


Optimizing Model Land Use and Crop Productivity in Agroforestry Farms for Food Security of Small Farmers in Burundi

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Abstract

Burundi faces major agricultural constraints, including land fragmentation, soil erosion, limited access to inputs, inadequate infrastructure and demographic pressures that exacerbate food insecurity. In order to address the multiple challenges faced by farmers in rural areas, a study on improving agricultural productivity and food security in Burundi through optimized land use and diversified farming practices in agroforestry systems has been carried out. The study area is the communes of Giheta and Rutegama, all located in Burundi's humid plateau livelihood zone, and involved 164 households grouped in coffee growing cooperatives supervised by the cooperative consortium CO-COCA. The study uses a mathematical programming model to determine optimal crop selection based on factors such as production costs, yields and market demand. The findings of the study revealed significant insights into the demographic and socio-economic characteristics of the sampled population. Notably, 98.8% of respondents were engaged in agriculture, confirming the predominantly agricultural nature of Burundi. The results indicated that maize is the most important crop, occupying 33.9% of the average total cultivated area, followed by cassava at 26.5% and bananas at 19.4%. Together, these three crops accounted for a substantial portion of the total cultivated area, highlighting their significance in local agriculture. Beans and potatoes also play a role, occupying 14.4% and smaller areas, respectively. In terms of profitability, the study provides a detailed analysis of profit margins by crop. Bananas emerges as the most profitable crop, with a profit margin of 97.3%, followed closely by cassava at 96.1% and rice at 90.5%. These crops not only offered substantial

yields relative to their production costs but also benefited from strong market demand. Other crops, such as beans (71.3%), coffee (70.3%), and vegetables (54.5%), also demonstrated considerable profitability, although they occupied smaller cultivated areas. Conversely, crops like pigeon peas (4.1%), potatoes (7.6%), and sweet potatoes (7.6%) exhibited the lowest profit margins, which may discourage farmers from investing in them unless other incentives, such as ecological benefits or local consumption needs, are present. Regarding the results, we therefore recommend to promote policies supporting agroforestry, improve market access and develop infrastructure to exploit these benefits.

Keywords

Optimization, Land Use, Crop Productivity, Agroforestry, Smallholder Farmers, Burundi

1. Introduction

Burundi, a country experiencing rapid population growth, faces the increasing challenge of a rugged topography that limits arable land [1]. Optimizing agriculture in this context has proven to be highly complex, influenced by a multitude of factors such as limited resources and uncertainty in pricing and weather conditions [2]. Consequently, efficient management of small plots, utilization of traditionally unused spaces, crop diversification, and adoption of new agricultural technologies are imperative [3]. Interest in agricultural issues has grown significantly in recent years, primarily because agriculture serves as a means of diversifying household and national economies [4]. The agricultural sector in Burundi provides a vital source of income and employment for both rural households and urban agricultural product traders [5]. Agricultural production in Burundi is diverse and depends on crop species, respective crop treatments and cultivation system, production costs, yield and its respective profit. [6]. Each crop also requires specific operations at particular times of the year, and choices made regarding the operational calendar significantly impact the overall profitability of the agricultural production system [7]. Every operation on a specific crop incurs a specific cost, which can vary greatly depending on the type of labor. The resulting profits for each crop depend on annual weather conditions, crop yield per hectare, costs of crop establishment, and the selling prices at harvest. Since these factors vary greatly among years, income planning is highly uncertain for farmers [8]. Thus, improving these adverse factors affecting the agricultural productivity in Burundi can significantly impact farm productivity and profitability, and [9], additionally provide environmental benefits by a more efficient use of limited natural resources in the context of climate change [10]. Mathematical programming models are often used to analyze and enhance farm productivity by addressing crop selection, crop rotation and association, agricultural production planning as well as allocation of crop production areas and input resources. In this context, the profitability of a farm depends on a

selection of crops that minimize the costs associated with all operations required to successfully produce it and maximize expected revenue. It is important to note that crop selection problem is subject to real-world constraints such as the quantity of available resources (cultivable area, labor availability, and production inputs) and the organization of the operations involved in managing each crop.

2. Problem Statement

In Burundi, smallholder farmers face a multitude of challenges that hinder their ability to produce sufficient food for their families and generate income to meet basic needs and invest for future generations [11]. Several factors contribute to low productivity and food insecurity. The country's topography fuels soil erosion, reducing soil fertility and water retention capacity, especially on the steep, eroded lands [12]. Economically, the low purchasing power in rural Burundi prevents smallholder farmers from acquiring quality inputs like fertilizers, improved seeds, and pesticides, due to their high cost [13]. Furthermore, smallholders rely heavily on traditional tools, limiting labor efficiency and reducing agricultural yields [14]. Many farmers lack modern agricultural training due to limited technical knowledge [15]. Additionally, the local varieties cultivated are often old and unproductive. Population growth has led to a high land fragmentation and reduction of arable land per capita, further reducing agricultural productivity [16]. Unsustainable agricultural practices, such as slash-and-burn, contribute to soil degradation and biodiversity loss [17]. Limited access to water for irrigation, especially during droughts, exacerbates these challenges. Climate change events, such as droughts and floods, disrupt agricultural production cycles and reduce yields [18]. Inadequate market infrastructure further limits smallholders' access to markets and reduces their income [19]. Past and present conflicts and instability have displaced populations, destroyed infrastructure, and disrupted agricultural activities [20]. Pests and diseases affect crops and livestock, reducing agricultural production [21]. Therefore, urgent action is required to combat these adverse challenges to reduce rural poverty and improve food security and reduce rural poverty in Burundi. Hereby it is essential to implement comprehensive strategies that address the root causes of these problems.

3. Research Background

3.1. Agriculture and Climate Change in Burundi

To stimulate production, the Government of Burundi has continuously implemented various agricultural policies, particularly to improve the living conditions of rural populations [22]. Some of these agricultural policies focus on improving agricultural production through the introduction of improved seed varieties, the promotion of the use of fertilizers and pesticides, and the dissemination of modern agricultural technology packages [23]. Improving access to land through the implementation of land tenure security programs to guarantee farmers' rights over their holdings has been and continues to be another government initiative to increase production [24]. In Burundi, agricultural policies also aim to diversify

agricultural production by encouraging, the production of export crops to generate additional income and, the development of livestock farming by improving animal breeds, combating animal diseases, and promoting intensive livestock farming [25]. Burundi has also strengthened the bargaining power of producers and improved access to credit through the establishment of dynamic agricultural cooperatives, which has in turn strengthened agricultural product marketing systems [26]. Despite all the government's initiatives to improve the living conditions of rural populations, Burundi continues to face numerous challenges that hinder Burundian agricultural production. These include land fragmentation, which limits the adoption of modern techniques, limited access to credit that impacts appropriate investments in farms, and the low added value of agricultural products due to highly volatile selling prices, making production planning difficult and reducing household food security [27]. In addition, there is a lack of agricultural production infrastructure, including roads, markets, and storage systems. Further, Burundian agricultural products do not always meet international quality and food safety standards, which limits the access to export markets.

3.2. Agroforestry and Community Resilience

To maximize community resilience, several agricultural practices are emerging to try and combat the vicious cycle for small-scale producers in Burundi [28], one of which is agroforestry that combines the advantages of agriculture and forestry and contributes to improving farmers' livelihoods, protecting the environment, improving soil fertility and crop productivity and strengthening the resilience of rural communities in the face of global changes. Agroforestry is a practice that consists of associating trees with crops and/or livestock, offering numerous possibilities to improve food security and restore degraded ecosystems in Burundi [29]. This practice provides producers with environmental benefits such as improving soil fertility, combating erosion, enhancing biodiversity, mitigating the effects of climate change, on the one hand, and economic benefits through the diversification of income sources such as fruit trees, timber trees, and medicinal plants can generate additional income for farmers by promoting resistance to market fluctuations on the other hand [30]. In terms of food security, agroforestry offers many services including (1) the diversification of agricultural products [31]; (2) the improvement of the quality of agricultural products as trees provide shade and protect crops from the wind and improve soil quality, resulting in higher yields and better quality products [32]; (3) the development of new markets, especially for non-timber forest products, such as fruits, nuts, and beekeeping products, which can be sold on local or national markets [33]; (4) the reduction of production costs due to the provision of firewood, manure, and other products from trees, which reduce production costs [34]. Furthermore, agroforestry contributes to carbon sequestration, which can generate additional income through international carbon trade [35]. Indeed, agroforestry is a suitable and adaptable practice that offers a sustainable solution to the challenges of land scarcity in Burundi [36]. It therefore may contribute to improve food security and strengthen

the resilience of agricultural systems.

3.3. Effective Agroforestry System

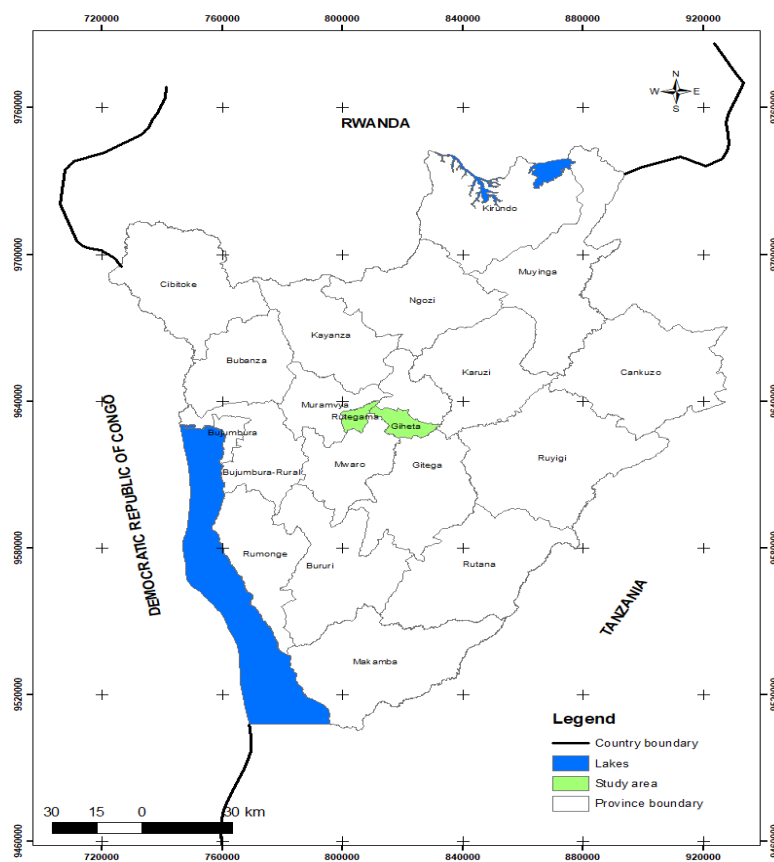
Generally, certain conditions are necessary for agroforestry to optimally address the challenges of increasing agricultural productivity in Burundi [37]. In-depth Knowledge of soil ecosystems, climates, and local crops is essential to select the most suitable tree species and agroforestry systems is essential. Further it is important to involve farmers as local actors in the design and evaluation of agroforestry practices to ensure a sustainable adoption of the new practices [38]. Successful dynamic innovation networks emerge from different knowledge bases to balance local roots and global supply directives to combine different income strains to sustainable ends. In this regard, the involvement of long term partners with organic agriculture expertise was an asset within this network and sample of local farmers. The selection of agroforestry tree species should also consider growth speed, adaptation to local conditions, economic value, and the ability to improve soil fertility [39]. Further, agroforestry systems with diverse species and crops helps to reduce risks associated with diseases, pests, and market fluctuations [40]. It is also worth exploring market development options in dynamic innovation networks (DINs) for non-timber forest products and quality agricultural products to ensure the profitability of agroforestry as another source of monetary and food income. Finally, an integrated approach, combining research, training, market development, and public policies, is essential to guarantee the success of such agroforestry practices in Burundi and meet the specific needs of farmers. With this in mind, the University of Burundi, through the Faculty of Agronomy and Bioengineering, is conducting an Agroforestry project funded by the state of Baden-Württemberg on promoting sustainable agricultural practices through the integration of trees and shrubs with crops. It aims to combat soil erosion, enhance land fertility, and involve local farmers in planting trees.

4. Study Area and Justification

This study was conducted in the communes of Giheta (Gitega Province) and Rutegama (Muramvya Province), located in the humid central plateau livelihood zone of Burundi (see map of study area below). The study sample consisted of farm households belonging to the coffee cooperatives “MBONERAMIRYANGO” (Giheta) and “Usine Coopérative Nyarunazi (UCN)” (Rutegama). These cooperatives members are involved in organic coffee production in agroforestry systems, under the supervision of the Consortium of Coffee Cooperatives (COCOCA). These communes were selected due to their socio-economic and geographic similarities, as well as their involvement in organic agriculture¹. The tropical savanna climate, characterized by a dry season and a rainy season, is conducive to the cultivation of coffee and other food crops. The average altitude of 1500 to 2000 meters,

¹Naturland e.V. as international and worldwide organic farmers association trained and counceled organic forest best practices, structuration of mixed cultivation and organic pest control. The Naturland Fair standard in addition provided market access for coffee beans into fair trading supply chains aiming for living incomes.

coupled with annual rainfall of 1150 to 1500 mm, provides favorable conditions for agriculture [41]. It is also characterized by a tropical climate with a short dry season of four months (June-September). Temperatures are generally cool, with averages ranging from 17.3°C to 22.1°C [42]. These agro-climatic characteristics, combined with limited access to infrastructure, make the optimization of land use and crop productivity particularly relevant in this region. Indeed, improving the food security of rural households while preserving natural resources is a major challenge in this context. By focusing on Communes Giheta and Rutegama, the study generates valuable insights into the challenges and opportunities of agroforestry in typical Burundian contexts. The findings will inform the development of site-specific agroforestry practices that are adapted to local conditions and the needs of local communities in terms of land use and crop productivity. Furthermore, the research contributes to the development of evidence-based policies and programs that promotes sustainable land use and improve livelihoods in Burundi. The selection of Communes Giheta and Rutegama for this study on agroforestry and land use optimization is likely based on their representativeness of Burundian agricultural challenges, their suitability for agroforestry implementation, and their accessibility for research activities (Figure 1).



Source: [8].

Figure 1. Map of study area.

Socio-economically, the communes of Giheta and Rutegama are essentially rural, with an economy heavily dependent on agriculture practiced by small-scale family farms. Sources of income vary in the study area, and include the sale of agricultural produce, livestock, timber, handicrafts, quarrying, trade in various products and inter-urban transport [43]. The main economic development players in the study area are farmers, livestock breeders, traders, craftsmen, decentralized government services, non-government players (Agricultural Producers' Organizations, Trade Unions, etc.) and the private sector.

5. Research Methodology

5.1. Sampling and Data Collection

In this section, we present all the methods and techniques used to carry out this research. The first step was a literature review that led us to the exposition and description of certain theoretical and empirical concepts related to the topics covered. It is of paramount importance in that it allowed us to grasp and internalize the meaning and overall orientation of the subject. We developed a qualitative and quantitative socioeconomic questionnaire that was administered to farmers in the research area to assess the socioeconomic situation of the sample households ($n = 164$). The questionnaire was digitized from the computer using the KoBoCollect software. Data collection was carried out during the month of March 2023. As the study aims to capture information from an entire production year, we had to consider the data from the last production year, *i.e.*, the 2021-2022 crop year using smartphones in which the questionnaire was incorporated. The questionnaire focused mainly on general household identification, specific characteristics of crops cultivated, general characteristics of farms, sources of income, and finally the household's food security and nutrition component. Afterwards, the forms completed on the smartphones were transferred to the server to be downloaded in Excel format before processing and analysis. The target population of our research is all households in the aforementioned communes, belonging to the Coffee Cooperatives Consortium (COCOCA). Sampling was also used to determine the households to be surveyed, based on their practice in agroforestry systems. Thus, a total sample of 164 households in the two communes was the subject of our research.

5.2. Data Preparation and Analysis Tools

In this study, Python 3.12 version was the main programming language used for socio-economic data analysis, due to its ability to provide a versatile environment for statistical calculation and visualization [44]. For data manipulation and analysis, a powerful Python library called Pandas was used. It facilitates the reading of data files, the management of missing values and the manipulation of DataFrames for exploratory analysis. We also used the NumPy library to handle large multidimensional arrays and matrices, as well as a collection of mathematical functions to operate on these arrays. This is essential for efficient numerical calculations and

operations. We also made use of exploratory data analysis tools such as Matplotlib, a comprehensive library for creating static, animated and interactive visualizations in Python. It was used to plot histograms, scatter plots and box plots to understand distributions and relationships between data. Built on Matplotlib, the seaborn library was used to enhance visualizations by providing a high-level interface for drawing attractive statistical figures [45]. It was used to generate pair plots and heat maps to visualize correlations between variables.

5.3. Python Tools and Purpose

Tool	Purpose
Pandas	Data manipulation and analysis, including data cleaning, transformation, and exploratory data analysis.
NumPy	Efficient numerical computations, including array operations, linear algebra, and random number generation.
Matplotlib	Creating static, animated, and interactive visualizations, such as line plots, bar charts, and scatter plots.
Seaborn	Building on Matplotlib, providing a high-level interface for creating attractive and informative statistical graphics.
Scikit-learn	Implementing various machine learning algorithms, including classification, regression, clustering, and dimensionality reduction.
Statsmodels	Performing statistical modeling and hypothesis testing, including regression analysis, time series analysis, and econometrics.

Before starting all the manipulations with python, we first imported the calculation, analysis and visualization libraries, as shown in the figure below.

```
import pandas as pd
import matplotlib.pyplot as plt
import seaborn as sns
import scipy
import statsmodels.api as sm
```

5.4. Modeling Framework

In our study, mathematical programming is used to develop a land-use optimization model with the aim of improving crop productivity for rural farmers through a better combination of production factors (land, labor and capital) and thus overcoming rural poverty in Burundi. The aim is to enable a better selection of crops according to the areas available and the production costs associated with each crop. Agricultural production is measured by the sum of the market value of all crops produced, whether sold or consumed by the household. The agricultural production of each food crop is multiplied by the average market price of the crop concerned. Since farmers in the region undertake many activities in their production systems, for reasons of simplicity, activities in the model are limited to crop production.

For this model, $x_{p,j}$ is the area (in hectares) allocated to crop j on plot p for the respective year. The aim is to maximize overall profit, taking into account the costs and revenues associated with each crop.

To this end, we use the following function to maximize profit

$$\text{maximize } Z = \sum_{p=1}^P \sum_{j=1}^M (P_j \times x_{p,j} - C_{p,j} \times x_{p,j}) \quad (1)$$

where:

P_j : Revenue per hectare for crop j ,

C_j : Production cost per hectare for crop j ,

$x_{p,j}$: The area allocated to crop j on plot p ,

P : Total number of plots,

M : Total number of crops available

As a constraint, the total area used on each plot p must not exceed its available area S_p :

$$\sum_{j=1}^M x_{p,j} \leq S_p \quad \forall p \quad (2)$$

The total cost of production must not exceed the available budget B

$$\sum_{p=1}^P \sum_{j=1}^M C_j \times x_{p,j} \leq B \quad (3)$$

By ensuring a minimum yield R_j (in tons) for each priority crop j we have

$$\sum_{j=1}^M x_{p,j} \times Y_j \geq R_j \quad \forall j \in \text{priority crops} \quad (4)$$

where: Y_j is the average yield (tons/ha) of the crop j .

It should also be noted that for strategic reasons (market, environment), certain j crops may have a maximum area U_j :

$$\sum_{p=1}^P x_{p,j} \leq U_j \quad \forall j \quad (5)$$

There are also other crops that must be grown on a minimum area L_j :

$$\sum_{p=1}^P x_{p,j} \geq L_j \quad \forall j \quad (6)$$

However, in the logic of the farmers in the study area, some crops are grown on extremely large areas and others on small ones. This is to help manage the balance between economic, social, environmental and strategic priorities. This helps to ensure sustainable production, protect soils and natural resources, and meet short- and long-term food and economic needs, on the one hand, and may also depend on the socio-economic importance attached to the crop by the household.

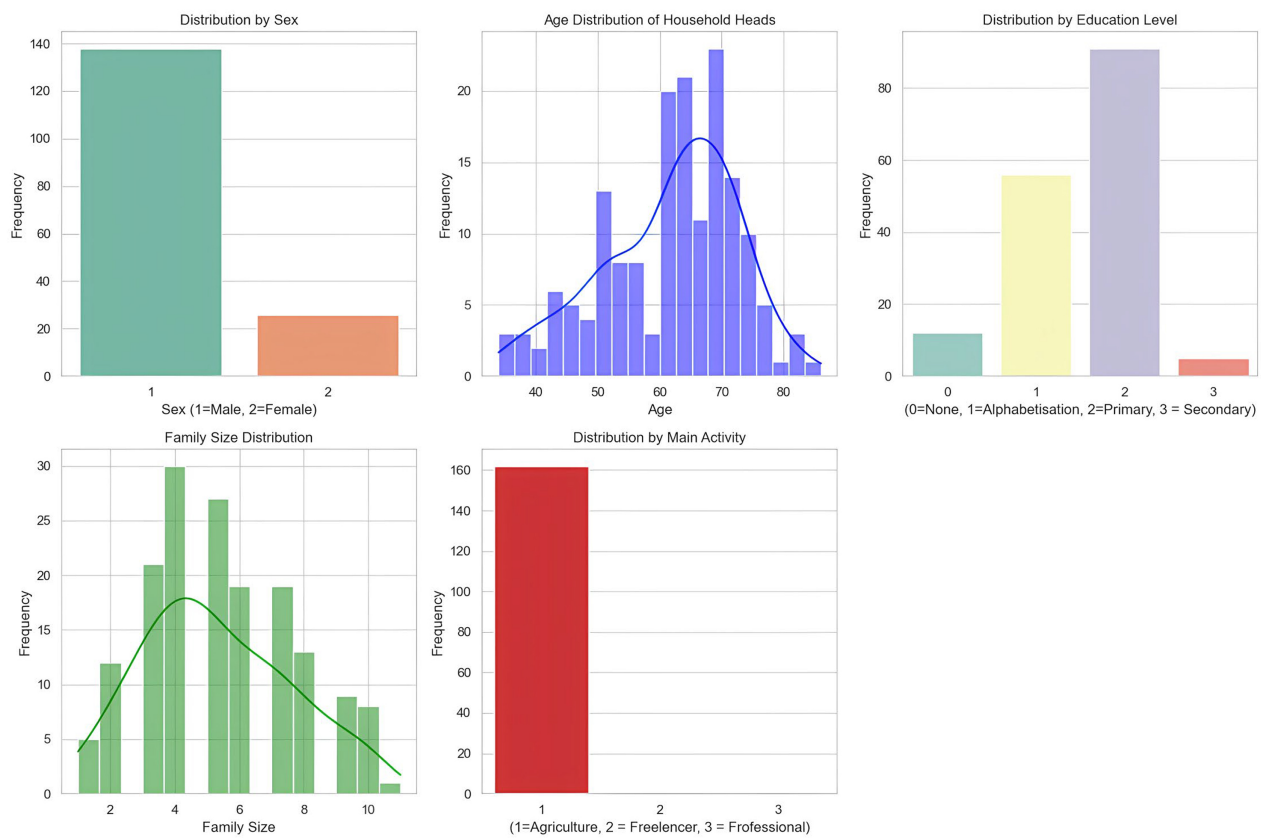
6. Results

6.1. Demographic Characteristics

Figure 2 provides a general overview of the demographic and socio-economic

structure of the sampled population in the purely rural communes of Giheta and Rutegama. Further description of household’s characteristics in terms of gender, Age, Education, family size and main economic activity in the provinces of Giheta and Rutegama, Burundi

The traditional structure of a Burundian household remains based on the presence of a male household head: a husband, an older brother, or a son. When this structure collapses or disintegrates due to the death, divorce, or abandonment of the household head, women acquire a status that this patriarchal and patrilineal society usually denies them [46]. The distribution of household heads by gender shows that our survey reached a sample dominated by male household heads (84.1%) while only 15.9% are female. Historically, rural societies in Burundi, like many other African cultures, have assigned specific roles to men and women [47]. Men are often perceived as the primary decision-makers within the household and community, including matters of resource management and agricultural production. This same male dominance among the sampled household heads reflects the role of men in economic decision-making within Burundian households. It is therefore essential to consider these results when designing development policies and programs aimed at promoting gender equality and empowering women.



Sources: Own data analysis.

Figure 2. Household characteristics.

The age distribution of household heads shows that they are predominantly older. The average age of household heads is 61.7 years, with the distribution peaking around 60 - 65 years, a noticeable drop in frequency is observed below 50 years and above 75 years. The distribution is unimodal and slightly skewed to the right, indicating fewer younger household heads. This is significantly higher than the average found in the Burundi National Agricultural Survey (47.4 years) [48]. This average highlights that the population involved in coffee farming in Burundi is composed of older individuals, despite the labor-intensive nature of this crop [49]. It can also be deduced that the younger population, with an average age of 35.7 years, is less attracted to this export crop and instead engages in crops and activities that provide quicker financial returns [50]. Regarding education levels, the results reveal a critical situation in the study area. Most household heads have a primary education level (55.5%). 34.1% have alphabetization or basic literacy, 7.3% have no education, and only 3.0% have a secondary education. The low percentage of secondary education highlights a significant gap in educational attainment among household heads. These proportions reflect the reality of the level of education in Burundi in the past century, particularly in rural areas, where families did not see opportunities for development through educating their children. This situation can also be attributed to the lack of educational infrastructure in past years, where the average distance to schools exceeded 10 kilometers. This limited access to schools and educational opportunities [51]. For others, the challenge was rooted in the economic priorities of rural families, which favored child labor for economic reasons over their schooling.

In terms of household size in the study area, the average family size is 5 members. The distribution is roughly normal, with the highest frequency occurring between 4 and 6 members. The majority of families are moderately sized, which might align with typical demographic trends in rural areas. Larger families indicate joint family structures in specific cases, which is common in developing countries [52]. In rural Burundi, this is explained by the role of children in agricultural work within households, where they are often considered additional labor, encouraging families to have many children. It should also be noted that access to contraception methods may be limited, particularly in rural areas [53]. The distribution of household economic activities in the sample shows that a vast majority (98.8%) of respondents are engaged in agriculture, confirming Burundi's predominantly agricultural nature. Overall, these findings reflect the challenges Burundi faces in terms of development. This is exemplified by low education levels and dependence on agriculture, which are factors contributing to the persistence of poverty and inequality. Thus, the rural exodus of young people seeking better-paying jobs leads to a shortage of labor in rural areas, exacerbates population aging, and strains social protection systems, thereby reducing agricultural production capacity. Furthermore, limited access to education, healthcare, and other social services hampers human development and underscores the need for public policies to improve living conditions in rural areas, particularly in education,

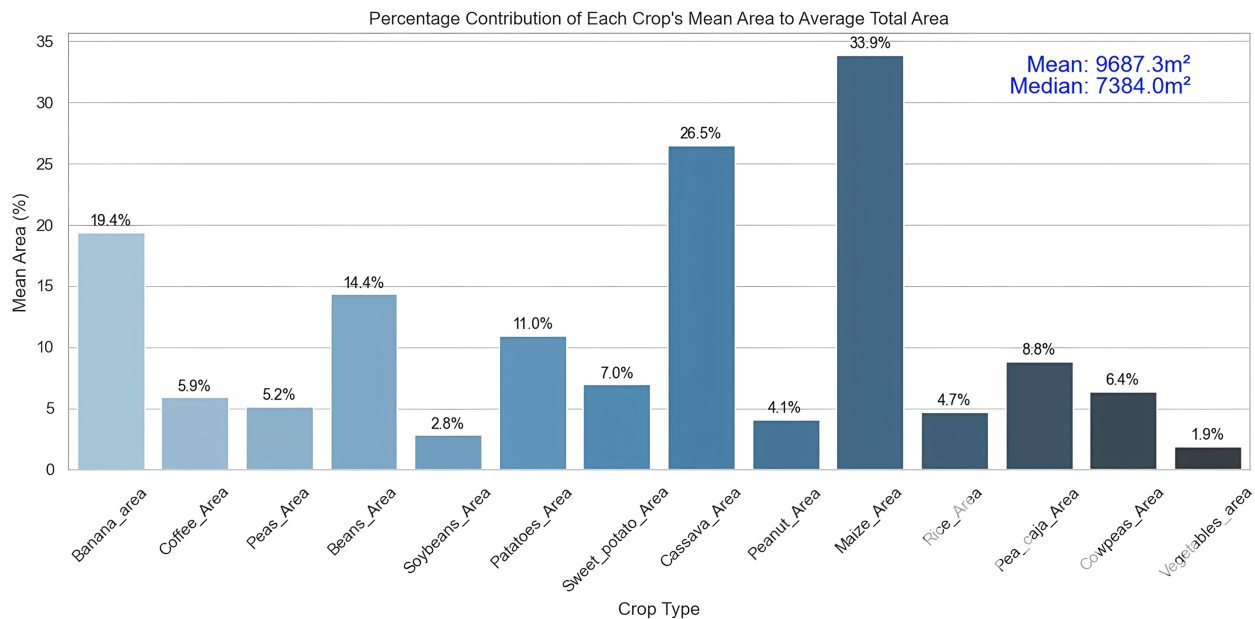
healthcare, and economic development.

6.2. Agriculture and Area by Crop

A wide range of crops are grown in Burundi, with disparities in terms of exploitable area. Some crops dominate in terms of surface area, while others are grown on much smaller areas.

Figure 3 shows that the area devoted to maize is the largest (33.9%) of the average total cultivated area in the study area, making it the most important crop among those grown by farmers. This shows that maize is the speculative crop in the study area, either because of its high demand, adaptability or nutritional importance. Cassava (26.5%) and banana (19.4%) are the next most important crops. Together with maize, these three crops make up a significant proportion of the total cultivated area, indicating their importance in local agriculture. Beans (14.4%) and potatoes (11.0%) also have a notable share, suggesting that they are relatively important, but less so than maize, cassava and bananas.

Other crops such as soya (2.8%), peas (5.2%) and vegetables (1.9%) have minimal contributions, which could mean that they are niche or complementary crops grown in the study area. As for the mean and median areas, **Figure 3** shows the mean total area to be 9687.3 m², and the median 7384.0 m². Thus, the fact that the mean is higher than the median suggests a positively asymmetrical distribution, where some crops (such as maize) are grown on much larger plots than others. The three main crops (maize, cassava and banana) dominate, with a combined contribution of around 79.8% of the total cultivated area. Other crops have a relatively minor contribution, with vegetables having the smallest share, suggesting



Source: Own data analysis.

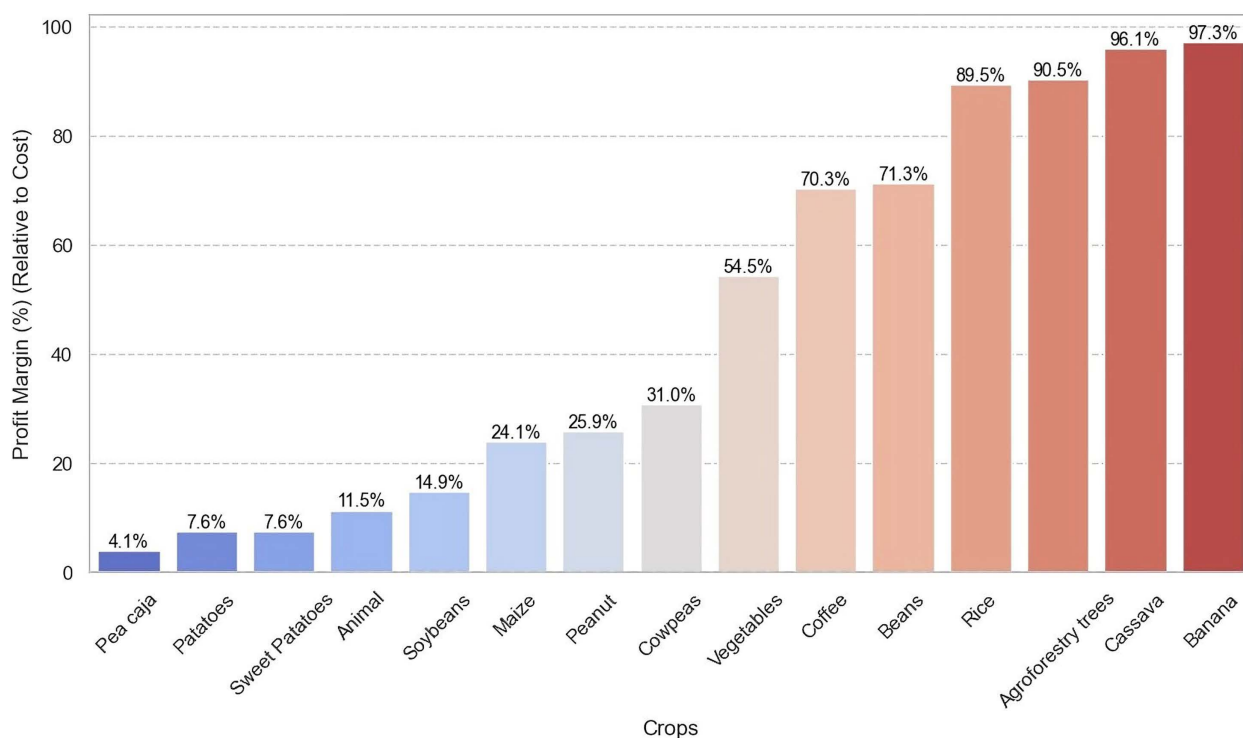
Figure 3. Crop types and area per crop (only for Non-Zero Values).

a diversity of practices in the study area. However, the predominance of maize, cassava and bananas suggests that these crops are essential for household food security or economic production. The low contribution of certain crops (e.g. vegetables, soybeans, cowpeas) may point to opportunities to diversify farming practices or encourage the cultivation of high-value-added products. The high proportion of land devoted to maize, cassava and bananas may influence resource allocation decisions, such as irrigation, fertilizers and subsidies in the study area.

6.3. Profit Margin by Crop in the Study Area

Figure 4 highlights the relative profit margin in relation to the cost of production, taking into consideration the crops grown and animals raised in the study area.

According to **Figure 4**, bananas (97.3%), cassava (96.1%) and rice (90.5%) have the highest profit margins. These crops offer substantial yields in relation to their costs, probably due to strong market demand, relatively low production costs, or both. Their profitability is in line with the high land allocation observed in **Figure 3**, particularly for bananas and cassava. Beans (71.3%), coffee (70.3%) and vegetables (54.5%) also show considerable profitability. These crops may not dominate the cultivated area, but they still offer significant financial incentives to farmers. Pigeon peas (4.1%), potatoes (7.6%) and sweet potatoes (7.6%) have the lowest profit margins. So the low profitability seen for these crops may discourage farmers from investing in them, unless there are other incentives such as ecological benefits or local consumption needs. Crops such as maize (24.1%), groundnuts (25.9%) and



Source: Own data analysis.

Figure 4. Profit margin by crop (relative to cost) using mean values (ascending order).

cowpeas (31.0%) have moderate profit margins, making them less financially attractive than highly profitable crops such as bananas and cassava. These crops may still be grown for cultural reasons, for crop rotation or for specific market niches.

However, crops such as bananas, cassava and rice are both highly profitable and occupy large cultivated areas, indicating their overall importance to the agricultural economy. Conversely, crops such as pigeon peas and vegetables are less profitable despite occupying smaller areas, which could indicate niche or subsistence use. As a result, farmers may give priority to high-margin crops (e.g. bananas, cassava) in order to maximize yields. Support for lower-margin crops, such as potatoes or pigeon peas, may be necessary to ensure their continued cultivation if they play a vital nutritional or ecological role. To this end, policymakers could seek to improve the profitability of low-margin crops through subsidies, improved technologies or market interventions. Investments in infrastructure and supply chains for moderately profitable crops, such as coffee and vegetables, could further boost profits. The wide gap in profitability between crops offers the opportunity to diversify farming systems by introducing or improving more profitable crops, while maintaining crop rotation practices to ensure sustainability.

6.4. Optimization Approach

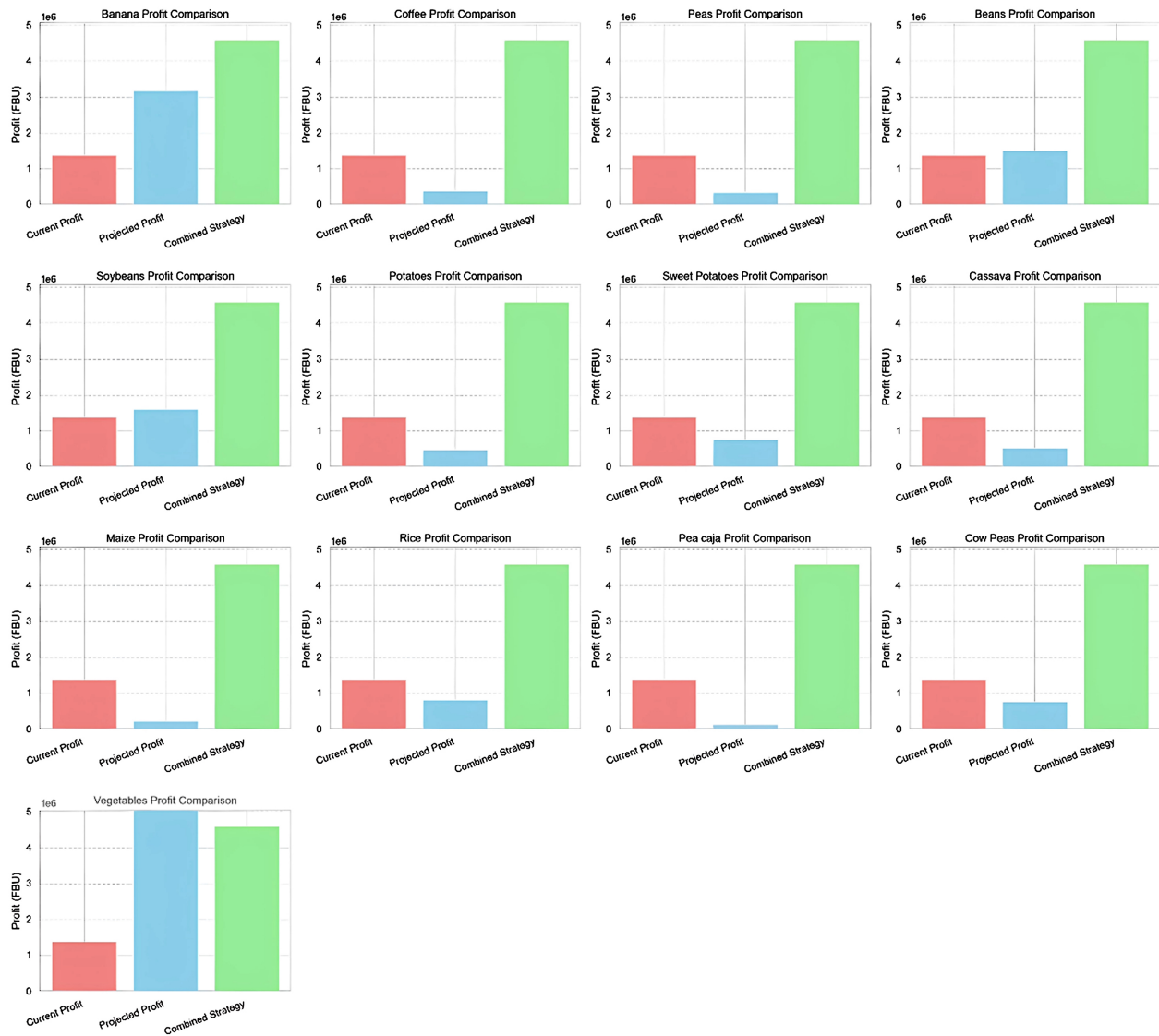
This approach to optimizing agriculture in the study area in particular, and in rural areas in general, involves strategic management aimed at improving productivity and sustainability. It involves the efficient use of resources and the development of activities complementary to existing production lines. By diversifying crops and techniques, farmers can mitigate risks and ensure greater economic stability. We assessed three profit scenarios. Current profits for each crop, taking into account the production costs allocated to each crop (scenario 1—current). profits by allocating the entire arable area to a single crop (scenario 2—monoculture), and the strategy where crops are combined in an area available at household level, with a better selection based on the performance of each crop in terms of production costs, yields (scenario 3—Agroforestry optimized)

For the first scenario (red bars), this profit represents the current income received by farmers using their traditional farming practices, without any optimization of farmland allocation. For some crops, actually traditional farming seems to outperform monocultures in the majority of cases (9/13 cases). Secondly, with traditional farming practices, farmers often prioritize food self-sufficiency to the detriment of income maximization. The projected profit (monoculture) with the second scenario (blue bars) illustrates what farmers could earn by allocating all their land to a single crop. It is higher than the current profit for 4/13 cases including banana, vegetables, beans, and soybeans. However, the total allocation of land to a single crop can increase yields through specialization, but this entails significant risks including farmers' exposure to price fluctuations or economic shocks, soil fertility depletion, increased vulnerability to pests and reduced climatic resilience. The third scenario (Green Bars) represents the maximum profit farmers could achieve by allocating their land to the three most profitable crops, selected on the

basis of their margin profit. This strategy generates the highest profits in most cases (12/13 cases) illustrating the benefits of diversification and optimized land allocation. It also offers diversified production, reduces the risks associated with dependence on a single crop and stabilizes income. So, by concentrating on high value-added crops, farmers can meet local or regional demand while maximizing their profits and the agroforestry systems allow multiple use of limited land and can offer prospects for younger people to stay in the area thanks to higher yields.

7. Conclusion and Perspectives

The ultimate aim of this research is to highlight a land-use optimization model for higher crop productivity on agroforestry farms. The results show that current agriculture in Burundi is primarily subsistence-based, with staple crops such as bananas, beans, cassava, sweet potatoes, potatoes, soybeans, maize, and export crops. However, the results presented in **Figure 5** suggest that a transition to more market-oriented and commercial agriculture (considering the margin profits generated by crop) could yield substantial income. Coffee, despite being a traditional export crop in Burundi, shows relatively low profit margins for small-scale farmers. This could be attributed to high production costs, local price volatility, and a lack of local processing. Efforts to improve value chains, particularly in specialty coffee, and/or valuable Fairtrade markets, could enhance its profitability and subsequently support both microeconomic and macroeconomic structural development. Membership in a cooperative such as COCOCA, which handles the international marketing of the coffee, should offer advantages while COCOCA coffee is part of a fair trade system that includes fair and better payment [54]. Regarding the combined strategy that demonstrates better profitability for farmers, it highlights the economic advantages of more strategic land management. Policymakers and development agencies should promote agricultural planning tools and entrepreneurship training to help farmers make better decisions in crop selection. Additionally, improving transportation infrastructure, price stabilization mechanisms, and marketing networks is essential to enable farmers to operate with greater certainty in projecting production and profits. Furthermore, the development of agricultural product processing industries could add value, diversify income sources, and increase employment and household income in rural Burundi. Since young people often perceive agriculture as unattractive, developing more profitable and modernized, more innovative and networked value chains could encourage their participation, thereby contributing to rural development. Entrepreneurship Education could and should be provided to youngsters in training networks on site [55]. Diversifying crops and agricultural practices, such as agroforestry systems that incorporate more resilient crops like cassava and bananas, could help mitigate the impacts of climate shocks on agricultural income and enhance income source diversification. These are necessary conditions for optimizing land use and crop productivity to ensure sustainable food security in rural Burundi. On the sociodemographic results male and old farmers seem to dominate the coffee production, also a risk in the



Source: Own data analysis.

Figure 5. Profit comparison: Current vs projected vs combined strategy.

future if young people don't want to engage in coffee production and it is very labor intensive, with this case, coffee production needs promotion to be oriented for young people. Thus, the observation that younger generations in Burundi are less involved in coffee production presents a significant challenge to the sustainability of this vital sector. As recommendations, to ensure the future of Burundian coffee, a multifaceted approach is necessary to make farming more attractive and sustainable for young people. Enhancing the value chain and market access is vital to improve the profitability of coffee farming. Establishing local processing and roasting facilities can add value to coffee beans, creating higher-paying jobs within the country. Connecting farmers to fair trade and specialty coffee markets can provide access to premium prices and foster sustainable trade relationships. Developing strong brands for Burundian coffee can enhance its reputation in international

markets, attracting discerning consumers willing to pay a premium for quality. Investing in education and skill development is crucial to equip young people with the knowledge and skills necessary for successful coffee farming. Vocational training programs in coffee farming, processing, and business management can empower young people with practical skills. Promoting entrepreneurship in the coffee sector through access to finance, mentorship, and market linkages can encourage young people to establish their own coffee businesses. Integrating practical agricultural education into school curricula can expose young people to the opportunities and challenges of farming, fostering a new generation of informed and engaged farmers. Diversifying income sources through complementary activities like livestock rearing, agroforestry, and tourism can enhance livelihoods and reduce reliance on coffee alone. Improving access to basic services like healthcare, education, and infrastructure in rural areas can enhance the quality of life for farmers and their families. Establishing social safety nets can protect farmers from shocks and vulnerabilities, such as crop failures and price fluctuations, providing a safety net and reducing the risk associated with farming. Finally, fostering community engagement and empowerment is crucial for the long-term success of the coffee sector. Supporting the formation of youth farmer groups can provide a platform for knowledge sharing, collective action, and advocacy. Empowering women in the coffee sector by providing them with equal access to resources, training, and decision-making opportunities is essential for gender equity and sustainable development. Strengthening community-based organizations can play a vital role in promoting sustainable coffee farming practices, improving livelihoods, and advocating for the needs of farmers. Based on the results highlighted, the model clearly shows how farmers could select more productive and highly profitable crops like banana, agroforestry trees, cassava, rice, beans, coffee, and vegetables. Therefore, future research should integrate climatic, environmental, and institutional factors to optimize land use strategies and crop productivity. Alongside this, it is crucial to address systemic issues such as limited access to inputs, inadequate infrastructure, and market inefficiencies. A transition to modernized, diversified, and market-oriented agriculture could not only improve rural livelihoods but also contribute to the country's overall economic development.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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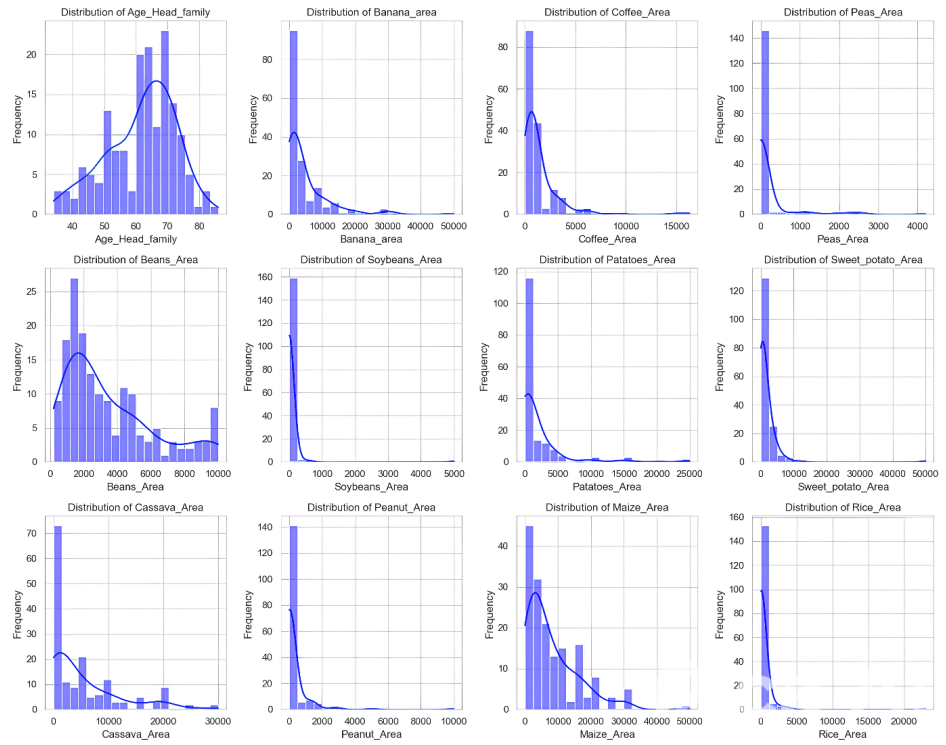
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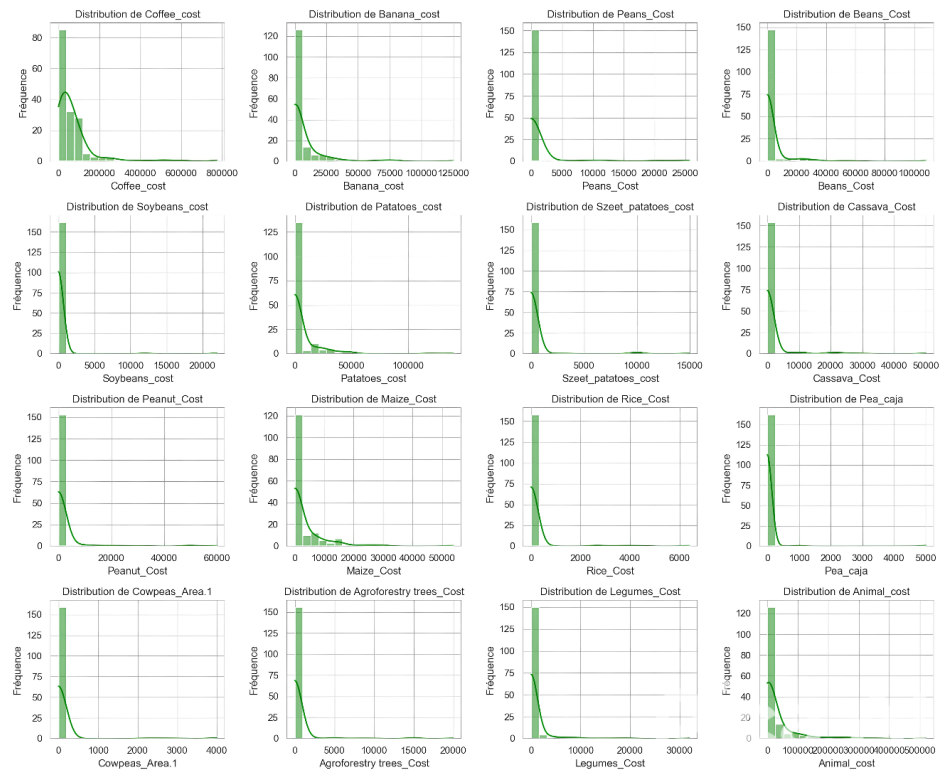
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Appendix

1) Data visualization for some variables used in the optimization model.



2) Data visualization for crop production cost.



3) Data visualization for crop net income.

