulation. These dimensions collectively confer a regional identity to the mesoregion, a construction over time by the local society. In total, the study area consisted of 26 mesoregions, which together covered a total area of 4.7 million square kilometers (**Figure 1C**).

The study of interactions between seed production and climatic variables focuses specifically on the Baixo Amazonas mesoregion, located in the northwest of the state of Pará (**Figure 1D**). Baixo Amazonas is the most important mesoregion for Brazil nut production in the state of Pará's non-timber forest extraction [6]. The Baixo Amazonas mesoregion consists of 13 municipalities (county) that make up the territory: Alenquer, Almeirim, Belterra, Curuá, Mojuí dos Campos, Faro, Juruti, Monte Alegre, Óbidos, Oriximiná, Prainha, Santarém, and Terra Santa, with an estimated population of 785,000 inhabitants in 2022 [28]. The region covers an area of 340,000 square kilometers, roughly the size of Germany (357,000 square kilometers).

2.2 Brazil nut production data

The information regarding Brazil nut seed (**Figure 2**) production was obtained from sources at the Brazilian Institute of Geography and Statistics [6]. IBGE conducts annual data collection through the administration of questionnaires in each municipality within the study area. IBGE gathers this information by consulting agricultural



Figure 2.
Seeds of Bertholletia excelsa (Brazil nut). Photo source: Diego Oliveira Brandão.

and livestock establishments, industries, companies, government agencies, and other organizations involved in Brazil nut extraction, using the reference year as the survey's base. The dissemination of data is carried out through the IBGE Automated Recovery System (SIDRA), under the Production of Vegetable Extraction and Forestry (PEVS) survey, Table 289, and is accessible openly and online. The information regarding the quantity of Brazil nut seed production is expressed in tons. The data used covers the period from 1990 to 2021 and was collected for all mesoregions within the study area (**Figure 1C**).

2.3 Climatic variable data

Monthly climate data for precipitation, relative humidity, and temperature (average and maximum) were obtained from the Meteorological Database (BDMEP) of the National Institute of Meteorology of Brazil [29] to represent the climatic variations in the Baixo Amazonas mesoregion. These climate data originated from meteorological station 82,178, located in the municipality of Óbidos, Pará, Brazil, in the Baixo Amazonas mesoregion. This station is at an altitude of 54.7 meters, latitude -1.905° S, and longitude -55.52° W, and operated from January 1927 until July 2021, currently being closed. The data covered the period from 1989 to 2020 and were requested on July 24 and August 28, 2023.

The monthly climate data was transformed into annual climate data using the arithmetic mean. This calculation was done by summing the monthly values and dividing the result by 12 (the number of months in a year). However, in some cases, monthly climate data for certain variables were not available from the BDMEP. To fill in these missing data, the monthly arithmetic mean for the period from 1989 to 2020 was used. However, it's important to mention that the maximum and average temperature data for the years 2019 and 2020 were also unavailable, and it wasn't possible to fill them with the arithmetic mean. The missing data represented 4% of precipitation data, 2% of relative humidity data, and 2% of temperature data (average and maximum).

Finally, annual climate data for Vapor Pressure Deficit (VPD) was obtained. However, INMET did not provide VPD data at the Óbidos station [29]. Therefore, the VPD calculator [30] from the College of Agriculture and Life Science at the University of Arizona was used to obtain annual climate data for VPD from annual climate data for relative humidity and average temperature obtained at the Óbidos station. VPD data is a climatic variable used to assess plant water stress [31]. MS-Excel software was used to process the climate data.

2.4 Data analyses

Analyses of variations in Brazil nut production were conducted for the Brazilian Amazon and the 26 mesoregions studied between 1990 and 2021 and are presented graphically. These results were also presented with statistics including minimum, maximum, arithmetic mean, and standard deviation. All the graphical figures presented were created by the authors using the software MS-Excel, R, and QGIS.

The Baixo Amazonas mesoregion (PA) was selected as the case study to assess the impact of climatic variables on the temporal fluctuations in Brazil nut production. This region, besides being one of the largest Brazil nut producers in the Amazon, also provides long-term time series of climatic data. Therefore, simple linear regression analyses were conducted to investigate the relationship between Brazil nut production and each of the five climatic variables.

The regression analyses were conducted using the climatic data from the same year in which the Brazil nut production data were recorded (referred to as the ‘base year’). Additionally, climatic data from 1 year before seed collection were correlated with the seed production observations in the base year. This allowed for the assessment of potential delays in the response of Brazil nut production to annual climatic variations. Before conducting these analyses, the Shapiro-Wilk test was performed to check the normality of the seed production data, including residual analysis.

The values of intercept, slope coefficient, adjusted R-squared, and p-value estimated by the models were presented in the figure depicting the relationship between seed production and climatic variables. The intercept and slope coefficient represent the model’s fitting parameters. The R-squared value and p-value indicate the explanatory power of the model and its significance. Hypothesis testing and model construction were conducted using the statistical software R, version 4.3.1 [32].

3. Results

3.1 Annual Brazil nut production in the Brazilian Amazon

Brazil nut seed production in the Brazilian Amazon between 1990 and 2021 exhibited significant variations (**Figure 3**). Annual production ranged from a minimum of 21,468 tons (1996) to a maximum of 50,521 tons (1990). The years with relatively lower production were 1992, 1993, 1996, 1997, 1998, 1999, 2003, and 2017, representing the lower 25% of the data when production was below 27,008 tons. On the other

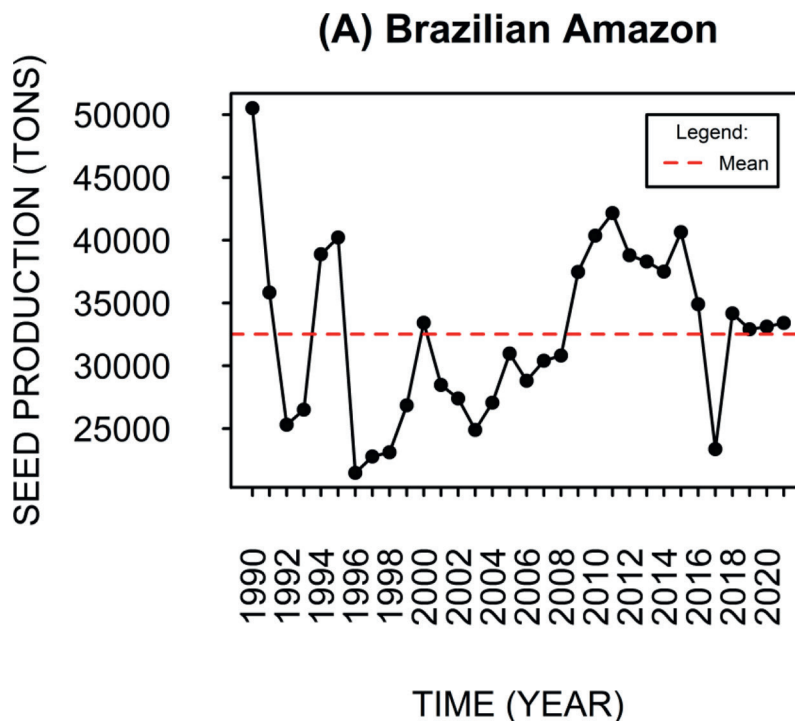


Figure 3.
Quantity of seeds produced in the Brazilian Amazon between 1990 and 2021. Data source: IBGE [6].

hand, the years with higher production were 1990, 1994, 2010, 2011, 2012, 2013, and 2015, representing the upper 75% of the data when production exceeded 37,701 tons. The average annual production was 32,525 tons, with a dispersion around this average indicated by a standard deviation of 6844 tons.

The average seed production in the 26 studied mesoregions showed significant variability (**Figure 4**). Out of these mesoregions, a total of 18 had seed production during the analyzed period (**Table 1**). On the other hand, eight mesoregions did not record any seed production during the study period. Among these, six were located in the states of Maranhão (Norte Maranhense, Oeste Maranhense, and Centro Maranhense) and Mato Grosso (Centro Sul Mato-grossense, Nordeste Mato-grossense, and Sudoeste Mato-grossense). The other two mesoregions that did not have seed production were Vale do Juruá (AC) and Norte do Amapá (AP). These results highlight significant differences in seed production among the mesoregions during the study period (**Figure 4; Table 1**).

Regarding the most productive mesoregions, five stood out in terms of average seed production volume (**Figure 5**): Vale do Acre (AC), Sul Amazonense (AM), Baixo Amazonas (AM), Centro Amazonense (AM), and Madeira Guaporé (RO). These five mesoregions are within the upper 75% of the average data (3rd quartile) and are located along a diagonal that extends from the northeast to the southwest of the Brazilian Amazon.

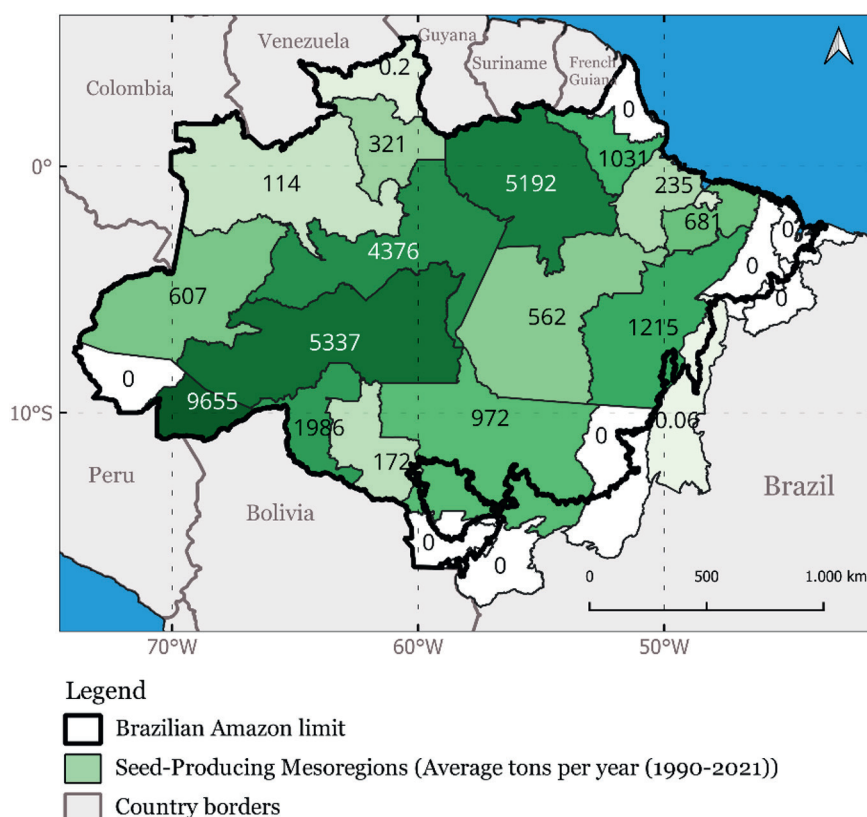


Figure 4.
 The average Brazil nut production in the Brazilian Amazon mesoregions from 1990 to 2021. Data source: IBGE [6].

Mesoregion (State)	Minimum (year)	Maximum (year)	Mean	Standard deviation
Vale do Acre (AC)	3378 (1997)	17,497 (1990)	9665	3623
Sul Amazonense (AM)	87 (1992)	10,378 (1994)	5337	1834
Baixo Amazonas (PA)	2156 (1999)	10,235 (1990)	5192	1781
Centro Amazonense (AM)	101 (1992)	10,049 (2009)	4376	2630
Madeira Guaporé (RO)	364 (1997)	6424 (2000)	1986	1378
Sudeste Paraense (PA)	582 (2021)	2872 (1991)	1215	563
Sul do Amapá (AP)	390 (2009)	2250 (1990)	1031	610
Norte Mato-grossense (MT)	230 (1997)	2234 (2011)	972	730
Nordeste Paraense (PA)	434 (1996)	1237 (2016)	681	248
Sudoeste Amazonense (AM)	2 (1993)	1033 (2010)	607	316
Sudoeste Paraense (PA)	126 (2017)	2118 (1990)	562	435
Sul de Roraima (RR)	0 (1992–1997)	2230 (2018)	321	658
Marajó (PA)	137 (1990)	335 (2015)	235	56
Leste Rondoniense (RO)	31 (2002)	581 (1998)	172	151
Norte Amazonense (AM)	0 (1991)	358 (2014)	114	123
Metropolitana de Belém (PA)	4 (1994–1995)	121 (2015)	57	40
Norte de Roraima (RR)	0 (*)	6 (2017)	0.2	1
Ocidental de Tocantins (TO)	0 (*)	2 (2017)	0.06	0.36

**Every year except for 2017.
Data source: IBGE [6].*

Table 1.
Statistics for the quantity (in tonnes) of Brazil nut seeds produced between 1990 and 2021 in the 18 mesoregions of the Brazilian Amazon.

These five mesoregions accounted for 73.6% to 85.7% of the annual seed volume in the Brazilian Amazon between 1990 and 2021 (**Figure 5**, **Table 1**). On average, these mesoregions contributed 81.2% of the annual production, with a variation indicated by a standard deviation of 3.5%. This is significant, considering that these five mesoregions cover only 29% (equivalent to 1.354 million square kilometers) of the total study area or 33% of the area where Brazil nut production (totaling 4.070 million square kilometers) occurred during the analysis period. Despite the high production, annual variability remains significant (**Figure 6**).

The variation in the seed production pattern was remarkable. For example, mesoregions like Sudeste Paraense (PA) and Sul do Amapá (AP) showed a declining trend in production, whereas Norte Mato-grossense, Sul de Roraima (RR), and Marajó (PA) exhibited a growing trend (**Figure 7**). This variation in seed production highlights the need for more in-depth research to understand the nuances behind these fluctuations.

3.2 Climatic trends observed at the Óbidos Station in the Baixo Amazonas

The data precipitation and temperature data provided an understanding of the monthly climatic conditions at the Óbidos station (**Figure 8**). The highest amounts of

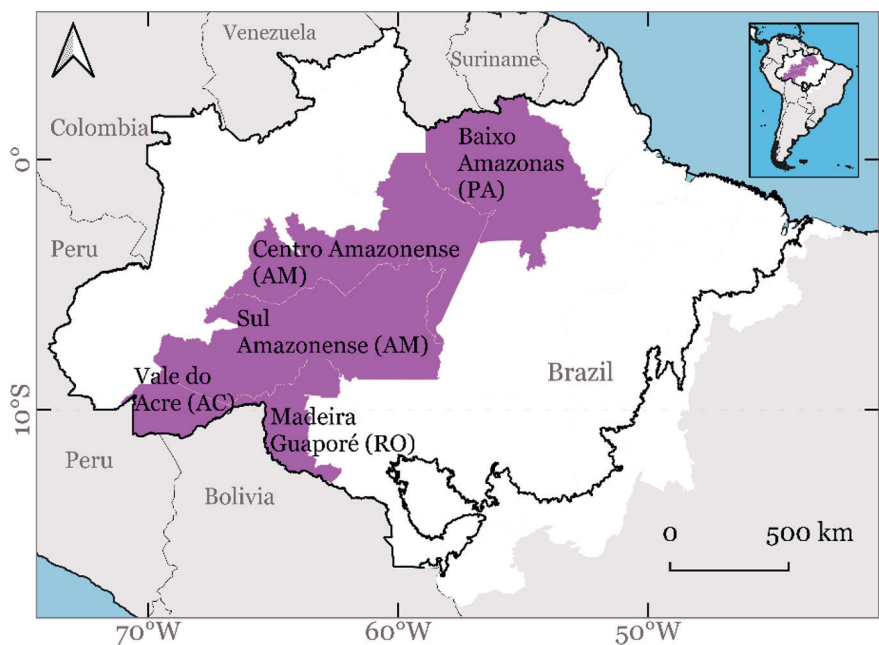


Figure 5.
Major Brazil nut producing mesoregions. Data source: IBGE [6].

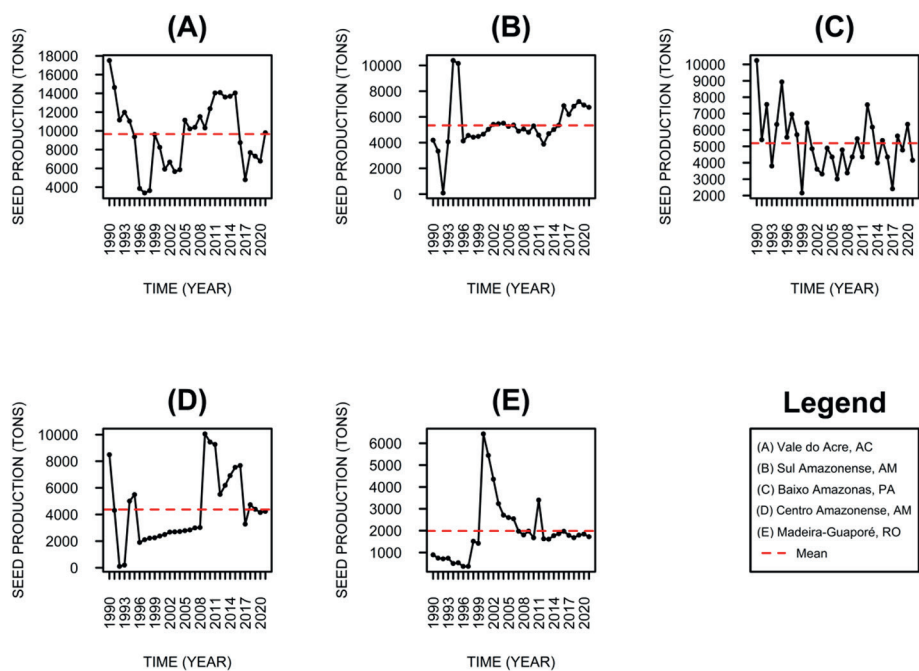


Figure 6.
Representation of the annual variation in Brazil nut seed production in the five most productive mesoregions between 1990 and 2021: (A) Vale do Acre, AC. (B) Sul Amazonense, AM. (C) Baixo Amazonas, PA. (D) Centro Amazonense, AM. (E) Madeira-Guaporé, RO. Data source: IBGE [6]. The dotted red line represents the arithmetic mean of seed production during the study period

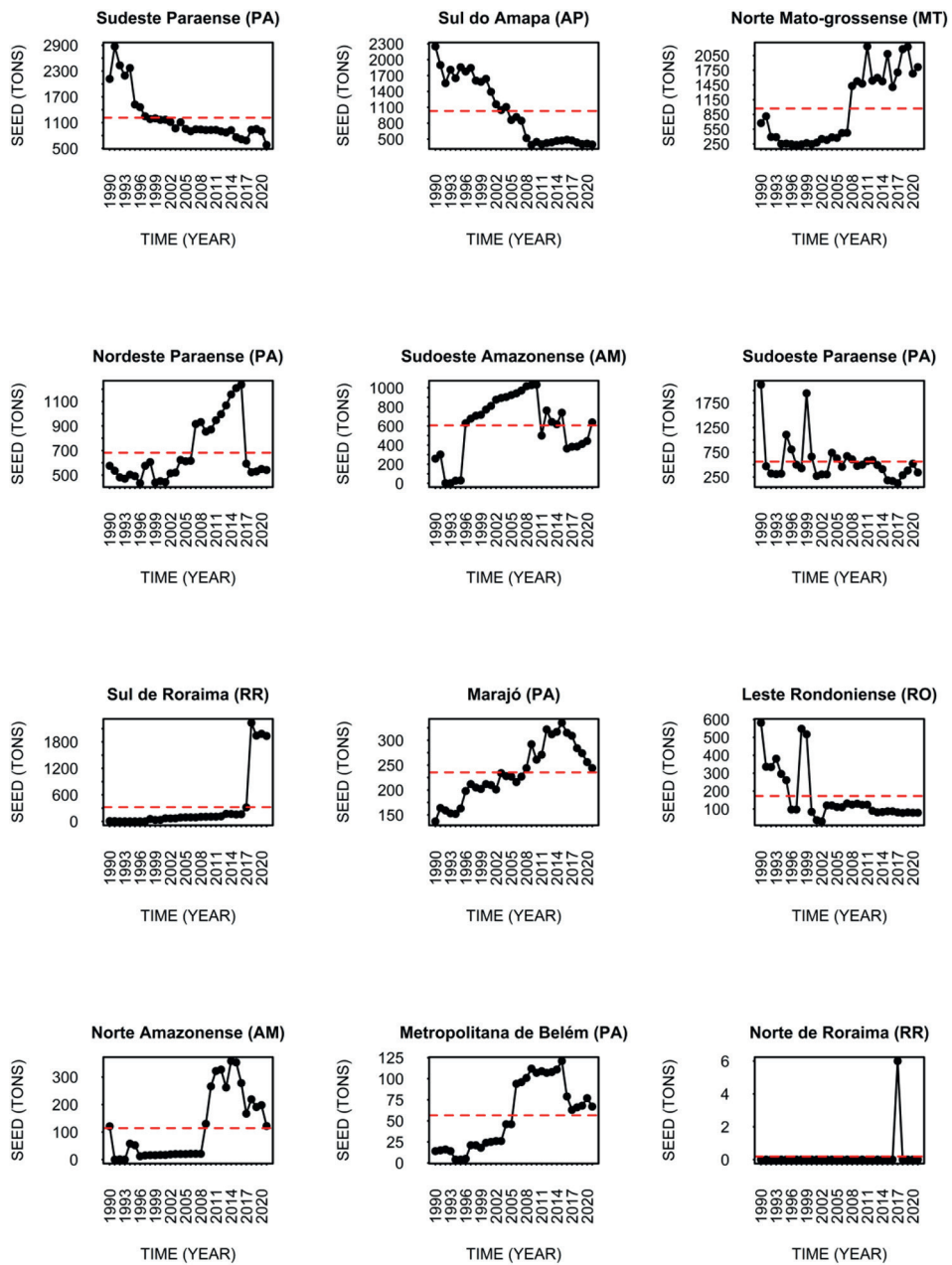


Figure 7.

The mesoregions of the Brazilian Amazon with an average Brazil nut production ranging from 0.2 to 1215 tons per year between 1990 and 2021. Data source: IBGE [6]. The dotted red line represents the arithmetic mean of seed production during the study period.

rainfall occurred during the austral summer, from December to February, extending into the autumn months of March to May. On the other hand, the driest months, from June to October, coincided with average and maximum temperatures, especially during the transition from the dry season to the wet season in October. In fact, temperatures were lower in February and March and higher in October.

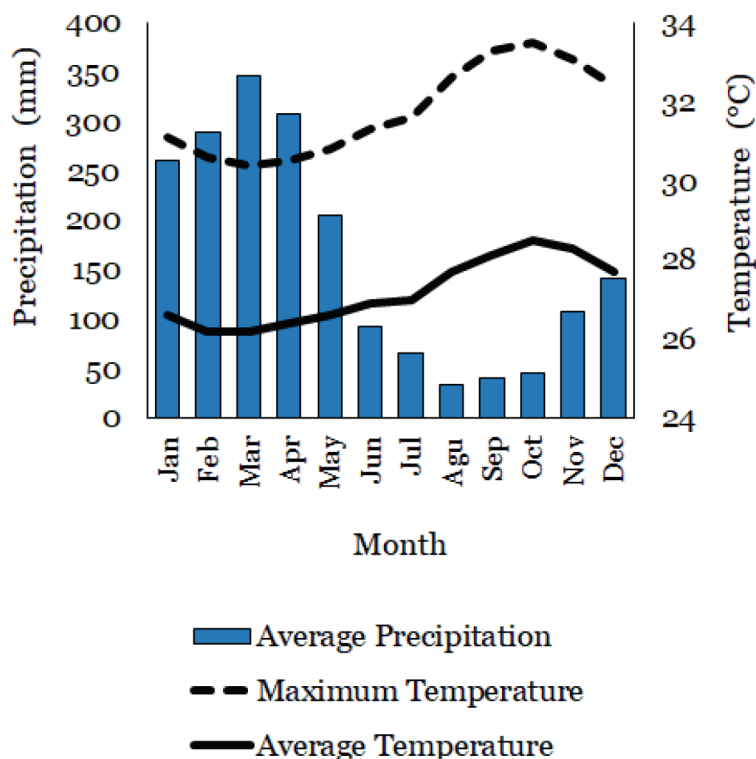


Figure 8.
Climatological normal at the Óbidos station in the Baixo Amazonas mesoregion (PA) during the period from 1989 to 2020. Data source: INMET [29].

The observed data also provided an overview of the average annual climatic conditions and their variability (standard deviation) between 1989 and 2020 (**Figure 9**). The average precipitation was 1943 millimeters (± 314 mm), with the lowest volume of 1209 mm in 1992 and the peak of 2624 mm in 2008. The average relative humidity was 82.8% ($\pm 1.75\%$), with the lowest record of 80.2% in 2017 and the highest of 86.7% in 1992. The annual average VPD was 0.62 kilopascals (± 0.08 kPa), ranging from 0.47 in 1994 to 0.74 in 2016. In turn, the average and maximum temperatures were observed at 27.15°C ($\pm 0.43^\circ\text{C}$) and 31.73°C ($\pm 0.47^\circ\text{C}$), respectively. These temperatures recorded their lowest values in 1990, at 26.34°C and 30.66°C, respectively. On the other hand, the highest values were recorded in 2016 and 1998 at 27.83°C and 32.33°C, respectively.

It was possible to visually observe some trends in the climatic data over the analyzed period (**Figure 9**). While there is no trend in total precipitation, the VPD showed an increasing trend, reflecting the rise in average temperatures and the decrease in relative humidity over the years. Average and maximum temperatures also increased during the study period. **Figure 9** provides a more detailed visual representation of the climatic data collected at the meteorological station located in Óbidos.

It's important to note that many of the climatic variables are correlated (**Figure 10**). As VPD and average and maximum temperatures increase, relative humidity tends to decrease. On the other hand, no significant linear relationships were observed between temperature and total precipitation, as well as between relative humidity and total precipitation.

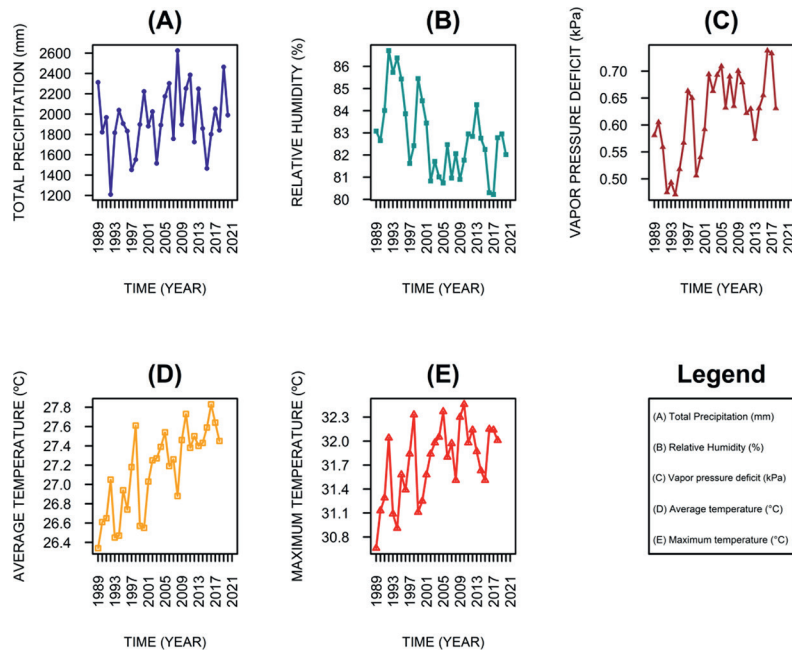


Figure 9. Climatic variability in the Baixo Amazonas mesoregion between 1989 and 2021: (A) Total precipitation. (B) Relative humidity. (C) Vapor pressure deficit. (D) Average temperature. (E) Maximum temperature. Data source: INMET [29], University of Arizona [30].

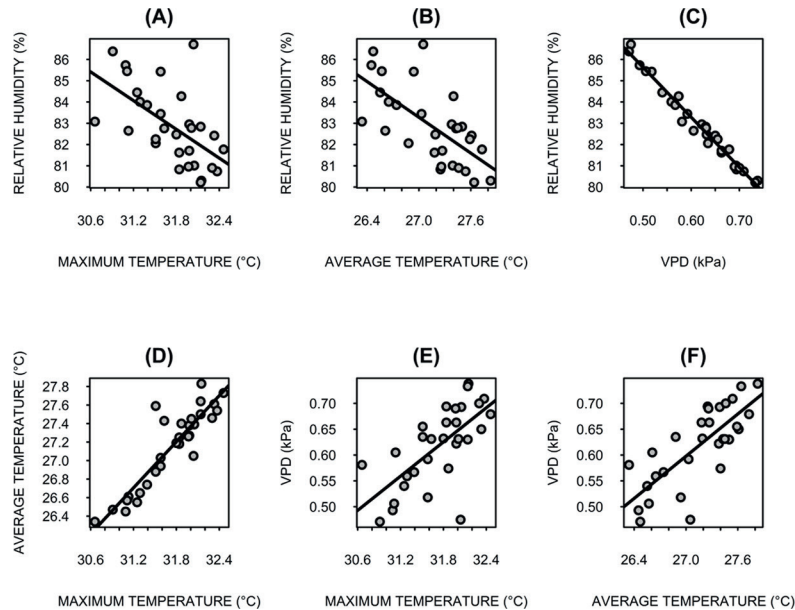


Figure 10. Significant relationships between climatic variables in the Baixo Amazonas between 1989 and 2020: (A) Relative humidity and maximum temperature. (B) Relative humidity and average temperature. (C) Relative humidity and vapor pressure deficit. (D) Average temperature and maximum temperature. (E) Vapor pressure deficit and maximum temperature. (F) Vapor pressure deficit and average temperature. Data source: INMET [29], University of Arizona [30].

3.3 Relationships between seed production and climatic variables in the Baixo Amazonas

Brazil nut seed production in the Baixo Amazonas (PA) varied over the period from 1990 to 2021. The lowest value was recorded in 1993, with 3797 tons, while the peak occurred in 1990, with 10,235 tons (**Table 1**). Despite the annual fluctuations, the data analysis did not reveal a significant relationship between seed production and climatic conditions during the fruit collection year. This suggests that climatic variations did not have a direct and linear influence on seed production in the same year.

On the other hand, there are significant relationships between variations in seed production from the base year and climatic variables from 1 year before seed

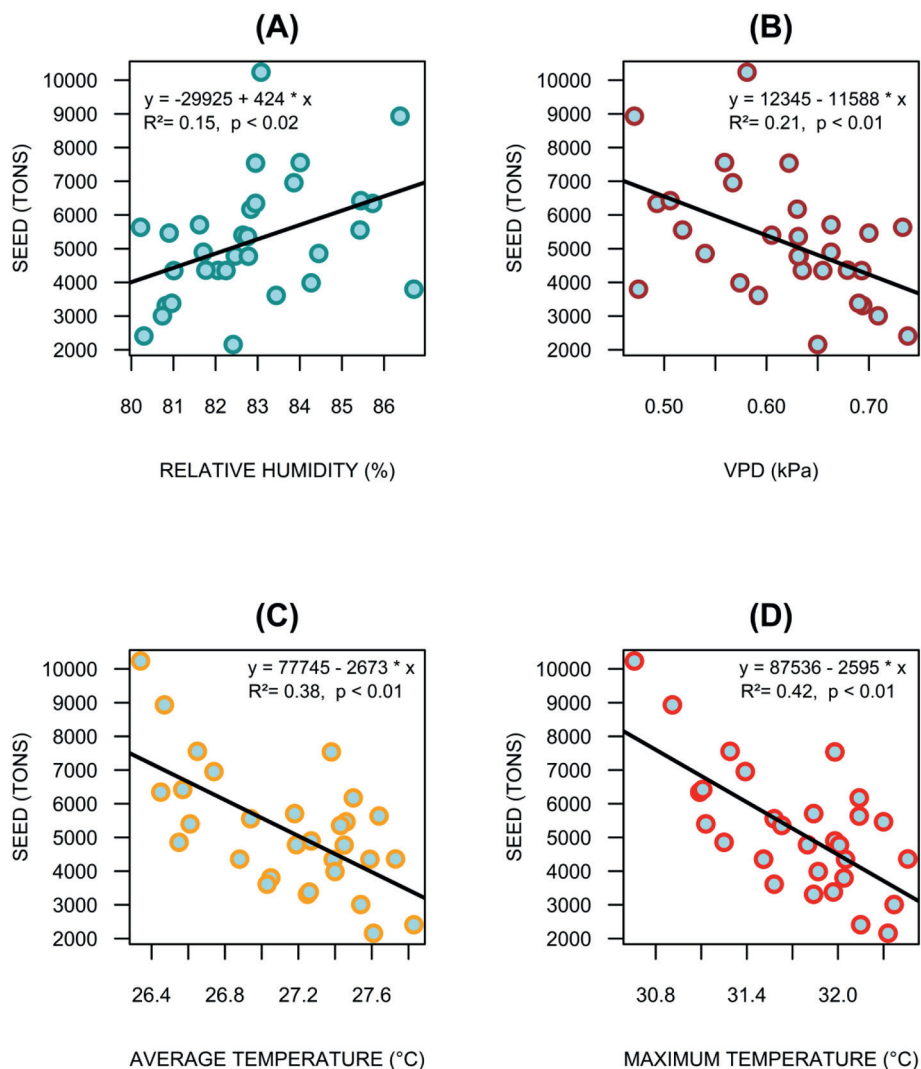


Figure 11. Representation of the linear regression models between seed production and climatic variables in the Baixo Amazonas: (A) Seed and relative humidity. (B) Seed and vapor pressure deficit. (C) Seed and average temperature. (D) Seed and maximum temperature. Only significant relations are presented ($p < 0.05$). Data source: IBGE [6], INMET [29], University of Arizona [30].

collection, indicating significant associations between the climatic conditions of the preceding year and nut production in the base year. Although there is no linear relationship with total precipitation, the other climatic variables exert an influence on seed production. While relative humidity has a positive influence, VPD and temperature have a negative influence on seed production (**Figure 11**).

Regarding relative humidity, the results of the linear regression estimated a slope coefficient of 424. This indicates that a 1% increase in relative humidity is associated with an increase of 424 tons of seeds. The model suggests that approximately 15% of the variability in seed volume was explained by relative humidity.

Regarding VPD, the results of the linear regression estimated a slope coefficient of -11.588 . This indicates that a 0.1 unit increase in the VPDt variable is associated with a decrease of 1.158 tons of seeds. The model suggests that approximately 21% of the variability in seed volume was explained by the VPD.

The results of the linear regression analysis showed slope coefficients of -2673 and -2595 for the average temperature and maximum temperature variables, respectively. This implies that a 1°C increase in temperature is associated with an average decrease in seed volume ranging from 2595 to 2673 tons. Temperature measures explain between 38–42% of the variability in seed volume. This indicated that average and maximum temperatures played an important role in explaining variations in seed volume in the Baixo Amazonas (PA).

To sum up, as temperatures rise (1°C increase), it leads to an increase in VPD (0.14 increase), which in turn contributes to a decrease in seed production at order of 1622 tons. This relationship highlights the sensitivity of seed production to climatic factors, particularly temperature and VPD, which can have a substantial impact on harvesting outcomes.

4. Discussion

4.1 Variability of Brazil nut production in the Brazilian Amazon

The analysis of seed production in the Brazilian Amazon from 1990 to 2021 revealed significant variability, a result that has also been observed in other mesoregions within the study area. For example, in the Vale do Acre (AC), areas located approximately 30 km apart showed differences of more than three times in the number of fruits during the period from 2010 to 2019 [33]. In the Sul de Roraima mesoregion, a difference of 52 times was observed between the year of highest production and the year of lowest production during the period from 2006 to 2012 [34]. Regarding fruit production per tree, the observed variation ranged from 12 to 216 [34]. Therefore, the variability identified in this study is consistent with the variability found at the population and tree levels of *B. excelsa*.

The contrast in seed production in the studied area can be explained by variations in soil chemistry. The availability of phosphorus has been associated with higher Brazil nut fruit production [33] as it improves physiological characteristics of trees such as electron transport and gas exchange and increases nutrient efficiency, including nitrogen, potassium, calcium, and magnesium [35]. In fact, phosphorus availability in the Amazon is higher near the Andes [36], where the Vale do Acre (AC) mesoregion is located, characterized in this study with the highest average annual seed production (**Figure 2**). Furthermore, a relatively higher total phosphorus content in the drainage basins of the Solimões, Juruá, Purus, and Amazon rivers [37] can

explain the location of the five most productive mesoregions for Brazil nut, as shown in the results of this study (**Figure 2**). This suggests that the area with the highest seed production, extending diagonally from southwest to northeast of the Brazilian Amazon (**Figure 3**), is associated with regions with greater phosphorus availability.

Deforestation may potentially explain a part of the variation in seed production in the study area. In fact, the negative relationship between increasing deforestation and Brazil nut seed production has been observed since the 1950s in the mesoregions of Tocantins, Maranhão, and Pará [38–40]. Previous studies have examined deforestation rates and Brazil nut seed production and found significant and negative relationships across the entire Brazilian Amazon [41]. In this context, the reduction in seed production is a direct result of the loss of Brazil nut trees, but it is also related to the effects of fragmentation, forest fires, loss of pollinators, and climate change attributed to deforestation [42]. This indicates that seed production tends to decrease as deforestation proceeds in the studied mesoregions.

Ecological interactions have also been associated with variability in fruit production. CARDOSO et al. [43] found that canopy size and the proximity between trees are significantly related to fruit production, with higher production for trees with larger canopies and trees that are closer to each other, which was attributed to greater pollination efficiency. Several studies suggest a negative relationship between the activities of Brazil nut pollinators (*Eulaema mocsaryi* and *Xylocopa frontalis*) and the presence of smoke from wildfires and an increase in environmental temperature [44, 45]. This indicates that in more fragmented forests, such as in the mesoregions of North Maranhão (MA), West Maranhão (MA), Central Maranhão (MA), Central South Mato Grosso (MT), Northeast Mato Grosso (MT), Southwest Mato Grosso (MT), and Western Tocantins (TO), the lower seed quantity could be related to a reduction in pollinator efficiency.

4.2 Influence of climate variation on Brazil nut production in the Baixo Amazonas

The analyzed data did not reveal a significant relationship between climatic variables and the volume of Brazil nuts in the Baixo Amazonas when considering data from the same year. This underscores the complexity of the fruiting process and highlights the importance of not only considering the climatic conditions of the base year in seed production in the Amazon. In fact, according to Maués [17], the process between anthesis and fruit dispersal spans 14 months. Therefore, the lack of a significant relationship between the analyzed climatic variables and the volume of Brazil nuts when considering data from the same year may be related to the reproductive development cycle of *B. excelsa*.

On the other hand, significant relationships were found between the volume of Brazil nuts from the base year and climatic variables from 1 year before seed collection, except for total precipitation. In fact, previous studies did not identify significant changes in precipitation in the Baixo Amazonas when analyzing the period from 1973 to 2013 [46]. In the Central Amazonian mesoregion, in the municipality of Tefé, fruiting between 2013 and 2018 was not correlated with precipitation [47], corroborating the results of the present study. However, seed production in other mesoregions may be influenced by precipitation. This was evident in the Sul do Amapá mesoregion, where an association was observed between low precipitation and reduced production [18], and in the Sul Amazonense (AM) mesoregion, where a relationship was noted between excessive precipitation and Brazil nut tree mortality [48], potentially reducing fruit production.

Air relative humidity had a positive effect on the volume of Brazil nut production. This possibly occurred because, under conditions of high air relative humidity,

stomatal pores tend to remain open, favoring the assimilation of carbon dioxide (CO₂) by Brazil nut trees. The assimilation of CO₂ is essential for photosynthesis, which is the process by which plants convert CO₂ and sunlight into glucose and other sugars [49]. These substances are essential for fruit development, and it is possible to argue that air relative humidity can positively influence the production of Brazil nut fruits in the Baixo Amazonas mesoregion.

However, relative humidity in the Baixo Amazonas showed a decrease between 1989 and 2020 (**Figure 9 A**). Lower air relative humidity in a pasture area in the Baixo Amazonas was also significantly related to lower fruit production when compared to fruit production in a forest fragment [43]. Although higher relative humidity creates favorable conditions for fruit production [31], it is important to note that other climatic variables, such as VPD and temperature, are significantly related to relative humidity (**Figure 10**). In fact, air relative humidity has been decreasing as VPD and average and maximum temperatures are increasing. This trend raises concerns about Brazil nut fruit production in the study area.

The increase in VPD has effects on the growth and reproductive development of plants. Although studies are limited, scientific literature indicates that an increase in VPD reduces the number of flowers and may cause changes in fruit composition, resulting in significant reductions in productivity [31]. Furthermore, reduced photosynthesis, changes in gas exchange (stomatal conductance), alterations in architecture, changes in hormonal production, and increased transpiration rate are other biophysical and biochemical changes associated with increased VPD [31, 50]. This corroborates with the results of the present study, which showed a reduction in seed volume preceded by years with higher VPD.

The increase in global temperature has intensified atmospheric demand for evaporation [51] and has led to an exponential increase in VPD in the atmosphere [52]. In the Amazon region, this increase in VPD is more pronounced during the dry season, which is a natural phenomenon caused by seasonal variation in solar radiation and the northward migration of the Intertropical Convergence Zone over South America [53]. However, it is important to note that the increase in VPD is also related to deforestation and forest fires caused by human activities [54]. Therefore, the combination of global climate change and land-use changes in the Amazon raises concerns about the ongoing reduction in Brazil nut production as VPD increases in the region.

Regarding temperature, it was possible to observe a significant influence of temperature measurements from 1 year before seed collection. Similar results were observed by Pastana et al. [18]. These authors identified a negative relationship between Brazil nut production and temperature anomalies occurring in the third quarter before harvest in the Sul do Amapá mesoregion. Notably, these authors highlighted that the 2017 fruiting season showed a production reduction twice as large as the average for the period from 2005 to 2018.

Increasing temperature affects how plants produce organic compounds [49]. This happens because temperature influences enzymes in the leaves, leading to changes related to fruit production [55]. As the temperature rises, chemical reactions in the leaves increase, but they reach a maximum point when enzymes become deactivated, and the enzymatic structure is affected by the heat. These chemical changes affect photosynthesis, especially the action of the enzyme Rubisco, which is essential for converting CO₂ and water into glucose and oxygen using solar energy [55].

Field studies have demonstrated a reduction in gross ecosystem productivity in the Amazon forest when temperatures exceed 27°C [56]. In the study area under analysis, the average temperature ranged from 26.34°C to 27.05°C, with an average of 26.62°C,

from 1989 to 1993. In the period from 2014 to 2018, the average temperature fluctuated between 27.43°C and 27.83°C, with an average of 27.59°C. These data indicate a temperature increase of 1.49°C in the mentioned intervals, considering the difference between the lowest and highest recorded average temperatures (**Figure 9**), while the average Brazil nut production decreased from 6666 tons to 4505 tons between these periods. Therefore, physiological changes associated with rising temperatures are likely reducing fruit production in the Baixo Amazonas mesoregion.

The years characterized by the lowest seed production volumes were 1992, 1993, 1996, 1997, 1998, 1999, 2003, and 2017. These years coincide with El Niño events, a recurring natural phenomenon resulting in abnormal warming of equatorial Pacific Ocean waters and surface temperatures over the Amazon. In the case of the El Niño event in November 2015, a temperature anomaly of 2.5°C was recorded in the Amazon [57]. El Niño events were observed during the study period in the years 1991/1992, 1993, 1994/1995, 1997/1998, and 2015/2016 [57, 58]. The World Meteorological Organization estimated that El Niño is likely to be positive from December 2023 to February 2024 [59]. These results suggest a relationship between past El Niño events and a reduction in Brazil nut production in the Baixo Amazonas mesoregion, which may repeat in future El Niño events.

Finally, temperature variation can interfere with the plant-animal interactions in the reproductive cycle of Brazil nut. Cavalcante et al. [44] studies showed a high inverse correlation between temperature increase and a reduction in the activity of *B. excelsa* pollinators (*Eulaema mocsaryi* and *Xylocopa frontalis*). Temperature increase also favors wildfires, which, according to observations from local producers, the smoke would be reducing the activity of Brazil nut pollinators, even in years when the number of flowers is higher, resulting in low fruit production [45]. Therefore, ecological interactions involving Brazil nut pollinators could be compromised in years when temperatures are higher, potentially reducing seed production.

4.3 Sustainability in Brazil nut production in the Amazon

The analysis of interactions affecting Brazil nut production in the Amazon region emphasizes the urgency of a sustainable approach. Achieving temperature goals of no more than 1.5°C is imperative to avoid a critical point of irreversible losses. For example, the models in this study indicate that a 2°C increase could result in decreases ranging from 5190 to 5346 tons of seeds (**Figure 11 C; D**), approaching the average production volume in the analyzed period, calculated at 5192 tons (**Table 1**).

Furthermore, the implementation of industrialization processes emerges as a prominent element to add value and mitigate losses resulting from temperature increases [60]. However, industrialization in the Amazon still poses a significant challenge in the context of sustainable development. For instance, when 532 municipalities were examined, only 17 nut processing facilities were found, scattered across 16 different municipalities [41].

Industrial technology can increase the value of products derived from nuts, multiplying it from two to five times [42]. In previous years, fresh nuts, along with their shells, were purchased by factories for prices ranging from US\$ 0.30 to 4.12 per kilogram. Nuts destined for oil production were traded at prices ranging from \$0.3 to \$1, while dehydrated nuts for consumption fluctuated between \$1.5 and \$4.12. The oil resulting from the pressing of the nuts reached a value of \$13 per kilogram, and dehydrated nuts (**Figure 12**) were sold for \$15. These examples highlight the intrinsic potential for increasing the added value of primary products through the establishment of basic technological infrastructure [42].



Figure 12. Dehydrated seeds of *Bertholletia excelsa* (Brazil nut) produced by Cooperativa Mista Agroextrativista do Rio Unini (COOMARU) in the Norte Amazonense (AM) mesoregion. Photo source: Diego Oliveira Brandão.

Strategies to address the challenges posed by the temperature increase and its effects on Brazil nut production in the Amazon also require investments in research and the development of nut varieties more adapted to climate change. Additionally, the adoption of agroforestry systems in degraded and abandoned areas emerges as a viable solution. Proper climate change management involves the use of management systems that allow for more precise control of environmental variables such as temperature and relative humidity. Studies have highlighted the direct influence of these factors on fruit yield [31, 61], emphasizing the need for proactive approaches.

Additionally, the transition to agroforestry systems offers significant advantages. By enabling more efficient management, these systems have the potential to generate surpluses of forest products. This contrasts with the predominant extractive systems in the current Brazil nut production chain, providing a more sustainable approach to the market [62, 63]. Therefore, by investing in research, variety development, and agroforestry systems, it is possible to address the impacts of climate change on Brazil nut production.

5. Conclusions

The annual Brazil nut seed production in the Brazilian Amazon concentrated in five mesoregions between 1990 and 2021. Data analysis did not reveal a significant relationship between climatic variables and Brazil nut volume in the Baixo Amazonas mesoregion when considering data from the same year. However, significant relationships were identified between the volume of Brazil nuts in the base year and climatic variables from 1 year before seed collection, except for total precipitation. While relative humidity has a positive influence on seed volume, vapor pressure deficit and temperature had negative effects.

Maximum temperature stood out as the most influential climatic variable in the annual variation of Brazil nut production in the Baixo Amazonas. The trends of

increasing temperatures and the consequent reduction in relative humidity result in an increase in vapor pressure deficit. This observation casts a new perspective on the impacts of climate change in the Amazon region on the Brazil nut market. These observations are a cause for concern, as *B. excelsa* seeds have played a fundamental role in the livelihoods of Indigenous communities for thousands of years and local communities for centuries.

To conserve Brazil nut production, it is essential to curb global temperature rise, invest in industrial processes, adopt Brazil nut varieties better adapted to climate change, and restore Brazil nut occurrence lands with agroforestry systems. These measures can not only contribute to maintaining and increasing the annual production of Brazil nut but also add value to the products, preserving the importance of this ecosystem service in providing food and income for those living in the Amazon. Without the implementation of these measures, Brazil nut production is susceptible to the negative impacts of climate change.

New studies are important to expand knowledge about annual variations in Brazil nut production, including in terms of economic value. Additional research can explore whether climate variations affect other mesoregions to determine if the results observed in this study can be generalized or specific only to the Baixo Amazonas. Finally, it is relevant to understand how the synergistic interaction between global climate change and land use changes, especially deforestation, can impact on Brazil nut production.

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Conflict of interest

The authors declare no conflict of interest.

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