

Article

Commodities from Amazon Biome: A Guide to Choosing Sustainable Paths

Richard Luan Silva Machado , Rosangela Rodrigues Dias, Mariany Costa Deprá, Adriane Terezinha Schneider , Darissa Alves Dutra, Cristiano R. de Menezes, Leila Q. Zepka  and Eduardo Jacob-Lopes *

Rural Sciences Center, Federal University of Santa Maria, UFSM, Roraima Avenue 1000, Santa Maria 97105-900, RS, Brazil; richard.machado@acad.ufsm.br (R.L.S.M.); ro.rosangelard@gmail.com (R.R.D.); marianydepra@gmail.com (M.C.D.); adriane.schneider@acad.ufsm.br (A.T.S.); darissa.alves@acad.ufsm.br (D.A.D.); cristianoufsm@gmail.com (C.R.d.M.); zepkaleila@yahoo.com.br (L.Q.Z.)
* Correspondence: ejacoblopes@gmail.com; Tel.: +55-55-3220-8822

Abstract: The exploitation of the Amazon biome in search of net profit, specifically in the production of cocoa (*Theobroma cacao*) and açai (*Euterpe oleracea*), has caused deforestation, degradation of natural resources, and high greenhouse gas (GHG) emissions, highlighting the urgency of improving the environmental, economic and social sustainability of these crops. These species were selected for their rapid expansion in the Amazon, driven by global demand, their local economic relevance, and their potential to either promote conservation or drive deforestation, depending on the production system. This study analyzes the pillars of environmental, social, and economic sustainability of cocoa and açai production systems in the Amazon, comparing monoculture, agroforestry, and extractivism to support forest conservation strategies in the biome. Analysis of the environmental life cycle, social life cycle, and economic performance were used to determine the carbon footprint, the final point of workers, and the net profit of the activities. According to the results found in this study, cocoa monoculture had the largest carbon footprint (1.35 tCO₂eq/ha), followed by agroforestry (1.20 tCO₂eq/ha), açai monoculture (0.84 tCO₂eq/ha) and extractivism (0.25 tCO₂eq/ha). In the carbon balance, only the areas outside indigenous lands presented positive carbon. Regarding the economic aspect, the net profit of açai monoculture was USD 6783.44/ha, extractivism USD 6059.42/ha, agroforestry USD 4505.55/ha, and cocoa monoculture USD 3937.32/ha. In the social sphere, in cocoa and açai production, the most relevant negative impacts are the subcategories of child labor and gender discrimination, and the positive impacts are related to the sub-category of forced labor. These results suggest that açai and cocoa extractivism, under responsible management plans, offer a promising balance between profitability and environmental conservation. Furthermore, agroforestry systems have also demonstrated favorable outcomes, providing additional benefits such as biodiversity conservation and system resilience, which make them a promising sustainable alternative.

Keywords: agroforestry system; carbon footprint; extractivism; life cycle assessment; monoculture



Academic Editor: Jungbo Baek

Received: 11 May 2025

Revised: 28 May 2025

Accepted: 31 May 2025

Published: 2 June 2025

Citation: Machado, R.L.S.; Dias, R.R.; Deprá, M.C.; Schneider, A.T.; Dutra, D.A.; de Menezes, C.R.; Zepka, L.Q.; Jacob-Lopes, E. Commodities from Amazon Biome: A Guide to Choosing Sustainable Paths. *Commodities* **2025**, *4*, 8. <https://doi.org/10.3390/commodities4020008>

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1. Introduction

The destruction of tropical forests not only increases carbon dioxide (CO₂) in the atmosphere but also creates a negative feedback loop in which expanding deforestation causes an increase in global temperatures and a decrease in rainfall, which in turn can cause forest droughts and an increase in forest fires [1]. Ecological succession, developed over

millions of years, resulted in the formation of this rainforest, but intensive human activities have caused manipulation, altering natural or ecological processes that no longer follow the expected patterns. Since the 1950s, the Amazon biome rainforest has lost 20% of its original forest cover, and up to 28% of the remaining forest has been partially destroyed [2]. This is mainly due to the high levels of deforestation over the years, related to the expansion of infrastructure, the implementation of development projects, the intensified exploitation of natural resources, and the expansion of industrial agriculture and livestock farming [3]. For the Amazon, these calls highlight a critical moment: a tipping point that, if crossed, could convert the lush rainforest into a more arid and degraded biome [4].

In light of these environmental pressures, it is crucial to examine key agricultural commodities in the Amazon that are both economically significant and environmentally impactful. In this context, we can include cocoa (*Theobroma cacao*), considered an essential crop in several tropical countries due to the income it provides to many farmers. It also plays a key role as a raw material in the global chocolate production chain. In Brazil, in 2023 the country produced around 274,000 tons of cocoa beans, of which around 55% (151,000 tons) came from the Amazon, generating gross revenue of USD 353 million [5,6]. Another notable commodity is açaí (*Euterpe oleracea*). In the Amazon, the fruit not only supplies the domestic market but also accounts for more than 95% of global açaí exports. It is important to highlight that the main form of export is frozen pulp, whose production increased from 87,470 tons in 1987 to 1.08 million tons of pulp in 2022. In 2023, production reached 1.60 million tons, generating a gross revenue of USD 1.12 billion [7]. However, this expansion has caused a reduction in species and functions in the Amazon ecosystem, turning the spotlight to research on sustainable management practices in the production of these crops [8].

Despite the importance of cocoa and açaí crops, the emissions associated with their production require the adoption of new ecological management strategies to maintain the pillars of sustainability. Native forests are an essential global resource, and play a role in a wide range of ecosystem services, from climate regulation to population support and the development of a forest-based bioeconomy. In this context, extractivism refers to the non-destructive harvesting of native forest products, such as açaí and cocoa, typically carried out by traditional or indigenous communities, using knowledge transmitted through generations. These systems are rooted in territorial and cultural practices and maintain the forest structure while enabling income generation. This distinguishes extractivism from agricultural systems that require land conversion or intensive management. Furthermore, it has been advocated as a crucial strategy for the sustainable use of tropical forests, poverty reduction, and the provision of biological services in macro- and microclimatic regulation [9].

Currently, the cultivation of cocoa and açaí in monocultures, combined with the use of agrochemicals, is leading to deforestation and, consequently, loss of shade, biodiversity, increased carbon emissions, and soil degradation [10]. However, these commodities also play an important role in the global market and must be carefully analyzed in light of the state of the art. In turn, integrated production, through agroforestry systems, land use practices that combine perennial trees such as cocoa and açaí, or agricultural crops in the same area, has been presented as a promising solution, reducing the vulnerability of crops to climate change and promoting production that is more harmonious with native forests [11–13].

In cocoa and açaí agroforestry, both crops are intercropped spatially: cocoa is planted in double rows between açaí trees, mimicking forest structure while allowing productive integration. These systems are distinct from monocultures, which involve intensive single species cultivation, and from extractivism, which rely on naturally occurring trees, often

managed by traditional and Indigenous communities. These three models differ significantly in terms of land use intensity, carbon emissions, and biodiversity conservation potential. For example, emissions in açai systems are influenced not only by farming but also by processing steps such as pulp freezing, while extractivism avoids land conversion and use of inputs altogether. Clarifying these distinctions is essential for understanding the environmental and social metrics adopted in this study.

These systems contribute to reforestation and generate significant environmental benefits, such as increased biodiversity, lower local temperatures, greater humidity, and improved resilience to changing climatic conditions [14,15]. Therefore, adopting an alternative path for cocoa and açai production is essential to promote harmony with the biome and increase crop resilience in the face of climate change [16]. Although intensive monocultures can aid in the reforestation process, they often do not favor sustainable agricultural practices or agricultural diversification, which are essential for ecological resilience. In contrast, agroforestry systems demonstrate superiority in promoting long-term environmental preservation, due to their ability to integrate biodiversity and natural cycles. Several studies indicate that the implementation of agroforestry systems can serve as a strategy for the conservation of the Amazon biome [11,17–19], but few studies comprehensively compare the different production systems (monoculture, agroforestry, and extractivism) under environmental, economic, and social lenses in the Amazonian context [20,21].

In this context, the main objective of this study is to analyze cocoa and açai production scenarios in the Amazon, considering monocultures, agroforestry systems, and extractivism, by assessing their carbon footprint (using global warming potential (GWP)), economic return (gross revenue, total revenue, net profit, and net present value (NPV)), and social sustainability (workers endpoint category). This comprehensive evaluation is essential to support sustainable land-use decisions that promote climate resilience, environmental conservation, and equitable socio-economic development in the Amazon biome, ensuring that cocoa and açai production contributes to both local well-being and global climate action.

2. Materials and Methods

2.1. Life Cycle Assessment (LCA)

This study followed the structure established by the International Organization for Standardization (ISO), which encompasses four distinct phases, namely: (i) definition of the objective and scope; (ii) life cycle inventory (LCI); (iii) life cycle impact assessment (LCIA); and (iv) interpretation of results [22,23].

2.1.1. Environmental Life Cycle Analysis (E-LCA)

Definition of the Objective and Scope of Environmental Life Cycle Assessment

The main objective of applying E-LCA was to evaluate the carbon footprint of perennial açai (*Euterpe oleracea*) and cocoa (*Theobroma cacao*) crops in the Amazon Biome in monoculture, agroforestry, and native forest scenarios. Data collection for theoretical evaluation was substantiated by data consolidated by classic bibliographic references.

Functional Unit and System Limits of Environmental Life Cycle Assessment

The functional unit defined as one hectare of area. The system boundaries were defined as “cradle-to-gate”. Four production models were evaluated: cocoa monoculture, açai monoculture, cocoa and açai agroforestry systems, and cocoa and açai extractivism. The crop cultivation cycle in monoculture and agroforestry systems was set at three years. Emissions related to transportation, infrastructure, equipment maintenance, and harvesting were not accounted for, as these crops are harvested manually and their transportation does not result in significant emissions during production. The design of the areas allocated to

cocoa and açai monocultures took into considered spacing of 3.0×3.0 m and 4.0×4.0 m with arboreal density of 1100 and 600 per hectare, respectively [24,25]. The agroforestry system involved planting cocoa trees in double rows (3.0×3.0 m) between rows of açai trees, arranged spatially at 4.5×9 m, with an arboreal density of 770 cocoa trees and 180 açai trees per hectare [14]. In extractivism, the growth of other arboreal species was considered, and a density of 300 cocoa trees and 150 açai trees per hectare was established [26]. The arboreal density of extractivism in the native forest was based on the geographic and climatic conditions, as well as the historical occurrence of anthropogenic and natural disturbances. The presence of açai palms in the native forest due to their proximity to floodplain areas, providing a favorable environment for the growth of these palms. The system boundaries and technical characteristics of the evaluated scenarios are presented in Figure 1. The spatial arrangements are shown in Figure 2.

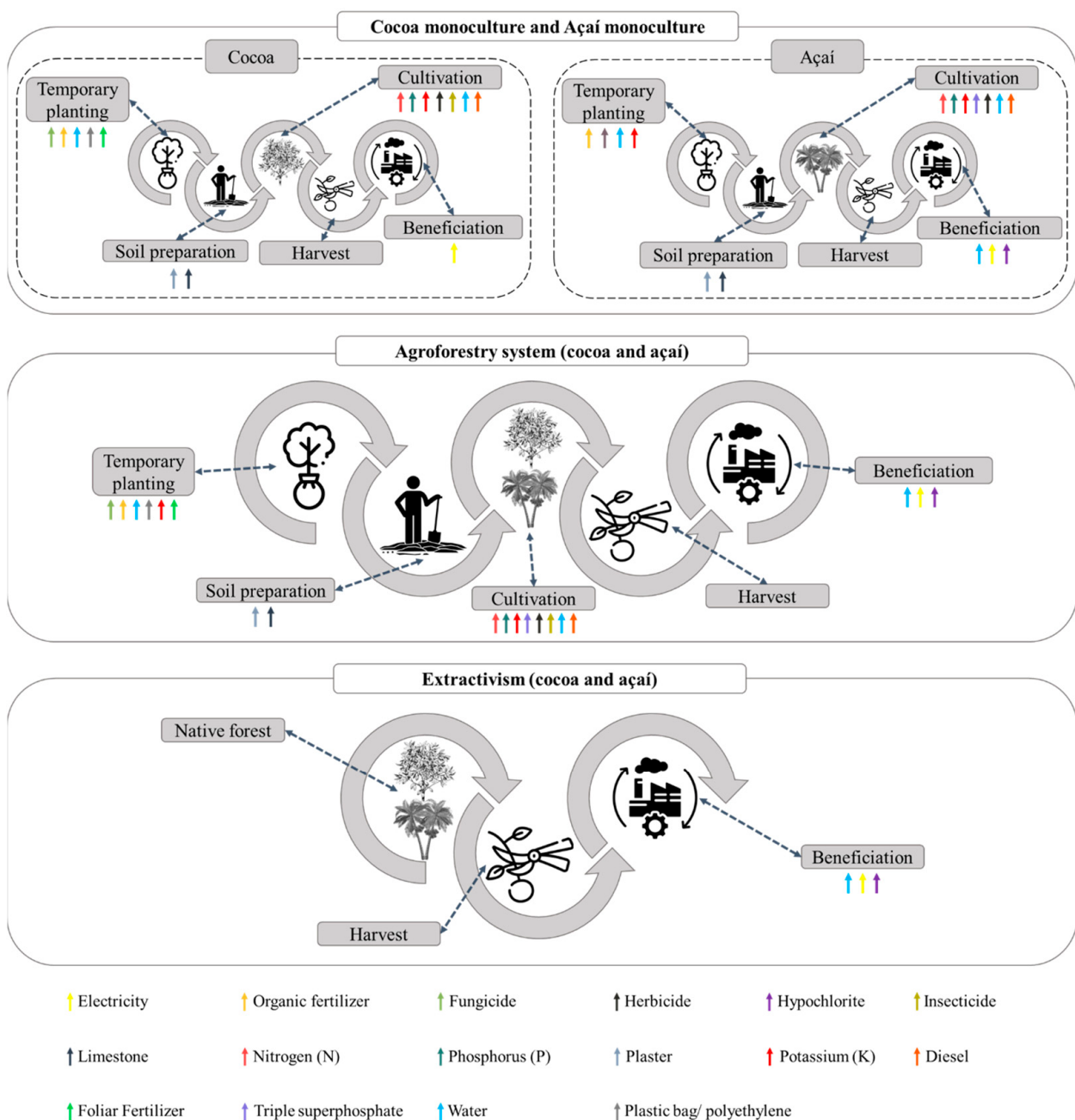


Figure 1. System boundaries for cocoa monoculture and açai monoculture, Agroforestry system (cocoa and açai), and Extractivism (cocoa and açai).

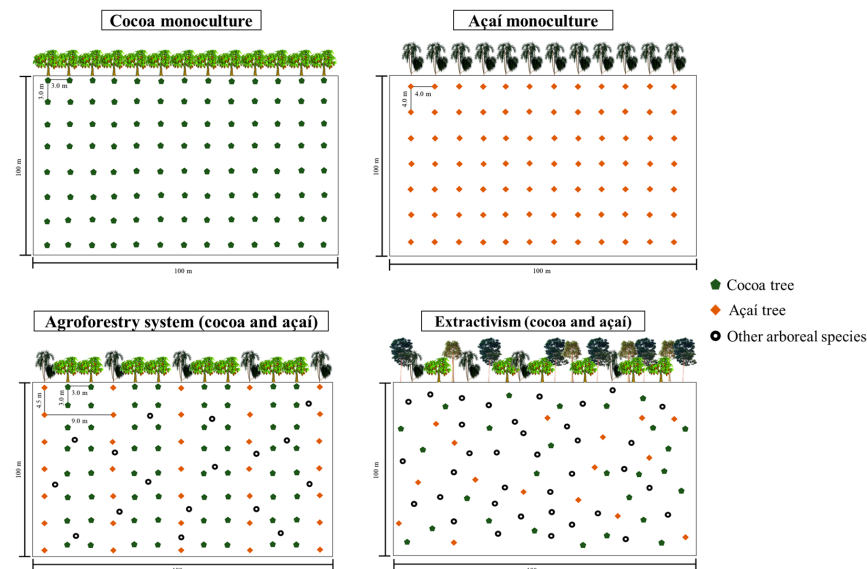


Figure 2. Schematic diagram of the spatial arrangements of Cocoa monoculture, Açaí monoculture, Agroforestry (cocoa and açaí), and Extractivism (cocoa and açaí).

Environmental Life Cycle Inventory (E-LCI)

The requirements for the production of Amazon biome commodities were listed in Tables 1–3 of the (E-LCI).

Table 1. Material and energy requirements for cocoa and açaí production per hectare.

Process	Unit	Amount	
		Cocoa	Açaí
Temporary planting			
<i>Input</i>			
Fungicide	kg/ha	3.18	-
Foliar Fertilizer	kg/ha	1.10	-
Fertilizer organic	kg/ha	180.80	280.00
Potassium	kg/ha	-	0.15
Water irrigation	m³/ha	1.10	0.20
Plastic bag/polyethylene	kg/ha	0.67	0.36
Preparing soil			
Plaster	kg/ha	500.00	500.00
Limestone	kg/ha	1000.00	1000.00
Cultivation			
Fertilizer	-		
Nitrogen	kg/ha	105.60	100.20
Phosphorus	kg/ha	64.51	127.80
Potassium	kg/ha	52.82	169.20
Triple superphosphate	kg/ha	-	80.00
Pesticides	-		
Herbicide	kg/ha	11.00	3.00
Insecticide	kg/ha	10.00	-
Water irrigation	m³/ha	95.62	232.50
Diesel irrigation	L/ha	19.09	46.41
<i>Output (i)</i>			
Cocoa	kg/ha	935.00	-
Açaí (fresh fruit)	kg/ha	-	3600.00
Beneficiation			
Cocoa	kg/ha	935.00	-
Açaí (fresh fruit)	kg/ha	-	3600.00
Water	m³/ha	-	1.66
Hypochlorite	L/ha	-	2.48
Electricity	kwh/ha	8409.70	1086.00
<i>Output (ii)</i>			
Cocoa beans	kg/ha	935.00	-
Pulp açaí	kg/ha	-	2160.00

Adapted from [13,27–41]. The terms in bold represent the steps of the production system. Terms in italics represent inventory inputs and outputs for the system shown.

Table 2. Material and energy requirements for cocoa and açai production per hectare in the context of agroforestry.

Process	Unit	Amount	
		Cocoa	Açaí
Temporary planting			
Input			
Fungicide	kg/ha	2.23	-
Foliar Fertilizer	kg/ha	0.77	-
Fertilizer organic	kg/ha	126.56	84.00
Potassium	kg/ha	-	0.05
Water irrigation	m³/ha	0.77	0.06
Plastic bag/polyethylene	kg/ha	0.47	0.11
Preparing soil			
Plaster	kg/ha	350.00	150.00
Limestone	kg/ha	700.00	300.00
Cultivation			
Fertilizer	-		
Nitrogen	kg/ha	73.92	30.06
Phosphorus	kg/ha	45.16	38.16
Potassium	kg/ha	36.97	50.76
Triple superphosphate	kg/ha	-	24.00
Pesticides	-		
Herbicide	kg/ha	7.70	0.90
Insecticide	kg/ha	7.00	-
Water irrigation	m³/ha	66.93	69.75
Diesel irrigation	L/ha	13.36	13.92
Output (i)			
Cocoa	kg/ha	654.50	-
Açaí (fresh fruit)	kg/ha	-	1080.00
Beneficiation			
Cocoa	kg/ha	654.50	-
Açaí (fresh fruit)	kg/ha	-	1080.00
Water	m³/ha	-	0.50
Hypochlorite	L/ha	-	0.74
Electricity	kwh/ha	5886.79	325.94
Output (ii)			
Cocoa beans	kg/ha	654.50	-
Pulp açai	kg/ha	-	648.00

Adapted from [13,27–42]. The terms in bold represent the steps of the production system. Terms in italics represent inventory inputs and outputs for the system shown.

Table 3. Material and energy requirements for cocoa and açai production per hectare in extractivism.

Process	Unit	Amount	
		Cocoa	Açaí
Beneficiation			
<i>Input</i>			
Cocoa		309.60	-
Açaí (fresh fruit)		-	2100.00
Water	m ³ /ha	-	0.97
Hypochlorite	L/ha	-	1.45
Electricity	kwh/ha	4204.85	633.79
<i>Output</i>			
Cocoa beans	kg/ha	309.60	-
Pulp açaí	kg/ha	-	1260.00

Adapted from [28,30,32,37,38,40]. The terms in bold represent the steps of the production system. Terms in italics represent inventory inputs and outputs for the system shown.

Environmental Life Cycle Impact Assessment (E-LCIA)

The potential environmental impacts were determined using the ReCiPe 2016 method for traditional life cycle assessment (Midpoint, World—Hierarchist version), as described by [42] and consistently applied according to [43]. Specifically, the global warming potential (GWP), a midpoint indicator, category was used to quantify the carbon footprint. The calculation model is provided in Equation (1), and the characterization factors used are detailed in the Supplementary Material (Tables S1 and S2).

$$GWP = \sum GWP_i \times m_i \quad (1)$$

where GWP is the environmental sustainability category expressed in tons of CO₂ equivalent (tCO₂eq), i refers to each greenhouse gas considered over a 100-year time horizon, GWP_i are the characterization factors of substance i , and m_i is the mass of emissions of substance i (in tons).

It is important to note that the carbon footprint estimates presented here are subject to methodological limitations. The data for agricultural emissions relies in part on secondary sources and standard emission factors, which may not fully reflect local variability in management practices. Additionally, the study distinguishes between emissions from cultivation (for example, land preparation, fertilization, irrigation) and emissions from post-harvest processing, such as cocoa bean drying and açai pulp freezing, which are often more energy-intensive and depend on infrastructure. While the approach follows established LCA guidelines, improvements in data granularity and inclusion of additional indirect emissions (for example, transport, equipment lifecycle) could enhance the accuracy of future assessments.

Carbon Balance

The methodology developed by the GHG Protocol for Agriculture [44], as described in Equation (2), expressed in tons of carbon dioxide equivalent (tCO₂eq), was used to determine the carbon balance. The Carbon capture values were estimated from secondary data available in the literature [31,45,46], adjusted according to tree species and planting densities specific to each system. In the extractivism and agroforestry systems, only the capture value corresponding to cocoa and açai trees was accounted for. In addition, estimates for native forest areas were incorporated based on values reported by [47]. These data indicate that native forests located within indigenous lands emit approximately 0.60 tCO₂eq per hectare per year and capture about 2.2 tCO₂eq per hectare per year. Outside indigenous lands, emissions increase to 3.2 tCO₂eq per hectare per year, while carbon capture reaches 2.5 tCO₂eq per hectare per year. It is important to highlight that these areas of native forest, inside and outside indigenous lands, do not strictly cover cocoa and açai production. Were used exclusively as a conceptual reference to exemplify, from the point of view of the carbon balance, the effects of forest preservation or degradation. Therefore, these scenarios were included only in the carbon assessment and were not part of the economic and social analyses.

$$CO_2 Balance = CO_2 emissions - CO_2 capture \quad (2)$$

where $CO_2 emissions$ correspond to the total de CO₂, expressed in tons of CO₂ equivalent (tCO₂eq), associated with cocoa and açai production systems—monocultures, agroforestry, extractivism—as well as native forest areas located inside and outside indigenous lands, based on life cycle inventory data. $CO_2 capture$ refers to the carbon capture potential of the arboreal components, specifically cocoa (*Theobroma cacao*) and açai (*Euterpe oleracea*) trees, whose capture rates were estimated from literature values and scaled according to

the planting density and structure of each production model. In the case of native forest areas, carbon flux values were adopted from reference estimates available in the literature, encompassing both natural uptake and emission processes.

2.1.2. Social Life Cycle Analysis (S-LCA)

Definition of the Objective and Scope of Social Life Cycle Analysis

The objective of the Social Life Cycle Assessment (S-LCA) in this study was to assess the social impacts on workers involved in direct production activities of cocoa and açai in the Northern region of Brazil. The scope was restricted to direct impacts occurring at the production stage of these commodities, without including upstream or downstream processes in the supply chain (for example, inputs such as fertilizers, energy, or transportation). Therefore, this approach does not fully characterize a full life cycle perspective and can be more accurately described as a cradle to gate analysis. This delimitation is consistent with data availability and is used to characterize the direct social conditions at the point of production of these commodities. The analysis was primarily based on secondary data from the Brazilian Institute of Geography and Statistics [48] and complemented by a literature review on social issues in the agricultural sector. When specific data on subcategories such as child labor, freedom of association, and collective bargaining were not available for cocoa and açai, broader data from the Brazilian agricultural sector were used, prioritizing national-level sources; when unavailable, regional data or international references were considered, covering monocultures, agroforestry systems, and extractivism. The sources supporting the social assessment are listed in the Supplementary Material, Table S3.

Functional Unit and System Limits of Social Life Cycle Analysis

To assess the social impact on workers, a scale of -2 , -1 , 0 , $+1$, $+2$ was used, assigning weights that reflect the degree of social impact. $+2$: Ideal compliance; $+1$: Above basic compliance; 0 : Within basic compliance by local and international laws; -1 : Below basic compliance; -2 : Does not meet basic compliance. Furthermore, a direct numerical quantity was not adopted for the functional unit as described by [49]. The system limits were defined from cradle to gate. The data used refers to the year 2022.

Social Life Cycle Inventory (S-LCI)

In the social life cycle inventory, data collection was directed towards the Northern region of Brazil, since this covers a vast area of the Amazon biome. Data were incorporated on the remuneration for the production of each crop, the total number of workers involved in the production cycle, the affiliation of employees to unions, the number of children and adolescents present in paid work, and the inclusion of employers on the government list of workers in conditions analogous to slavery. National legislation on labor issues served as a reference for the fundamental requirements.

Social Life Cycle Impact Assessment (S-LCIA)

The Guidelines for Social Life Cycle Assessment of Products published by the United Nations Environment Programme and the Society of Environmental Toxicology and Chemistry (UNEP/SETAC) were used to assess potential social impacts [49]. In this study, equality of opportunity/discrimination (gender and ethnicity), freedom of association and collective bargaining, salary and benefits, forced labor, and child labor were the midpoint impact categories addressed. The inventory data were adjusted based on the baseline requirements established by the assessment scales, as presented in Table S3.

2.1.3. LCA Interpretation

The interpretation of the E-LCI, E-LCIA and S-LCI, S-LCIA of the E-LCA and S-LCA of cocoa and açai production aims to transform data and information into actionable insights to promote environmental and social sustainability. Understanding these results in a comprehensive and critical way makes it possible to drive innovation, promote agricultural responsibility, in order to contribute to a resilient future in the Amazon biome in the face of climate change and social impacts.

2.2. Economic Analysis

The economic analysis was conducted for cocoa monoculture, açai monoculture, the agroforestry system, and extractivism, based on the preparation of cash flow statements for each production model. Unlike LCA methods, which assess environmental or social impacts per functional unit, economic analysis applies a financial lens, using actual cash flows to calculate indicators such as net profit and NPV. While LCA provides system-wide impact monitoring, it often ignores financial viability. In contrast, economic modeling captures profitability over time, which together provides complementary insights into sustainability. The analysis involved calculating gross revenue, total revenue, net profit, and net present value (NPV) to assess the financial sustainability of the systems. Gross revenue was calculated by multiplying productivity by the sales price, set at USD 8.80/kg for cocoa and USD 4.10/kg for frozen açai pulp (Equation (3)). Total revenue was obtained by subtracting taxes from gross revenue (Equation (4)). Net profit was determined by subtracting production costs from total revenue (Equation (5)). Net present value (NPV) was calculated according to [50,51] (Equation (6)), by summing the present values of revenues and expenses throughout the production cycle. Productivity data for each crop were obtained from the life cycle inventory, considering a cultivation cycle of three years, the average time required for these crops to reach commercial fruit production. Production costs for each system were sourced from [52] and the National Supply Company [53]. Commodity prices were estimated based on data from [51,54]. A discount rate of 12.25% per year was applied, comprising 1.5% from the Rural Worker Assistance Fund, 6.13% from the long-term interest rate of the National Bank for Economic and Social Development (BNDES), and 4.62% corresponding to the Broad National Consumer Price Index (IPCA). The exchange rate used was USD 0.18 [55].

$$GR = P \times SP \quad (3)$$

$$TR = GR - T \quad (4)$$

$$NP = TR - PC \quad (5)$$

where P is the productivity produced per hectare, SP is the sales price, GR is the gross revenue from product marketing, T is the taxes that are paid on marketing, NP is the net profit obtained by the products, TR is the total revenue that corresponds to the value left after deducting taxes, and PC is the production cost that includes all expenses from planting to processing.

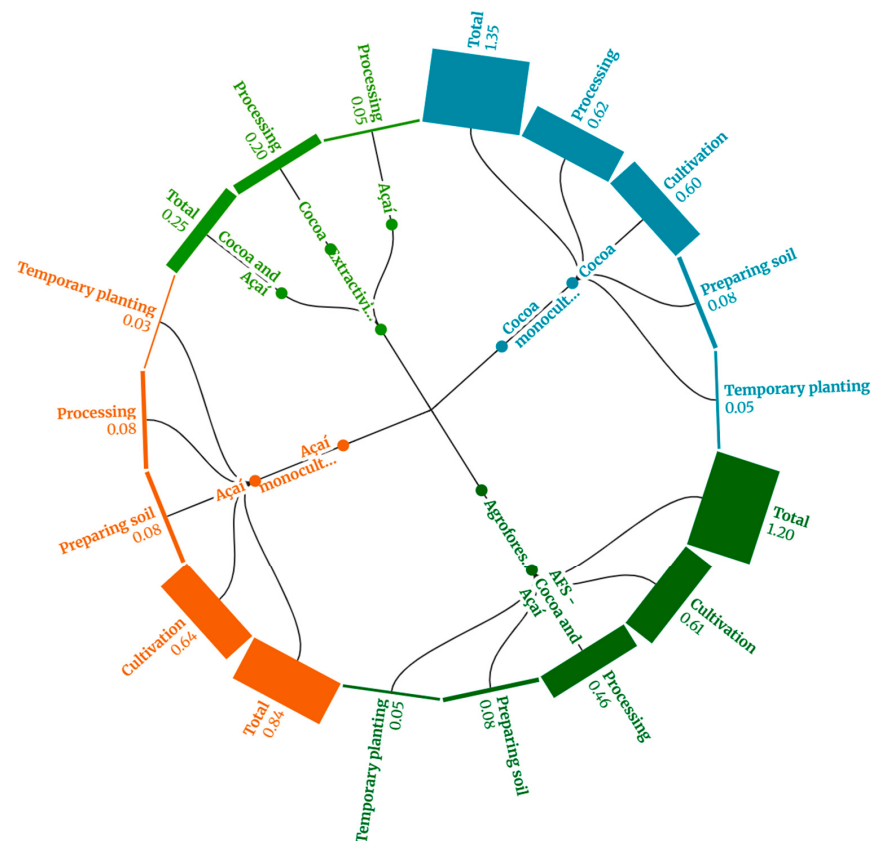
$$NPV = \sum_{t=0}^T \frac{Rt}{(1 + itotal)^t} - \sum_{t=0}^T \frac{Ct}{(1 + itotal)^t} \quad (6)$$

where Rt is the net cash inflows during period t , Ct is the net cash outflows during period t , $itotal$ is the discount rate, t is the number of periods in years, and T is the total number in years.

3. Results and Discussion

3.1. Environmental Performance

Figure 3 illustrates the CO₂ equivalent emissions associated with cocoa and açai production under different systems, monoculture, agroforestry, and extractivism, highlighting the substantial variation in environmental impact among them. Among all the systems analyzed, the lowest emissions were observed in extractivism, around 0.25 tCO₂eq, followed by açai monoculture, which recorded 0.84 tCO₂eq. Agroforestry systems recorded 1.20 tCO₂eq, while cocoa monoculture had the largest carbon footprint, with emissions of approximately 1.35 tCO₂eq. The lowest tCO₂eq emissions were for cocoa and açai extractivism. In this system, cocoa beneficiation contributes to approximately 80% of emissions and açai beneficiation to 20%. It is worth noting that cocoa beneficiation, which accounts for the largest share of emissions, has a larger electrical footprint when compared to açai beneficiation, because cocoa beans are dried in temperature-controlled ovens [37]. It is not surprising that extractive cocoa and açai production was the best, as it does not include steps such as temporary planting, soil preparation and cultivation as in other systems. Crop production under environmentally friendly practices, without the use of agrochemicals, as occurs in native forests, results in lower greenhouse gas emissions compared to conventional production [56].



scenarios	tCO ₂ eq
Cocoa monoculture	1.35 ^d
Açaí monoculture	0.84 ^b
Agroforestry (cocoa and açai)	1.20 ^c
Extractivism (cocoa and açai)	0.25 ^a

Figure 3. Carbon footprint values (tCO₂eq) for cocoa and açai monoculture, agroforestry systems and extractivism. Different letters indicate statistically significant differences between means by Tukey's test ($p < 0.05$).

On the other hand, among the monoculture systems evaluated, the highest tCO₂eq emissions were for cocoa monoculture. Temporary planting, soil preparation, cultivation, and processing of cocoa contributed 1.59 times more emissions than those of açai [57]. This can be attributed in part to the disparity in tree density between cocoa and açai, requiring greater use of agrochemicals to support the cocoa monoculture system. Evidently, in the context of monocultures, the choice of açai appears to be the best option for the environment and also for reforesting areas in the biome. Furthermore, among all scenarios, it is the second-best option in terms of greenhouse gas emissions, after extractivism.

However, when comparing agroforestry with açai monoculture, the latter showed, on average, a 29.2% lower carbon footprint. This can be explained because the agroforestry system presents a lower density of açai trees. The fact that there are fewer açai trees per hectare results in less need for inputs and energy, as can be seen in Tables 1 and 2 of the life cycles inventories. At this point, it is important to note that adjusting the density and choosing of each arboreal species can improve the resilience of the agroforestry system [17].

Simultaneously, another relevant aspect in evaluating açai and cocoa production systems is the role of CO₂ capture. This approach allows a more accurate and balanced assessment of the environmental impact of these forestry practices, providing support for decision-making. Given the conditions evaluated in this study, the results show that the CO₂eq balance, presented in Figure 4, reflects the particularities of each system for cocoa and açai production, highlighting the variation in emissions and carbon capture capacity between monocultures, agroforestry systems, and extractivism.

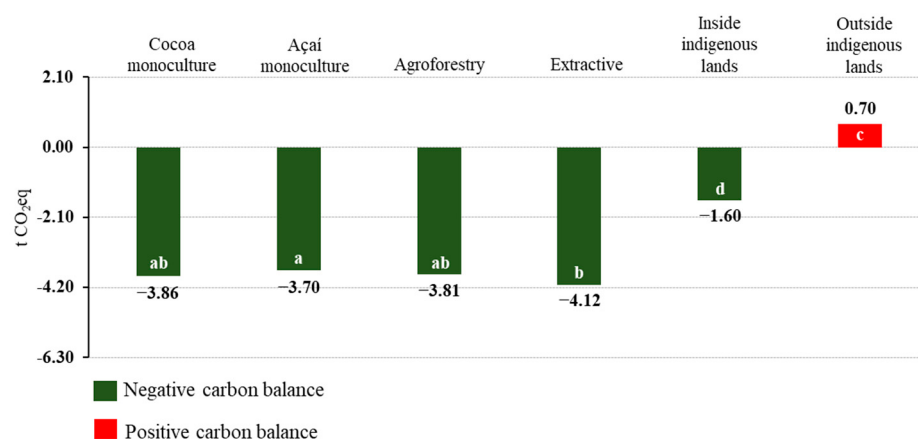


Figure 4. Characterized values of the balance of net emissions of tCO₂eq from monoculture production systems, agroforestry systems, extractivism, native forests inside and outside indigenous lands. Different letters indicate statistically significant differences between means by Tukey's test ($p < 0.05$).

As illustrated in Figure 4, the carbon balance indicates negative values for cocoa monocultures, açai monocultures, agroforestry, extractivism, and areas located inside indigenous lands. On the other hand, outside indigenous lands, it presented a positive value (0.70 tCO₂eq), evidencing the significant influence of the territorial context on carbon capture. Among these systems, extractivism stands out with the greatest potential for carbon sequestration (−4.12 tCO₂eq), followed by cocoa monoculture (−3.86 tCO₂eq), agroforestry (−3.81 tCO₂eq), and açai monoculture (−3.70 tCO₂eq), indicating the capacity to function as effective carbon sinks. However, it is important to note that these differences are not all statistically significant, especially among cocoa monoculture, agroforestry, and açai monoculture, which share overlapping groupings. The difference observed between forest areas inside and outside Indigenous lands, where traditional management practices promote more efficient carbon carbon, highlights the effective-ness of these approaches in mitigating carbon dioxide emissions. And outside indigenous lands, it demonstrates

that changes in unsustainable management practices, such as the adoption of intensive cultivation systems, can increase emissions.

It is worth noting that areas outside indigenous lands, even with a positive carbon balance, face pressures such as deforestation, mining, and agriculture, which compromise their capacity to sequester carbon dioxide. The dynamics of climate change intensify the challenges of maintaining carbon capture in any ecosystem. Extreme weather events and biodiversity loss can affect the ability of forests to sequester carbon, even in areas with traditional and sustainable management practices. The relatively lower sequestration in indigenous lands ($-1.60 \text{ tCO}_2\text{eq}$), though still negative, may reflect constraints in management intensity or environmental degradation pressures that limit their full carbon capture potential.

Also, in Figure 4, most of the results indicate that almost all of the systems evaluated function as carbon sinks, capturing more CO_2 from the atmosphere than is released. Cocoa monoculture ($-3.86 \text{ tCO}_2\text{eq}$) and açai monoculture ($-3.70 \text{ tCO}_2\text{eq}$) stand out as positive contributions in this context, representing beneficial levers for the Amazon. Although the literature often criticizes monoculture for its negative impacts on the environment [58,59], under the premises of this study, which include high tree density and specific management practices, monocultures can play a significant role in CO_2 capture, as can agroforestry systems, extractivism, and areas within indigenous lands. Furthermore, cocoa and açai monocultures, agroforestry systems, extractivism, and areas within indigenous lands may offer opportunities for revenue generation through carbon credit mechanisms, given their function as carbon sinks. However, it is important to highlight that the extractive and agroforestry scenarios assessed did not include CO_2 capture by other tree species, which could have resulted in even more significant carbon sequestration estimates. These systems act as carbon sinks and play a crucial role in mitigating climate change by absorbing more CO_2 than they emit. Furthermore, their full potential is often underestimated when tree species diversity or belowground biomass are not fully considered in the assessments.

The preservation of biodiversity goes beyond the carbon capturing capacity of monocultures. Extractivism in native forests reveals the structural complexity and biological richness of these ecosystems, playing an essential role in maintaining ecological cycles, protecting the soil, regulating water levels, and providing habitat for countless species [60]. Agroforestry systems also balance agricultural productivity with environmental preservation. Although they do not provide immediate resilience, they are more aligned with the natural dynamics of the forest, integrating agricultural production with biodiversity. While monocultures can be effective in sequestering carbon under certain management conditions, they tend to simplify ecosystems, reduce biodiversity, and make crops more vulnerable to environmental stressors, especially in full sun cultivation. This reduction in ecological complexity limits the ability of monocultures to provide a broader range of ecosystem services compared to more biodiverse systems such as extractivism and agroforestry. However, extractivism may also lead to ecosystem degradation if poorly managed, which reinforces the potential of biodiverse agroforestry systems as more structured and adaptable alternatives for sustainable land use.

3.2. Economic Performance of Production Systems

Furthermore, balancing economic sustainability is crucial, especially in regional development contexts. In this sense, Figure 5 presents the values of gross revenue, net profit, net pre-sent value and productivity for the production systems. The highest gross revenue obtained, within the developed systems, was for the açai monoculture USD 8856/ha and the lowest for the cocoa monoculture USD 7554.8/ha. For net profit, the values were USD 6783.44/ha for the açai monoculture, USD 6059.42/ha for extractivism, USD 4505.55/ha

in agroforestry and USD 3937.32/ha for cocoa monoculture. In the results, the NPV of all the production systems analyzed were positive. Regarding productivity, cocoa, and açai monocultures had productivity of around 935 kg/ha of cocoa beans and 2160 kg/ha of frozen açai pulp. For the agroforestry system, it was around 654.5 kg/ha of cocoa beans and 648 kg/ha of açai pulp, while in the extractive systems, it was 309.6 kg/ha of cocoa beans and 1260 kg/ha of açai pulp. These differences are mainly due to the higher density of productive trees per hectare in monoculture systems, compared to agroforestry and extractive systems. Productivity values refer to processed forms—cocoa beans (after fermentation and drying) and frozen açai pulp (after pulping). This distinction ensures consistency between productivity and emissions. Differences may also reflect product density and harvesting systems (tree vs. palm), which influence yield and efficiency.

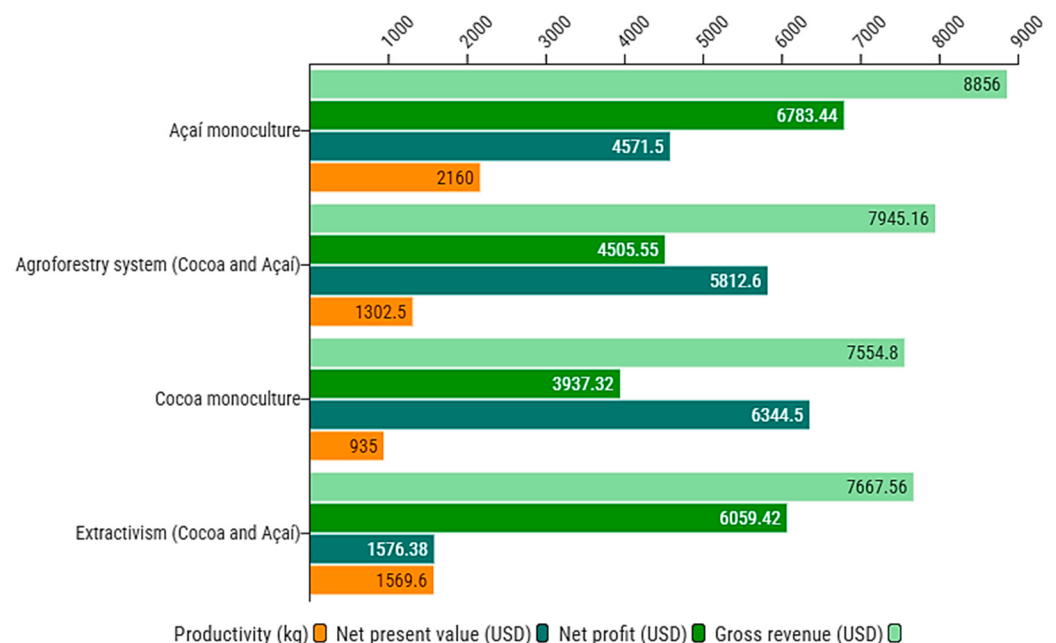


Figure 5. Financial indicators for monoculture, agroforestry and extractivism scenarios.

Based on these results, açai monoculture has the best financial performance compared to extractivism, agroforestry systems, and cocoa monoculture. When comparing financial returns, it is also important to consider how each production model uses land, inputs, and labor. These factors directly influence not only costs and revenue but also the broader sustainability trade-offs among the systems. The main factors related to the financial performance of açai monoculture were productivity per area and the commercialization price of açai. As shown in Figure 5, extractivism, followed by agroforestry systems, ranks second and third in economic aspects, respectively. This result can be explained by the ability to provide several high-value products with low operating costs [61].

In the agroforestry system, the integration of different crops increased net profits compared to cocoa monoculture, not only by diversifying income sources but also by interactions between crops [61–63]. This productive integration in agroforestry systems mitigates the economic vulnerability associated with dependence on a single crop, reducing the impacts of price fluctuations and demand for agricultural commodities [11]. Furthermore, in the long term, these interactions recreate habitats and perform functions similar to native forests, promoting a restorative area in landscapes degraded by human disturbances. The harmonious coexistence between cocoa and açai agricultural production and environmental regeneration paves the way for sustainable development, balancing economic and ecological needs and promoting the biodiversity of the biome.

Evidently, monoculture can offer short-term financial returns, but as already mentioned, its instability in the commodity market and high production costs can compromise the economic sustainability of producers. In contrast, the agroforestry system, in addition to extractivism, by combining cocoa production with other crops and forest conservation, demonstrates greater resilience to external shocks and provides more lasting environmental and social benefits, in line with the principles of eco-economics [64]. Furthermore, agro-forestry can provide an additional source of income through ecosystem services, as provided for in Brazilian Law No. 14,119/2022 [65], which establishes a legal framework to value the services provided by those who conserve ecosystems and promote biodiversity. For example, estimating economic values for services for food production (Brazil nuts), supply of raw materials (rubber and timber), climate regulation, and mitigation of CO₂ emissions can generate significant economic values. These values range from USD 56.72 to USD 737 per hectare per year, depending on the location and services provided. Furthermore, the transition from monocultures to agroforestry systems is reinforced by the expectation that these systems can support biodiversity and ecosystem functions approaching those of native forests. While not identical in complexity, agroforestry enhances structural diversity, and, together with extractivism, especially those with high palm and tree densities, plays a vital role in maintaining ecological balance and resilience. They can revitalize the biome, promoting biodiversity recovery and efficient land use. For example, ref. [14] reveal that the combination of cocoa and rubber trees can reduce land equivalence, concluding that 2.45 ha and 1.41 ha of rubber and cocoa monoculture, respectively, would be needed to obtain the production of 1.0 ha of intercropping between these crops.

In the context of cocoa monoculture, this presents the worst financial performance, mainly attributed to the high cost of production, associated with the intensive use of agrochemicals in the system [17]. The use of agrochemicals in monoculture systems is well documented, particularly in cocoa production, while agroforestry systems typically require fewer chemical inputs due to their diversified structure and ecological interactions. This scenario is also reflected in the agroforestry system analyzed, where cocoa is combined with açaí cultivation [66]. The greater allocation of resources and more complex management result in significantly higher costs compared to açaí monoculture and extractivism. This suggests that the adoption of other crop combinations, such as native species or those with greater economic viability, could optimize results, reduce costs, promote greater efficiency in the use of resources, and improve both the financial and environmental aspects of the system.

Regarding the net present value (NPV), this is a crucial indicator that demonstrates long-term projections, as it assesses the current value of future cash flows discounted at a rate that reflects the opportunity cost of capital. Considering projected future revenues and investment costs. Although all production systems presented positive NPV, cocoa monoculture (USD 6344.50/ha) was the most financially attractive, followed by agroforestry (USD 5812.60/ha), açaí monoculture (USD 4571.50/ha) and extractivism (USD 1576.38/ha). However, cocoa and açaí extractivism are considered the most advantageous in weighted terms.

3.3. Social Sustainability

A social assessment is essential so that the trade-offs between economic viability and sustainability are not neglected. In this sense, Figure 6 presents the midpoint categories evaluated in the study, referring to the workers endpoint category. In this sense, Figure 6 shows the midpoint categories evaluated in the study, referring to the workers endpoint category.

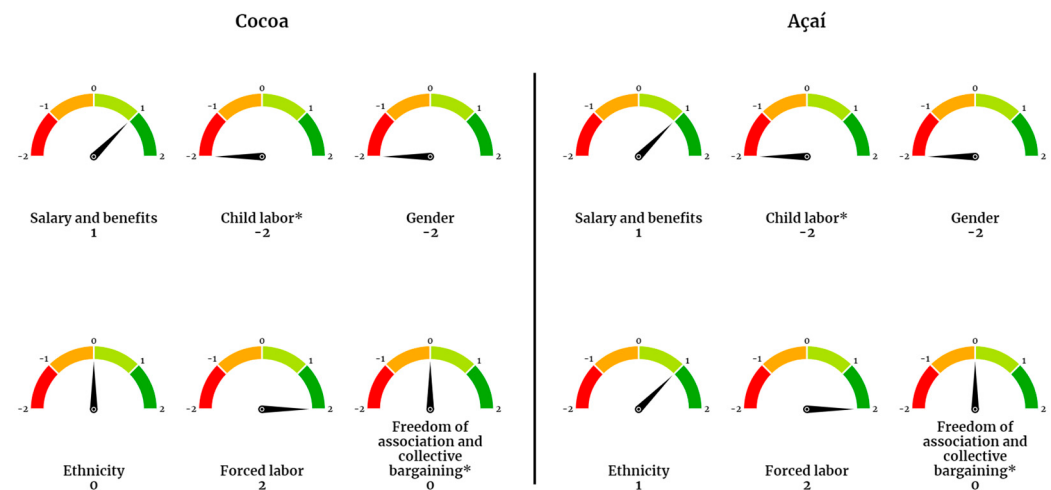


Figure 6. Classification of the social life cycle analysis of cocoa and açai commodities present in the northern region of Brazil. +2: Ideal compliance; +1: Above basic compliance; 0: Within basic compliance by local and international laws; −1: Below basic compliance; −2: Does not meet basic compliance. * Corresponds to data from the primary sector, covering all activities related to monocultures, agroforestry systems, and extractivism of the biome.

As shown in Figure 6, cocoa and açai production presents, among the subcategories evaluated, only the forced labor at an ideal level of compliance (+2). Related to this, it is noted that there is a very low risk of the existence of induced work involved in these crops from the S-LCA perspective. This is often explained by the idea that forced labor is much less widespread than child labor, which in turn has a negative impact. This is pointed out in other countries, for ex-ample in Ghana and Côte d’Ivoire, demonstrating that forced labor corresponds to a small portion of the problem for the category of workers [67]. Little scientific evidence provides explanations for the existence of this type of labor in cocoa and açai production, but those that shed light on the problem are limited to the migrant labor force. However, the claim that forced labor is limited to this factor is an oversimplification and misleading, as it is a complex and multifaceted problem that requires a comprehensive and humanitarian approach.

As for the child labor subcategory, alarmingly, it is among the two worst subcategories evaluated in the study, allocated on the worst scale (−2). In Brazil, the Federal Constitution establishes the prohibition of work for children under 16 years of age, except as apprentices from the age of 14. The 2022 Continuous National Household Sample Survey indicates that 4.9% of children and adolescents, between 5 and 17 years of age, were in a situation of child labor, totaling 1.9 million young people [49]. It is worth highlighting that the agricultural sector, including the production of cocoa and açai, is one of the main responsible for this practice, making these products socially unsustainable. Therefore, there may be a very high risk that much of the chocolate purchased and consumed globally may have been produced using child labor.

Açaí was also assessed as having a negative impact on the child labor subcategory (−2). Short stature and unfavorable socioeconomic conditions contribute to the irregular employment of minors, due to the morphology of the palm, which is tall and thin, favoring the employment of minors. In 2021, published reports revealed the serious risks to which these children are exposed, such as handling chainsaws, climbing tall trees, and disproportionate machetes, increasing the risk of fatal accidents [68]. In addition, the location in tropical areas increases the incidence of insects and pests, resulting in a high use of pesticides and, consequently, exposing these children to these chemicals [69].

According to the result of the subcategory salary and benefits, both cultures had a social impact above basic compliance (+1). For açaí, the scenario remains the same, presenting a social impact above compliance. Regarding the subcategory equal opportunities/discrimination, gender issues have the same impact in both cultures (−2), often the social identity of men and women is pre-shaped. Although women play an important role in the production of these commodities, they often face challenges. Generally explained by the fact that employment opportunities, financial returns, and working conditions are not equitable between genders [70]. In contrast, in a recent study [71] highlighted in this subcategory a negative impact on cocoa production in countries such as Ghana and Ivory Coast, emphasizing that both attributed a high risk of very low salary, making it impossible for cocoa producers to even have a decent life.

The impact on the subcategory of equal opportunities based on ethnicity resulted in 0 for cocoa and +1 for açaí. In cocoa, modernization industrial, by prioritizing efficiency, sacrificing traditional knowledge, and exploiting labor, especially in areas with less ethnic diversity, can result in a significant ethnic impact [72]. However, it is worth noting that family farmers are essential for sustainable cocoa production in the Amazon, boosting the local economy while also adding value to the market that seeks to prioritize overall sustainability [13]. In the case of açaí, the social impact focused on the ethnic issue may be more significant, since açaí production is strongly linked to traditional communities, such as riverside and indigenous populations in the Amazon, being the main source of subsistence for these communities. In this context, ethnicity is also understood as the preservation of traditional knowledge and cultural practices. Similarly, extractivism in this study refers not only to harvesting from native forests but also to culturally embedded practices that reflect the ancestral management of forest resources by traditional and Indigenous communities.

The subcategory of freedom of association in cocoa and açaí production, data from 2022, indicates that 16.5% of workers were unionized. In this sense, both crops meet the requirements established by law. Although there are barriers or lack of understanding for mass membership, there is opportunity for association. Furthermore, unionization can be considered a social innovation that can help them overcome structural barriers and promote the inclusion of practices with a bias toward social, economic, and environmental sustainability [73].

3.4. Integrated Interpretation, Limitations and Sustainability Trade-Offs

Although extractivism presented the lowest NPV, they stood out for having the highest net profit and the lowest carbon footprint. This highlights a limitation of the NPV metric, which does not fully capture environmental externalities or ecological benefits. From a broader sustainability perspective, native forest systems maximize long-term returns through climate regulation, biodiversity conservation, and ecosystem services that are not reflected in conventional financial indicators. Therefore, using NPV in isolation may overlook the socio-environmental value of systems like extractivism and agroforestry, which play essential roles in resilience and sustainability beyond immediate monetary returns.

Although their NPV is the lowest, they stand out for presenting the highest net profit and the lowest impact on CO₂eq emissions. In this sense, native forest maximizes sustainable financial return in the long term and contributes significantly to the mitigation of climate change, maintaining low levels of CO₂eq emissions. Furthermore, it plays a crucial role in regulating climatic, hydrological, and biogeochemical cycles, and in maintaining air humidity and safety standards, providing broad and sustainable ecological benefits. These benefits, however, depend on well-regulated extractivist practices, since without proper management of harvesting intensity and tree density, the ecological resilience of native forests may be compromised. Although the results of the study show that

monocultures can play a role in carbon capture, extractivism is essential for forest resilience. Agroforestry can become a long-term alternative, and the economics of these systems choose açai monoculture.

It is difficult to verify these results with those of other similar studies due to the scarcity of literature on S-LCA, E-LCA, and financial indicators in cocoa and açai production. In this sense, government surveys are the main sources of this information and indices. Furthermore, this research gap is consistent with the initial objective of expanding the literature on the social impacts of cocoa and açai production in the Amazon biome from an S-LCA perspective. The scarcity of social data can also lead to the exclusion and technical attention of certain subcategories of workers, underestimating the extent of the problem in the Amazon region. It is worth noting that the social results presented reflect regional aggregate data and do not fully capture the differences between production systems. For example, extractivism tends to require more labor and promote greater local attachment, while monoculture involves greater mechanization and use of agrochemicals, with specific implications for workers.

Therefore, due to the scarcity of published data and measurable indicators, it is necessary to expand the repertoire of social metrics used in S-LCA to improve its accuracy and applicability. Furthermore, agroforestry systems can represent an interactive alternative, promoting income diversity and social inclusion, but they still lack specific data that would allow for more robust social analyses. Although this assessment contains an initial knowledge base, more complete and updated data are needed, which future studies should focus on. Currently, challenges persist, such as low female participation and child labor in cocoa and açai production. However, the positive impact related to the ethnic culture of açai can open paths for more equitable production.

Another limitation of the study is the lack of gender-disaggregated data on child labor in cocoa and açai production. This restricts the ability to assess how gender roles may influence the type and intensity of tasks performed by children, potentially obscuring important social vulnerabilities.

The main limitation of the extractive scenario is related to the counting and mapping of tree species, especially in estimating density per hectare. The natural occurrence of açai and cocoa in the Amazon biome is highly variable, and there may be areas with higher or lower concentrations of these species. This heterogeneity makes it difficult to standardize data and may impact the accuracy of carbon accounting and productivity. Therefore, the estimate of density per hectare should be interpreted with caution, considering regional ecological fluctuations.

Given this scenario, the protection of native forests and the promotion of sustainable agroecological practices become even more urgent. By valuing traditional knowledge and implementing management practices that respect natural cycles, it is possible to reconcile food production and biodiversity conservation, contributing to the mitigation of climate change and ensuring long-term sustainability.

4. Conclusions

The insights provided in this study reveal that in relation to environmental charges, cocoa monoculture proved to be the largest contributor to the carbon footprint (1.35 tCO₂eq/ha), followed by agroforestry (1.20 tCO₂eq/ha), açai monoculture (0.84 tCO₂eq/ha) and extractivism (0.25 tCO₂eq/ha). In the carbon balance, all systems presented negative values, unlike for areas outside indigenous lands. In economic terms, açai monoculture had a net profit 1.72 times greater than that of cocoa monoculture, 1.50 times greater than the agroforestry system, and 1.12 times greater than extractivism. On the other hand, social analysis points to signs of inequality in the distribution of opportunities among ethnic

groups and possible occurrences of child labor in certain production chains. Such issues, associated with socioeconomic vulnerability, require more in-depth empirical investigation. Additionally, the limited availability of disaggregated social data highlights the need to expand measurable social indicators in S-LCA, allowing for more accurate and inclusive assessments.

Finally, opting for a trade-off focused on extractivism in the Amazon biome can be a long-term strategic solution. It offers a robust approach to combine agricultural productivity with environmental conservation, demonstrating a sustainable and responsible use of resources. This strategy often involves compensations between short-term economic gains and the long-term maintenance of ecosystem services. Although extractivism, especially of açai, has a low carbon footprint and good financial performance, it can entail ecological and social risks, such as resource depletion and labor exploitation, if there is no strict control over harvesting, land use, and working conditions. On the other hand, without requiring absolute preservation, agroforestry systems promote balance between society and nature, offer benefits to biodiversity, and mimic the ecological functions of native forests. Despite lower short-term profits, they have long-term potential for sustainable restoration and climate adaptation. These systems highlight that maximizing immediate profit or reducing labor intensity may come at the expense of environmental resilience, reinforcing the need for integrated approaches. It is proposed that it is possible to generate wealth while keeping the forest standing, using sustainable strategies such as the carbon credit market, strengthening the bioeconomy and payment for ecosystem services. However, the effectiveness of these mechanisms depends on regulatory clarity, institutional capacity, market access, and the active participation of local communities—factors that need to be addressed for successful implementation. Moreover, aligning these strategies with broader frameworks such as the United Nations Sustainable Development Goals (SDGs), particularly goals related to climate action (SDG 13), life on land (SDG 15), and poverty reduction (SDG 1), can increase their global relevance and reinforce their contribution to international climate and sustainability targets. It is essential to consider, in addition to agriculture, production models that value forest resources and promote conservation, pointing out viable ways to balance economic prosperity and environmental sustainability.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/commodities4020008/s1>, Table S1. Characterization factors of CO₂ emission factors per kg of product/substance in cocoa production; Table S2. Characterization factors of CO₂ emission factors per kg of product/substance in açai production; Table S3. Basic attributes stipulated for the social impact analysis of stakeholder worker subcategories; Table S4. CO₂ emission for the production of 1 hectare of cocoa; Table S5. CO₂ emission for the production of 1 hectare of açai.

Author Contributions: Conceptualization, R.L.S.M. and E.J.-L.; methodology, R.L.S.M., A.T.S., R.R.D., M.C.D. and D.A.D.; data curation, R.L.S.M., A.T.S. and D.A.D.; writing original draft preparation, R.L.S.M.; writing review and editing, E.J.-L.; supervision, C.R.d.M. and L.Q.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Financial support for this research was provided by the Coordination for the Improvement of Higher Education Personnel (CAPES).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are all included in the article/Supplementary Materials. Additional questions can be directed to the corresponding author(s).

Acknowledgments: The authors would like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES).

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Araujo, E.C.G.; Sanquetta, C.R.; Dalla Corte, A.P.; Pelissari, A.L.; Orso, G.A.; Silva, T.C. Global review and state-of-the-art of biomass and carbon stock in the Amazon. *J. Environ. Manag.* **2023**, *331*, 117251. [CrossRef] [PubMed]
2. Kröger, M. *Extractivisms, Existences and Extinctions: Monoculture Plantations and Amazon Deforestation*; Taylor & Francis: Boca Raton, FL, USA, 2022; p. 176. [CrossRef]
3. Huera-Lucero, T.; Lopez-Piñeiro, A.; Torres, B.; Bravo-Medina, C. Biodiversity and Carbon Sequestration in Chakra-Type Agroforestry Systems and Humid Tropical Forests of the Ecuadorian Amazon. *Forests* **2024**, *15*, 557. [CrossRef]
4. Gatti, L.V.; Basso, L.S.; Miller, J.B.; Gloor, M.; Gatti Domingues, L.; Cassol, H.L.; Tejada, G.; Aragão, L.E.; Nobre, C.; Peters, W.; et al. Amazonia as a carbon source linked to deforestation and climate change. *Nature* **2021**, *595*, 388–393. [CrossRef]
5. ICCO—International Cocoa Organization. *Quarterly Bulletin of Cocoa Statistics: Edition No. 4—Volume 49—Cocoa Year 2022/23*; ICCO: Abidjan, Côte d’Ivoire, 2023. Available online: <https://www.icco.org/november-2023-quarterly-bulletin-of-cocoa-statistics/> (accessed on 3 September 2024).
6. IBGE—Instituto Brasileiro de Geografia e Estatística. Cocoa Production in 2022. 2024. Available online: <https://www.ibge.gov.br/explica/producao-agropecuaria/cacau/br> (accessed on 18 August 2024).
7. EMBRAPA—Brazilian Agricultural Research Corporation. Açaí: Weed Control. EMBRAPA Portal: Eastern Amazon, 2024. Available online: <https://www.embrapa.br/agencia-de-informacao-tecnologica/cultivos/acai/producao/tratos-culturais/manejo-de-perfilhos-limpeza-das-touceiras-e-controle-do-mato> (accessed on 3 September 2024).
8. Schneider, A.T.; Dias, R.R.; Deprá, M.C.; Dutra, D.A.; Machado, R.L.S.; de Menezes, C.R.; Zepka, L.Q.; Jacob-Lopes, E. The Intersectionality Between Amazon and Commodities Production: A Close Look at Sustainability. *Land* **2024**, *2024*, 13. [CrossRef]
9. Rosenfeld, T.; Pokorny, B.; Marcovitch, J.; Poschen, P. Bioeconomy based on non-timber forest products for development and forest conservation-untapped potential or false hope? A systematic review for the Brazilian amazon. *For. Policy Econ.* **2024**, *163*, 103228. [CrossRef]
10. Marconi, L.; Armengot, L. Complex agroforestry systems against biotic homogenization: The case of plants in the herbaceous stratum of cocoa production systems. *Agric. Ecosyst. Environ.* **2020**, *287*, 106664. [CrossRef]
11. Niether, W.; Jacobi, J.; Blaser, W.J.; Andres, C.; Armengot, L. Cocoa agroforestry systems versus monocultures: A multi-dimensional meta-analysis. *Environ. Res. Lett.* **2020**, *15*, 104085. [CrossRef]
12. Rosati, A.; Borek, R.; Canali, S. Agroforestry and organic agriculture. *Agrofor. Syst.* **2021**, *95*, 805–821. [CrossRef]
13. Parra-Paitan, C.; Verburg, P.H. Accounting for land use changes beyond the farm-level in sustainability assessments: The impact of cocoa production. *Sci. Total Environ.* **2022**, *825*, 154032. [CrossRef]
14. Gama-Rodrigues, A.C.; Müller, M.W.; Gama-Rodrigues, E.F.; Mendes, F.A.T. Cacao-based agroforestry systems in the Atlantic Forest and Amazon Biomes: An ecoregional analysis of land use. *Agric. Syst.* **2021**, *194*, 103270. [CrossRef]
15. Vizuite-Montero, M.; Carrera-Oscullo, P.; Barreno-Silva, N.D.L.M.; Sánchez, M.; Figueroa-Saavedra, H.; Moya, W. Agroecological alternatives for small and medium tropical crop farmers in the Ecuadorian Amazon for adaptation to climate change. *Agric. Syst.* **2024**, *218*, 103998. [CrossRef]
16. Freitas, M.A.B.; Vieira, I.C.G.; Albernaz, A.L.K.M.; Magalhães, J.L.L.; Lees, A.C. Floristic impoverishment of Amazonian floodplain forests managed for açaí fruit production. *For. Ecol. Manag.* **2015**, *351*, 20–27. [CrossRef]
17. Mattalia, G.; Wezel, A.; Costet, P.; Jagoret, P.; Deheuvels, O.; Migliorini, P.; David, C. Contribution of cacao agroforestry versus mono-cropping systems for enhanced sustainability. *A Rev. A Focus yield. Agrofor. Syst.* **2022**, *96*, 1077–1089. [CrossRef]
18. Scordia, D.; Corinzia, S.A.; Coello, J.; Vilaplana Ventura, R.; Jiménez-De-Santiago, D.E.; Singla Just, B.; Castaño-Sánchez, O.; Casas Arcarons, C.; Tchamitchian, M.; Garreau, L.; et al. Are agroforestry systems more productive than monocultures in Mediterranean countries? A meta-analysis. *Agron. Sustain. Dev.* **2023**, *43*, 73. [CrossRef]
19. Ariza-Salamanca, A.J.; Navarro-Cerrillo, R.M.; Crozier, J.; Stirling, C.; Mancini, A.; Blaser-Hart, W.; González-Moreno, P. Drivers of cocoa yield and growth in young monoculture and agroforestry systems. *Agric. Syst.* **2024**, *219*, 104044. [CrossRef]
20. Deprá, M.C.; Dias, R.R.; Zepka, L.Q.; Jacob-Lopes, E. Building cleaner production: How to anchor sustainability in the food production chain? *Environ. Adv.* **2022**, *9*, 100295. [CrossRef]
21. Dias, R.R.; Sartori, R.B.; Schneider, A.T. Food Sustainability Index. In *Smart Food Industry: The Blockchain for Sustainable Engineering*; CRC Press: Boca Raton, FL, USA, 2024; pp. 25–33.
22. ISO-14040; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO—International Standard Organization: Geneva, Switzerland, 2006.

23. ISO-14044; 2006 Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO—International Organization for Standardization: Geneva, Switzerland, 2006.
24. Nalley, L.L.; Dixon, B.L.; Popp, J.S. An optimal phased replanting approach for cocoa trees with application to Ghana. *Agric. Econ.* **2014**, *45*, 291–302. [\[CrossRef\]](#)
25. Utomo, B.; Prawoto, A.A.; Bonnet, S.; Bangviwat, A.; Gheewala, S.H. Environmental performance of cocoa production from monoculture and agroforestry systems in Indonesia. *J. Clean. Prod.* **2016**, *134*, 583–591. [\[CrossRef\]](#)
26. Piasentin, F.B.; Saito, C.H. The different methods of cocoa cultivation in southeastern Bahia, Brazil: Historical aspects and perceptions. *Bulletin of the Emílio Goeldi Museum of Pará. Hum. Sci.* **2014**, *9*, 61–78. [\[CrossRef\]](#)
27. Silva, C.E.; Gonçalves, J.F.D.C.; Feldpausch, T.R.; Luizão, F.J.; Moraes, R.R.; Ribeiro, G.O. Nutrient use efficiency by pioneer species grown on degraded pastures in central Amazonia. *Acta Amaz.* **2006**, *36*, 503–512. [\[CrossRef\]](#)
28. Waheed, M.A.; Jekayinfa, S.O.; Ojediran, J.O.; Imeokparia, O.E. Energetic analysis of fruit juice processing operations in Nigeria. *Energy* **2008**, *33*, 35–45. [\[CrossRef\]](#)
29. Veloso, C.A.; Silva, A.; Sales, A. Management of NPK fertilization in the formation of açaí in a Yellow Latosol of northeastern Pará. *Encycl. Biosph.* **2015**, *11*, 2175–2182.
30. Bezerra, V.; Freitas-Silva, O.; Damasceno, L.; Mamede, A.; Cabral, L. Sensory Analysis and Consumers Studies of Açaí Beverage After Thermal, Chlorine and Ozone Treatments of the Fruits: Sensory Analysis and Consumers Studies. *J. Food Process. Preservation.* **2016**, *41*, e12961. [\[CrossRef\]](#)
31. Ortiz-Rodríguez, O.O.; Villamizar-Gallardo, R.A.; Naranjo-Merino, C.A.; García-Caceres, R.G.; Castañeda-Galvís, M.T. Carbon footprint of the colombian cocoa production. *Eng. Agrícola* **2016**, *36*, 260–270. [\[CrossRef\]](#)
32. Ogunsina, B.S.; Adeyemi, M.A.; Morakinyo, T.A.; Aremu, O.J.; Bamgboye, A.I. Direct energy utilization in the processing of cocoa beans into powder. *Agric. Eng. Int. CIGR J.* **2017**, *19*, 213–218.
33. Carvalho, J.E.U.D.; Nascimento, W. Technological innovations in the propagation of Açaí palm and Bacuri. *Rev. Bras. De Frutic.* **2018**, *40*, e-679. [\[CrossRef\]](#)
34. Recanati, F.; Marveggio, D.; Dotelli, G. From beans to bar: A life cycle assessment towards sustainable chocolate supply chain. *Sci. Total Environ.* **2018**, *613*, 1013–1023. [\[CrossRef\]](#)
35. Trinh, L.T.K.; Hu, A.H.; Lan, Y.C.; Chen, Z.H. Comparative life cycle assessment for conventional and organic coffee cultivation in Vietnam. *Int. J. Environ. Sci. Technol.* **2020**, *17*, 1307–1324. [\[CrossRef\]](#)
36. Walling, E.; Vaneekhaute, C. Greenhouse gas emissions from inorganic and organic fertilizer production and use: A review of emission factors and their variability. *J. Environ. Manag.* **2020**, *276*, 111211. [\[CrossRef\]](#)
37. De Araujo, M.K.D.C.; de Cristo Silva, R.R.; da Silva, M.A.P.; Antunes, A.M. Cocoa almonds (*Theobroma cacao* L.) submitted to different temperatures and drying times in northern Brazil. *Braz. J. Dev.* **2022**, *8*, 77409–77421. [\[CrossRef\]](#)
38. Carneiro, A.O.; Silva, e.H.B.C. Energy balance in the production of mango pulps: From cultivation to storage. *Electron. J. Environ. Manag. Technol.* **2022**, *10*, 82–92.
39. Queiroga, V.; Mendes, N.; Gomes, J.; Lima, D.; de Melo, B.; Queiroz, A.; Albuquerque, E. AÇAÍ (*Euterpe oleracea* Mart.) Fruit Production on Dry Land and Use. 2023, 1 v. ISBN: 978-65-00-77777-7. Available online: <https://www.researchgate.net/publication/374505968> (accessed on 10 September 2024).
40. Salgado-Aristizabal, N.; Agudelo-Patiño, T.; Ospina-Corral, S.; Álvarez-Lanzarote, I.; Orrego, C.E. Environmental Life Cycle Analysis of Açaí (*Euterpe oleracea*) Powders Obtained via Two Drying Methods. *Processes* **2023**, *11*, 2290. [\[CrossRef\]](#)
41. Idawati, I.; Sasongko, N.A.; Santoso, A.D.; Sani, A.W.; Apriyanto, H.; Boceng, A. Life cycle assessment of cocoa farming sustainability by implementing compound fertilizer. *Glob. J. Environ. Sci. Manag.* **2024**, *10*, 837–856. [\[CrossRef\]](#)
42. Huijbregts, M.A.; Steinmann, Z.J.; Elshout, P.M.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; Van Zelm, R. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [\[CrossRef\]](#)
43. Jacob-Lopes, E.; Zepka, L.Q.; Deprá, M.C. *Sustainability Metrics and Indicators of Environmental Impact: Industrial and Agricultural Life Cycle Assessment*; Elsevier: Amsterdam, The Netherlands, 2021. [\[CrossRef\]](#)
44. Protocol, G.H.G. Metodologia do GHG Protocol da Agricultura. *Greenh. Gas Protoc.* **2014**, 1–54.
45. Zelarayán, M.L.; Celentano, D.; Oliveira, E.C.; Triana, S.P.; Sodré, D.N.; Muchavisoy, K.H.M.; Rousseau, G.X. Impact of manipulation on the total carbon stock of riparian forests in the Eastern Amazon, Brazil. *Acta Amaz.* **2015**, *45*, 271–282. [\[CrossRef\]](#)
46. Condé, T.M.; Condé, J.D.; Sousa, C.W.L. Açaí fruit production and carbon stock in managed plantations in Southeast of Roraima. *Rev. Agroambiente On-Line* **2020**, *14*, 1–15. [\[CrossRef\]](#)
47. Veit, P.; Gibbs, D.; Reytar, K. *Indigenous Forests Are Some of the Amazon's Last Carbon Sinks [Internet]*; World Resources Institute: Washington, DC, USA, 2023.
48. IBGE—Instituto Brasileiro de Geografia e Estatística. 2022. Available online: <https://www.ibge.gov.br/estatisticas/todos-os-produtos-estatisticas.html> (accessed on 2 September 2024).

49. Benoît Norris, C.; Traverzo, M.; Neugebauer, S.; Ekener, E.; Schaubroeck, T.; Russo Garrido, S. *Guidelines for Social Life Cycle Assessment of Products and Organizations 2020*; United Nations Environment Programme: Nairobi, Kenya, 2020.
50. Goncalves, N.; Andrade, D.; Batista, A.; Cullen, L.; Souza, A.; Gomes, H.; Uezu, A. Potential economic impact of carbon sequestration in coffee agroforestry systems. *Agrofor. Syst.* **2021**, *95*, 419–430. [\[CrossRef\]](#)
51. Goñas, M.; Rojas-Briceño, N.B.; Gómez Fernández, D.; Iliquin Trigoso, D.; Atalaya Marin, N.; Bravo, V.C.; Díaz-Valderrama, J.R.; Maicelo-Quintana, J.L.; Oliva-Cruz, M. Economic Profitability of Carbon Sequestration of Fine-Aroma Cacao Agroforestry Systems in Amazonas, Peru. *Forests* **2024**, *15*, 500. [\[CrossRef\]](#)
52. Barbosa, L.C.; Silva, C.G.N.; Silva, D.A.S.; Gutierrez, D.M.G.; da Silva, A.O.; do Nascimento, J.P.P.G.; de Jesus Matos Viégas, I.; Galvão, J.R.; da Silva, S.P. Cost analysis of açaí production, cultivar chumbinho (euterpe olearacea mart.) on a rural property in the municipality of Capanema-PA in 2019. *Braz. Appl. Sci. Rev.* **2020**, *4*, 491–509. [\[CrossRef\]](#)
53. CONAB Historical Series—Costs—Cocoa—2011 to 2023 (SB). 2024. Available online: <https://www.conab.gov.br/info-agro/custos-de-producao/planilhas-de-custo-de-producao/itemlist/category/843-cacau> (accessed on 25 July 2024).
54. Nogueira, A.K.M.; Santana, A.C.D.; Garcia, W.S. The dynamics of the açaí fruit market in the State of Pará: From 1994 to 2009. *Ceres Mag.* **2013**, *60*, 324–331. [\[CrossRef\]](#)
55. X-RATES, 2024. Brazilian Real Rates Table. Historic Lookup. Curr. Rates Your Bus. Available online: <https://www.x-rates.com/historical/?from=USD&amount=1&date=2024-07-16> (accessed on 24 July 2024).
56. Bandanaa, J.; Asante, I.K.; Egyir, I.S.; Schader, C.; Annang, T.Y.; Blockeel, J.; Kadzere, I.; Heidenreich, A. Sustainability performance of organic and conventional cocoa farming systems in Atwima Mponua District of Ghana. *Environ. Sustain. Indic.* **2021**, *11*, 100121. [\[CrossRef\]](#)
57. Vervuurt, W.; Slingerland, M.A.; Pronk, A.A.; Van Bussel, L.G.J. Modelling green-house gas emissions of cacao production in the Republic of Côte d’Ivoire. *Agrofor. Syst.* **2022**, *96*, 417–434. [\[CrossRef\]](#)
58. Asigbaase, M.; Dawoe, E.; Lomax, B.H.; Sjogersten, S. Biomass and carbon stocks of organic and conventional cocoa agroforests, Ghana. *Agric. Ecosyst. Environ.* **2021**, *306*, 107192. [\[CrossRef\]](#)
59. Yao, M.K.; Koné, A.W.; Otinga, A.N.; Kassin, E.K.; Tano, Y. Carbon and nutrient cycling in tree plantations vs. natural forests: Implication for an efficient cocoa agroforestry system in West Africa. *Reg. Environ. Change* **2021**, *21*, 44. [\[CrossRef\]](#)
60. Fassoni-Andrade, A.C.; Fleischmann, A.S.; Papa, F.; Paiva, R.C.; Wongchuig, S.; Melack, J.M.; Moreira, A.A.; Paris, A.; Ruhoff, A.; Barbosa, C.; et al. Amazon hydrology from space: Scientific advances and future challenges. *Rev. Geophys.* **2021**, *59*, e2020RG000728. [\[CrossRef\]](#)
61. Gomes, C.V.A. Economic cycles of extractivism in the Amazon from the perspective of traveling naturalists. Bulletin of the Emílio Goeldi Museum of Pará. *Hum. Sci.* **2018**, *13*, 129–146. [\[CrossRef\]](#)
62. Pérez-Neira, D.; Schneider, M.; Esche, L.; Armengot, L. Sustainability of food security in different cacao production systems: A land, labour, energy and food quality nexus approach. *Resour. Conserv. Recycl.* **2023**, *190*, 106874. [\[CrossRef\]](#)
63. Armengot, L.; Beltrán, M.J.; Schneider, M.; Simón, X.; Pérez-Neira, D. Food-energy-water nexus of different cacao production systems from a LCA approach. *J. Clean. Prod.* **2021**, *304*, 126941. [\[CrossRef\]](#)
64. Waldén, P.; Ollikainen, M.; Kahiluoto, H. Carbon revenue in the profitability of agroforestry relative to monocultures. *Agrofor. Syst.* **2020**, *94*, 15–28. [\[CrossRef\]](#)
65. Brazil. Law No. 14,119 of January 13, 2021. Institutes the National Policy on Payment for Environmental Services and Amends Laws No. 8212 of July 24, 1991, 8629 of February 25, 1993, and 6015 of December 31, 1973, to Adapt Them to the New Policy—Official Gazette of the Union, Brasília, DF. 2021. Available online: <https://www.in.gov.br/en/web/dou/-/lei-n-14.119-de-13-de-janeiro-de-2021-301303266> (accessed on 2 July 2024).
66. Caicedo-Vargas, C.; Pérez-Neira, D.; Abad-González, J.; Gallar, D. Agroecology as a means to improve energy metabolism and economic management in smallholder cocoa farmers in the Ecuadorian Amazon. *Sustain. Prod. Consum.* **2023**, *41*, 201–212. [\[CrossRef\]](#)
67. Perkiss, S.; Bernardi, C.; Dumay, J.; Haslam, J. A sticky chocolate problem: Impression management and counter accounts in the shaping of corporate image. *Crit. Perspect. Account.* **2021**, *81*, 102229. [\[CrossRef\]](#)
68. Tham-Agyekum, E.K.; Wongnaa, C.A.; Kwapong, N.A.; Boansi, D.; Ankuyi, F.; Prah, S.; Bakang, J.E.; Okorley, E.L.; Laten, E. Impact of children’s appropriate work participation in cocoa farms on household welfare: Evidence from Ghana. *J. Agric. Food Res.* **2023**, *14*, 100901. [\[CrossRef\]](#)
69. Villanueva, E.; Glorio-Paulet, P.; Giusti, M.M.; Sigurdson, G.T.; Yao, S.; Rodríguez-Saona, L.E. Screening for pesticide residues in cocoa (*Theobroma cacao* L.) by portable infrared spectroscopy. *Talanta* **2023**, *257*, 124386. [\[CrossRef\]](#) [\[PubMed\]](#)
70. Vinci, G.; Ruggeri, M.; Gobbi, L.; Savastano, M. Social Life Cycle Assessment of Cocoa Production: Evidence from West Africa. *Environ. Earth Sci.* **2024**, *13*, 141. [\[CrossRef\]](#)
71. Savchenko, Y.; Lopez-Acevedo, G.; Robertson, R. Globalization and the gender earnings gap: Evidence from Sri Lanka and Cambodia. In *World Bank Policy Research Working Paper*; World Bank: Washington, DC, USA, 2016; p. 7930.

72. Venturieri, A.; de Oliveira, R.R.; Igawa, T.K.; Fernandes, K.D.; Adami, M.; de Oliveira Júnior, M.C.; Almeida, C.A.; Silva, L.G.; Cabral, A.I.; Pinto, J.F.; et al. The sustainable expansion of the cocoa crop in the state of Pará and its contribution to altered areas recovery and fire reduction. *J. Geogr. Inf. Syst.* **2022**, *14*, 294–313. [[CrossRef](#)]
73. Futemma, C.; De Castro, F.; Brondizio, E.S. Farmers and social innovations in rural development: Collaborative arrangements in eastern Brazilian Amazon. *Land Use Policy* **2020**, *99*, 104999. [[CrossRef](#)]

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