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Agronomic and Economic Evaluation of Tree Species in Agroforestry Systems with Cocoa (*Theobroma cacao* L.) in Amazonas

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Abstract: Agroforestry systems (AFS) are beneficial ecosystems that increase cocoa productivity by providing shade and controlling pests. Despite deforestation, there is a transition towards more sustainable practices that combine diverse species with cocoa, generating economic and environmental benefits. This study evaluates AFS with cocoa in the Amazon region. Of the 72 farms evaluated, species diversity was observed, highlighting *Cordia alliadora* and *Calycophyllum spruceanum* with an importance value index (IVI) of 18.58% and 17.66%, respectively. Fruit trees such as Citrus limetta, Cocos nucifera, Mangifera indica, and Persea americana are common. The designed AFSs proved more profitable, generating revenue from the fourth year, while the conventional ones took longer. Indicators such as Net Present Value (NPV) and Internal Rate of Return (IRR) supported the efficiency of the designed AFS. Six optimal species were identified with specific distances and planting systems, providing up to 45.83% total shade in flat topography and up to 2405 annual shade hours on a 7° slope. These results highlight the economic and agronomic viability of AFSs designed for regional cocoa production.

Keywords: Peru; cocoa; diversity; agroforestry systems; economic analysis

1. Introduction

Agroforestry systems (AFS) are agroecosystems with multiple functions [1]. AFS impacts crop yields and provides relevant ecosystem services, such as climate regulation, supporting and preserving soil fertility, carbon storage, and conservation of genetic diversity [1,2,3]. The most researched agroforestry systems are coffee and cocoa production systems [4,5,6]. Cacao is traditionally grown in tropical agroforestry systems where the plants are grown in the shade to provide a favorable microclimate [7]. However, intensified cocoa management has reduced plant diversity and shade cover [6]. Although there has been an increase in the use of AFS with design, traditional methods persist in the face of a greater diversity of tree species in cocoa crops [4,6].

Shade agroforestry systems have been shown to have positive impacts on cocoa production. AFS serves multiple functions, such as providing shade to cocoa, organic matter through the decomposition of tree leaves, and nutrients stored in the soil. In addition, AFS helps suppress weeds and pest proliferation, as evidenced by studies conducted by [8,9]. In addition, AFSs are socio-economically viable systems where farmers deliberately integrate timber, fruit, or medicinal trees as shade mechanisms for cocoa [10].

Cocoa represents one of Peru's main high-value agricultural products, and most cocoa plantations are established using conventional slash-and-burn methods. These practices have significantly impacted the region's biodiversity [11]. Consequently, Amazonas is the seventh

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cocoa-producing region in Peru [12]. However, studies have yet to explore the diversity of trees associated with this crop within this area [13,14]. Agroforestry practices require rigorous training of producers and cooperative work for crop profitability [14]. Recently, it has been observed that producers are diversifying their plots by combining various indigenous timber or fruit species and are consequently gaining complementary economic and consumption advantages from cocoa cultivation [13,15]. However, this diversification is carried out empirically, incorporating native species such as *Cordia alliodora* [14]. This is due to the need for more scientific documentation on the species, composition, and variety of shade trees within cocoa AFS [16] since each species comprising AFS affects the physico-chemical traits of the soil [17]. To develop effective land-use transition policies that are more inclusive for smallholder cocoa farmers, it is imperative to comprehensively understand their preferences and the underlying reasons for their preference for a particular species [18].

Therefore, it is crucial to understand the diversity of tree species, their functions within the Agroforestry System (AFS), and their economic potential. In this context, this study focused on analyzing the fundamental role played by tree species in AFS with cocoa, focusing on agronomic and economic aspects relevant to the main producing areas of the Amazon region. The specific objectives were to characterize the diversity of forest species in Agroforestry Systems (AFS) in cocoa, to perform an economic analysis identifying the agronomic variables associated with tree species within the AFS with cocoa, and to determine the composition and spatial distribution of trees. In the AFS with cocoa using ShadeMotion.

2. Materials and Methods

2.1. Area Study

The study was carried out on the cocoa farms of two cooperatives: the multi-service cooperative APROCAM and the Central de Productores Agropecuarios de Amazonas (CEPROAA) whose farms are distributed in the districts of Aramango, Cajaruro, Copallín, El Parco, Imaza and La Peca, located within the provinces of Bagua and Utcubamba in the Amazonas region (Figure 1).

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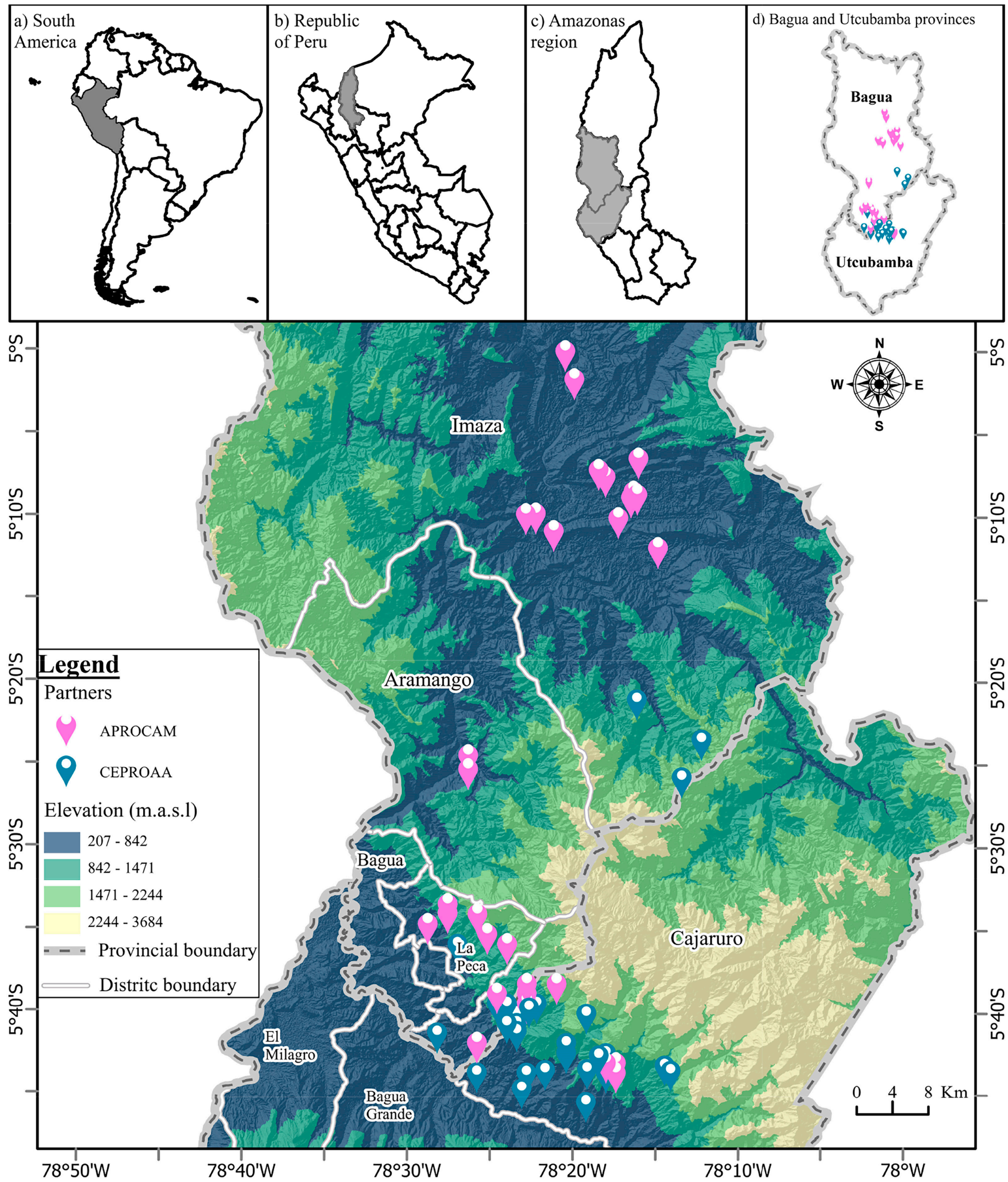

Figure 1. Geographical location of cocoa growing areas.

2.2. Selection of AFS Cocoa

Seventy-two farms implementing Agroforestry Systems (AFS) with cocoa crops were selected. An identification process was carried out through visits to the plots of each producer and exhaustive tours to identify irrigation areas, houses, water sources, and the tree species associated with cocoa. In addition, the slope of the land was evaluated, and the total area of each farm was determined during this sampling process.

The georeferencing of the plots, considered Agroforestry Systems (AFS), was carried out with a GPS, where the taking of points was carried out in the central part of the production unit. The inventory of species was also carried out through the application of an interview with each producer in their plots. The information collected lists the tree species found within the farm. Then, plant material of bark, leaves, flowers, and fruits was collected for their respective identification by Tobias Fremont, Researcher of the Bioversity International Alliance – CIAT, an agroforestry, ecology, and tree biodiversity expert.

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2.3. Of the Diversity of Forest Species Associated with Cocoa AFSs

The distance between the furrow and the plant was measured to calculate the density of tree species per hectare (ha), considering the type of agroforestry design. In addition, dasometric measurements were carried out that included total height (ht) and commercial height (hc), crown height, horizontal distance, crown angle, base angle, and diameter at chest height (DBH), using a hypsometer according to the methodology of [19]. Regarding the measurements of the DAP, a DAP greater than 5 centimeters and a height of 1.30 meters was considered. It began by measuring the circumference with a tape measure, and then the DAP was calculated. In addition, the crown radius was measured with tape from the trunk to the shaft. The following equation was used to calculate the DAP:

$$DAP = \frac{Circunferencial}{3.1416} \quad (1)$$

Likewise, tree species were evaluated to determine their use characteristics, such as wood, firewood, food, fodder, medicine, etc. Finally, information on the age of each forest tree was collected and subsequently used to give it an economic value.

Frequency

The relative abundance of the different species associated with cocoa on the farms was determined by the following equation:

$$\text{Frequency (F)} = \frac{\text{Frequency of a species}}{\text{Total number of sample plot}} \quad (2)$$

Wealth

To identify and quantify the different tree species that make up the structure of the AFS with cocoa, the Shannon equity index was used with the following equation:

$$E = \frac{H''}{H'\,max} = \frac{H'}{lnS} \quad (3)$$

Where E = Shannon Equity Index
H´ = Shannon Diversity Index
H'max = the maximum possible level of diversity within a given population
lnS = Natural logarithm of species richness.

Species Accumulation Curve

The accumulation curve of the different tree species associated with cocoa was determined using the following equation:

$$E(S) = \frac{1\sum -(N - N_i)/n}{N/n} \quad (4)$$

Where:
E(S)= expected number of species
N = total number of individuals in the sample
Ni = number of individuals of the i-th species
n= standardized sample size

Abundance Range Curve

The range-abundance curve of the different tree species associated with cocoa was calculated using Shannon's equity index, Simpson's and Margalef's index, using the following equation:

$$Simpson\ index = \frac{\sum(n_i(n_i - 1)}{N(N-1)} \quad (5)$$

Where:
N=total number of individuals in the sample
Ni-number of individuals of species i

$$Margalef\ Index = \frac{(S-1)}{lnN} \quad (6)$$

Where:
S = Total number of species
N = total number of individuals in the sample

Value Index (IVI)

The Importance Value Index (IVI) of [20,21] was used to describe a dominant species in the plots. The IVI was determined by adding its relative frequency (RD+RCC+RF) using the following equation:

$$Importance\ value\ (IVI) = RD + RCC + RF \quad (7)$$

$$Relative\ density\ (RD) = \frac{The\ density\ of\ a\ species}{Total\ density\ of\ all\ species} x\ 100 \quad (8)$$

$$Relative\ canopy\ cover\ (RCC) = \frac{Canopy\ cover\ of\ a\ species}{Total\ cover\ of\ all\ species} x\ 100 \quad (9)$$

$$Relative\ frequency\ (RF) = \frac{Frequency\ value\ of\ the\ species}{Sum\ of\ frequency\ of\ all\ species\ studied} x\ 100 \quad (10)$$

2.4. Economic Assessment of Conventional and Forested Agroforestry Systems

For the economic evaluation, specific adjustments and modifications were made according to the particular needs of this study by the methodology of [22].

The economic analyses were carried out using a comparison between the income and expenditure curve, incorporating the net profits with a focus on a conventional AFS and with an arrangement. Conventional AFS is an agroforestry system installed without technical criteria, while AFS with an arrangement is the ideal agroforestry system. The first three years of the AFS with cocoa are characterized by substantial investment in installation, maintenance, fertilization, and pruning, among other activities, with no income recorded.

Expenses

The cost analysis covered different components, starting with direct costs, which include the expenditure associated with cocoa seedlings, inputs for production, land preparation, and other tree species in the Agroforestry System (AFS). Likewise, direct labor was considered, which includes activities such as slashing and felling, burning, cleaning, construction of drains, application of agricultural lime, alignment, pruning, sucking, underpinning, removal of diseases and sprouting, as well as the installation of cocoa, opening of holes and planting of other tree species. Finally, indirect costs, such as phytosanitary control and other expenses, were included, representing 10% of total expenditures.

Revenue

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The income from the sale of cocoa in slime was considered, establishing a price of S/3.50 per kilogram. In addition, the income generated from the sale of tree species that have commercial value in the market within the study area was considered since the sale of forest products provides greater economic stability to the producer.

Assumptions

An analysis considered one hectare for producing an Agroforestry System (AFS), comparing a conventional AFS with an AS arrangement. The projection was made over 25 years, starting with installation in year 1, projecting cocoa production starting in year four and initially representing 50% of the plant's total yield. For fruit species, the year they begin to produce after their installation in the AFS was considered, and yields were projected for the following years. Similarly, forest species' usable age was assessed, considering an investment to obtain a return by selling wood. It is important to note that during this period, the total harvesting of the wood of a species is not carried out. Instead, a specific amount is kept to be later replaced, thus ensuring the continuity of the AFS cycle.

Economic Indicators

The net present value was calculated using the following formula:

$$VAN = \sum_{i=1}^{n} \frac{BN_i}{(1+r)^i} - I \tag{11}$$

Where:
NPV: Net Present Value
BN-i.: Net profit in period i
I: Initial Investment
n: Shelf life
i: Period
A: Discount Rate

Thus, a NPV > 0 means that the investment in the study area has profits above the required return (discount rate), while a NPV < 0 demonstrates the existence of losses. To find the Internal Rate of Return (IRR), the discount rate was calculated by zero-matching the NPV. An IRR > r refers to the fact that the system gives a return above the opportunity cost or discount rate, while if the IRR < r, it shows that the profitability does not reach the minimum required.

To calculate this indicator, it was necessary to consider the net benefits and investment costs. It was evaluated taking into account the following: Whether the C/B >1 is considered to be profitable. Whereas, a C/B ≤ 1 needs to be changed. The formula used was as follows:

$$\frac{\sum BN}{\sum CI} = C/B \tag{12}$$

Where:
BN: Net Profit
CI: Investment Costs

The comparison of the profitability indicators between a conventional Agroforestry System (AFS) and one with design, the Net Present Value (NPV), and the Internal Rate of Return (IRR) were evaluated considering a discount rate of 20%. This choice is justified by the nature of the rural agricultural activity, which is characterized by considerable risk arising from several factors. Based on the methodology of Zavala et al. (2018), a reference rate greater than 15% was used due to the risks and uncertainties in a cocoa agroforestry arrangement, both in the flat and lowland parts and to the flooding of rivers, diseases, and pests, in this particular case a reference rate of 20% was used.

Cash flow from agroforestry systems

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Cash flow was calculated as the difference between income and expenditure in each year during the projected 25 years for both a conventional agroforestry system and an arrangement system.

Composition and Spatial Distribution of Trees in AFS With Cocoa

Based on [24]'s methodology, ShadeMotion 5.1.47 software was used to model the sun's position for an entire year, calculating its azimuth and elevation angle every hour from 9 am to 3 pm. Using the coordinates and characteristics of the trees, cast their shadows on the ground, considering the opacity of the canopy and foliage. The shading frequency of each cell in the grid was determined, allowing shadow overlap. This facilitated the identification of an ideal agroforestry system, considering the shape and position of the shadows according to the tree species, flat or sloping terrain, and various crown shapes. Slopes of 0° and 7° were evaluated in a 1 Ha study area.

Data analysis

An analysis of variance between groups was performed with a margin of error of 5%. Linear correlation analysis was then performed using Pearson's Correlation Coefficient [24]. In addition, ShadeMotion 5.1.47 software was used for the characterization, and R software was used for ANOVA support. For the calculation of the diversity indices, Shannon and Simpson used the packages BiodiversityR, vegan, ggplot2, FactoMineR, corplot, and factoextra.

3. Results

3.1. Evaluation of the Diversity of Species Associated with Cocoa AFSs

The inventory of the species identified in the cocoa plots has been carefully recorded (Table S1). An exhaustive analysis reports species that are not very abundant and not very noticeable in the representation (Figure S1). Figure 2 shows the frequency and species richness of the evaluated AFS, where *Cordia alliadora* is the most frequent timber species in cocoa AFS. However, regarding the number of individuals, *Calycophyllum spruceanum* is the dominant species, followed by *Cordia alliadora*. As for the fruit species, the widespread presence of *Citrus limetta*, *Cocos nucifera*, *Mangifera indica*, and *Persea americana* stands out.

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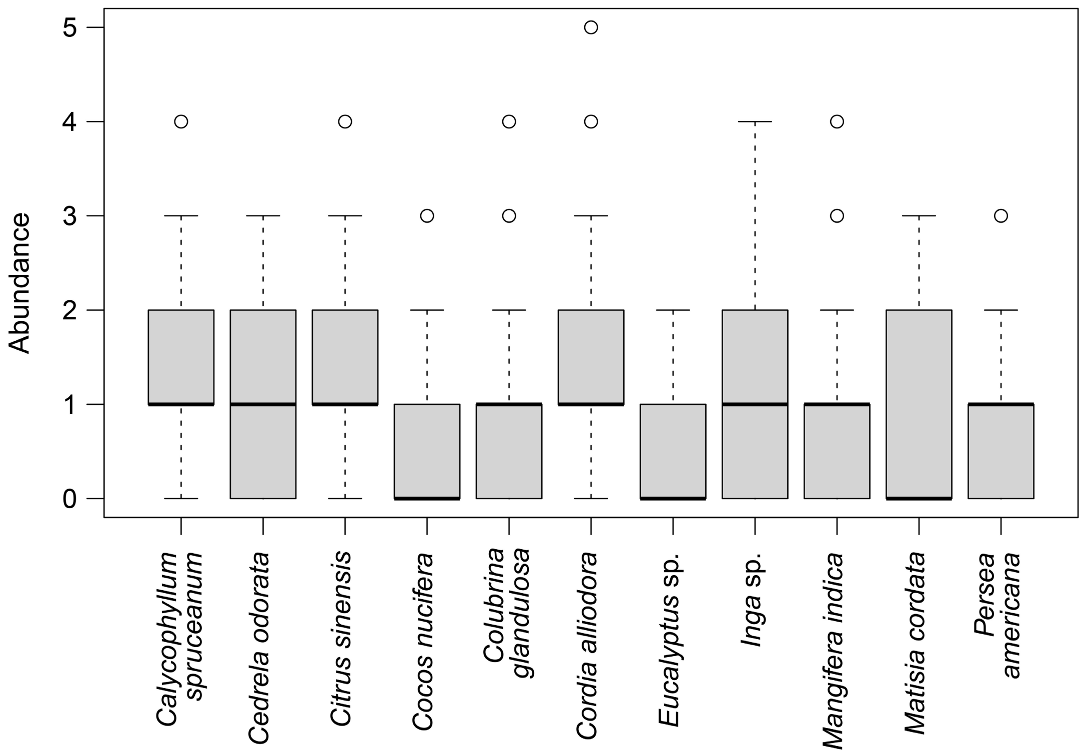

Figure 2. Box and whisker diagram representing species frequency and richness.

The line across the box in the center of the chart represents the median, a crucial value that signals the midpoint of this abundance distribution. The whiskers in the diagram extend from the box to the extreme values, not exceeding 1.5 times the interquartile range (IQR). Any point beyond these whiskers is classified as an outlier and displayed as an individual point on the graph.

Likewise, the accumulation of tree species in cocoa farms was represented by georeferenced data in various locations (Figure 3). This analysis reveals remarkable patterns in the distribution of tree species diversity as a function of geographic location. In particular, in the localities of San Juan de la Libertad, La Cruz, José Olaya, and Naranajo Alto (district of Cajaruro), locality Pakun (district of Imaza) and San Francisco (district of La Peca) stand out for a significant richness of tree species associated with cocoa cultivation with values from 0 to 5 as a representation of maximum diversity of species (Figure 3; Table S1). These areas are characterized by the continuous addition of new varieties of species as data collection progresses, culminating in maximum diversity in the first five plots, with the climax in the locality of Laguna in the district of Cajaruro (Figure 3; Table S1). Also, as data collection progressed in subsequent plots, botanical collection stabilized since species had already been identified, indicating a lower addition of new species.

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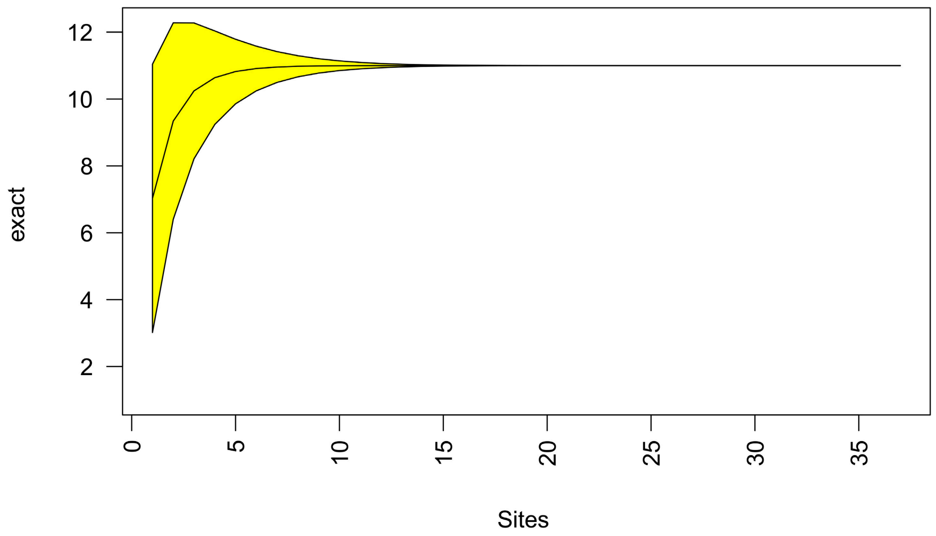

1. El Tigre
2. San Juan de la Libertad
3. Naranjo Alto
4. Concordia
5. José Olaya
6. Nuevo Piura
7. Pakun
8. San Francisco
9. La Cruz
10. Pan de Azúcar
11. San José Bajo
12. Lluhuana
13. Pakuy
14. Santa fe
15. Yamanakat
16. Santa Isabel
17. Umukai
18. Alto Pakui
19. Diamante Bajo
20. La Curva Santa Cruz
21. Santa Ana
22. Humbate
23. Diamante Alto
24. El Paraiso
25. Numparque
26. Chonza Alta
27. Tolopampa
28. Duship
29. La Reserva
30. Shambo
31. La Palma
32. Caserío del Shambo
33. Caña Brava
34. El Porvenir
35. Nueva Florida
36. Lagunas

Figure 3. Graph of the accumulation curve of species ("Y" axis) concerning the locations of these species ("X" axis).

In this scientific context, we make a detailed graphical representation of the range-abundance curve, a critical component to understanding the distribution of tree species in the environment of cocoa farms. Among the species that stand out in this representation, *Cordia alliodora* occupies a position of maximum relative abundance. This is followed by *C. spruceanum* and *C. odorata*, two timber species of great relevance in cocoa cultivation. In addition, there is a significant presence of fruit species, such as orange (*C. sinensis*), mango (*M. indica*), avocado (*P. americana*), and coconut (*C. nucifera*), which occupy prominent positions in terms of relative abundance within the ecosystem of cocoa farms (Figure 4).

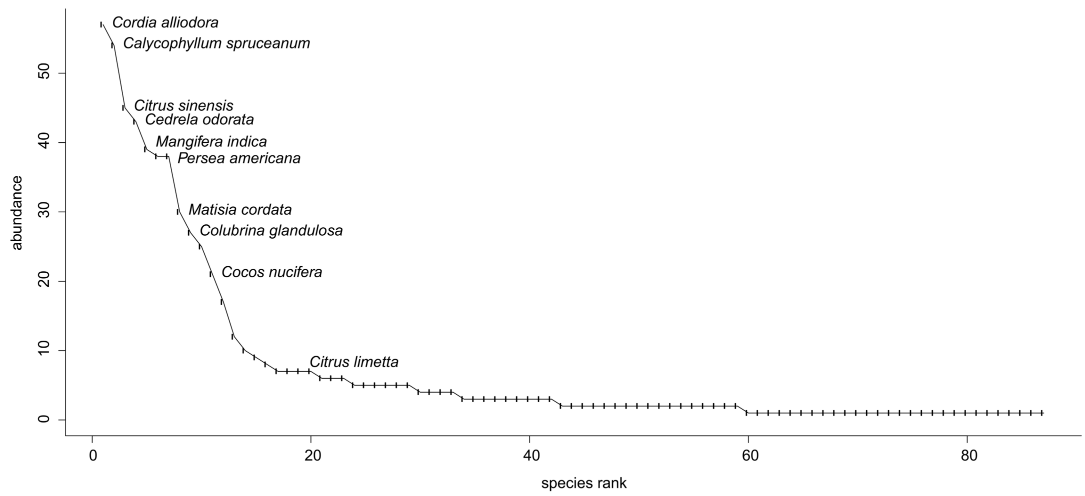

Figure 4. Range-abundance curve of agroforestry species in cocoa.

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The IVI reveals that the two most important species are *C. alliodora* and *C. spruceanum*, with a total IVI of 18.58% and 17.66%, respectively (Table 1). Most species have an IVI of less than 10%.

Table 1. Most Important Species Importance Value Index (IVI>2).

Species	Relative Density	Frequency Relative	Relative Coverage	IVI
Cordia alliodora	8.72%	1.15%	8.72%	18.58%
Calycophyllum spruceanum	8.26%	1.15%	8.26%	17.66%
Citrus sinensis	6.88%	1.15%	6.88%	14.91%
Cedrela odorata	6.57%	1.15%	6.57%	14.30%
Mangifera indica	5.96%	1.15%	5.96%	13.08%
Inga sp.	5.81%	1.15%	5.81%	12.77%
Persea americana	5.81%	1.15%	5.81%	12.77%
Matisia cordata	4.59%	1.15%	4.59%	10.32%
Colubrina glandulosa	4.13%	1.15%	4.13%	9.41%
Swietenia macrophylla	3.82%	1.15%	3.82%	8.79%
Cocos nucifera	3.21%	1.15%	3.21%	7.57%
Eucalyptus sp.	2.60%	1.15%	2.60%	6.35%
Guazuma crinita	1.83%	1.15%	1.83%	4.82%
Ocotea sp.	1.53%	1.15%	1.53%	4.21%
Hura crepitans	1.38%	1.15%	1.38%	3.90%
Grevillea robusta	1.22%	1.15%	1.22%	3.60%
Artocarpus altilis	1.07%	1.15%	1.07%	3.29%
Citrus limetta	1.07%	1.15%	1.07%	3.29%
Citrus reticulata	1.07%	1.15%	1.07%	3.29%
Croton cf. draconoides	1.07%	1.15%	1.07%	3.29%
Averrhoa carambola	0.92%	1.15%	0.92%	2.98%
Cedrelinga cateniformis	0.92%	1.15%	0.92%	2.98%
Guadua sp.	0.92%	1.15%	0.92%	2.98%
Annona muricata	0.76%	1.15%	0.76%	2.68%
Aspidosperma polyneuron	0.76%	1.15%	0.76%	2.68%

Calculations for topography of 0° inclination resulted in a frequency of solar motion every hour for one year. Six tree species were found to be the most suitable for use as an ideal agroforestry system: three timber species (*C. spruceanum* = Capirona, *C. alliadora* = laurel, *C. odorata* = cedar) and three fruit species (*C. nucifera* = coconut; *M. indica* = mango and *C. sinensis* = orange). Among the timber species already described, the species of *C. spruceanum*, the suitability of distance was 15 m x 15 m with a total of 49 plants per ha, the species of *C. alliadora* with a distance of 20 m x 20 m making a total of 25 plants per Ha and the species of C. odorata was determined in a random planting system with a total of 7 plants per hectare. ha (Figure 5A). As for the three fruit species such as coconut, it was best to plant them as living fences, with a total of 32 plants every 6 meters for 200 linear meters; the mango and orange species were best planted in a conventional system with a total of 6 plants per hectare (Figure 5A). In total, 2214 shade hours were obtained during a year with a total shade percentage of 45.83% with 8 hours of sunlight per day. On the other hand, using a slope of 7° for an

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ideal agroforestry system (Figure 5B), a total of 2405 shade hours were determined for a whole year and a total shade percentage of 41.9% with 8 hours of light per day.

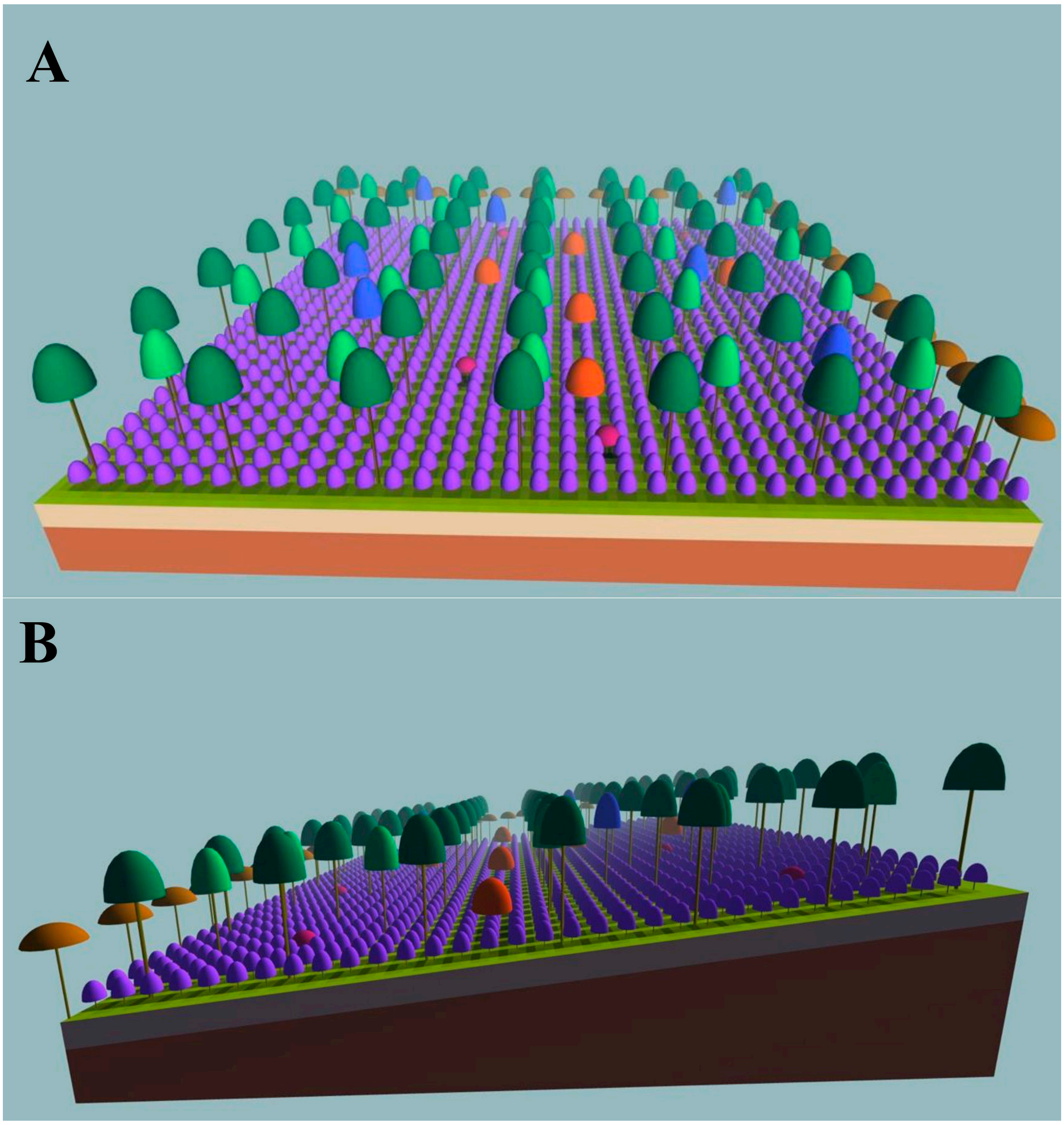

Figure 5. ShadeMotion simulation of an ideal agroforestry system with slopes of 0° (A) and 7° (B).

3.2. Economic Analysis

The remarkable results begin in the fourth year, with cocoa production in a conventional system and an arrangement design (Figure 6A-B). The diversification of the AFS is observed in the sixth year with the incorporation of species such as *A. muricata*, *C. limetta*, and *C. nucifera*, contributing to the increase in net profits. The scenario becomes even more promising in years 15 and 16, when timber species such as *C. spruceana* and Eucalyptus sp are harvested, adding significantly to the income from cocoa and fruit trees in the following years they maintain constant income until year 25. At this point, the income curve experiences an exponential increase thanks to the additional harvest of timber species (Figure 6A-B). In contrast, in conventional AFS, profits are obtained from the fifth year onwards (Figure 6A). At the same time, with AFS with design, superior performance is revealed, initiating revenue generation as early as the fourth year (Figure 6B). In AFSs with design, it is important to note that, although positive income is maintained, there is a decrease in net profits (Figure 6B). This decline in net profits does not indicate an economic decline; rather, it is directly linked to a strategic investment necessary for efficiently harvesting fruit and

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timber species. In this context, the systematic planning and design of the AFS shows its value by improving the production of fruit species and anticipating the timber harvest in subsequent years. Conventional AFSs effectively generate revenue, while designed AFSs are a more effective and cost-effective strategy (Figure 6B).

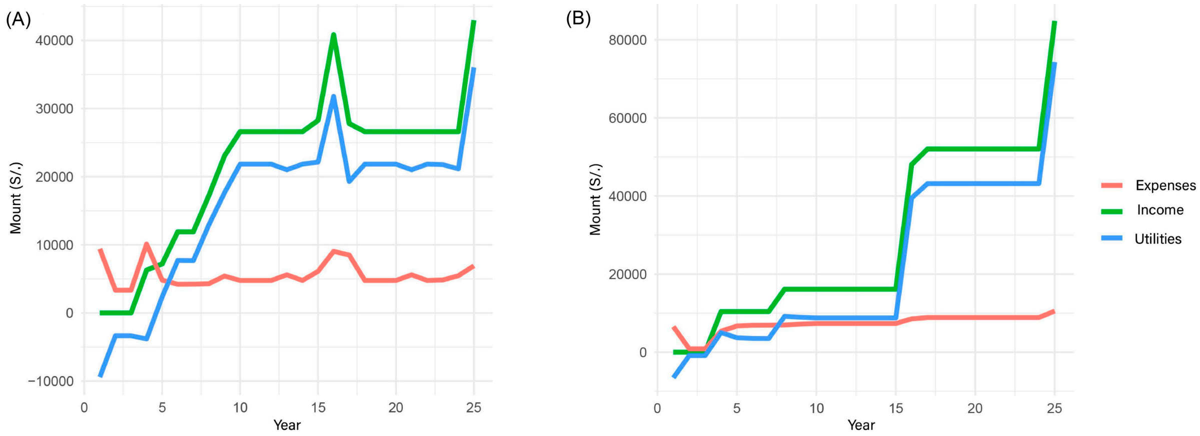

Figure 6. The income and expenditure curve, incorporating net profits, focuses on conventional AFS (A) and design (B).

Both AFSs exhibit a negative index in the initial three-year phase, reflecting the lack of production affecting revenues (Figure 7A-B). From the fourth year onwards, a significant change can be seen in both AFSs. In conventional AFS, despite incipient revenues, the index reaches -0.4, indicating that these revenues are insufficient to cover costs (Figure 7B) fully. In contrast, in the AFS with design, the strategic combination of cocoa production and fruit species in the fourth year results in a positive index, indicating early efficiency in income generation (Figure 7B). On the other hand, conventional AFSs achieve financial stability with the regular harvest of fruit species from the fifth year onwards, generating consistent income. However, in year 17, a decrease in the index is observed due to the harvesting of timber species, which implies additional labor costs. By year 18, the index recovers, anticipating an upcoming harvest of timber species (Figure 7A).

In contrast, AFS with design demonstrates a more favorable behavior from the fourth year onwards. Combining cocoa production and fruit species for marketing maintains the positive index. When timber species reach their optimum age for harvest, the index experiences a significant increase, surpassing even conventional AFS and doubling its yield (Figure 7B).

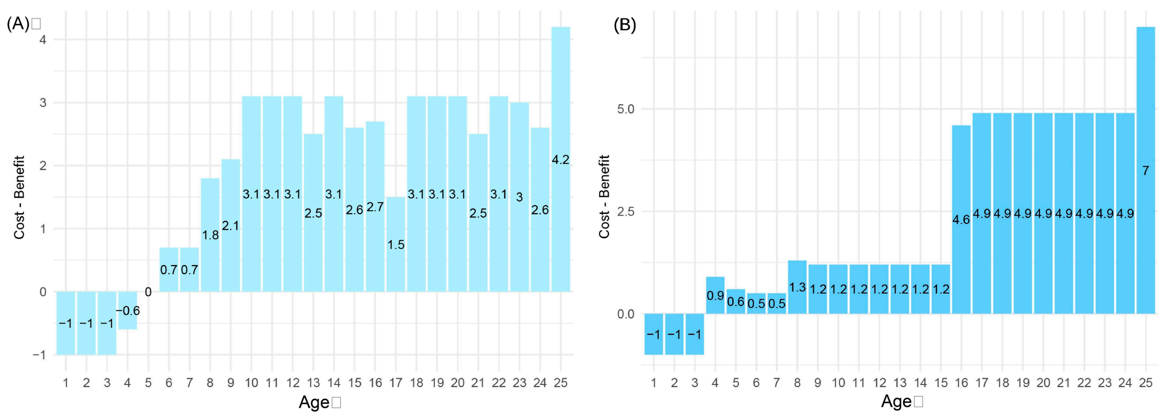

Figure 7. The benefit-over-cost ratio of the revenue generated and the costs associated with implementing and managing a conventional AFS (A) and a AFS with design (B).

Finally, comparing the profitability indicators between a conventional Agroforestry System and one with design shows that the NPV, which projects future earnings throughout the 25 years of the

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study, revealed a solid value of S/ 28,099.00 for conventional AFS. This result consolidates the viability of the investment, suggesting that the project is economically sound. At the same time, the 24% IRR exceeded the discount rate, indicating that the investment generates a profitable return over time (Table 2). In contrast, AFS with design has an NPV of S/ 27,466.00 and a significantly higher IRR of 28%. This higher IRR underlines the speed of return compared to conventional AFS. These results support the notion that AFS, by design, not only preserves core production without adverse impact but has the potential to generate additional revenue in the medium to long term (Table 2).

Table 2. Profitability indicators under a conventional AFS and an arrangement AFS approach.

Profitability Indicators	Conventional AFS	AFS with design
Discount rate	20%	20%
NPV	28099	27466
IRR	24%	28%

4. Discussion

Characterization of AFSs

The traditional AFSs investigated in this study exhibit a clear differentiation regarding their diversity and geographic distribution. The analysis also allowed us to identify outliers in the abundance distribution, which indicate species that require special attention in management and conservation, such as *C. alliadora*. Based on the type of forest species found in cocoa crops, we determined that they do not fit a traditional agroforestry system. There is a great diversity of timber, fruit, and medicinal species associated with cocoa, which, from now on, we call "agroforest." *C. alliodora* is the species most frequently associated with cocoa crops, although, in terms of individual count, the most predominant species in agroforests is *C. spruceanum*. These two species are characterized by their significant value in the local market as timber, as supported [14]. Cocoa farmers frequently employ *C. spruceanum* and *C. alliodora* because of their benefits. However, [26] have identified other species, such as avocado (P. americana) and mango (M. indica), as suitable to coexist with cacao trees in an ecologically friendly way. The deliberate transformation of the landscape may be indicated by the tendency observed among many producers to associate fruit, timber, and medicinal trees [10]. These agroecosystems, with their high level of anthropization, serve as food, timber, medicine, and shade cocoa [15].

The abundance of dominant tree species, namely *C. alliodora*, *C. spruceanum*, and *C. odorata*, significantly influences the biodiversity and structure of the existing forest in the context of cocoa cultivation. The timber species *C. spruceanum* and *C. odorata* are essential for providing timber, necessary for agroecosystems, and have an important economic and ecological value. The importance of the sustainability of cocoa cultivation is highlighted by its contribution to the structure and stability of the forest. However, it is an inadequate replacement for natural forests in terms of botanical composition, tree community, and spatial structure [27], although the diversity of its shade tree component can serve as ecological corridors, improving the isolation of fragmented plant and animal species [27].

On the other hand, the study of cocoa-based agroforestry systems is very significant as it allows us to investigate whether additional species can be incorporated into cocoa-based agroforestry systems in the context of sustainable agroforestry systems [18]. AFSs generate social and environmental benefits without compromising the economic aspect of agricultural production [28], as well as the conservation of floral diversity and agricultural management practices [29]. In addition, management practices for economic diversification could be improved by providing shade and services [16]. Therefore, local and regional governments must intervene to improve agroforestry practices, as only some species are suitable for use in an AFS in cocoa. Therefore, local and regional

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governments must intervene to improve agroforestry practices since not any species is suitable for use in a cocoa FFS, and although there is limited scientific evidence on which species are the most appropriate, in some cases it is recommended to switch to late successional species such as Cedar (*Cedrela* spp.), Mahogany (*Swietenia* spp.), Eucalyptus (*Eucalyptus* spp.). Not only does this increase the conservation potential for the long-term maintenance of cocoa cultivation, but it should also be done gradually and carefully considering architecture, functionality, services, and growing products [16,30].

Economic analysis

Not only do AFSs have significant practical implications for farmers and managers, but they also contribute to the body of knowledge in the sustainable management of agroforestry systems, offering a comprehensive and accurate approach to decision-making, as they are important for income diversification, promoting greater economic security for cocoa farmers [8,31,32]. For example, the average annual production of cocoa is 1357 kg/year, multiplied by the price of S/ 3.50, resulting in an approximate income of S/ 6 295.70. However, this income is used for the maintenance of the farm, generating negative indices. By implementing a AFS with design, revenues of S/ 7,197.80 are estimated from the fifth year, considering a constant production adjusted for the average inflation rate of 4.3%, which marks the beginning of sustainable net profits of S/ 2,379.30. This perspective highlights the importance of long-term planning and strategic design of agroforestry systems. This sustained and growing income pattern offers an optimistic outlook for the long-term economic viability of AFS, highlighting the importance of planned and sustainable strategies in agroforestry management [15]. These results have significant practical implications for farmers and managers and contribute to the body of knowledge in the sustainable management of agroforestry systems, offering a comprehensive and accurate approach to decision-making [8,9].

Therefore, the intensification of AFS is feasible for agriculture within a land conservation strategy [33] since these practices present an opportunity to defend the preservation of indigenous biodiversity. In addition, these systems offer multiple public services by providing traditional food and medicines to producers. These strategies have proven beneficial in protecting and strengthening the resilience of cocoa crops during severe climate change events. Similarly, it is imperative to implement these systems to utilize soil resources effectively and prevent the expansion of cocoa plantations through unregulated deforestation, as is the case with coffee farming. To address this problem, the European Union has banned procuring goods from deforested regions [34]. These agreements should be developed in collaboration with relevant authorities to ensure support for the appropriate use and allocation of diverse agroforestry species in cocoa AFSs, as optimizing ecosystem services in AFS requires consideration of socio-cultural and economic service interactions [35].

ShadeMotion

The results obtained using ShadeMotion provide a detailed perspective on modeling sun position and shadow projection in cocoa agroforestry systems. Throughout the year, each cell's shading frequency in the grid can be determined by calculating the azimuth and elevation angle of the sun each hour. This is essential to identifying an optimal agroforestry system. An accurate assessment of shade distribution is possible by considering leaf and crown opacity, which is essential for maximizing the production efficiency of cocoa and other cultivars [24].

In addition, determining the suitability of specific tree species and their respective planting distances and densities contributes significantly to the design of efficient agroforestry systems in the northeastern region of Peru. Together, these results provide a solid basis for the planning and management of agroforestry crops, ensuring optimal resource use and long-term sustainable production.

5. Conclusions

According to the Range-Abundance curve, the most common plant species in cocoa crops is *Cordia alliodora*, while *Calycophyllum spruceanum* is present but less frequently. Other species discovered in the AFS include orange (*Citrus sinensis*), cedar (*Cedrela odorata*), mango (*Mangifera indica*), avocado (*Persea americana*), sapote (*Matisia cordata*), shaina (*Colubrina glandulosa*), coconut (*Cocos nucifera*) and lime (*Citrus limetta*). These findings are complemented by geographic variations revealing remarkable patterns, with locations such as San Juan de la Libertad and Pakun showing a significant richness of tree species associated with cacao. The continuous addition of new varieties of species highlights the diversification dynamics in different locations, peaking in the town of Laguna.

The benefit-to-cost ratio highlights the early effectiveness of design-based AFS in generating revenue, while conventional AFS experiences difficulties in covering upfront costs. Profitability indicators show that both AFSs are economically sound, but AFS with design has a higher IRR, suggesting a faster return and higher profitability in the long run. Finally, the simulation with ShadeMotion demonstrates the viability of both flat and sloping terrain, indicating strategic planning for planting species.

Identifying cocoa cultivation species is crucial to executing conservation plans to preserve traditional cocoa farming practices. Collaborative efforts must be multidisciplinary between government and private entities to improve cocoa crop yields.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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