

Article

Effects of Traditional Agroforestry Practices on Cocoa Yields in Côte d'Ivoire

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Abstract: Agroforestry is promoted as a practice at the crossroads of sustainability and productivity objectives; however, many agroforestry programmes have had mixed effects due to a lack of understanding of the compatibility of the species supplied to farmers with cocoa and a failure to take account of their knowledge in designing the programmes. This paper, therefore, examines the effects of socio-economic and agroforestry factors on cocoa yields in Côte d'Ivoire, West Africa. The data used come from surveys of 150 farmers in three areas of the country: Bonon, Soubré and Biankouma. The choice of these areas was based on an east–west gradient, reflecting the evolution of the cocoa loop. The Bayesian Information Criterion method and multiple linear regression were applied to identify the species and their relationship with yield. The results showed that certain species, such as *Citrus* sp., *Cordia senegalensis*, *Isoblerlinia doka*, *Morinda lucida*, *Morus mesozygia* and *Raphia hookeri* increased in yield; on the other hand, *Anthonotha manii* was found to reduce in yield. Finally, labour and insecticides contributed to yield increases. The statistical analysis can be supplemented with agronomic and ecological analyses to improve species management on cocoa farms.

Keywords: cocoa yield; agroforestry; cocoa; species; linear regression



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1. Introduction

The sustainability of cocoa production is a major issue for Côte d'Ivoire, given the depletion of forest resources in this country, which remains the world's leading producer of this crop. For agricultural exports, the sustainability of price rises over the long term is a crucial issue for farmers and other players in the sector. According to [1], a country that benefits from a steady rise in international prices can expect to face technical and social challenges related to replanting over the next 15 to 20 years, as orchards age and prices plummet. Cocoa farms in Côte d'Ivoire are currently facing environmental challenges such as deforestation, soil exhaustion and climatic fluctuations, which threaten the sustainability of production [2,3]. In this context, agroforestry presents itself as a potential strategy for improving the resilience of production systems and increasing yields [4,5]. Defined as a practice integrating trees with traditional farms, agroforestry is often put forward as an innovative solution combining sustainability and productivity. This approach has many advantages, particularly in terms of biodiversity, environmental protection and improving farmers' living conditions [6–9]. The practice of agroforestry is therefore attracting a great deal of international interest and has given rise to several programmes that have mobilised more than USD 10 billion since the 1992 United Nations Earth Summit in Rio [10,11]; however, most of these interventions have had mixed effects. The programmes have not succeeded in defining a clear position on agroforestry, and while some agroforestry interventions have significantly increased agricultural yields, others have drastically reduced productivity and taken land out of production in favour of conservation [11].

To consolidate opinions on agroforestry, it is necessary to understand the trade-off between trees and productivity, given the complexity of the interactions between tree

species and crops. This is essential to guide producers' choices. On this subject, the conclusions are mixed; while some studies emphasise the benefits of agroforestry in improving yields, others show the opposite. In a positive view of agroforestry on crop yields, there is sufficient evidence. In a meta-analysis, Ref. [5] showed that agroforestry increased overall median maize yields. Similar results have been found around the world [12–16]. This reinforces the idea that integrating trees into cropping systems can be a viable strategy for increasing the resilience of farming systems to climate change and land degradation. In addition to increasing yields, agroforestry can also improve biodiversity [17,18], reduce soil erosion [19,20] and improve water management [21–48]. By providing shade, trees are able to reduce water stress on crops by increasing the availability of moisture in the soil [22]. Moreover, some tree species can fix nitrogen, enriching the soil with nutrients essential for crops [31]. All these studies highlight the importance of agroforestry in improving crop productivity. Although the effects of agroforestry may vary according to local contexts and the species used, the potential benefits for agricultural productivity and environmental sustainability make it a promising practice to promote [17,23,24].

However, several other studies show results to the contrary. In Central America and West Africa, monoculture cocoa systems have been shown to be more productive than agroforestry systems [25,26]. Ref. [27] found similar results in Bolivia, where they demonstrated that monocultures were 41% more productive than agroforestry systems. A study by [28] confirms these earlier results. These authors carried out a meta-analysis comparing agroforestry with full-sun systems, selecting 52 articles from 10 producing countries. The results showed that cocoa yields in agroforestry systems were 25% lower than those in monocultures. Furthermore, in another meta-analysis on the effect of shade on Arabica coffee yields, Ref. [29] found a negative relationship between agroforestry and coffee productivity.

Furthermore, one of the underlying problems of current agroforestry programmes is that they often focus on environmental benefits without giving sufficient importance to the compatibility of tree species with crops, or to the integration of farmers' local knowledge. Yet farmers' traditional farming practices, based on decades of observation and experimentation, can provide a solid foundation for optimising the performance of agroforestry systems.

In the literature, certain species have already proved their worth and are strongly recommended. These include *Gliricidia sepium*, *Erythrina* sp., *Acacia albida* and *Ziziphus mauritiana* [13,14,16,22,31]. These species are known for their beneficial effects on crops. They improve soil fertility, provide adequate shade and increase yields. *Gliricidia sepium*, for example, is widely used for its ability to fix nitrogen in the soil, enriching the soil and promoting plant growth. *Erythrina* sp. is valued for its role in providing moderate shade, crucial for protecting crops from excess sun. *Acacia albida*, also known as *Faidherbia albida*, is known to improve soil structure and increase water availability, which is particularly beneficial in arid areas. *Ziziphus mauritiana* is renowned for its ability to adapt to diverse environments while offering significant ecological benefits. Continued research in this area is therefore useful for refining agroforestry practices and improving the productivity of cocoa plantations.

In view of the wealth of arguments on the results of agroforestry in the world, it seems necessary to examine the specific case of three ecological zones in Côte d'Ivoire. These are Bonon, a former cocoa production area; Soubré, the current major production area; and Biankouma, which has great production potential but whose ecological characteristics are very different from those of the other production areas. This paper therefore aims to determine the combined effects of species associated with cocoa and inputs used on farm yields in each zone. This makes it possible to highlight the interactions between the tree species associated with cocoa trees and orchard productivity. The assumption supported in this work is that the combination of tree species and agricultural inputs significantly influences the yield of Ivorian cocoa farms. The rest of the paper presents the methodology, results and discussions and finally the conclusion.

2. Materials and Methods

2.1. Study Area

This study was carried out in three cocoa-producing areas in Côte d'Ivoire belonging to the network of agroforestry plots in the Cocoa4Future project observatory (<https://www.cocoa4future.org/le-projet/les-zones-d-intervention> (accessed on 7 August 2024)). These sites were selected according to the east–west gradient, which corresponds to the evolution of the main cocoa-producing areas in Côte d'Ivoire. The sites (Figure 1) are located in Bonon in the centre-west, Soubré in the south-west and Biankouma in the west. The Bonon site is the epicentre of the second cocoa production zone, which saw high production in the 1990s. The Soubré site is representative of the current cocoa production zone par excellence. Finally, the Biankouma site in the west of the country is considered to be the future major cocoa production zone [3–33]. It has seen strong growth in cocoa production since 2010.

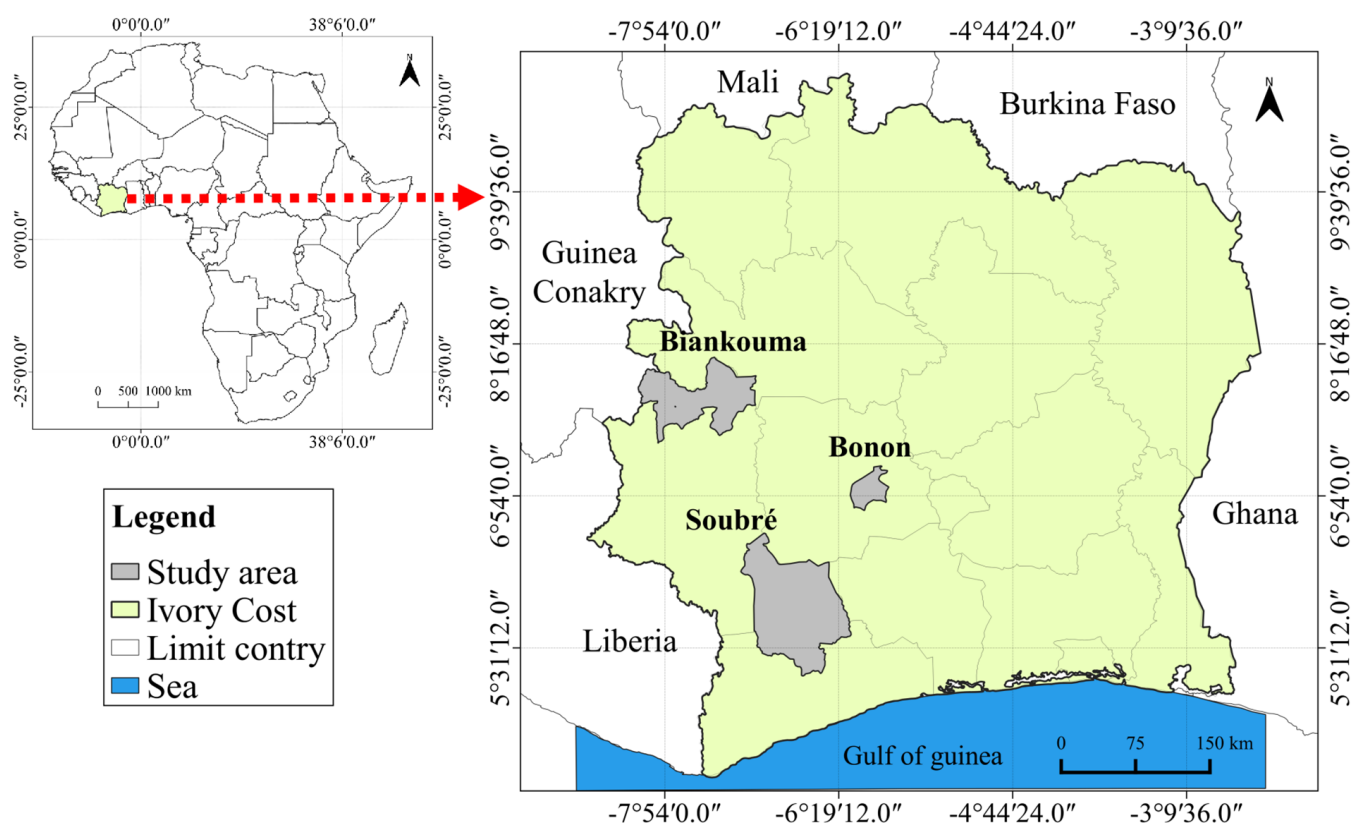


Figure 1. Map of the study area.

2.2. Sampling and Data Collection

One hundred and fifty (150) cocoa farms were randomly sampled on the three sites, i.e., 50 farms per site. The data used in this study are primary data collected as part of the Cocoa4Future project observatory.

Two main types of data were collected: socio-economic data, obtained using a questionnaire, and floristic data, collected using an inventory form. The floristic data consisted of an exhaustive inventory of all the woody species associated with cocoa trees. The socio-economic data used mainly concerned cocoa production over the last 5 seasons (2018 to 2022), areas measured using GPS, quantities of inputs used and the amount of labour on farms.

Socio-economic data were collected in three phases: the first in 2020, the second in 2021 and the last in 2022. Technicians resided on-site and collected information daily, which allowed for the correction of potential biases during the data collection phases. For the floristic data, the plot was first delineated using GPS to determine the area and the plot map.

Then, the plot was accessed to inventory the tree species associated with the cacao trees. Each species was inventoried and georeferenced, allowing for a comprehensive census of the species.

2.3. Choice of Variables

In this study, we consider two main components: a socio-economic component consisting of work time and the quantities of inputs used, and a biodiversity component, consisting of all the tree species associated with cocoa. We assume that the time farmers spend working on cocoa farms and the quantity of inputs used are likely to influence the yield and productivity of the orchards. The socio-economic variables used are specified in Table 1.

Table 1. Socio-economic variables and their descriptions.

Variables	Descriptions
Performance	Dependent variable expressing the quantity of cocoa produced per hectare
Quantity of work (Qwo)	Quantitative variable indicating the time spent maintaining the plot. It is expressed in man-days (MDs).
Quantities of inputs used	
Organic fertilisation (OrgF)	Quantity of organic matter used (chicken droppings, livestock waste, etc.). This is expressed in bags per hectare (bags/ha).
Chemical fertilisation (ChiF)	Quantity of chemical fertiliser used (NPK, Yara, etc.). This is expressed in kg/ha.
Fungicide (Fung)	Quantity of fungicide used in L/ha
Herbicide (Herb)	Quantity of herbicide used in L/ha
Insecticide (Insec)	Quantity of insecticide used in L/ha

Source: the authors.

The species present on farms can create a microclimate by modifying temperature, humidity and light levels [34], which in turn can affect the growth and productivity of cocoa trees. Understanding which species contribute most to this beneficial microclimate is therefore essential for optimising yields. Given the relatively large number of species present on cocoa farms, it is necessary to apply a rigorous selection method to identify the species that potentially have the greatest impact on yield.

To achieve this, the statistical model selection method known as the Bayesian Information Criterion (BIC) was used. This method makes it possible to compare different models and choose the one that offers the best compromise between complexity and fit to the data. In addition, in order to better represent the species on the matrix using BIC, we divided the floristic database into compartments.

The Bayesian Information Criterion is calculated according to Equation (1):

$$BIC = -2\log(L) + k\log(n) \quad (1)$$

where $\log(L)$ is the log-likelihood of the estimated model; k is the number of model parameters; and n is the number of observations.

Using the BIC, we identified models that include only the species that have the greatest influence on yields; thus, selecting the most relevant species using BIC enabled us to better understand and optimise the factors influencing cocoa yields. The BIC was calculated using the Package leaps in R 4.4.0

2.4. Model Formulation

To analyse the combined effect of labour, inputs and associated species on cocoa farm yields, we constructed a regression model, keeping other parameters such as soil type and rainfall constant. Thus, assuming that we have n farms, p species, q inputs and a quantity of labour L , the yield (Y) from each farm i can be modelled as a function of the presence and density of the species X_{ij} (where j represents the species), the quantity of inputs W_{ik} (where k represents the input) and the amount of labour L input.

The multiple linear regression model can be written as Equation (2):

$$Y_i = \beta_0 + \sum_{j=1}^p \beta_j X_{ij} + \sum_{k=1}^q \gamma_k W_{ik} + \delta_i L_i + \varepsilon_i \quad (2)$$

where Y_i is the yield of farm i ; β_0 is the intercept of the model; β_j is the regression coefficient associated with species j ; X_{ij} is the presence or density of species j on farm i ; γ_k is the regression coefficient for input k ; W_{ik} is the quantity of input k used on farm i ; δ_i is the regression coefficient for labour; L_i is the quantity of labour contributed to farm i ; and ε_i is the error term for farm i .

We compared the socio-economic and agroforestry characteristics of the farms according to ecological zones and crop systems in order to identify the specificities that emerge. To compare the cropping systems, the farms were divided into two categories. Those with a density of cacao-associated species less than or equal to 10 were considered as full-sun systems, while those with a density greater than 10 were classified as agroforestry systems [49]. Principal component analysis (PCA) was used to verify the specificities between ecological zones according to the species associated with cocoa. This step gives us a better understanding of regional variations. In addition, we carried out a multicollinearity test to check that there was no excessive linear correlation between the explanatory variables. We also performed the Breusch–Pagan test [42] to detect the presence of heteroscedasticity and the Ramsey RESET test [43] to check that the model was correctly specified. These tests guaranteed the robustness and reliability of the results of our regression model.

3. Results

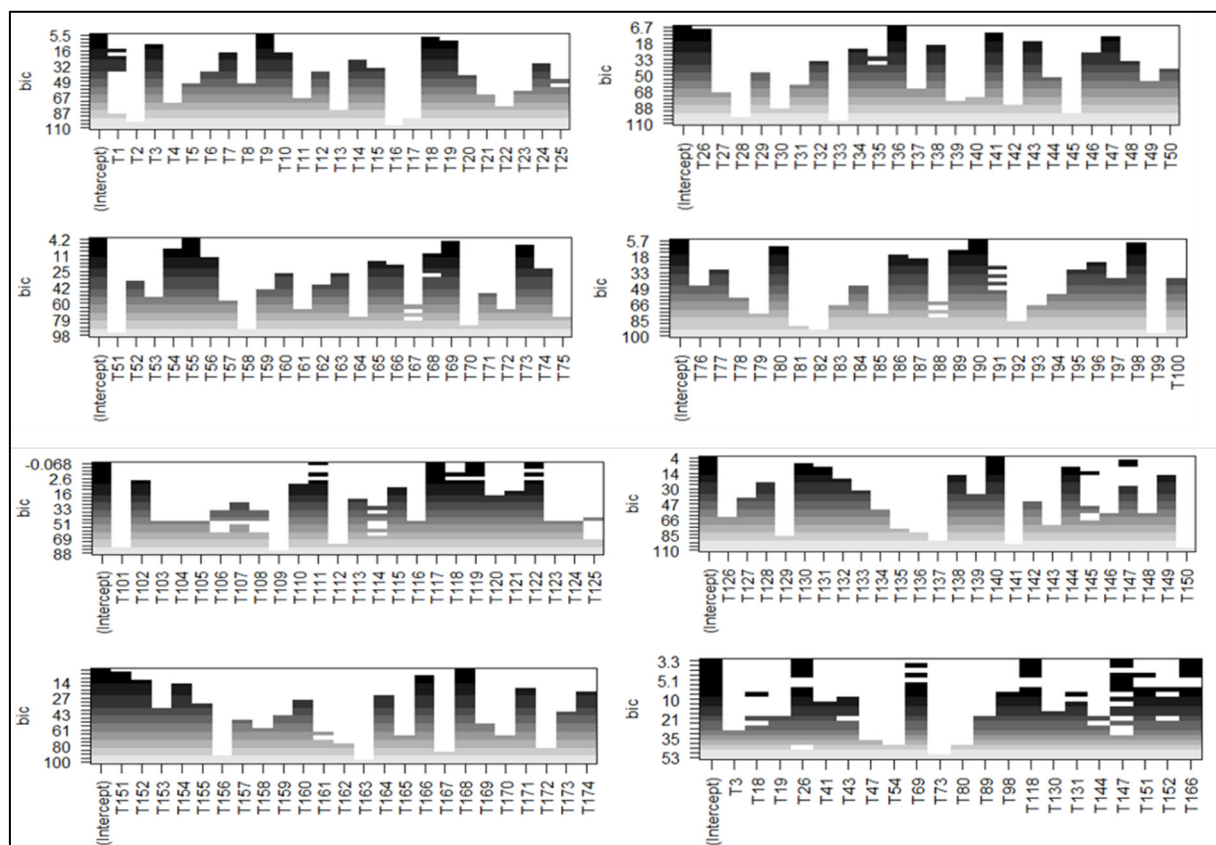
3.1. Species Selection

At the end of the inventories, we obtained a total of 174 species associated with cocoa. After calculating the BIC, we obtained the graphs in Figure 2, which represent a summary of the species selection models. The BIC is optimal for the line at the top of each graph, indicating the best model in terms of the trade-off between complexity and fit to the data. Based on this criterion, we retained a model comprising 14 species, namely *Citrus* sp., *Anthonotha manii*, *Blighia unijugata*, *Cordia senegalensis*, *Isobertlinia doka*, *Milicia* sp., *Morinda lucida*, *Morus mesozygia*, *Musanga cecropioides*, *Nauclea diderrichii*, *Raphia hookeri*, *Sterculia oblonga*, *Trilepisium madagascariense* and *Vernonia amygdalina*. The names of these species and their codification are given in Table 2. The selection of 14 variables out of a total of 174 initial variables shows a significant reduction in the complexity of the model. As a result, the model focuses on the factors with the greatest effect on yield.

Table 2. Names of species selected from the BIC.

No.	Description (Species)	Coding
01	<i>Citrus</i> sp.	T9
02	<i>Anthonotha manii</i>	T26
03	<i>Blighia unijugata</i>	T36
04	<i>Cordia senegalensis</i>	T55
05	<i>Isoberlinia doka</i>	T90
06	<i>Milicia</i> sp.	T111
07	<i>Morinda lucida</i>	T117
08	<i>Morus mesozygia</i>	T118
09	<i>Musanga cecropioides</i>	T119
10	<i>Nauclea diderrichii</i>	T122
11	<i>Raphia hookeri</i>	T140
12	<i>Sterculia oblonga</i>	T147
13	<i>Trilepisium madagascariense</i>	T166
14	<i>Vernonia amygdalina</i>	T168

Source: Authors based on survey data.

**Figure 2.** Choice of species potentially influencing yield using the BIC.

Based on the species selected, the regression model can then be written as follows:

$$Y_i = \beta_0 + \beta_1 T_9 + \beta_2 T_{26} + \beta_3 T_{36} + \beta_4 T_{55} + \beta_5 T_{90} + \beta_6 T_{111} + \beta_7 T_{117} + \beta_8 T_{118} + \beta_9 T_{119} + \beta_{10} T_{122} + \beta_{11} T_{140} + \beta_{12} T_{147} + \beta_{13} T_{166} + \beta_{14} T_{168} + \beta_{15} Qwo + \beta_{16} OrgF + \beta_{17} ChiF + \beta_{18} Fung + \beta_{19} Herb + \beta_{20} Insec$$

3.2. Information on Variables

The statistics of the variables summarised in Table 3 show that the average cocoa yield is 602.77 kg per hectare in the study areas. The species selected were not uniformly distributed across all the farms visited, with some being completely absent from certain farms. The frequency of the presence of these species varied considerably from one farm to another. For example, a species such as *Cordia senegalensis* was found on only one farm, while other species such as *Citrus* sp. were found on around 65% of the farms surveyed.

Table 3. Descriptive statistics of model variables.

Variables	Observation	Average	Standard Deviation
Yield (kg)	150	602.77	439.28
Quantity of work (MD)	150	88.66	57.73
Quantity of organic fertiliser (bags/ha)	8	15.30	12.23
Quantity of chemical fertiliser (kg/ha)	26	153.65	208.91
Quantity of fungicide (L/ha)	35	25.61	31.43
Quantity of herbicide (L/ha)	48	1.71	1.28
Quantity of insecticide (L/ha)	131	2	1.60
<i>Citrus</i> sp.	98	1.57	1.71
<i>Anthonotha manii</i>	2	0.35	0.02
<i>Blighia unijugata</i>	19	0.67	0.48
<i>Cordia senegalensis</i>	1	1	-
<i>Isobertinia doka</i>	3	1	0.34
<i>Milicia</i> sp.	53	0.64	0.11
<i>Morinda lucida</i>	78	0.89	0.86
<i>Morus mesozygia</i>	8	0.41	0.19
<i>Musanga cecropioides</i>	5	1.08	2
<i>Nauclea diderrichii</i>	2	0.86	0.80
<i>Raphia hookeri</i>	21	0.80	0.63
<i>Sterculia oblonga</i>	4	0.54	0.29
<i>Trilepisium madagascariense</i>	3	0.45	0.34
<i>Vernonia amygdalina</i>	23	1.62	2.70

Source: Authors based on survey data.

3.3. Comparison between Ecological Zones

The results in Figure 3 show that yields were better in the old production zones of Bonon and Soubré, with average yields of 719 kg/ha and 680 kg/ha, respectively, compared with the new production zone of Biankouma, where the yield was 492 kg/ha. Yields were also more stable in Bonon than in Soubré and Biankouma. Figure 3 shows that yield variability was lower in Bonon, while Soubré and Biankouma showed greater dispersion in the data.

Figure 4 completes the analysis in Figure 3, showing how yields changed in the three ecological zones over the 5 years of observation. Yields stagnated at around 410 kg/ha in Biankouma during the first three years of monitoring; however, yields rose sharply in the last two years, from 410 kg/ha to 672 kg/ha. On the other hand, in the old production zones of Bonon and Soubré, yields fell over the years, so that yields were better in the new Biankouma zone in the last year.

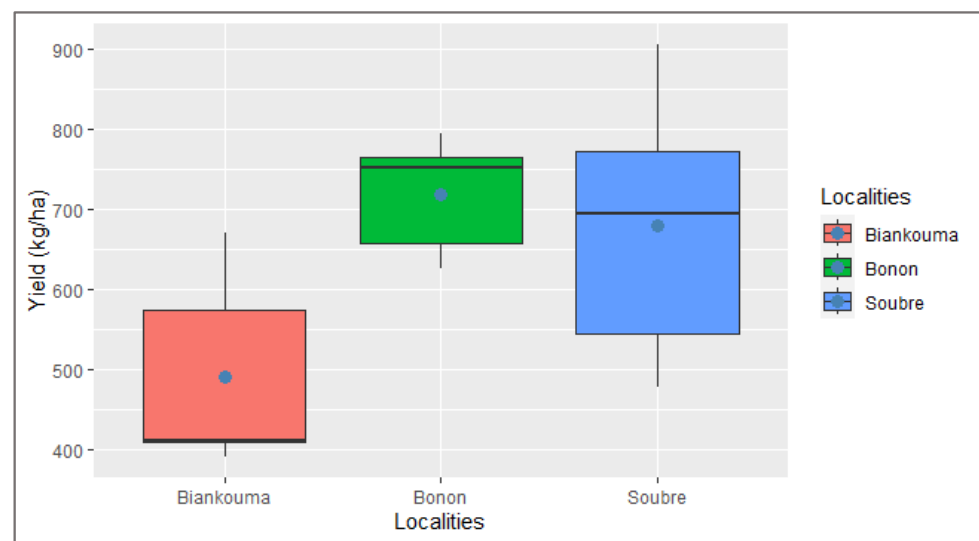


Figure 3. Distribution of zones by yield (2018–2022).

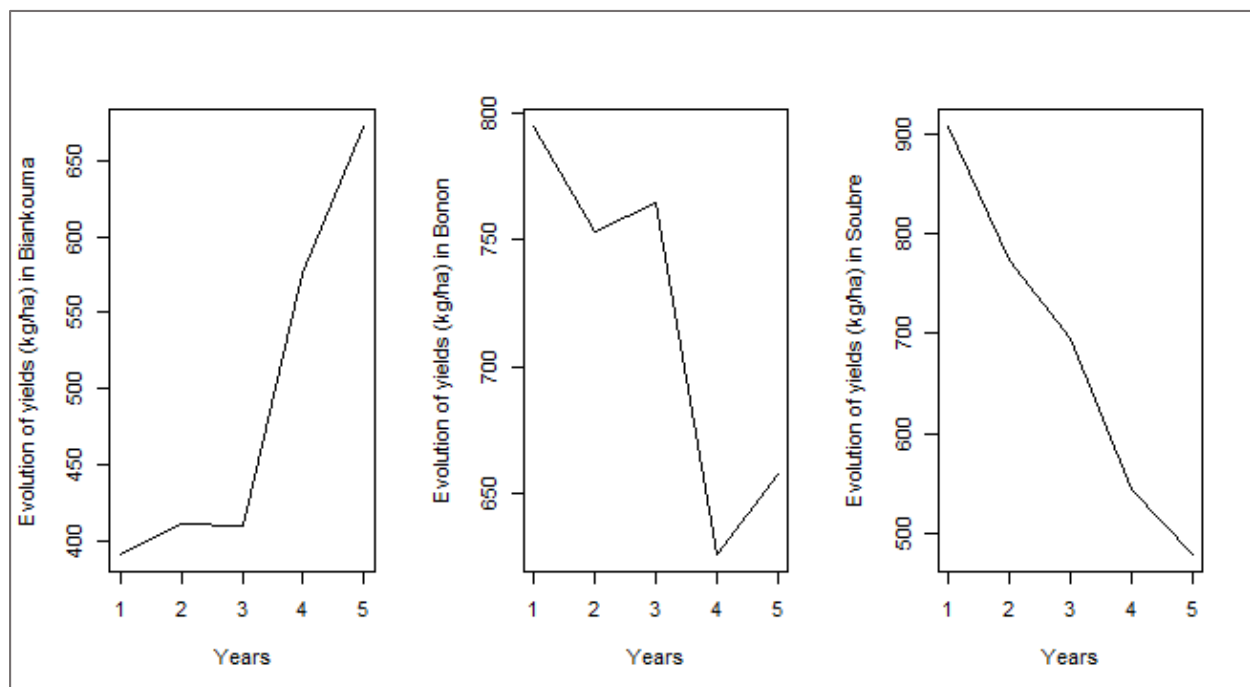


Figure 4. Yield trends in the zones from 2018 to 2022.

PCA (Figure 5) shows that there is variability between ecological zones in terms of the species that can potentially influence cocoa yields. Each ecological zone seems to harbour particular plant species that can play a crucial role in crop yields. Species such as *Nauclea diderrichii*, *Musanga cecropioides* and *Vernonia amygdalina* are specific to the Soubré locality; species such as *Cordia senegalensis*, *Isoblerlinia doka* and *Raphia hookeri* are specific to Biankouma; as for Bonon, it is characterised by species such as *Morus mesozygia*, *Anthonotha manii*, *Trilepisium madagascariense* and *Blighia unijugata*.

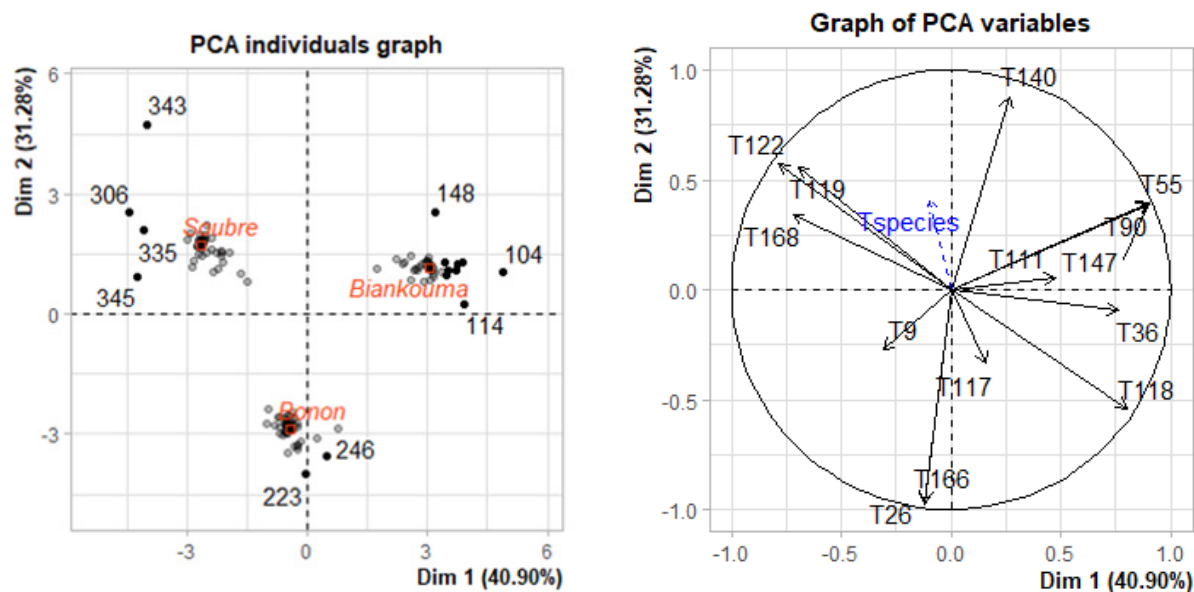


Figure 5. Graphical representations of ecological zones as a function of species according to axes 1 and 2 of the PCA.

3.4. Yield Dynamics Based on Cropping Systems

The results presented in Figure 6 show that yields were higher in full sun compared to agroforestry systems over the 5 years of observation. The average yield under full sun is 659.84 kg/ha, while it is 618.37 kg/ha in the shaded system. However, the *t*-test, conducted after checking the normality of the data (Appendix A Figure A1), indicates that there is no significant difference between the two types of cropping systems. There was a general trend of declining yields in both systems over these 5 years. Nevertheless, yields are more stable in agroforestry than under full sun. The year 2021 had the lowest yields; however, there was a recovery in yields the following year in agroforestry, while they continued to decline under full sun.

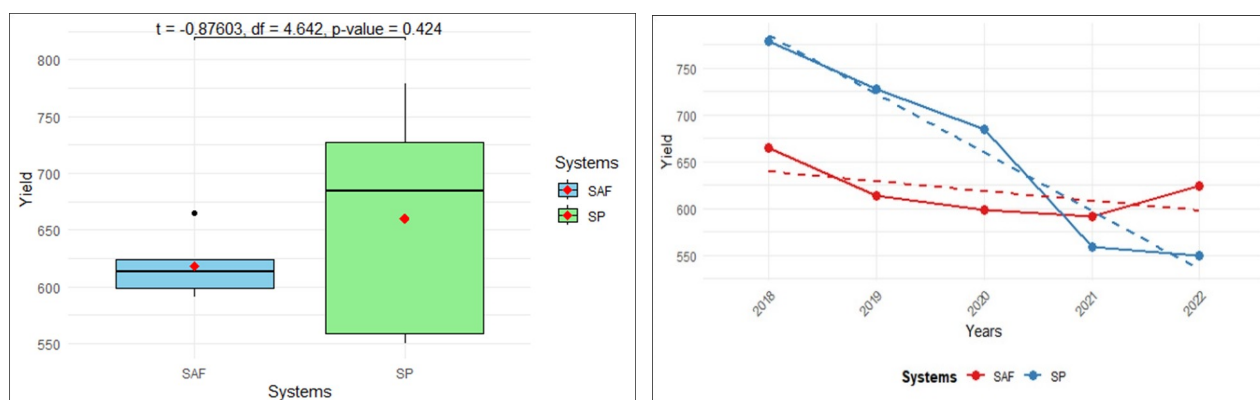


Figure 6. Evolution of yields according to cropping system.

3.5. Combined Effect of Inputs and Species on Yield

Multiple linear regression was used to determine the combined effect of inputs and species on yield. The results reported in Table 4 show that the model is globally significant at the 1% threshold (p -value < 0.01). In addition, the model showed a good fit, with a coefficient of determination (R^2) of 0.5966. Other quality tests were also carried out, namely the multicollinearity test and the Breusch–Pagan Ramsey RESET test. The results of these tests are summarised in Tables 4 and 5 and show that the model is robust.

Table 4. Results of other statistical tests of the quality of the linear regression model.

Test	Test Statistics	p-Value	Null Hypothesis	Conclusion
Heteroscedasticity test	chi2	0.8602	Homoscedasticity of residuals	We do not reject Ho
Residual normality test	z	0.00039	Normal distribution of residuals	We do not reject Ho
Model specification test	F	0.3284	Satisfactory specification	We do not reject Ho

Source: Authors based on survey data.

Table 5. Variance inflation factor for predictor variables.

Variables	VIF	1/VIF
Quantity of insecticide	2.42	0.413547
<i>Citrus</i> sp.	2.40	0.417017
<i>Nauclea diderrichii</i>	2.22	0.449629
Quantity of work	1.80	0.554767
<i>Musanga cecropioides</i>	1.68	0.596546
Quantity of fungicide	1.61	0.622868
<i>Trilepisium madagascariense</i>	1.52	0.656445
<i>Raphia hookeri</i>	1.51	0.662344
<i>Anthonotha manii</i>	1.45	0.689848
<i>Blighia unijugata</i>	1.42	0.702678
<i>Milicia</i>	1.38	0.724755
<i>Sterculia oblonga</i>	1.35	0.738070
Quantity of organic fertiliser	1.34	0.745273
<i>Morinda lucida</i>	1.28	0.778686
Quantity of herbicide	1.28	0.782817
<i>Isobertlinia doka</i>	1.26	0.795973
<i>Morus mesozygia</i>	1.25	0.800799
<i>Cordia senegalensis</i>	1.17	0.852146
Amount of chemical fertilisation	1.09	0.913775
<i>Vernonia amygdalina</i>	1.09	0.921617
Average FIV	1.53	

Source: Authors based on survey data.

The results in Table 6 show that certain species, such as *Citrus* sp., *Cordia senegalensis*, *Isobertlinia doka*, *Morinda lucida*, *Morus mesozygia* and *Raphia hookeri*, had a statistically significant and positive effect on yields. On the other hand, only *Anthonotha manii* had a statistically significant and negative effect on yields. Among the inputs used, only insecticides proved significant, with a positive effect on yields. Finally, the variable “Work” was significant and had a positive effect on yield.

Table 6. Results of the multiple linear regression model.

Variables	Coefficients	Standard Error	t	p-Value
Quantity of work	1.537	0.571	2.69	0.008 ***
Quantity of organic fertiliser	4.530	7.002	0.65	0.519
Amount of chemical fertilisation	0.193	0.248	0.78	0.438
Quantity of fungicide	−1.279	1.679	−0.76	0.448
Quantity of herbicide	16.888	25.829	0.65	0.514
Quantity of insecticide	129.881	23.361	5.56	0.000 ***
<i>Citrus</i> sp.	44.080	24.181	1.81	0.071 *
<i>Anthonotha manii</i>	−1541.597	743.994	−2.07	0.040 **
<i>Blighia unijugata</i>	−150.429	104.591	−1.44	0.153

Table 6. Cont.

Variables	Coefficients	Standard Error	t	p-Value
<i>Cordia senegalensis</i>	1034.723	325.928	3.17	0.002 ***
<i>Isobberlinia doka</i>	408.037	170.945	2.39	0.018 **
<i>Milicia</i> sp.	−4.592	64.418	−0.07	0.943
<i>Morinda lucida</i>	79.410	36.374	2.18	0.031 **
<i>Morus mesozygia</i>	791.183	270.333	2.93	0.004 ***
<i>Musanga cecropioides</i>	−62.394	83.510	−0.75	0.456
<i>Nauclea diderrichii</i>	314.959	308.043	1.02	0.308
<i>Raphia hookeri</i>	139.717	83.442	1.67	0.096 *
<i>Sterculia oblonga</i>	57.848	296.232	0.20	0.845
<i>Trilepisium madagascariense</i>	106.149	407.381	0.26	0.795
<i>Vernonia amygdalina</i>	−16.861	21.507	−0.78	0.434
Constant	121.028	56.098	2.16	0.033
Number of observations	150			
F (20, 129)	9.54			
Prob > F	0.0000 ***			
R-squared	0.5966			
Adj R-squared	0.5340			
Root MSE	299.87			

Legend: *** significant at 1%, ** significant at 5%, * significant at 10%.

4. Discussion

The results obtained show that the average cocoa yield in the three study sites is relatively low due to the persistence of diseases, particularly the Cocoa Swollen Shoot Virus (CSSV), in former production areas such as Soubré [46,47]. Diseases such as CSSV remain a major threat to cocoa productivity [35,36,45]. In affected areas, infected plants show signs of reduced growth and a significant drop in yields, orchestrated by successive mortality of cocoa plants [37–44]. However, the yields obtained in our study remain slightly higher than those found by [30], which were in the order of 204 kg/ha to 403 kg/ha. This study also reported relatively low yields from Ivorian cocoa farms. This difference may be linked to the specific nature of the study areas and to variations in agricultural practices, climatic conditions and soil types between the different regions.

Analysis of the pre-selected species shows great variability between farms. These species are not evenly distributed across all the farms visited, and some species such as *Cordia senegalensis* and *Anthonotha manii* are completely absent from 99% of the farms. This variability can be attributed to a number of factors, including farmers' individual preferences, local soils and climate conditions and cultivation practices specific to each region. The diversity of species present on farms also reflects farmers' choices in terms of agroforestry management and their traditional knowledge, which can influence the selection and integration of species into cropping systems. Indeed, in a meta-analysis, Ref. [38] confirmed that people's traditional knowledge is an essential element in the selection and conservation of species for future generations. This diversity in species distribution indicates major variations in agroforestry practices and environmental conditions on different farms.

Econometric regression showed that of the inputs used, only insecticides had a statistically significant effect, contributing positively to yields. This finding highlights the importance of pest control practices in cocoa growing. Insecticides play a crucial role in reducing losses caused by insect pests, which can otherwise cause considerable damage

to cocoa plants and reduce yields. Indeed, the study by [39] showed that treatments to improve pollination in cocoa farms proved beneficial when combined with insecticide treatment. This suggests that insecticides protect cherelles from insect pests, giving them a strong chance of increasing cocoa yields. However, this increased reliance on insecticides also raises environmental and sustainability concerns, as they can have negative impacts on biodiversity [48]. Therefore, it is essential to continue to research and promote sustainable alternatives, such as integrated pest management practices, which combine the judicious use of insecticides with other ecological methods for more effective and environmentally friendly control [48]. Surprisingly, fertilisers, whether organic or chemical, had no significant effect on yields. This can be explained by the fact that the effects of the fertilisers applied are not immediate, but may be felt later. Nutrients from fertilisers may take time to become fully integrated into the soil and be absorbed by plants, especially in agroforestry systems where soil and nutrient dynamics are more complex [41]. Furthermore, Ref. [41] has shown that litter from a species such as *Gliricidia sepium* takes an average of 3.6 months to decompose; however, mineralisation may take longer depending on environmental conditions.

Furthermore, the amount of labour provided by the farmer had a positive effect on cocoa yield. This result corroborates the study by [32], which shows that the amount of family labour mobilised increases the level of yield in traditional farms. From an economic point of view, labour intensity is not only an important lever for optimising costs, but also a crucial factor in guaranteeing high yields and good farm results. Practices such as regular maintenance of plantations, pruning of cocoa trees, control of diseases and pests and careful harvesting of pods all require constant attention and sustained effort on the part of farmers.

We identified six species that have a positive effect on cocoa yields. These are *Citrus* sp., *Cordia senegalensis*, *Isoberlinia doka*, *Morinda lucida*, *Morus mesozygia* and *Raphia hookeri*. These species proved particularly beneficial to cocoa crops because of their various contributions to the agricultural ecosystem. They can create a microclimate favourable to the development of cocoa trees while offering complementary benefits in terms of managing the water and nutrients available in the soil. Conversely, we observed that *Anthonotha manii* has a negative effect on cocoa yields. It is likely that this species competes with cocoa trees for soil nutrients and water, which could explain its negative impact on production. In addition, certain legumes present on cocoa farms, such as *Gliricidia* sp. and *Erythrina* sp. mentioned by [22,31], are known for their ability to fix nitrogen. This nitrogen fixation improves the availability of this essential nutrient, thereby promoting the proper development of cocoa fruits and reducing the risk of early fruit abortion [31].

In addition to their importance in optimizing cacao yields, these species can play complementary roles for farmers and the economy as a whole. *Citrus* fruits such as *Citrus sinensis*, *Citrus maxima*, *Citrus reticulata* Blanco and *Citrus limon* occupy an important place in the diet of rural populations due to their richness in essential vitamins [50]. These fruits are also indispensable in the food and pharmaceutical industries and provide farmers with an additional source of income [51]. They also play a key role in economic empowerment, particularly for women. These women, specializing in fruit trading, supply major urban areas in the country, such as the capital market in Abidjan. Through their dynamism, they contribute not only to the local economy but also to the export of citrus fruits to neighbouring countries like Mali and Burkina Faso.

Morinda lucida is widely used by farmers to treat various diseases, particularly malaria, as confirmed by recent studies [52]. This plant is therefore a valuable resource for rural communities, often far from modern healthcare facilities. *Morinda lucida* also plays a crucial role in biodiversity conservation. Its fruits serve as a food source for species such as *Treron calvus* (the green pigeon). By nourishing these birds, the plant supports local ecosystems and promotes biological diversity, a key factor for the resilience of ecosystems in the face of climate change and human pressures.

Isoberlinia doka is also of great importance, not only for its potential income as timber [53] but also for its medicinal applications in treating scorpion stings, diabetes, ulcers,

wounds and coughs [54]. *Morus mesozygia*, traditionally used to treat diabetes, has seen its effectiveness confirmed by recent studies. It thus enriches the repertoire of α -glucosidase inhibitor agents, offering new therapeutic prospects [55].

Raphia hookeri stands out for its versatile use. Not only is this plant used in construction and the manufacture of traditional beds, but it is also used to produce traditional wine [56]. Moreover, its grains, rich in carbohydrates, present a nutritional quality superior to some common staple foods [57]. In pharmacology, *Raphia hookeri* plays a key role, particularly in the treatment of diabetes [56]. Finally, *Cordia senegalensis* offers promising applications in modern medicine. According to a study by [58], this plant may be effective in treating skin conditions and preserving perishable food products.

In addition to their contribution to agriculture, these species are key to health, nutrition and the economy, hence the importance of preserving and promoting them for sustainable development. These results highlight the importance of selecting compatible tree species to optimise yields in cocoa agroforestry systems. They also underline the need for further research to identify other beneficial species and refine management practices to improve the productivity and sustainability of cocoa plantations. To encourage the widespread adoption of these species, the government and vulgarisation services, such as ANADER, should incorporate their importance into their action plans. The country's agricultural research services, such as the CNRA, could also experiment with these associations under controlled conditions to validate their effectiveness.

5. Conclusions

The aim of this study was to examine the combined effect of socio-economic and agroforestry factors on cocoa farm yields. The analyses showed that agroforestry practices varied from one ecological zone to another. Farmers in Soubré seem to prefer species such as *Nauclea diderrichii*, *Musanga cecropioides* and *Vernonia amygdalina*. Those in Biankouma mainly opt for *Cordia senegalensis*, *Isobertinia doka* and *Raphia hookeri*. As for Bonon, it is characterised by species such as *Morus mesozygia*, *Anthonotha manii*, *Trilepisium madagascariense* and *Blighia unijugata*. Yields were better in the old production zones in Bonon and Soubré than in the new production zone in Biankouma between 2018 and 2022. However, the trend reversed in the last year, with a marked improvement in yields in Biankouma, the new production zone. The trends over the 5 years of observation show that yields were higher in the full sun system compared to agroforestry; however, these yields were more stable in agroforestry.

The results of the econometric regression show that certain species, such as *Citrus sp.*, *Cordia senegalensis*, *Isobertinia doka*, *Morinda lucida*, *Morus mesozygia* and *Raphia hookeri*, have a positive effect on yields. On the other hand, only *Anthonotha manii* had a negative effect on yields. Of the inputs used, only insecticides had a significant and positive effect on yields. Finally, the amount of labour favoured an increase in yields. In view of these results, it is important to better examine the potential of traditional practices in order to facilitate the co-construction of agroforestry innovations. Statistical analysis could also be combined with agronomic and ecological analysis to provide more practical recommendations for species management on cocoa farms. In addition, replication of this type of study on a larger scale is necessary to deepen our understanding of the relationship between agroforestry and cocoa farm productivity.

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Appendix A

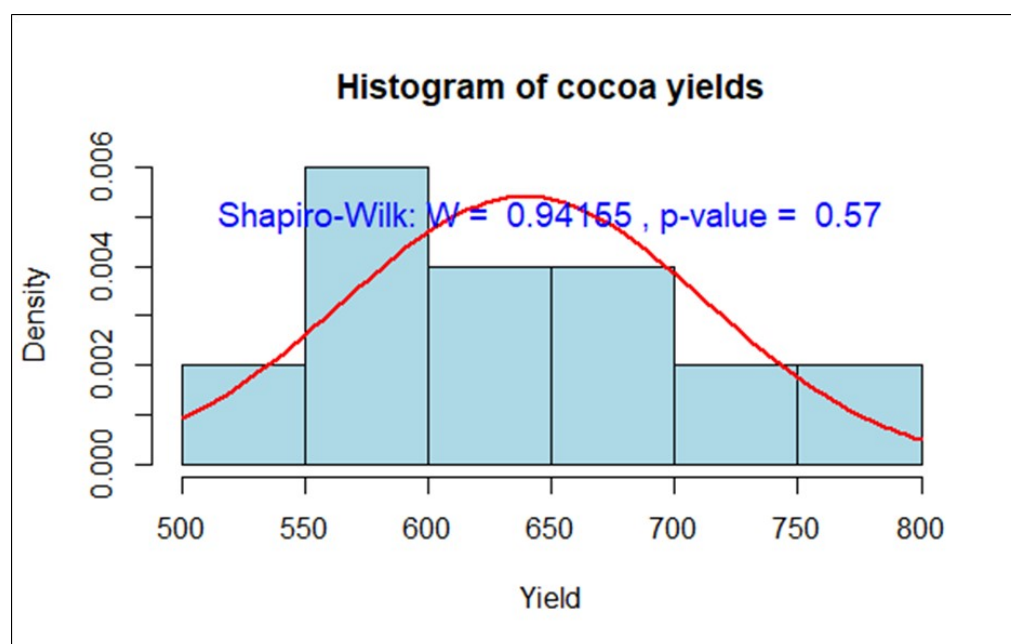


Figure A1. Verification of normality of cocoa yield data.

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