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Cover Story

Tuanjie (meaning unity) Village belongs to Yangxi Town, Jiande City, Hangzhou City, Zhejiang Province, with an area of 10.83 square kilometers, 1,012 mu of arable land, 12,733 mu of woodland, and 1,738 villagers, including 578 "She ethnic" villagers. More than 200 years ago, the ancestors of the "She ethnic" group migrated to Tuanjie Village and joined hands with local Han villagers to build a beautiful homeland, becoming a big family of unity. The "She ethnic" group is one of China's 56 ethnic groups. Statistics show that there are about 746,000 members of the "She ethnic" group in China. Tuanjie Village combines "She ethnic" characteristics with local resources to develop rural tourism industry such as B&B, farm study tour for primary and high school students and team building for corporate, university or government department etc.

Tuanjie Village has also developed special agriculture, such as growing strawberries, and some villagers have become "Strawberry Masters". "Strawberry Master" has brought high-quality varieties and professional technology to 27 provinces in China, and their strawberry planting area outside Jiande City has reached more than 70,000 mu. "Strawberry Master" has become a brand of high skilled talent brand "Jiande Master", driving the high-quality development of the strawberry industry. Strawberry industry has become the most influential "Golden Card" of Jiande City agriculture, and Jiande City has also become "The hometown of Chinese strawberries".

(Xiaolai Shen, Director of Jiande Bureau of Agriculture and Rural Affairs, Jiande City, Zhejiang Province, China.)

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About the Journal

Agricultural & Rural Studies (**A&R**, **ISSN 2959-9784**) is an exclusively digital, open-access journal dedicated to advancing interdisciplinary scholarship at the critical nexus of agricultural sustainability, rural revitalization, and farmer well-being. Published quarterly, **A&R** features a range of content types—including original research, reviews, perspectives, and commentaries—serving as a professional and innovative platform for rigorous academic dialogue and global knowledge dissemination.

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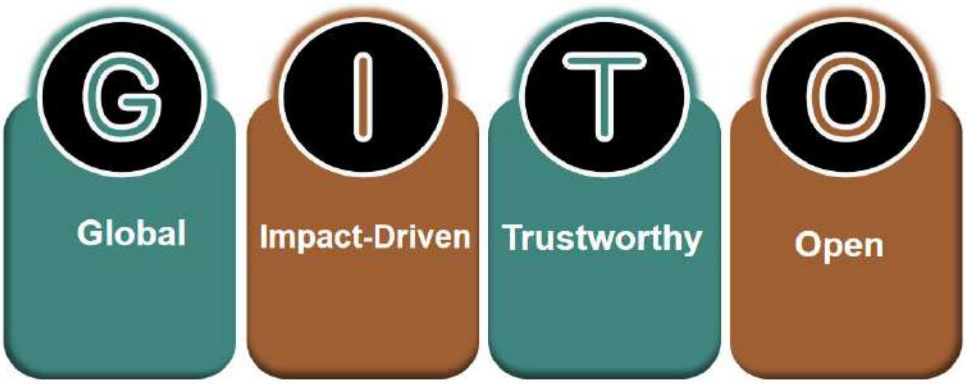

Agricultural & Rural Studies

Article

Malian Farmers' Perception of Sustainable Agriculture: A Case of Southern Mali Farmers

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Abstract: This study was conducted in the Klela district, Sikasso region of Mali, and aimed to evaluate farmers' perceptions regarding sustainable agriculture while identifying key factors that influenced these perspectives. Using a face-to-face survey with 110 randomly selected farmers, a comprehensive 19-item scale was employed to measure the perception levels of sustainable agricultural practices, scored on a 5-point Likert scale. The analysis highlighted a spectrum of perception levels among participants: 12.7% exhibited the lowest perception, 38.2% had a low perception, 31.8% had a medium perception, and only 17.3% had a high perception. Notably, a majority (50.96%) held perceptions below the average level. Through multiple regression analysis, several factors were identified as influential in shaping these perceptions. Family involvement in farming and weekly working days were negatively associated, whereas daily working hours and household size demonstrated a positive correlation. Additionally, the sources of information regarding sustainable agriculture significantly impacted farmers' perception levels, as indicated by the chi-square test results. The research underscores the necessity for targeted extension programs designed to augment farmers' understanding of sustainable agriculture, aiming to translate these perceptions into attitudes and practical actions effectively. This study contributes valuable insights, emphasizing the significance of tailored interventions geared toward enhancing sustainable agricultural practices among farmers in Mali, with the potential to positively influence their agricultural behaviors.

Keywords: sustainable agriculture; farmer's perception; Mali

1. Introduction

Mali, situated in the Sahel region, features an agricultural-based economy, with a significant portion of its population engaged in this sector. The vitality of the agricultural sector has immense influence over various aspects of the nation's economy, including employment, rural household incomes, trade balance, and food security. It accounts for approximately 41% of the gross domestic product (GDP) within the West African States region (Coulibaly, 2021). Mali's economic landscape is primarily characterized by agricultural and forestry activities, which serve as the principal income source for both households and the state. Approximately 80% of the Malian workforce is employed in agriculture, contributing 38% to the country's GDP (Konate et al., 2020; World Bank, 2021).

Mali's agricultural policies are geared toward elevating the agricultural sector's contribution to the national economy. Recent policy initiatives have concentrated on increasing cereal, particularly rice, production while diminishing state involvement in the management of the cotton sector. These policies enhance Mali's food security, boost producer incomes, and improve the country's trade balance through increased cereal exports. A significant portion of the state budget allocated to agriculture, approximately one-quarter, is directed toward rice-related irrigation projects and input subsidies (Fond International de Développement Agricole, 2020). Mali aligns with the Maputo commitment by allocating at least 14% of its public resources to agriculture over the past decade. However, the 2012 political crisis significantly shifted the priorities of Mali's economy toward defense expenditures.

In the context of sustainable agriculture, Mali introduced the Agricultural Orientation Law on December 14, 2005, as a fundamental pillar of its long-term agricultural development policy. This law governs and defines Mali's agricultural development and underscores the importance of sustainable natural resource management. The strategy for land development acknowledges the

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challenges arising from drought due to the country's weather conditions. Equally crucial is the water control policy, in alignment with the integrated sustainable water resources management policy, as a key component of the agricultural development strategy. Despite the provisions outlined in the Agricultural Guidance Act, the actual implementation of sustainable agriculture policies remains limited. Good agricultural practices are primarily observed in the production of mangoes intended for export to developed countries.

However, the agricultural sector in Mali faces significant environmental threats, including drought, desertification, climate change, and other factors that adversely affect agricultural activities (Moseley, 2005). In response to these challenges, the Malian government, along with local civil society organizations, is actively engaged in safeguarding the country's agricultural sector through the implementation of sustainable agriculture practices. Sustainable agriculture encompasses farming methods that are both environmentally and economically sustainable. These practices enhance soil fertility, conserve natural resources, and increase farmers' incomes. By adopting sustainable agricultural methods, Mali aims to boost productivity by improving soil fertility, preventing desertification by safeguarding against soil erosion, and bolstering the income of agricultural farmers. The promotion of sustainable farming methods by the government and local civil society organizations is instrumental in securing the future of Mali's agricultural sector (World Bank, 2019)

Today, with a growing population and an increasing demand for food, the importance of the agricultural sector has become even more pronounced. However, without sustainable agricultural practices, farming activities can have harmful impacts on the environment and natural resources (Falconnier, et al., 2018). Therefore, in developing countries such as Mali, the sustainability of agriculture takes on paramount significance. These practices encompass more efficient irrigation methods, soil conservation techniques, the use of environmentally friendly pesticides, and the establishment of fairer systems for trading agricultural products.

According to the Organization for Economic Co-operation and Development (OECD), agricultural activities are directly responsible for 17% of greenhouse gas emissions. Environmental experts point out that the primary greenhouse gas emissions from agriculture include nitrogen dioxide (N_2O) emissions from soil, manure, and herbivore urine, as well as methane emissions from ruminants and rice paddies. Given its status as a major agricultural producer in West Africa, Mali must prioritize environmental considerations in its agricultural policies to promote a healthier environment.

The Food and Agriculture Organization (FAO) is actively working to raise awareness about climate change through its project on integrating climate change resilience into agricultural production for food security in rural areas of Mali (N'Danikou et al., 2017). According to the report, this project has significantly contributed to enhancing the knowledge and technical capacities of farmers despite climate change. For environmental, social, and economic reasons, adopting sustainable agriculture is highly recommended to address the challenges posed by climate change. Increasing the sustainability of agriculture among farmers can be achieved by reducing practices such as overfilling the soil and minimizing the use of pesticides and chemical fertilizers (Adesida et al., 2021).

With globalization and health crises, the health quality of products has become important for consumers. For this purpose, standards accepted by all countries in the world and named GLOBALGAP have been developed (Ersoy et al., 2017). Considering the new global standards, sustainable agricultural practices are important for farmers in Mali to increase their share in international markets.

In addition, farmers, suppliers, and agricultural development actors in African countries do not have sufficient knowledge about the environmental impacts of pesticides (Le Bars et al., 2020). Fertilizers, such as pesticides, that are used unconsciously by farmers also have negative impacts on soil biodiversity.

To double its production in five years (2014–2018), the Malian government increased subsidies for chemical fertilizers. The use of pesticides increases yields by reducing losses from pests or diseases (Le Bars et al., 2020). However, while the use of these agricultural inputs enables yield increases, it is crucial to use agricultural production methods that respect nature because of the links between the intensive use of agricultural inputs and biodiversity degradation. The situation in developing countries is more serious. Because farmers use pesticides banned in developed countries. Public authorities also fail to take the necessary measures to ban pesticides that are harmful to humans and the environment (Mamane, 2015). According to research in Moldova, agricultural policy orientation is dominated by increasing agricultural production without much concern for environmental impacts. This is also true for most developing countries, and Mali in particular. According to a 2021 study by Adesida et al. (2021), the extensive application of chemical inputs combined with the use of input subsidies, including intensive tillage, has led to severe soil degradation and erosion in Moldova (Adesida et al., 2021).

These problems can be addressed through a sustainable agricultural system approach. According to research, sustainable agriculture can help farmers increase their production and income. According to previous studies conducted by Aydın Eryılmaz et al. (2018), good agricultural practices allow farmers to increase their gross margin. Sustainable agriculture is multidimensional, with an economic dimension in terms of increasing farmers' incomes, a social dimension in terms of providing healthy food to the population, and an environmental dimension in terms of ensuring a better world for future generations (Ansari & Tabassum, 2018). Combating climate change will require profound social, economic, and technological changes, many of which are costly and require large investments. Therefore, it is imperative to combine climate and development issues, and a transformation to sustainable agriculture is required.

With the subsidy policy for agricultural inputs in Mali, farmers tend to use more chemical fertilizers and pesticides. Therefore, it is important to understand the perceptions of farmers toward sustainable agriculture. This study was conducted in the Sikasso region, the agricultural production center of Mali. The Sikasso region is the richest region in Mali in terms of agricultural production, and food surpluses are distributed throughout the country. According to the Ministry of Agriculture's report, fertilizer use by farmers in the Sikasso region is 71% higher than that in other regions. This high fertilizer use is linked to the production of crops such as maize and cotton and market-oriented horticultural crops.

Many countries attempt to achieve food security through agricultural policies that increase agricultural productivity without considering the impact of agricultural policies on sustainability. The overall objective of this study is to characterize the perception of sustainable agriculture among farmers in Mali and identify the factors that influence their perceptions. Based on this main objective, this study aims to identify the socioeconomic factors affecting farmers' perceptions of sustainable agriculture, the impact of agricultural information sources on farmers' perceptions of agriculture, the relationship between agricultural input subsidy policy and farmers' perceptions of sustainable agriculture, and to recommend appropriate policies to ensure sustainability in Mali's agriculture.

2. Materials and Methods

2.1. Material

The sampling method used in this study involved a combination of random and stratified sampling techniques. Firstly, the district of Klela, in the Sikasso region, was selected as the research area due to its importance in agricultural production, particularly in maize and cotton cultivation. This decision was motivated by the region's reputation for intensive farming practices and the availability of data from the regional agricultural directorate.

Within the Klela district, two villages were identified as distinct strata: Lutana and Dougoumoussou. Each village was characterized by its farmer population, with Lutana numbering 100 farmers and Dougoumoussou 84, according to data from the regional directorate of agriculture.

To ensure representative sampling, a proportional stratified random sampling method was employed. This involved determining the sample size for each village according to its proportion of the total farming population in the district. For example, if Lutana represented 54% of the total farming population and Dougoumoussou 46%, the sample size for Lutana would be 59 and for Dougoumoussou 51.

Once the sample sizes had been determined, farmers were randomly selected from the household lists in each village. This process was designed to minimize selection bias and ensure that every farmer had an equal chance of being included in the sample. However, despite these precautions, potential biases may remain, such as non-response bias or the under-representation of certain farmer sub-groups due to logistical constraints or other factors.

The sample volume was determined using the proportional sample volume method. According to this method, the formula for calculating the sample volume, based on the known or estimated proportion (p) of individuals with a specific characteristic within a finite main population of size N, is as follows:

$$n = \frac{N_p(1-p)}{(N-1)\sigma^2_{\hat{p}x} + p(1-p)} \quad (1)$$

n = Sample size

N = Number of farmers in the villages covered by the survey

p = 0.5 (for maximum sample size), Estimated proportion of farmers aware of sustainable agriculture

σ_{px}^2 = Variance of the Rate (from the equation 1.645*σp = 0.05 for 90% confidence interval, 0.05 margin of error; σp = 0.03039)

The sample size was calculated at 110 according to a 90% confidence interval and a 5% margin of error. The number of farmers interviewed in each district was determined by considering the ratio of the districts to the total number of farmers (Table 1).

Table 1. Number of farmers in the sample by village.

Villages	Number of Farmers	%	Number Entering the Sample
Dougoumousso	84	46	51
Lutana	100	54	59
Toplam	184	100.00	110

Source: Mali Rural Economy Institute (IER).

Before conducting the survey, visits were made to the villages to update the list of farmers. An explanation of the survey's purpose was provided to the traditional village chiefs of the two villages. Simple random sampling was employed through a list of farm managers to select participants for this study's surveys. Expert support was obtained from specialists at the Mali Rural Economy Institute to conduct these surveys. The primary data used in this research were collected through a survey conducted in February and March 2022. The data collected pertain to the previous production period. To minimize data loss, surveys were administered using tablets and the KoBoCollect application, which is commonly used in research by international organizations. As a secondary data source, various organizations and databases were consulted, including the World Bank, FAO, OECD, European Statistics, the U.S. Department of Agriculture, and InsatMali. This included previously published research, conference papers, articles, books, and reports related to the subject matter.

2.2. Method

2.2.1. Determining the Sustainability Index

To establish the sustainable agriculture index, this study employed a 19-item scale that has been used in previous research on farmers' perceptions of sustainable agriculture (Adeola & Adetunbi, 2015). This scale was also used by Hayran et al. (2018). Farmers were tasked with rating each of the 19 items on a 5-point Likert scale, where 1 indicated "strongly disagree," 2 represented "somewhat agree," 3 denoted "moderately agree," 4 signified "somewhat agree," and 5 conveyed "strongly agree." Each question allowed for a maximum score of 5 points. Consequently, if a producer assigned five points to every question (195 = 95), it indicated a very high perception of sustainable agriculture. Conversely, if a producer rated each question with a minimum of 1 point (119 = 19), their perception of sustainable agriculture was considered low. In this study, a producer's perception of sustainability could assume any value between 19 and 95.

The following formula was used to compute the farmer perception index, as outlined by Hossain et al. (2018).

$$FSAPI = \sum_{i=1}^{19} \sum_{j=i}^{5} M_i N_j \tag{2}$$

FSAPI refers to the Farmer Sustainable Agriculture Perception Index. In the context of this study, "M_i" denotes the perception of farmers regarding sustainable agricultural practices or statements on sustainability. A value of 1 is allocated to each practice or statement if the farmer is cognizant of it, whereas a value of 0 is designated otherwise. "N_j" assesses the farmers' awareness level of a specific sustainable agricultural practice or statement, utilizing a 5-point Likert scale ranging from "very low" to "very high". Ratings for awareness levels range from 1 to 5, correspondingly. A higher index signifies a more favorable perception of sustainable agriculture among farmers, while a lower value indicates a greater lack of awareness regarding sustainable farming practices. The farmers' collective perception of agricultural sustainability is computed by determining the simple arithmetic mean of the indices, while the average perception of sustainability for each practice or statement is derived by dividing the total sum of the indices by the total number of practices or statements. Farmers are typically ranked based on their level of perception of sustainable agriculture, utilizing standard deviation intervals from the mean, consistent with the approach outlined by Sadati et al. (2010) and Hayran et al. (2018).

p = very low: min ≤ p < (mean − standard deviation),
q = low: (mean − standard deviation) ≤ q < mean,

r = moderate: mean ≤ r < (mean + standard deviation),
s = high: (mean + standard deviation) ≤ s ≤ max.

Using these intervals, farmers' perceptions of sustainable agriculture are divided into four levels: very low, low, moderate, and high (Füsun Tatlıdıl et al., 2009; Van Thanh et al., 2015). Cronbach's alpha was used to estimate the reliability of the questionnaire and the internal consistency of the composite score (Kayacan & Demirbaş, 2022). The Cronbach's alpha value obtained from the analysis was calculated as 0.846. Because this value falls within the range of 0.80 ≤ alpha ≤ 1, the scale used is considered highly reliable.

2.2.2. Analysis Methods

The data obtained from the survey were analyzed using Statistical Package for the Social Sciences 23 (SPSS version 23). In this study, descriptive statistics (mean calculation, frequency, percentage, etc.) were used to characterize the socioeconomic status of the farmers (age, gender, income). For each variable in the study, the normality of the distribution was assessed using the Kolmogorov–Smirnov test. Because the data did not exhibit a normal distribution, the Mann–Whitney U test was applied to determine whether there was a relationship between the farmers' use of input subsidies and their perception of sustainable agriculture.

To determine whether there was a relationship between farmers' perceptions of sustainable agriculture and the agricultural information sources they accessed, the chi-square test was used. In addition, a multiple regression model analysis was conducted to determine to what extent the selected socioeconomic characteristics influenced farmers' perceptions of sustainable agriculture.

2.2.3. Regression Model

Regression analysis is a statistical method for studying the relationships between several variables and predicting the results using these relationships. This study aims to answer questions regarding the existence and strength of relationships between variables, the prediction of future dependent variables, and the influence of specific variables or groups of variables on results. When a single independent variable is used, this is referred to as univariate regression analysis, whereas the use of several independent variables is referred to as multivariate regression analysis. The latter simultaneously considers the variations of the independent and dependent variables.

Multivariate regression analysis is a powerful tool for understanding and modeling complex relationships between different variables. It enables us to study how several factors can influence a given dependent variable and provides essential information for decision-making in a variety of fields, from scientific research to public policy planning (Uyanık & Güler, 2013). The multivariate regression analysis model is expressed as follows.

$$Y = \beta_0 + \beta_i X_i + \ldots + \beta_n X_n + \varepsilon \quad (3)$$

Y = Dependent variable
X_i = Independent variable
β_i = Parameter
ε = Error

As is common in many previous research studies aimed at identifying the factors influencing farmers' perceptions of sustainable agriculture, a multiple regression model was employed in this study. The model included 18 explanatory variables, which were identified through a synthesis of the literature related to sustainable agriculture to explain the farmers' perception of sustainable agriculture (Table 2). These variables were included in the model to understand the factors that affect farmers' perceptions of sustainable agriculture.

In this study, the variable inclusion and exclusion method, known as stepwise selection, was used within the regression model. With this approach, each variable is sequentially added to the model, and the model's performance is evaluated. If the added variable contributes to the model, it remains included. However, all other variables in the model were retested to assess whether they made a significant contribution. If they do not significantly contribute, they are removed from the model. This process allows the model to be explained using the minimum number of variables necessary.

Table 2. Description of variables used in the regression model.

Name of the Variables	Definition of Variable and Unit of Measure	Data Type
1. Dependent variable index	Sustainable agriculture score (Mn = 19; Max = 95; Standard Deviation = 10.38; Mean = 75.64)	Continuous variable (Index)
2. Independent variables	-	-
2.1 Socioeconomic characteristics	-	-
Duration of education	Number of years in school (years)	Continuous variable
Number of family members	(Person)	Continuous variable
Number of family members engaged in agriculture	(Person)	Continuous variable
Number of permanent individuals in processing	(Person)	Continuous variable
Hours of work in the field per day	(Hours)	Continuous variable
Number of working days in the field per week	(Year)	Continuous variable
Experience	(Year)	Continuous variable
Cooperative membership status	0) No, 1) Yes	Binary variable
Agricultural Extension Services	0) No, 1) Yes	Binary variable
Product Type	1) Cotton 2) Cereals 3) Livestock 4) Cotton and livestock 5) Cereals and livestock 6) Cotton and Cereals 7) Cereals, cotton and livestock	Polychotomous Variable
The type of livestock	1) Bovine 2) Bovie + ovine 3) Ovine + poultry 4) Cattle + poultry 5) Bovine + ovine + poultry	Polychotomous Variable
Total land area	Hectare	Continuous variable
Total cultivated land area	Hectare	Continuous variable
Total number of parcels	Number	Continuous variable
Animal assets of the farm	0) No, 1) Yes	Binary variable
Income from Agriculture	The franc of the Financial Community in Africa XOF	Continuous variable
Presence of non-agricultural income	0) No, 1) Yes	Binary variable
Agricultural Equipment	0) No, 1) Yes	Binary variable

3. Results

3.1. Socioeconomic Characteristics of Farm Managers

The research findings reveal significant gender disparities among Klela producers, with 86.4% being men and 13.6% women. Illiteracy is prevalent among farm managers, with 54.5% illiterate and 45.5% literate, averaging only 0.88 years of education. Education's pivotal role in agriculture is underscored, yet only 12% of Malian farm household heads have formal schooling. The average age of farm managers is 47, with 26.7 years of farming experience, highlighting their expertise.

The income level of producers reflects Mali's agricultural development, with a high rural poverty rate of 53.1%, disproportionately affecting agricultural households constituting 74% of Malian households. In 2021, the average income of producers was approximately 980,254. 54-FCFA (Table 3). In Klela, families are primarily nuclear but often include additional members. The average family size was 30.72, emphasizing the community's significance. Despite challenges such as mechanization and modernization lagging in Mali's agricultural sector, manual labor persists. Consequently, families heavily involve members in farming, with an average of 20 individuals per household. Producers spend an average of 8.55 hours per day and 5.21 days per week working in the fields, illustrating their commitment to agricultural livelihoods.

Table 3. Socioeconomic characteristics.

Variables	Freq.	%	Means	St. Dev.	Min	Max
Age			47	11,89	25	83
Experience			26.7	10,4	10	60
Female	15	13.6				
Male	95	86.4				
Single	1	0.9				
Married	109	99				
Year of reading			0.88	0.7	0	3
No literacy	60	54.5				
Literate	50	45.5				
Income			980,254.54	1,198,811	50,000	9,560,000
Number of family members			30.72	18.708	5	98
Number of family members engaged in agriculture			13.65	10.359	2	52
Working time/day			8.55	3.117	1	14
Working time/week			5.21	1.182	1	7
Total farmland (hectare)			30.23	16.349	1	75
Total amount of cultivated land (hectare)			14.18	15.276	1	60
Total number of plots			1.7182	0.81423	1.00	3.00

Analysis of agricultural production types in the research area revealed a significant presence of cotton, cereals, and livestock farming, with 41% of producers engaged in these activities, as indicated in Table 4. Mali's Sikasso region has emerged as a crucial hub for agricultural production, particularly in cotton cultivation, with 57.7% of producers actively involved in cotton and cereal farming. However, it is noteworthy that only a small percentage (1%) focused exclusively on cereals or a combination of cereals and livestock, suggesting a diversified approach to farming practices.

Livestock farming holds considerable economic significance in Sahelian countries, contributing between 20% and 25% of the gross domestic agricultural products in nations like Burkina Faso, Cape Verde, Mali, and others, with a growth rate of 5%. Rural farming, which encompasses livestock rearing, remains a primary form of agricultural production in the Sahel, with the region boasting substantial meat production potential. For instance, in 2006, estimates indicated a significant herd size of 63 million cattle, 168 million small ruminants, and over 6 million camels (Diawara et al., 2017).

Understanding the sources from which farmers acquire agricultural information is vital for effective policymaking. Table 3 illustrates the various channels through which farmers can access information on sustainable agriculture. While 17% rely on television broadcasts, over 24% use alternative sources beyond television, radio, researchers, and cooperatives. However, direct input from agricultural researchers is limited, with only 2% of producers citing them as a source of information. Radio broadcasts play a significant role in informing 15% of producers, whereas 20% rely on cooperatives for agricultural knowledge dissemination. These findings underscore the importance of diversifying communication channels to effectively disseminate information on sustainable agricultural practices to farmers.

Table 4. Livestock and Information Sources.

The type of livestock	Freq.	%
Bovine	4	3.6
Bovine + ovine	4	3.6
Ovine + poultry	3	2.7
Cattle + poultry	24	21.8
Bovine + ovine + poultry	70	63.6
Production type	-	%
Grain	1	1
Cereals and livestock	1	1
Cotton and Grain	63	57.3
Grain, Cotton, and Livestock	45	41
Channels	-	%
TV	19	17.3
Radio	17	15.5
Cooperative	23	20.9
Agricultural Extension Services	21	19.1
Researchers	3	2.7
Others	27	24.5

Source: Own survey, 2022.

3.2. Farmers' Perceptions of Sustainable Agriculture

3.2.1. Farmers' Perception Category

Within the scope of the study, the perception scores of 110 farmers were found to have a maximum value of 95 and a minimum value of 19. The mean score was 75.64, with a standard deviation of 10.38. These calculations allowed for the categorization of farmers into four groups based on their perception of sustainable agriculture, classified as very low (p), low (q), moderate (r), and high (s).

In Table 3, after categorizing the farmers' perceptions regarding sustainable agriculture, it was determined that 12% of the farmers within the research had a very low perception of sustainable agriculture (perception mean = 56.85). According to the analysis results, 38.2% of the farmers (perception mean = 70.33) exhibited a low level of perception, 31.8% (perception mean = 81) had a moderate level of perception, and only 17% of the farmers (perception mean = 89.15) possessed a high perception of sustainable agriculture (Table 5).

When comparing the results of the perception levels of the studied farmers regarding sustainable agriculture with a study conducted in Vietnam (Van Thanh et al., 2015), it is observed that there are similarities in the perception levels (low and moderate) of sustainability.

The predominance of below-average perceptions of sustainable agriculture among the study participants prompts discussion of the potential reasons behind this trend. Several barriers or challenges may contribute to this situation, requiring further exploration to inform appropriate intervention strategies.

Table 5. Perception of the sustainable agriculture category (n = 110).

Categories	Total Points	Frq.	Mean Perception	%
(p)	Very low: min ≤ p < (mean - standard deviation),	14	56.85	12.72
(q)	Low: (mean - standard deviation) ≤ q < mean	42	70.33	38.24
(r)	Medium: mean ≤ r < (mean + standard deviation),	35	81	31.84
(s)	High: (mean + standard deviation) ≤ s ≤ max	19	89.15	17.3
Total		110	-	100

Note: q = Very Low, p = Low, r = Medium, s = High.
Source: Own survey, 2022.

3.2.2. Factors Affecting Farmers' Perceptions of Sustainable Agriculture

The text discusses the results of a multiple regression analysis aimed at examining the factors influencing farmers' perceptions of sustainable agriculture. The stepwise analysis method was chosen, and 17 independent variables were included in the model; however, only 5 variables were considered significant by the model. The results show that the relationship level among the variables is R = 0.90, and the adjusted determination coefficient is $R^2 = 0.80$. This indicates that 80% of the total variation in farmers' perceptions of sustainable agriculture is explained by independent variables such as weekly working days, the number of family members engaged in agriculture, family size, and crop variety (Table 6).

However, the analysis revealed a negative relationship between the variable "total working days per week" and farmers' perceptions of sustainable agriculture (β = −0.0637 and significance level sig = 0.037). Similarly, the number of family members engaged in agriculture hurts farmers' perception (β = −0.550 and sig = 0.03). In contrast, the other variables in the model positively influence farmers' perceptions of sustainable agriculture. The number of working hours per day and the diversity of agricultural activities on the farm positively affect farmers' perceptions.

The text also cites a study by Füsun Tatlıdil et al. (2009) in Kahramanmaraş, Turkey, which found that the type of agricultural production activity significantly influenced farmers' perceptions of sustainable agriculture. In the current study, the type of agricultural activity is included in the model as a positive factor affecting farmers' perceptions of sustainable agriculture. The variety of agricultural activities is related to the economic dimension of sustainable agriculture, such as the integration of livestock into farming or crop diversification. Overall, the study's findings suggest that various factors, including working conditions, family size, and the diversity of agricultural activities, influence farmers' perceptions of sustainable agriculture. These factors shed light on the social and economic aspects of sustainable agriculture.

Table 6. Multiple regression estimates of farmers' perceptions of sustainable agriculture (n = 110).

Model	B	Bêta	t	Sig.
(Constant)	3.25	0.68	4.75	.000*
Total hours of work in the field/day	0.55	0.62	0.18	.008*
Total working days/week in the field	−0.253	−0.63	−3.12	0.037*
Number of family members	0.008	0.04	2.07	0.05**
Number of family members engaged in agriculture	−0.16	−0.55	−2.327	0.03**
Production activity	0.15	0.48	2.126	0..05**

Notes: $R^2 = 0.80$; F = 3.94; Durban Watson test = 2.35, sig. p value < 0.01*; 0.05** and 0.10*** is significant.
Source: Own survey, 2022.

The text discusses the influence of farmers' education levels, age, and experience on their perception of sustainable agriculture. This study highlights the role of education in supporting the adoption of new agricultural technologies, citing previous research by McBride and El-Osta (2002), Bouréma et al. (2021), and Adégbola et al. (2011). Education has traditionally been a significant factor in agricultural research.

Furthermore, the text mentions a study that identified farmers' experience as a crucial factor in the adoption of modern agricultural technologies (Bouréma et al., 2021). A study conducted in Nigeria by Adeola and Adetunbi (2015) found that factors such as age, education level, and experience had an impact on farmers' perceptions of sustainable agriculture.

Interestingly, the text also refers to a study conducted in Iran by Allahyari et al. (2008), which found that age, education level, and experience were not significant factors influencing the perception of sustainable agriculture among the sample of academic staff in that context. In contrast, the present study suggests that variables such as age, experience, and education level do not significantly impact the perception of sustainable agriculture among farmers. The text speculates that this may be related to the generally lower education level of the farmers in the study and the fact that most of them are young farmers.

In summary, the text highlights the varying roles of education, experience, and age in influencing farmers' perceptions of sustainable agriculture, drawing on research from different regions. It notes that the specific findings of this study may be attributed to the young age and low education level of the participating farmers.

3.3. Perception Levels of Farmers According to Age Groups and Information Sources

When examining the levels of sustainable agriculture perception among farmers alongside their ages, it is observed that farmers aged between 41 and 56 years exhibit the highest percentage of sustainable agriculture perception, at 54.55%. Farmers with significantly low perceptions of sustainable agriculture are predominantly found in the 25–40 age group, accounting for 50.00%. Furthermore, farmers with a moderate level of sustainable agriculture perception are predominantly in the 41–56 age range, with the highest proportion at 53.13% (Table 7). These findings emphasize the significance of considering age groups when developing policies related to sustainable agriculture.

Table 7. Distribution by age category and perception level of farmers (n = 110).

Perception Categories	Age categories								
	25–40	**%**	**41–56**	**%**	**57–70**	**%**	**71–85**	**%**	**Total**
P	7	50.00	5	35.71	2	14.29	0	0.00	14
Q	15	35.71	14	33.33	9	21.43	4	9.52	42
R	8	25.00	17	53.13	7	21.88	0	0.00	32
S	7	31.82	12	54.55	3	13.64	0	0.00	22
Total	37	-	48	-	21	-	4	-	110

Source: Own survey, 2022.

The findings regarding the relationship between farmers' sustainable perception levels and sources of information, which is one of the objectives of the study, are presented in Table 7. To determine if there is a relationship between information sources about sustainable agriculture and the sustainable perception levels of farmers, sustainable agriculture information sources were categorized into two groups: formal agricultural information sources (TV, radio, publishers) and informal sources (neighbors, relatives). According to the results of the chi-square test, a significant relationship between the sustainable agriculture level of farmers and sustainable agricultural information channels was accepted at a significance level of 5% (Table 8). The analysis results indicate that farmers with low sustainable agriculture perception levels tend to rely more on informal sources of information.

In line with these findings, Hayran et al. (2018) also concluded that farmers' communication with publishers and researchers is an important factor influencing farmers' perceptions of sustainable agriculture (Hayran et al., 2018). The use of agricultural radio programs to promote new technologies can have positive and lasting effects on farmers' perceptions of sustainable agriculture. Previous studies, such as those conducted by Van Thanh (2015), have demonstrated the positive impact of TV programs on the perception of sustainable agriculture among banana farmers. This finding suggests that mass media, such as radio and television, can play a crucial role in disseminating information and raising farmers' awareness of sustainable farming practices (Haq et al., 2022).

Table 8. Distribution of farmers' perception levels according to information sources (n = 110).

Information sources	Perception Category		Total	%	Chi-square
	(q + p)	(r + s)			
Formal resources	33	50	83	75.45	
No formal resources	22	5	27	24.54	0.00
Total	55	55	110	100	

Notes: Sig. p-value < 0.05 indicates significance; q = Very Low, p = Low, r = Medium, s = High.
Source: Own survey, 2022.

3.4. Relationship Between the Use of Agricultural Input Subsidies and Farmers' Perceptions of Sustainable Agriculture

Following the global food crisis in 2007–2008, West African countries, including Mali, decided to increase fertilizer usage per hectare from 8 kg to 50 kg to improve agricultural productivity, food security, and nutrition (Kone et al., 2019; Samake et al., 2007). To achieve this goal, they implemented subsidy policies for agricultural inputs. Despite these efforts, agricultural productivity and fertilizer usage remain low. Various aspects of these subsidy programs, such as targeting farmers, transparency in contract allocation, and private sector participation, etc., contribute to explaining the performance of fertilizer subsidy policies. In Mali, fertilizer subsidies constitute an increasing share of agricultural sector expenditures. After the 2007 global food and nutrition crisis, budget resources allocated to fertilizer subsidies increased significantly, from approximately 11 billion FCFA to approximately 40 billion FCFA between 2009 and 2017. However, these subsidies have not yielded the expected results (Kone et al., 2019).

Table 9. Use of pesticide subsidies (n = 110).

Input subsidy status of farmers	Freq.	%	Mean Perception	Z	Sig
Benefited farmers (0)	84	76.4	76.61	−2.16	0.03**
Farmers not benefiting (1)	26	23.6	72.5		

Note: Sig = 0.01* 0.05** and 0.10*** is significant.
Source: Own survey, 2022.

Studies that consider the relationship between the sustainable agriculture perception of beneficiaries and non-beneficiaries of agricultural input subsidies are rare. This study aimed to determine whether there is a difference in sustainable agriculture perception between those who benefit from input subsidies and those who do not. However, because 98.18% (108) of the farmers within the scope of this study benefited from fertilizer subsidies, no comparison could be made. Additionally, 76.40% of the farmers in the study benefited from pesticide subsidies (Table 9). Note that agricultural input subsidies are a policy tool used by the Malian government to strengthen the capacity of farmers and support Mali's agricultural production and productivity. As seen in Table 9, the sustainable perception of the beneficiaries and non-beneficiaries of pesticide subsidies shows that, contrary to expectations, the perception of sustainability among the beneficiaries of pesticide subsidies is higher. This result indicates that the perception of sustainable agriculture among farmers has not yet been translated into sustainable agricultural practices. The difference in perceptions between beneficiaries and non-beneficiaries was statistically significant at the 5% level of significance (Table 9). This suggests that despite having a high perception of sustainability, farmers tend to benefit from subsidies if the government continues to provide pesticide subsidies.

4. Recommendations

Based on the results of this study conducted in the Klela district, Sikasso region of Mali, it is recommended to implement targeted extension programs aimed at enhancing farmers' understanding of sustainable agriculture. The study revealed varying levels of perception among participants, with a substantial proportion exhibiting perceptions below the average level. Given the identified influential factors such as family involvement in farming, working days, working hours, household size, and sources of information, tailored interventions are crucial to effectively translate these perceptions into attitudes and practical actions.

Specifically, extension programs should focus on addressing the identified influential factors to improve farmers' perceptions and ultimately promote sustainable agricultural practices. This may involve providing targeted training sessions, workshops, and demonstrations tailored to the needs and circumstances of farmers in the region. Additionally, leveraging various communication channels, including face-to-face interactions, radio broadcasts, and mobile applications, can enhance the dissemination of information on sustainable agricultural practices.

Furthermore, collaboration with local agricultural experts, organizations, and community leaders can facilitate the delivery of extension services and ensure their relevance and effectiveness. By targeting interventions to address the identified influential factors and enhancing farmers' understanding of sustainable agriculture, these programs can positively influence agricultural behaviors and contribute to the advancement of sustainable agricultural practices in Mali.

Although the study yielded significant insights, it is not devoid of limitations that may have influenced its outcomes. Selection and response biases may have affected the generalizability and accuracy of the findings. The omission of crucial variables such as socioeconomic factors and inadequate consideration of seasonal and long-term agricultural trends warrant further investigation. Nonetheless, the study offers valuable insights, underscoring the need to acknowledge and address these limitations in future research endeavors.

In conclusion, fostering sustainable agricultural practices in Mali requires collaborative efforts from governmental and international stakeholders, alongside targeted research focusing on adoption challenges and practices in specific regions like Sikasso to inform evidence-based agricultural policies.

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Agricultural & Rural Studies

Article

Rural Transportation and its Impact on the Output and Income Generated from Cashew Production in Selected Rural Settlements in Kwara State, Nigeria

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Abstract: Rural transportation plays a crucial role in agricultural production and livelihood of farmers in developing countries. Information on its impact on cashew's outputs and income is not clearly documented in the literature. Consequently, this study identified the types of roads and transport modes of cashew farmers, assessed the transport services patronized by cashew farmers, examined the annual outputs and income from cashew; and assessed the impact of transport on both in Kwara South Senatorial District Kwara State, Nigeria. Data used were obtained from 1,373 farmers systematically selected from thirty-six rural settlements in the study area. Responses were analysed using principal component analysis, regression analysis and correlation analysis. Results showed that tarred roads connected only about 44.4% of the settlements in the area. About 56.4% of respondents rated the transport services as good. Significant relationships were found between cashew output and; road condition ($b = -0.151$, $p = 0.000$) and; transport services ($b = -0.097$, $p = 0.000$), while, income from cashew was directly and significantly correlated with transport mode ($r = 0.059$, $p < 0.05$), road condition ($r = -0.153$, $p < 0.05$) and, transport services ($r = -0.096$, $p < 0.05$). The study concluded that variations in transport facilities only accounted for some level of spatial variations in both cashew's output and income in the study area and, recommended improvements of transport facilities to enhance increase in farmers' crop output and income to achieve improved rural livelihood.

Keywords: road conditions; rural transport; transport costs; transport service

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1. Introduction

Transport entails the transformation of the geographic attributes of freight and people from an origin to a destination and, adding to their values (Rodrigue, 2013). Transport creates enabling environment for the movement of freight and passengers from one place to another and facilitates exchange of goods and services in rural and urban areas within and across the countries. Rural transport (rural roads and rural transport services) plays vital roles in the development of agriculture and other rural socio-economic activities in Nigeria and other parts of the world. Basically, transport is an indispensable aspect of all agricultural practices as it encompasses the movement of farm inputs and outputs from supply to demand zones. Studies have shown that investment in transport lessens transport charges along rural roads, facilitates efficient delivery of farm inputs, promotes increase in farmers' outputs, improves accessibility of farmers' output to higher market potentials and enhances farmers' access to higher income from their investment in agriculture (Emran & Hou, 2013; Inoni & Omtor, 2009; Lokesha & Mahesha; 2016; Rodrigue, 2013; Sangwan, 2010; Tunde & Adeniyi, 2012).

Studies have shown that poor level of transport development militates against high level of agricultural outputs and aggravates poverty in most rural areas in Nigeria and other developing countries (Lokesha & Mahesha, 2016; Tunde & Adeniyi, 2012). The studies among others placed greater emphasis on the impacts of the roads leading to farming settlements on agriculture with inadequate attention on the impact that farmers' modes of transport and the transport services available to farmers have on the production of specific crops. Although, road building is important to agricultural development, meaningful and sustainable agricultural development cannot be achieved without the complementary role of rural transport services and modes of transport at the disposal of farmers. The inadequate, inefficient as well as costly transport services and transport modes available to farmers on the several dispersed routes leading to various rural settlements and farms in developing countries has been contributory to low level of agricultural productivity and low level of development in rural areas. Therefore, the study is poised to provide answers to the following questions: what are the conditions of roads to the sampled settlements? What are the types of modes of transport used by cashew farmers in the study area? What is the condition of transport services to the various settlements of cashew farmers? What are the outputs and income generated from the cultivation of cashews by its farmers in the study area? The main object of the study is to assess the impact of transport (transport modes and services) on both the outputs and income of cashew farmers in selected rural settlements in Kwara South Senatorial District, Kwara State, Nigeria. The remaining part of this paper focuses on the review of literature, study area, methodology, discussion of results, conclusion, and implication of the study.

2. Literature Review

Road transport is the most popular means of transport especially in rural areas of sub-Saharan Africa. Generally, access roads to most of the rural settlements in developing countries with farming as a major economic activity are in deplorable state (Blinpo et al., 2013). This may not be unconnected with poor rural road maintenance. For instance, over 70% of access roads to most rural settlements have been observed to be in deplorable state in Nigeria (Adeniji, 2000; Ipingbemi, 2008; Oyesiku, 2002). Rural roads maintenance in Nigeria is largely in the jurisdiction of various local governments (Central Bank of Nigeria, 2002). The poor implementation of the third tier of government typical of true federalism has contributed to the epileptic performances of the existing local government areas and impaired negatively on local government administration; this ultimately deprives the people at the grass roots to adequate access the developmental impact of the government as exhibited in high prevalence of deplorable rural roads in the country.

Earlier, poor rural roads development has been attributed to; the dispersed nature, low population and low income of rural areas as they slow down the time for the recovery of money spent on road construction (Abumere et al., 2002); inadequate finance (Aderamo & Magaji, 2010; Ajiboye & Olaogun, 2006; Ipingbemi, 2008); lack of continuity in government (Akunna, 2015); poor governance, high cost of road construction, substandard equipment and little or no competition among construction companies (Sperling & Claussen, 2004; Estache & Limi, 2009; Lall et al., 2009). Other factors in support of high prevalence of poor rural roads are corruption and lack of political will (Ipingbemi, 2008); poor fund management (Burgess et al., 2015) as well as ethnic favoritism and political clientelism (Ullman, 1956). The poor condition of rural roads negatively impacts on spatial interaction and effective mobilization of man and material resources necessary for attaining optimum agricultural and other rural socio-economic activities.

Although, areal differentiation is a necessary factor for spatial interaction (Creightney, 1993), complementarity, absence of intervening opportunity and transferability are other factors to be reckoned with. Transferability is highly instrumental to the economic and physical transferability of farm input and output from surplus to deficit locations. As a concept of spatial interaction, it connotes provision of access, especially good road (tarred) and good transport services (affordable, reliable, fast and competitive) capable of stimulating effective spatial interaction for optimal mobilization of man and material resources for increased level of productivity in agricultural and other rural socio-economic activities for the realization of higher income level and satisfaction. Accessibility is the ease with which passengers and, or goods reach other places measured in terms of time, cost and distance. Accessibility may be influenced by seasonality and transport services provided (Lebo & Schelling, 2001; Van de Walle, 2002; Rodrigue, 2013). Accessibility varies with seasons; it specifically depreciates in wet season on earth's surfaced roads as it becomes slippery, flooded, wet and rough; which increases the time, cost and stress expended on journeys along such roads and, ultimately lessens the ease of getting to desired destinations.

Rural mobility largely depends on good rural transport infrastructure (roads and the likes) and low-cost transport services (Hettige, 2006). This explains why provision of good rural transport infrastructure is regarded as a necessary but not sufficient condition for accessibility to farm, market centers or other locations; it must be complemented by efficient, reliable and affordable rural transport services for accessibility to be achieved (Ajiboye & Afolayan, 2009; Gachassin & Raballand, 2015). In other words, rural transport (rural roads and rural transport services plays crucial role in agricultural production. Generally, poor rural roads promote poor rural transport services. Poor roads are known to have undesirable effects on agricultural production (Ipingbemi, 2008) as it limits adequate access to farm inputs and militates against providing basic access of farm output to adequate market potential; this reduces profit from agricultural investment and, discourages high level of agricultural productivity (Dorosh et al., 2010).

Empirical findings have attributed relatively higher transport charges with untarred road settlements (Dorosh et al., 2010; Teravaninthorn & Raballand, 2008; Raballand et al., 2010). For instance, Ahmed and Rustagi (1987) associated the receipt of only 30–50% of the final market price by African farmers compared with 70–80% received by Asian farmers to the lower quality of road in African relative to roads in Asian countries. According to Jacoby and Minten (2009), intensive land cultivation is not economically rational in Africa due to high transport charges which heighten delivery price and almost eliminates the profit envisaged by farmers. High transport charges are associated with poor roads with negative impacts on the level of income accruable to farmers in Ilorin East, Kwara State, Nigeria (Tunde & Adeniyi, 2012). Although, the use of Intermediate Means of Transport of (IMT) has been adjudged to have contributed to the attenuation of the negative effects of distance and impacted positively on agricultural productivity of food farmers in Oyo north, Oyo state, Nigeria (Kassali et al., 2012). But, some Intermediate Means of Transport are known to have negative impacts. For instance, some motorcycle operators were observed to have inflated transport's fare due to scarcity of transport services especially in wet season in nine selected rural settlements linked by earth surfaced road in Tanzania (Porter et al., 2013). High transportation' fare allows people to be relatively immobile (Gollin & Rogerson, 2014), high transport' fare is associated with poor road quality. It has deprived most cattle farmers from selling their cattle at local market but relied only on farm gates sales with a reduced income level (Kyeyamwa, 2008), and negative impacts on profits accruable to the farmers. Several studies have been carried out on transport and agriculture within and outside Nigeria. For instance, in Nigeria, variations in road qualities have translated to farmers' accessibility to different levels of output and income from agricultural ventures in Osun state (Adedeji et al., 2014) and Ondo State (Olagunju, 2022). In a review of twenty-five documents relating to selected countries in Latin America and elsewhere, it was observed that improvement of small rural roads promoted agricultural production, employment, living standards and poverty reduction (Escobal & Ponce, 2008). Also, improvement in road quality was found responsible for the expansion of farm size in Nicaragua (Laird et al., 2023). Similarly, villages connected with all weathered roads in India were noticed to have recorded increase in the use of fertilizers, agro-chemicals and "improved" crop varieties due to better access afforded by the road (Aggarwal, 2018); the long-term effects are the attainment of increasing level of output and income from such crop.

Recently, Aboyeji & Aguda (2024), associated variation in outputs and income derived from cassava to spatial variations in the quality of roads connecting selected settlements in Kwara South Senatorial District, Kwara State in north central, Nigeria. The authors using principal component analysis specifically observed that the output Cassava varied significantly with transport services, while income from Cassava exhibited significant but weak inverse relationship with transport services. However, information is lacking on the specific impact of rural transport on outputs and income of cashews as a tree and important cash crop in the region. Consequently, this study identified the types of roads and modes of transport accessible to cashew farmers, assessed the transport services available to cashew farmers, examined the outputs and income from cashew farmers, and assessed the impacts of transport on both outputs and income of cashew farmers in Kwara South Senatorial District, Kwara State, Nigeria.

Cashew (*Anacardium occidentale L.*) is a tropical evergreen tree crop that originates from Brazil in South America. Cashew thrives in Latitudes 15º North and South of the Equator. It is of high economic relevance to the Benin Republic, Mozambique, Nigeria, Philippines, Sri Lanka, Tanzania, Ghana, India, and Vietnam (Adeigbe et al., 2015), The cashew tree has an irregular trunk and can grow as tall as 14 meters. The tree produces wood useful in making boats and charcoal gum and serves some medicinal value. Mature cashew trees have big, juicy apples hanging from their branches, to which the cashew nut is attached. The resin found in fruit shells is utilized to make plastics and as an insecticide. Juicy apples have a high reddish to yellow color and their pulp and juice can be fermented and distilled into liquor or processed into a variety of (astringent) fruit drinks. The cashew nut, or seed is usually consumed raw or processed to make cashew butter and cheese. Medicinally, cashew nuts lower blood pressure, lower cholesterol, enhance weight loss, improve skin, add fibers, promote shiny, healthy hair, and protect the eyes.

The significance of the study is based on the fact that it is a major source of food, income, industrial raw materials, and foreign exchange for many countries including Nigeria; which commenced its commercial cultivation around 1972. Only about 5% of the produce is processed locally. As at 2015, cashew trading amounted to 24 billion naira (160 million dollars) and over one million people depend on the cashew industry in Nigeria (Adeigbe et al., 2015). This study focused on Kwara South Senatorial District Kwara State, Nigeria because the ecological zone supports the cultivation of cashew.

3. Materials and Methods

3.1. Study Area

Kwara South Senatorial District, Kwara State is situated between latitude 8º0'7" N – 9º4'29" N and Longitude 4º29'48" E – 5º32'37" E in the North Central Geo-political zone of Nigeria (Figure 1). Seven Local Government Areas are included in the area: Ekiti, Ifelodun, Irepodun, Isin, Offa, Oke Ero, and Oyun. The populations of these Local Government Areas (LGAs) are approximately 48,212, 7,208, 173,539, 47,880, 158,181, 48,550, and 71,004, in that order. The best way to characterize the climate of the study area is tropical, with harmattan occurring from December to January and distinct wet and dry seasons. Late March or early April marks the start of the wet season, which ends in late October or early November. Mean temperature ranges from 25°C to 30°C, and annual rainfall spans from 1,000 mm to 1,500 mm (Oyegun, 1983; Olaniran, 2002). There is neither severe drought nor excessive rainfall in the study area because it is located in a zone of transitional vegetation and climate. Guinea and derived savannas make up the majority of the vegetation type (Oyegun, 1983). Shear butter, acacia, and locust bean trees are common in the area. *Milicia excels* is a common tree in the region's wetter areas; in particular, it provides space for some sawmilling and lumbering operations in certain parts of the study area.

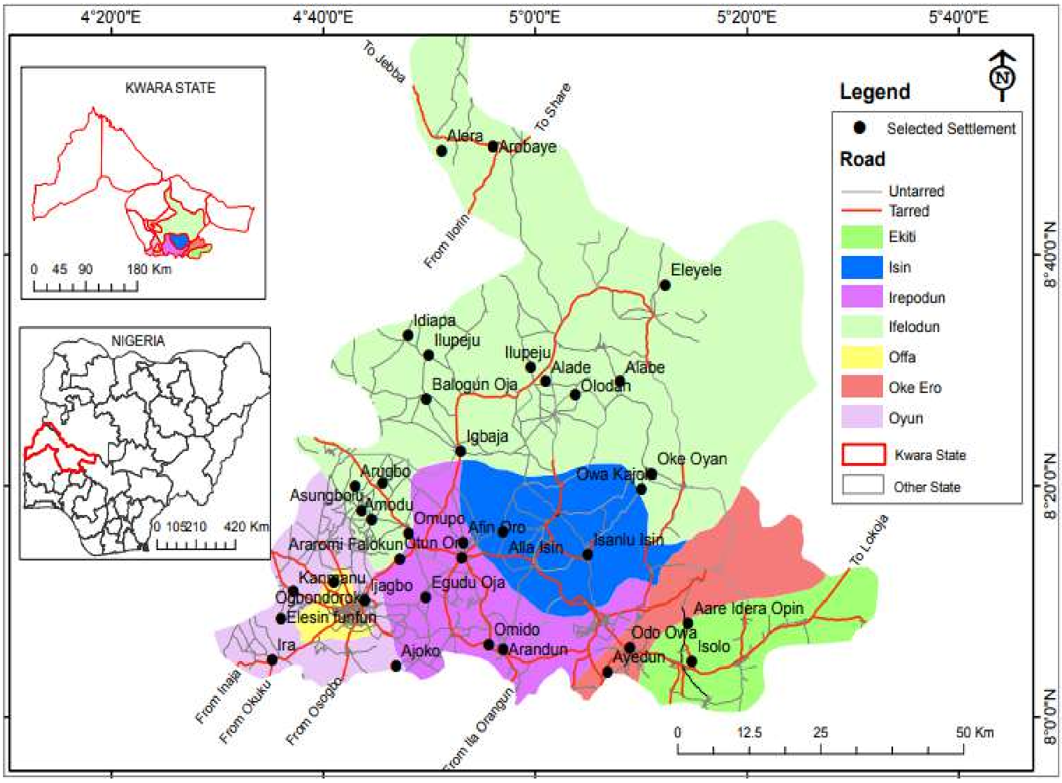

Figure 1. The study area, Kwara South Senatorial District in Kwara state, Nigeria (*Digitized from the Office of the Surveyor General of the Federation*).

Road transportation is the most widely form of transportation in the region. The majority of the settlement's roads are in terrible condition. The popularity of commercial motorcycle transport services in the area was largely due to the area's poor-quality roads and low freight and passenger traffic (Aboyeji, 2021). The vast area and great potential for growing a variety of crops make Kwara South Senatorial District an ideal study subject. In addition, food crops, particularly vegetables, cereals, legumes like groundnuts and cowpeas like beans and soy beans, are actively farmed by the farmers in the area. The area has a significant cashew crop as well. Its high returns on investment for farmers, resistance to drought, and capacity to flourish on a wide range of soil types are making it more and more well-known in the area (Aboyeji, 2021). Oil palm and cocoa are grown in wetter parts of Oke Ero, Isin, and Irepodun Local Government Areas. Additionally, prevalent in the region are livestock farming and nomadism. Agricultural and Rural Management Training Institute (ARMTI), Nigerian Stored Product and Research Institute (NSPRI), and National Center for Agricultural Mechanization (NCAM) are three federal government-owned agricultural institutions that are situated near the study area in the vicinity of Ilorin.

3.2. Materials and Methods

Data were obtained from primary and secondary sources. Primary data was derived through direct observations of conditions of roads to sampled settlements and administration of questionnaires to selected farmers in the study area while secondary data including map showing the local government areas and population figure were obtained from the office of Surveyor General and National Population Office, respectively.

Multi-stage sampling technique was employed for the choice of both settlements and respondents for the study. First, all the settlements in each of the seven LGAs in the Senatorial District were arranged according to their population sizes; obtained through the projection of 1991 population figure (used for being the only population figure of the area that presented the population of the study area on settlement's basis) to 2017 using the 1.03 percent growth rate for rural areas in Nigeria (World Bank Group, 2016). Subsequently, settlements with population of at most 19,999 categorized as rural settlements (Madu, 2010) were selected, this led to the emergence of 309 rural settlements; which were categorized to three groups; A (1−6,500), B (6,501–13000), and C (13,001–19,999), the population's group A, B, and C consisted of 293, 12, and 4 settlements, respectively. Second, in order to ensure the selection of at least one settlement from each group; 10%, 30%, and 45% of the settlements in population's group A, B and C, respectively were selected; which eventually resulted in the selection of 30, 4, and 2 settlements from population's group A, B, and C, respectively. In order to determine the number of households in each of the selected settlements. Projected 2017 population figure was divided by five which is the average household size in Nigeria (National Population Commission & ICF International, 2014). Third, from settlements in group A (1−6,500) residents, 10% of the households were sampled; having been suggested as suitable for rural research (Ogunsanya, 1987; Olawole, 2013). It additionally prevented selection of a large sample that might not be easy to manage given the time and financial resources available for the study. Also, because the numbers of highly populated settlements in the study area were few while a sample of 5% of households was chosen from population's group B (6,501−13,000) and group C (13,001−19,999) to enable representations of all strata in each LGA.

Furthermore, all households in each of the chosen settlements were numbered and listed in order to ensure objectivity in the selection of the households in the settlements. Additionally, the initial sample was selected through simple random sampling technique while subsequent samples were taken through systematic sampling technique from the lists at regular intervals of "K" until the desired numbers of households were fully selected. Also, in order to determine the interval "K," the value derived from the sample household size percentage of either 10% or 5% per settlement was divided by the total number of households listed in each settlement. In the end, the samples from each LGA were Ekiti (36), Ifelodun (407), Irepodun (327), Isin (113), Offa (6), Oke-Ero (263), and Oyun (221). A total of 1,373 copies of the questionnaire were distributed to heads of households who had been farmers for at least two years in the hopes that they would be able to supply sufficient and accurate information on the subject matter.

Both descriptive and inferential statistics were used in the data analysis process. Descriptive statistics, in particular frequencies and percentages, are presented using cross tabulation, table and bar graphs. On the other hand, inferential statistics, especially the Leven test statistics, were used to test homogeneity of variance. To avoid the difficulties and complexities involved in interpreting the findings based on the large samples (36 settlements) chosen for the study, settlements connected by the two categories of road quality (tarred and untarred) were used as basis for interpretation of result (Porter, 1995).

4. Results and Discussion

4.1. Types of Roads to Settlements

From major interstate roads to selected settlements, tarred roads connected only 44.4% of the settlements, while 55.6% of the settlements had untarred roads connecting them (Figure 2). It has been earlier observed that most roads to rural areas as headquarters of farming in developing countries are in deplorable state (Adeniji, 2000; Blinpo et al., 2013; Ipingbemi, 2008; Oyesiku, 2002; Aboyeji & Aguda, 2024). The persistently low quality of rural roads could not be dissociated from inadequate attention by local government administration saddled with the responsibility of rural road maintenance (Aderamo & Mogaji, 2010). This implied that the movement of both passengers (farmers and buyers and sellers of agricultural inputs and outputs) and freights (agricultural inputs and outputs; especially cashew in this case) largely occurred on low quality roads (Figure 2). Poor road and transport access makes it difficult for farmer to increase their farm sizes promote high level of agricultural productivity (Jacoby & Minton, 2009; Dorosh et al., 2010). This is because the associated high transport's fare in all geographical space (Teravaninthorn & Raballand, 2008; Raballand et al., 2010; Porter et al., 2013) as well as delays in the delivery of passengers and freights are known symbols of poor transport services. This buttresses earlier description of the grossly inadequacy and inefficiency of transport services in many parts of Africa (Porter, 2014).

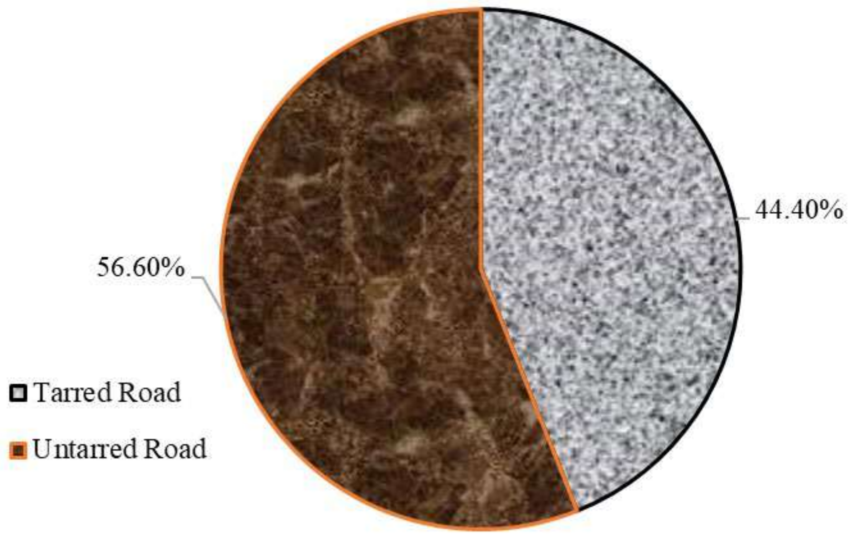

Figure 2. Percentage distribution of tarred and untarred roads to selected settlements in Kwara South Senatorial District, Kwara State.
Source: Author's survey, 2021.

Furthermore, local government area analysis showed that untarred roads connected 100%, 76.5%, 50%, 50%, 40%, and 28.6% of the selected settlements in Offa, Irepodun, Isin, Ekiti Oyun, and Ifelodun Local Government Areas, respectively (Figure 3). While at the time this research was conducted, all the settlements (100 percent) sampled in the Oke-Ero Local Government Area were connected by tarred roads. lack of attention to rural road maintenance is an important contributing factor to Nigeria's terrible rural road conditions (Aderamo & Magaji, 2010). High transport fares are associated with road of poor quality. The rough and rugged conditions of untarred roads potentially increase the operation cost of vehicle operators, which they in turn use to determine the charges on respective distances covered on such roads. For example, it has been observed that the fare of transportation is three times higher on untarred roads than on tarred roads (Ipingbemi, 2010). Also, previous studies have attributed seasonal variation in transport charges; especially hike in transport fare to the depreciating condition of roads especially in wet season; particularly because, during the rainy season the roads become muddy, slick, and challenging for cars to navigate in most of the untarred roads (Porter et al., 2013). Aikins and Akude (2015) stated in an identical manner how awful rural roads in Ghana are. Poor rural roads usually result in the receipts of low returns from farming's investment (Morgan et al., 2019). In other words, the high percentage of poorly maintained roads in the selected settlements in the study area has impacted negatively on both productivity and income of cashew farmers. Furthermore, it has been observed that 97% of the population affirmed the presence of seasonal variation in transport fare and 47.7% of the respondents constituting the majority of the population further affirmed 21−30% variation in transport charges with season in a part of Kwara State, Nigeria (Aboyeji, 2021).

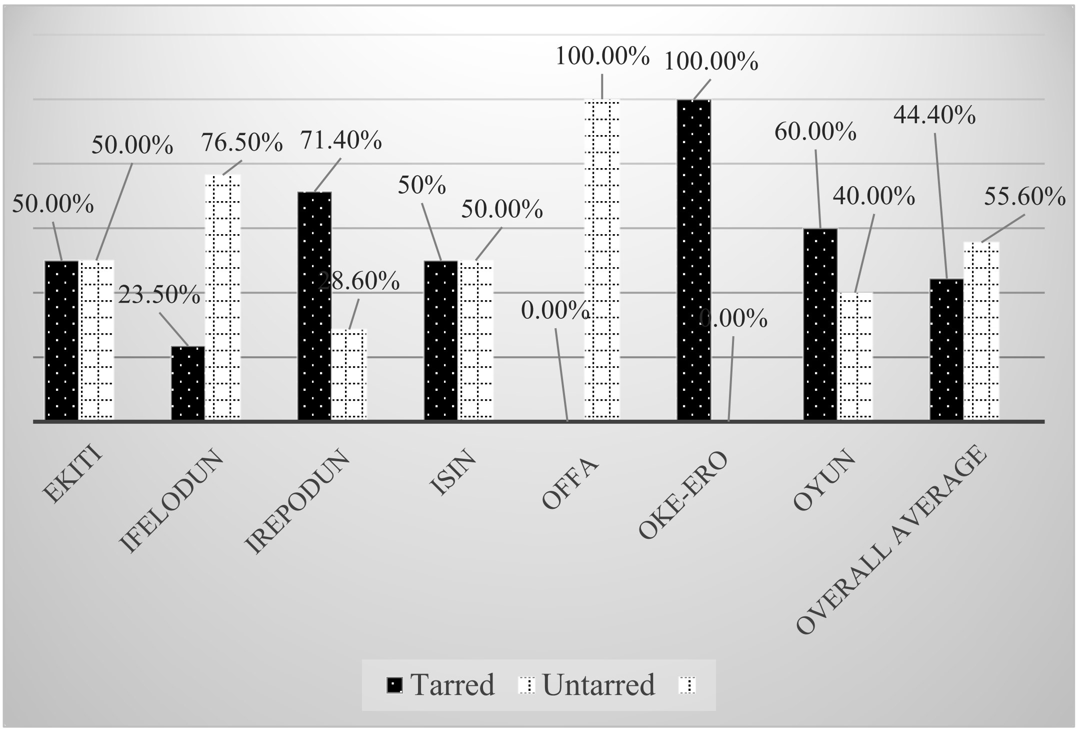

Figure 3. Percentage distribution of tarred and untarred roads in selected settlements in each local government area in Kwara South Senatorial District, Kwara State.
Source: Author's Survey, 2021.

4.2. Farmers' Regular Mode of Transport to and from Farm Sites

The results on the modes of transport that cashew farmers regularly used to transport themselves to and from the farm sites in the study area showed that the majority (51.8%) of the respondents were regularly trekking to and from their farm sites, 29.6% of the respondents used personal motorcycle, 6.6%, of the respondents employed commercial motor cycle, 6.3% of the respondents regularly used personal vehicles (car/buses/lorries) and the remaining 5.8% of the sampled farmers made use of commercial motor cycles for transport to and from the farm (Figure 4). The higher proportion of cashew farmers trekking to and from the farm were exposed to avoidable stress, tiredness and heat scourge earlier observed (Ogunsanya, 1987) with access to modes of transport. The end result is its negative impact on farmers' productivity. The study clearly shows that farmers in the region are yet to adequately appreciate the use of Intermediate means of Transport (IMT) and its attendant advantage in saving time and energy as observed by food farmers in Oyo North, Oyo state, Nigeria (Kassali et al., 2012). The use of bicycles by farmers was conspicuously absent in the study area. This may be as a result of their inability to appreciate the importance of bicycles as an intermediate means of transport as observed by Starkey et al. (2002) and Porter (2002). Earlier studies in the South western part of Nigeria also confirmed the unpopularity of bicycle as a mode of transport (Adeniji et al., 2000; Olawole, 2013); this might be due to their socio-cultural belief. On the other hand, it is pertinent to emphasis that the accessibility of 6.3% of the respondents to personal vehicles is a good development, especially because it is higher than the rate of vehicle ownership in Nigeria, which is 24 per 1,000 (Nairametrics, 2017) Nigeria's vehicle per population ratio is 0.06 per population (Federal Road Safety Corps, 2010).

The study examined the modes of transportation employed by farmers in the two categories of settlements and found that, while 49.9% of respondents in settlements connected by untarred roads traveled by foot to and from their farm sites, 53.9% of respondents in settlements connected by tarred road(s) did so. Furthermore, 26.2% of respondents in settlements connected by tarred roads compared with 32.6 percent of respondents in settlements connected by untarred roads reported using personal motorcycles as a means of transport to their farm and for the conveyance of agricultural input and output. In addition, 7.0% of respondents in settlements connected by tarred road(s), as opposed to 5.6% of the respondents in settlements connected by untarred road(s), employed personal vehicles, 8.0% of respondents in settlements connected by tarred road(s) compared with 5.3% of respondents in settlements connected by untarred road(s) employed commercial vehicles, and 4.8% of respondents in settlements connected by tarred road(s) compared with 6.7% of respondents in settlement connected by untarred road(s) employed commercial motorcycles as a means of transportation to and from their farm sites in the study area. These data indicate that a higher percentage of respondents used commercial motorcycle for farming related journeys in settlements connected by untarred roads than in settlements connected by tarred road; this perhaps served as a recompense for the subpar quality of the roads connecting their settlements.

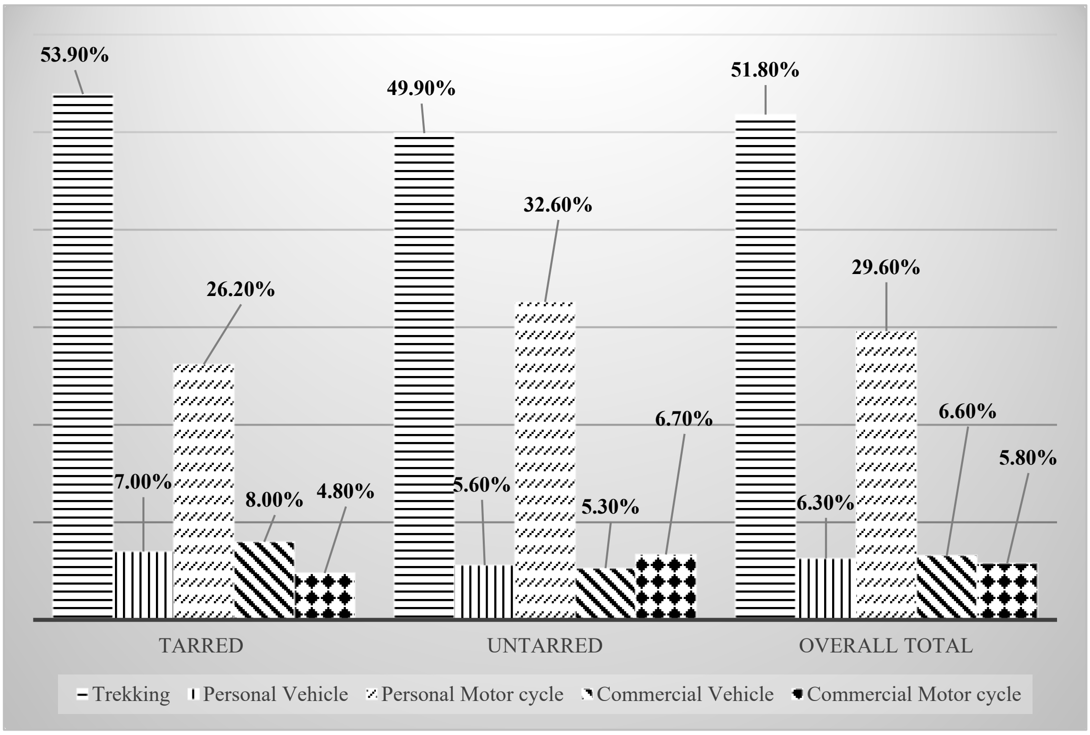

Figure 4. Farmers' regular modes of transporting farm input and output.
Source: Author's survey.

4.3. Farmers' Assessment of Conditions of Transport Services to Selected Settlements

The result on the perception of respondents on the condition of transport services to selected settlements revealed that 56.4% of respondents in the entire study area rated the transport services as good (Figure 5). The highest proportions (78.3%) of respondents who gave a "good" rating to the transport services were observed in Oke-ero LGA. The fact that tarred roads connected every settlement sampled in Oke-ero LGA may not be unrelated to this. On the other hand, only 10.9% of the respondents in the entire study area perceived the transport services to their respective settlements as very poor, the result further revealed that the highest proportion (33.3%) of those who gave a "very poor" assessment of the transport services was from Offa LGA; It should be reiterated 100% of the selected settlement (Ogbondoroko) in the LGA was connected by untarred road. Furthermore, 14.2% of the respondents in the entire study area rated the transport services to their respective settlements as poor, the highest proportion (17%) of respondents who gave a fair rating was observed from Ifelodun LGA, where 76.5% of the settlements were connected by untarred road. This depicted a positive correlation between high quality (tarred road) and good transport services and vice versa. The relatively higher transport cost associated with untarred road settlements (Teravaninthorn & Raballand, 2008; Raballand et al., 2010) considerably reduces the quality of transport services, increases the cost of conveying farm inputs and inputs, and impact negatively on gains from agricultural investments especially (Aboyeji & Aguda, 2021). It has been asserted that good transport services must be efficient, regular, reliable, and affordable (cheap) to promote growth in agricultural output (Porter, 2014). Besides, a situation where 100% of respondents in Ogbondoroko rated the transport services as poor was not unconnected with the fact that the road to that settlement was untarred. Untarred roads usually have difficulties in amalgamating buyers and sellers of agricultural output and inputs, respectively, and by so doing unnecessarily cheapens the price of agricultural produce and increases the cost of farm inputs; this ultimately reduces the proportion of gains from farming investments (Calmette & Kilkenny, 2011; Aboyeji, 2021; Aboyeji & Aguda, 2021).

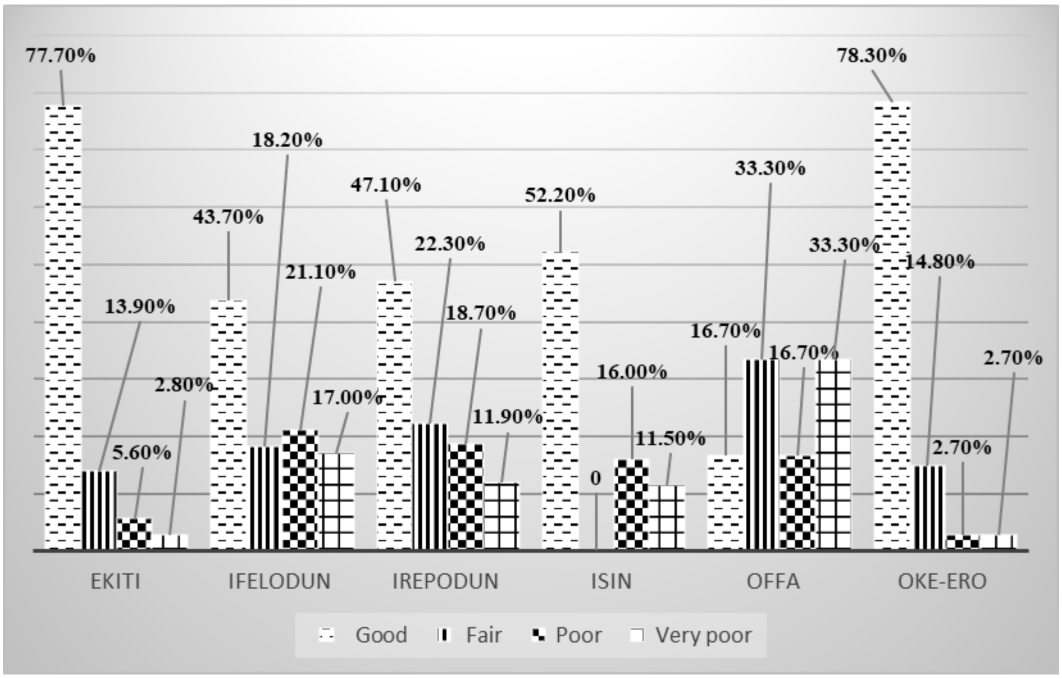

Figure 5. Assessment of conditions of transport services in selected settlements.

4.4. Annual Output Derived from Cashew

The result of the survey revealed that 40.3% of the respondents realized 1−10 bags of cashew per annum. The remaining 10.5% and 0.9% of the respondents annually realized 11−20 bags and 21−30 bags, respectively, while 48.3% of the respondents did not record of any output of cashew (Figure 6). The lack of records for cashew output could likely be attributed to the fact that the selected cashew farmers have just started the cultivation of the crop in the area. After analyzing cashew output in the two settlement categories, it was found that 20.2% of respondents in settlements connected by tarred road(s) and 20.1% in settlements connected by untarred road(s) respectively realized 50–500 kg of cashew on yearly basis. Furthermore, 66% of respondents in settlements connected by tarred road(s) as opposed to 39% of respondents in settlements connected by untarred road(s) reported realizing 550–1,000 kg of cashew annually. Remarkably, the majority of the respondents (27.4%) in settlements connected by tarred road(s) compared with 20.9% of respondents in settlements connected by untarred road(s) did not have a record of any cashew output on an annual basis.

Also, 6.6% of respondents in settlements connected by tarred road(s) as opposed to 3.39% of respondents in settlements connected by untarred road(s) realized 550–1,000 kg annually and the minority; 0.51% of respondents in settlements connected by tarred road(s) compared with 0.39% of respondents in settlements connected by untarred road(s) realized 1,050–1,500 kg of cashew. Interestingly, a majority (27.4%) of respondents in settlements connected by tarred road(s) compared to 20.9% in settlements connected by untarred road(s) did not have record of any output of cashew) annually. The result generally reveals that higher proportions of farmers in settlement connected by tarred roads realized the various output levels than those in settlements connected by untarred roads. Similar positive relationship between road quality and crop yields and income was observed in Ilaje, Ondo State, Nigeria (Olagunju, 2022) and in Kwara, State, Nigeria (Aboyeji & Aguda, 2024). However, the fact that higher proportion (6.6%) of respondents in settlements connected by untarred roads as against lower proportion (3.9%) in settlements connected by tarred roads had 1,050–1,500 kg of cashew may have occurred because most of the settlement connected by untarred road have relatively smaller population in the region. Therefore, it can be inferred that the observed higher proportion of cashew output in settlement connected by untarred roads is connected with access to larger farmland in the affected settlements. For instance, it has been asserted that as a settlement tends towards urban, proportion of available farmland near the city reduces as such settlement assumes residential, industrial and commercial functions (Beddington, 2010; Pham et al., 2011). The implication is that the farmers in the affected settlements connected by untarred roads with high output of cashew faces the additional challenge of payment of high transport's fare as observed in Amuro District, Kogi State, Nigeria (Ipingbemi, 2010); with negative impacts on gains accruable to cashew farmers. Earlier study in Ilorin also affirmed that poor road quality has negative impact on profit accruable to farmers (Tunde & Adeniyi, 2012).

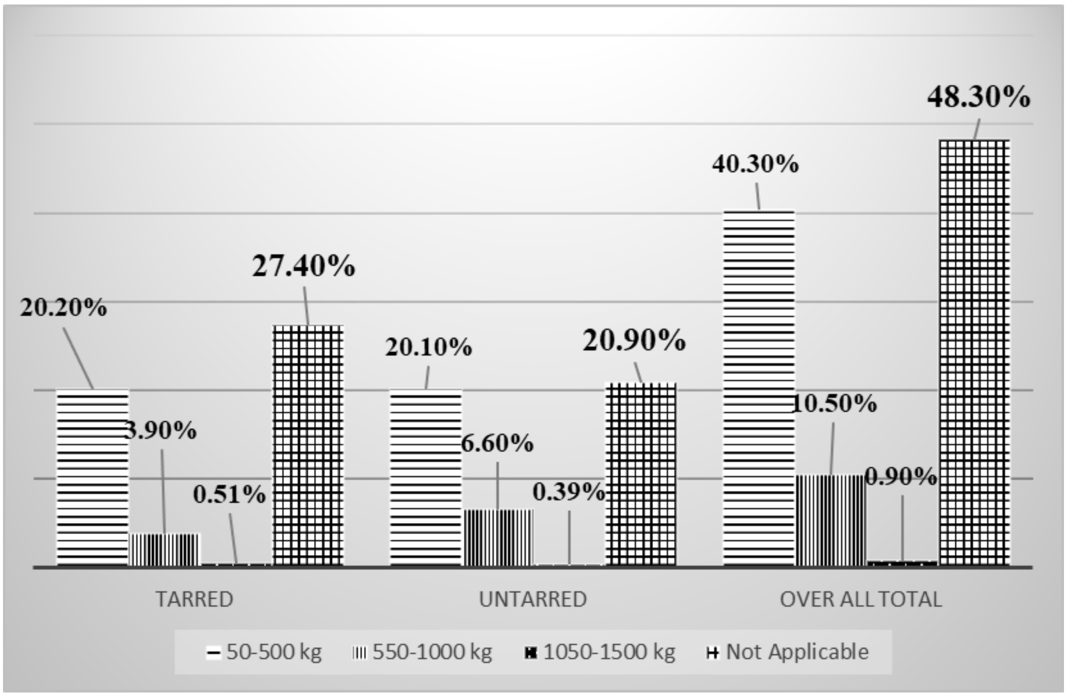

Figure 6. Annual output of cashew in kilograms along tarred and untarred roads in the study area.

Furthermore, local government by local government analysis of cashew output revealed that the highest proportion (59.3%) of cashew farmers realizing 50−500 kg was observed in Isin LGA, the highest proportion (30.1%) of cashew farmers realizing 550−1,000 kg was also observed in Isin LGA and the highest proportion (1.7%) of cashew farmers realizing 1,050−1,500 kg bags was also observed in Isin LGA (Figure 7).

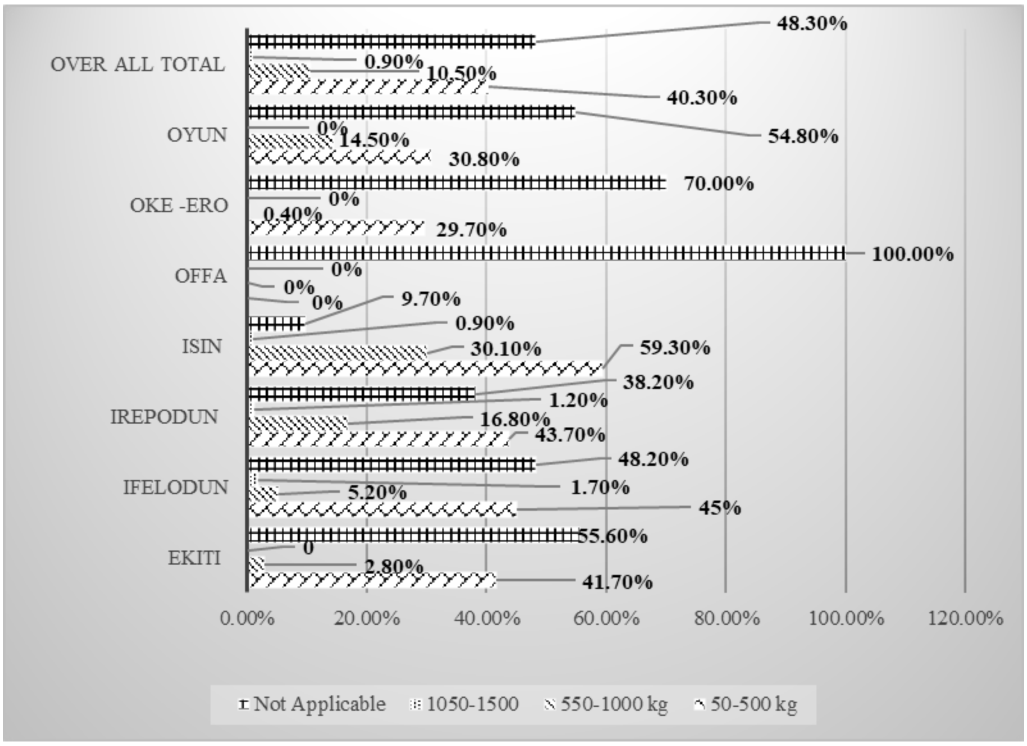

Figure 7. Annual output of cashew across local government area in the study area.
Source: Author’s survey.

4.5. Hypothesis Testing on Output of Cashew

Table 1 shows the result of the regression analysis used to investigate the impacts of transport facilities on cashew output in Kwara South Senatorial District. Six variables were examined.

Table 1. Coefficients of regression for cashew output.

Model	Unstandard-ized Coefficients		Stand Coef.	T	Sig.	Remark on H_0	R^2
	B	Std. Error	Beta				
Constant	4.160	0.142		29.267	0.000		0.046
Transport Mode	0.383	0.142	0.071	−.555	0.579	Rejected	
Road Condition	9.453	0.142	−0.151	−5.706	0.000*	Accepted	
Transport Cost	0.379	0.142	0.070	2.665	0.008*	Accepted	
Transport Services	−0.520	0.142	−0.097	−3.660	0.000*	Accepted	
Distance to Farm	−0.195	0.142	−0.036	−1375	0.169	Rejected	
Distance to Major Market	250	0.142	−0.046	1.756	0.079	Rejected	

Source: Authors' computation.
Note: Road Condition and Transport Services are the highest contributing (−0.151) predictors to explain the impact of transport infrastructures on crop production/output of cashews. a. *p<0.05: Dependent Variables for cashew outputs.

An examination of the standardized coefficient presented in Table 1 showed that the main influencing factors for cashew outputs were road condition, cost of transports, and transport services (b = −0.151, p = 0.00; b = 0.070, p = 0.008; b = −0.097; p = 0.00, respectively). Therefore, we accept H_1 and reject H_0 but Transport Mode, Transport Cost, Distance to Farm, and Distance to Major Market are not significant since their p values are greater than 0.05 ($p > 0.05$). Therefore, we accept H_0 and reject H_1.

Table 1 also shows a positive but weak relationship between cashew output and independent variables as the $R^2 = 0.046$, suggesting that the regression model accounts for about 4.6% of the variance in perception of the impacts of transport facilities on cashew output/yield. However, disparity has earlier been observed in the level of income accrued to farmers connected with good and bad transport conditions in Obokun Local Government Area of Osun state (Adedeji et al., 2014) and Ilaje, Ondo State, Nigeria (Olagunju, 2022), among others. In this particular study however, a significant inverse relationship has been observed between road condition and cashew output. Also, Kassali et al. (2012) observed that transport modes (Intermediate Means of Transport) significantly attenuated the negative effects of distance and impacted positively on productivity of food farmers in Oyo North, Oyo state, Nigeria. This study affirmed a positive relationship between transport modes and cashew outputs. The implication of the findings showed that increased farmers' access to more sophisticated/automobile modes cashew output increased; although this was not significant as depicted in Table 1. Therefore, it can be inferred that, the hypothesis that says "there is a significant relationship between transport facilities and cashew output (main hypothesis)" is rejected. Therefore, the null hypothesis that there is no significant relationship between transport facilities and cashew output is accepted. However, this study recommends the need for further studies on the factors responsible for the spatial variations between transport facilities and output levels where transport facilities accounted for less than 10% of spatial variations in output level. In this case, it is approximately 0.5% (see Table 1). Therefore, further explanations are needed.

4.6. Annual Income from Cashew

The surveyed result on the income derived by respondents from the cultivation of cashew per annum revealed that 2.6%, 2.2%, 10.1%, 14.6%, 10.6% and 11.6% of the respondent realized ≤ N 20,000, N 20,001−N 50,000, N 50,001−N 100,000, N 100,001−N 150,000, N 150,001−N 200,000 and > N 200,000, respectively; while 48.4% of the respondents did not respond (Figure 8) due possibly to non-involvement in the cultivation of cashew. The examination of the cashew income realized in the two categories of settlements showed that 1.7% of respondents in settlements connected by tarred road(s) compared with 0.9% of respondents in settlements connected by untarred road(s) realized ≤ N 20,000, annually; 1.6% of respondents in settlements connected by tarred road(s) compared with 0.6% of respondents in settlements connected by untarred road(s) realized

N 20,001–N 50,000; 5.9% of respondents in settlements connected by tarred road(s) compared with 4.2% of respondents in settlements connected by untarred road(s) realized N 50,000–N 100,000 and 9.9% of respondents in settlements connected by tarred road(s) compared with 1.5% of respondents in settlements connected by untarred road(s) realized N 100,001–N 150,000 per annum. Furthermore, the result additionally revealed that 5% of respondents in settlements connected by tarred roads in contrast with 5.6% of respondents in settlements connected by untarred roads, realized between N 150,001 and N 200,000 annually, and 8.9% of respondents in settlements connected by tarred roads, as opposed to 2.7% of respondents in settlements connected by untarred roads, realized more than N 200,000 annually from Cashew cultivation in the study area.

Generally, settlements connected with tarred roads had the highest proportion of farmers with various level of income range except with farmers realizing N 100,001–N 150,000 per annum where farmers from settlements connected by untarred had the highest proportion. Farmers there were certainly prone to payment of high transport fare transport their cashew product. This must have impacted negatively on their profit from cashew growing investment. The result equally revealed that the highest proportion of non-cashew grower was found in settlements connected by tarred roads; this may probably be because of availability of more farmland and farmers for producing cashews in settlements connected by untarred road(s) than in settlements connected by tarred road(s) and vice versa. Previous studies have observed a reduction of farmland with the expansion of settlements (van Vliet et al., 2017; Bercke et al., 2020). However, it is pertinent to state that the poor quality of road connecting settlements connected by untarred road(s) must have impacted negatively on the profit accruable to farmers in the area; especially due to the payment of relatively higher transport fare to convey cashew to the urban market.

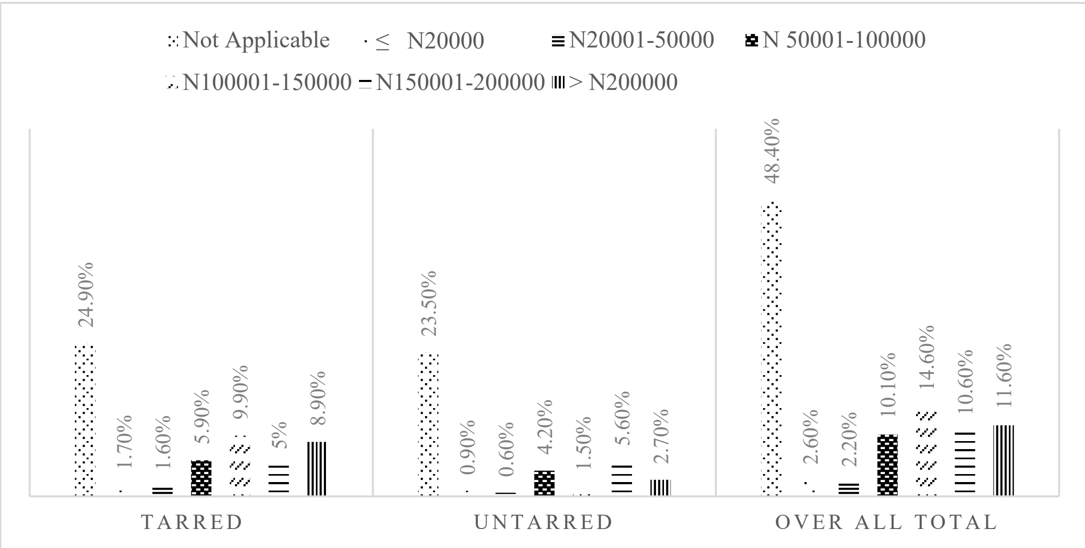

Figure 8. Annual income from cashew from settlements connected by tarred and untarred roads in the study area.
Source: Author's survey.

Furthermore, local government based analysis revealed that the highest proportion (4.1%) of farmers who realized ≤ N 20,000 from the cultivation of cashew was observed in Oyun LGA, the highest proportion (6.2%) of farmers who derived N 20,001−N 50,000 from the cultivation of cashew was observed in Isin LGA, the highest proportion (27.4%) of farmers that obtained N 150,001−N 20,000 and the highest proportion (31.0%) of farmers that got N 150,001−N 20,000 from the cultivation of cashew were observed in Isin LGA. The highest proportion (16.7%) of farmers who earned N 50,001−N 100,000 from the cultivation of cashew was observed in Ekiti LGA, the highest proportion (17.0%) of farmers realized N 100,001−N 150,000 from the cultivation of cashew was observed in Ifelodun LGA (Figure 9).

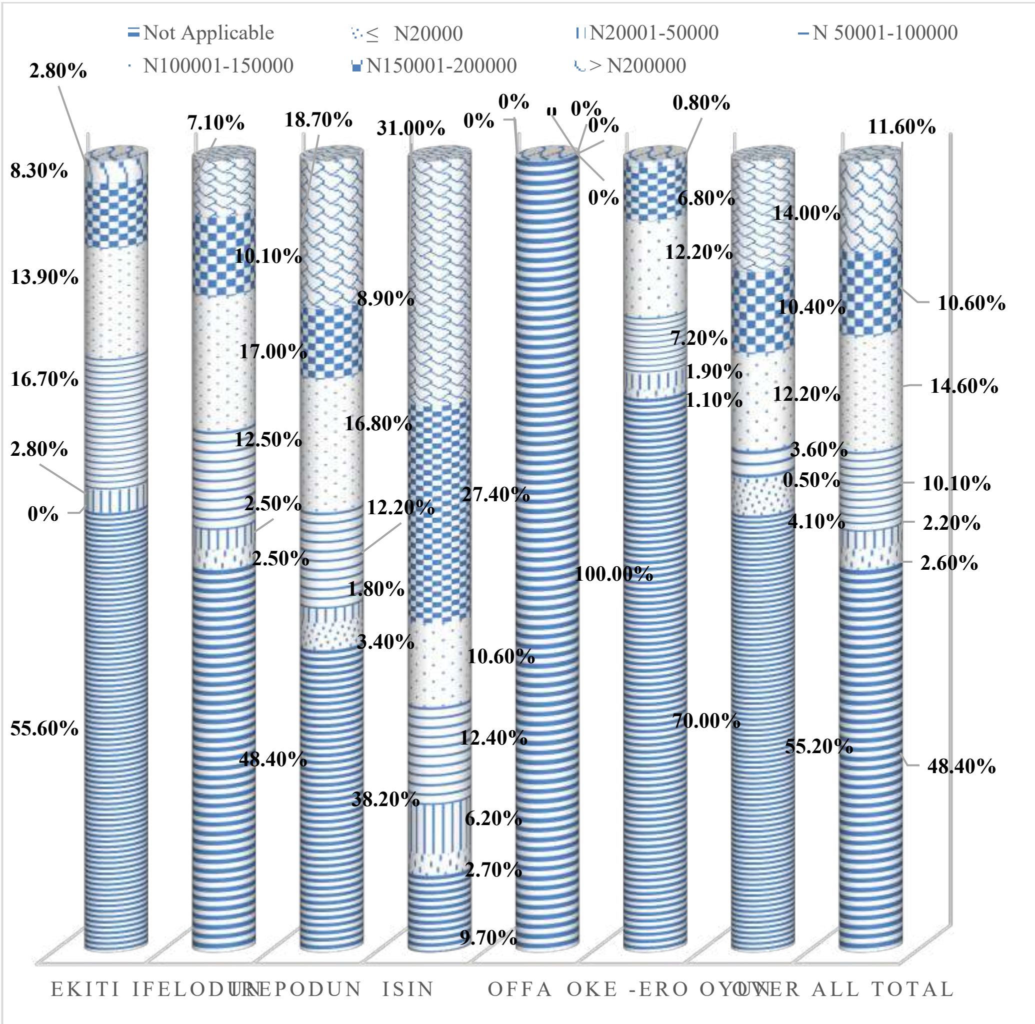

Figure 9. Annual income of cashew across local government area in the study area.

4.7. Hypothesis Testing on Income from Cashew

H_0: There is no significant relationship between transport facilities and income from cashew.

H_1: There is a significant relationship between transport facilities and income from cashew.

Table 2 shows the result of the regression analysis used to investigate the impacts of transport facilities on income derived from cashew in Kwara South Senatorial District. Six variables were examined.

Table 2. Correlation between transport facilities and income generated from selected crops.

		Transport Mode	Road Condition	Transport Cost	Transport Services	Distance to Farm	Distance to Major Market
Cashew Income	Pearson Correlation	0.059	−0.153	0.051	−0.096	−0.040	0.053
	Sig. (2-tailed)	0.029*	0.000*	0.060	0.000*	0.143	0.050*
	N	1,373	1,373	1,373	1,373	1,373	1,373

Source: Authors' computation.
Note: * Correlation is significant at the 0.05 level (2-tailed).

Lastly, whereas the relationships between income from cashew (cashew income) and each of the selected indices of transport facilities were weak ($r \leq 0.096$), the relationship between the income from cashew was directly and significantly correlated with transport mode ($r = 0.059$, $p = 0.029$) and distance to major market ($r = 0.053$, $p = 0.050$) but inversely correlated with road condition (r = −0.153, p = 0.000) and transport services (r = −0.096, p = 0.000) (Table 2). Income from cashew was significantly related to transport mode, road condition, distance to major markets, transport services, and distance to major markets but not with transport cost and distance to farm. Consequently, the null hypothesis that states that there is no significant relationship between transport facilities and income from cashews is accepted for "Transport Cost" and "Distance to Farm" while the main hypothesis that there is a significant relationship between transport facilities and income from cashew is accepted for "Road Conditions," "Transport Modes," "Transport Services," and "Distance to Major Market."

Furthermore, specific transport facilities were significant for specific crops. For instance, road conditions were significant for income generated from cashew. Earlier studies have associated farmers' access to higher income in locations having access to improved transport facilities as exhibited in Obokun Local Government Area of Osun state (Adedeji et al., 2014) and in Ilaje, Ondo State, Nigeria (Olagunju, 2022). Similarly, Aderamo and Magaji (2010) observed that poor road quality in Ilorin East LGA was responsible for high transport charges which in turns impacts negatively on the level of income accruable to farmers in the area.

4.8. Implication

The implication of the study is that high prevalence of poor road promotes high transport's fare and poor transport services generally; these impact negatively on impressive outputs and income from cashew and hinders the achievement of SDG 1 (ending poverty). By extension, prevailing rural roads militate against massive output of food crops and by so doing makes achievement of goal 2 (ending hunger) elusive in most sub-Saharan Africa. Therefore, it is hereby recommended that utmost attention should be given to construction of more access roads, rehabilitation of existing roads; through the formation of rural road maintenance agency at the local government area and community levels to encourage interconnectivity of rural roads, improvement of rural transport services through; introduction of tricycles and other fewer passengers' modes of transport, provision of soft loan for their procurement as well as establishment of market centers in more communities in order to improve the flow of passengers and freights traffic and improve accessibility of rural farm produce to better market potentials; which ultimately improves productivity level and economic fortunes of rural farmers.

5. Conclusion and Recommendations

The study investigated the condition of roads and transport services and assessed its impact on both outputs and income realized from cashew in selected rural settlements in Kwara South Senatorial District. The study observed that transport (rural roads and rural transport services) is a major determinant of the outputs and income realized from the cultivation of any given crop in any geographic space. The limitation of this study was finance and time inadequacy which informed the restriction of the assessment of transport services to the views of cashew farmers alone without the consideration of transporters' view who are the main actor in the transport business. The study recommends inclusion of transporters' view in further investigations on the topic in order to get a holistic assessment of the impact of transport on both outputs and income generated from cashew or other crops. Additionally, there is the need to shed light on other factors affecting variations in both output and income realized from cashew production in the two categories of settlements other than transport.

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Agricultural & Rural Studies

Article

Frequency and Sample Size to Minimize the Cost of a Rapidly Evolving Infectious Animal or Plant Disease

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Abstract: One of the major effects of global change is the spread of animal and plant diseases on farms. Besides the impact on the farms themselves, it is the whole rural world that is affected, through the possible disruption of value chains. Combating these diseases is therefore a crucial but costly problem. So, when faced with an infectious animal or plant pathology, how can we minimize the cost of the disease and of the sampling and analyses testing required to monitor its progress? First, we calculate the imprecision of the results as a function of the sample size and the prevalence of the disease. Then, depending on the desired precision and the prevalence of the disease, we calculate the required sample size. Finally, in the case of iterative sampling, depending on the cost of each sampling and testing event and the costs associated with the spread of the disease, we show on a quantitative example that there is an optimum, i.e. a relationship between the frequency and the sample size (number of samples) that allows the cost of the disease to be minimized. We show the optimum relationship between sample size and frequency, the relationship between minimum total cost and frequency, and finally, we show on a 3-dimensional graph, how the total cost evolves as a function of frequency and sample size.

Keywords: sampling; epidemic; epizootic; epiphytic; pathology; dynamics; economics; cost; risk; probability

1. Introduction

International communities are increasingly aware of the importance of both farm animal and crop health, as evidenced by the publications of the International Plant Protection Convention (see IPPC Secretariat, 2023) and of the World Organization for Animal Health (see World Organization for Animal Health, 2023). The subject of this paper is sampling to control the occurrence of rapidly spreading infectious animal or plant diseases: how many measurements should be taken, and how often, to minimize the cost of the disease plus the cost of the measurements? Each measure is costly, and too many would be prohibitive. On the other hand, if monitoring is too lax, there is a risk that the disease will develop and spread, with catastrophic consequences.

This multi-disciplinary work contributes to a whole range of studies and results, combining epidemiology, economics, and modeling, with the aim of not systematically seeking to eradicate pathologies, but to assess their costs in order to minimize them. In the same line of thought, Silal (2021) shows how multidisciplinary operational research can contribute to the efficient management of infectious diseases, with a particular emphasis on minimizing the costs of pathology detection. These studies include for example Han et al. (2020) on the bovine viral diarrhea virus for dairy and beef cattle herds.

The financial implications of our work are significant. To give just two examples, avian influenza, which mainly affects poultry farms, has cost the French government around 1.5 billion euros in 2022 alone (compensation for farmers, requisitions, euthanasia of animals, cleaning and disinfection...); not to mention the losses incurred by professionals in the processing industry. Anaplasmosis in cattle (see Railey & Marsh, 2021) raises the same kind of economic consequences and therefore induces the same sampling problems for early detection.

As far as plants are concerned, the estimated damage of Citrus "greening" disease (citrus Huanglongbing, or HLB) over the past 5 years before 2020 amounts in Florida alone, to over $1 billion per year, with nearly 5000 jobs lost annually (Li et al., 2020). In many countries, plum pox (or sharka) is a viral pathology affecting stone fruits. Surveillance and detection procedures are currently evolving in line with EU Regulation 2016/2031 (see Terreaux, 2023). It is therefore necessary to reorganize the monitoring of this disease. The continued production of these fruits (apricots, peaches, nectarines, etc.) in France is at stake. Other pathologies affecting cultivated plants

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that are the subject of similar questions include Xylella fastidiosa (see Burbank, 2022). Many other animal and plant diseases raise the same issues, but in the remainder of this article, we will use avian influenza as an example for application and illustration.

In a previous article (Terreaux, 2022), we calculated the sample size (number of animals to be tested) required on a farm to know with 99% or 95% confidence whether or not it is infected or not. Here, we complement this approach by taking into account the fact that the disease can emerge on the farm at any time, e.g. following poor biosecurity and contamination by a human vector, from infected premises, or from wildlife. Actually, the biosecurity measures implemented may vary greatly from one farm to another, depending on the specifications, objectives, and challenges of each farmer (see Fountain et al., 2023). On the other hand, we do not simply want to know with any degree of accuracy (99% or 95%) whether the farm is infected. Our aim is to minimize the total cost of the disease, i.e. the cost of sampling and testing, plus the cost of culling infected flocks, plus the cost of allowing disease to spread that may be asymptomatic, particularly if only a few animals are infected and shedding virus (e.g. ducks can shed virus for five days before the first symptoms appear).

The methods used to calculate these costs are very different: firstly, the costs are uncertain because the disease will spread in a non-deterministic way. The decision criterion can then be, as a first approximation, the minimization of the mathematical expectation of the costs: thus, if for a given farm at a given time, the probability of disease occurrence is p, it is not assumed that a proportion p of the animals are systematically infected. The situation is dichotomous: either all the animals are disease-free, or some are infected, in which case the disease spreads throughout the farm. The prevalence (proportion of infected animals) is therefore generally zero, but sometimes it becomes strictly positive (following infection) and then increases. The prevalence is assumed to increase asymptomatically until the disease is detected by sampling, the parameters of which – sample size (number of animals tested) and frequency (or periodicity) of testing - must be carefully chosen. The animals are then euthanized. Alternatively, sampling is inadequate, and the disease remains undetected until the number of affected animals is sufficient (prevalence exceeds a certain threshold) for some of them to die, or for the feed consumption of the herd to drop significantly, etc., and the disease becomes symptomatic. The herd is then culled. But the problem with the latter situation is that the disease will have been able to spread for longer and more widely outside the farm under investigation, at a much higher collective cost (via other farms) than would have been the case if the disease had been detected early.

The prevalence is therefore likely to change over time. In a previous article (Terreaux, 2022), we calculated the minimum sample size (minimum number of animals to be tested) for a prevalence of 5%. In section 2, we calculate the accuracy obtained as a function of sample size and prevalence. In section 3, we calculate the number of tests to be performed as a function of the prevalence to achieve 99% or 95% accuracy.

In section 4, we explicitly introduce the dynamics of pathology in the herd and assume that sampling is iterative: For the same observation duration T, instead of testing M animals once, we repeatedly test N animals p times, with M = pN. Again, the aim is no longer to achieve a given accuracy of measurement but to minimize the overall cost of the disease.

Sections 4.1. and 4.2. describe the model and show the arbitrary values chosen for the different parameters. Section 4.3. shows that, as expected, the longer the duration T, the larger the sample size required. In section 4.4. we show how the total cost reaches a minimum for a given duration T (associated with a number of animals to be tested – or sample size – calculated in section 4.2.). Finally, in section 4.4., we show how the total cost evolves as a function of the periodicity T (= 1/ frequency) of the measurements and of the sample size.

The model set up in Section 4, a simplified representation of reality with a set of parameters chosen for illustrative purposes, represents the dynamics of the disease within the farm under study. The occurrence of the disease and the detection or non-detection of the disease in the farm, if it is affected, are randomized by two nested Monte Carlo processes.

2. Measurement Imprecision as a Function of Sample Size and Prevalence

In Terreaux (2022) we showed that for a prevalence of *prev*, the sample size N (number of animals to be tested) to have an accuracy of at least α (e.g. α = 95%), considering a number y of animals in the herd, is so that (see too Wonnacott & Wonnacott, 1990; Mann, 2010; Weiss, 2011):

$$\frac{\dfrac{\left(y.(1-prev)\right)!}{N!\left(y.(1-prev)-N\right)!}}{\dfrac{(y)!}{N!\left(y-N\right)!}} \leq 1-\alpha \quad (1)$$

We will now assume that y = 8000 animals in the herd. We can calculate the precision of the measurement as a function of N (sample size). This is shown in Figure 1 for a prevalence of 5% and in Figure 2 if we vary this prevalence between 1% and 10%.

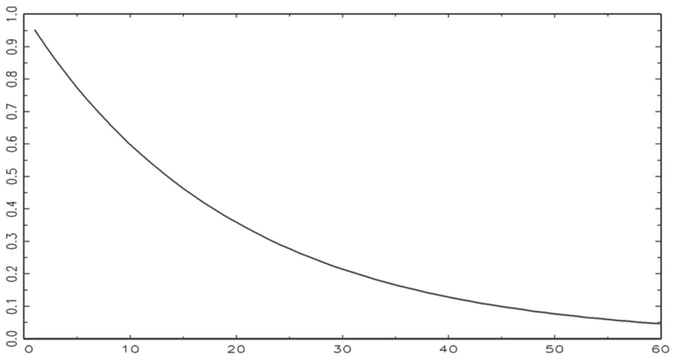

Figure 1. Measurement imprecision for 5% prevalence as a function of sample size. X-axis: sample size; Y-axis: imprecision (1- α) obtained.

Example: With 20 samples, the measurement imprecision is 36%; i.e. if the disease is present in the herd, there is a 36% risk of not detecting it.

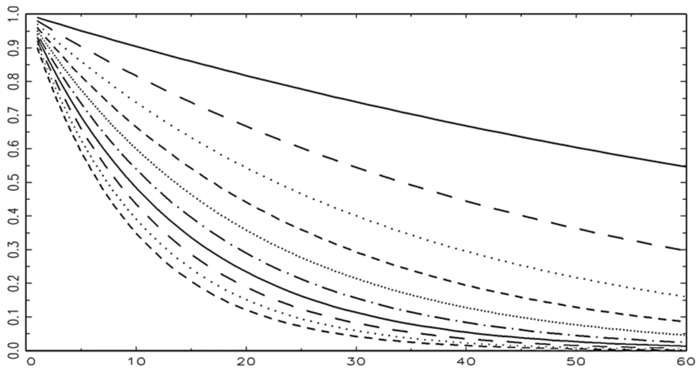

Figure 2. Measurement imprecision as a function of sample size for different prevalences. From top to bottom: prevalence of 1%, 2% … 10%.

Example: With 20 samples and a prevalence of 2%, the measurement imprecision is 67%; in other words, if the pathology is present in the herd, there is a 67% risk of not detecting it.

3. Sample Size as a Function of Prevalence

Using the same formula, we can calculate the number of samples needed to achieve 99% or 95% accuracy, depending on the prevalence. This is shown in Figure 3. We still assume that y = 8000.

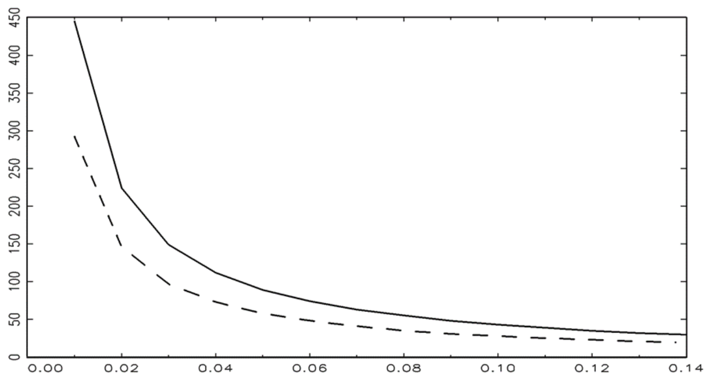

Figure 3. Sample size required to achieve a given accuracy: upper curve: 99%, lower curve: 95%. X-axis: prevalence; Y-axis: sample size.

Example: With a prevalence of 5%, 89 samples are required for 99% accuracy and 58 samples for 95% accuracy.

4. Iterative Sampling

Given that contamination of the farm with the disease can occur at any time, it seems interesting not to determine precisely whether or not this contamination has occurred at a given time t and, because of the prohibitive cost involved, not to repeat this measurement soon afterward, but to carry out periodic tests, albeit with a smaller sample size. The aim is therefore no longer to ensure the absence of the disease, but to minimize costs, both in terms of sampling and testing costs, and in terms of the costs associated with the spread of the disease (by preventing the prevalence from becoming too high, or the disease from becoming symptomatic). For example, for a large herd, instead of testing 60 individuals at once (see Terreaux, 2022: these 60 are sufficient to know whether a herd of size 8000 individuals, as in the numerical example above, or smaller, is affected by the pathology with 95% accuracy when the prevalence is 5%), we can repeatedly test, every T time steps, N individuals, with n < 60, N and T still to be calculated.

4.1. Iterative Sampling to Reduce Costs

Figure 4 shows the situation considered: sampling of N individuals every T time steps (here in days). The dotted arrow represents the time of onset of the disease. From this point on, the number of affected animals and their prevalence increase exponentially. This corresponds to a standard representation of the onset of the evolution of an infectious disease: a SIR model (see Murray, 2002; Terreaux, 2017) without R, i.e. without remission for some individuals.

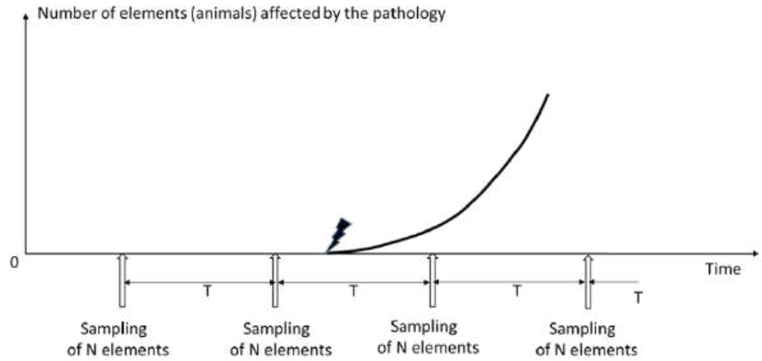

Figure 4. Schematic diagram showing the onset of the disease and the various sampling events separated by T.

We then apply a Monte Carlo procedure (see, for example, Fishman, 1995): starting from the initial time (t = 0), we simulate an initial trajectory over a horizon H: at each date t, the disease can appear on the farm with probability p, or else the herd remains healthy. From its onset at time t, it evolves exponentially with a coefficient δ (at each time step, i.e. for example every 24 hours, the number of infected individuals is multiplied by δ). This automatically increases the prevalence and therefore the probability of detecting the disease at the next sampling. If the disease is detected, the herd is culled at a cost of C1. The barn is then left empty for a quarantine period Q before a new herd is established. However, a sample size of only N animals, a low prevalence, and bad luck may mean that the disease is present but goes undetected. It will then continue to develop at the rate dictated by δ. If the prevalence exceeds Pmax, the disease becomes symptomatic and the herd is culled; the cost is C2, which is higher than C1 because the disease has spread in the meantime. This is followed by a quarantine period of the same duration before a new herd is established.

In total, this trajectory generates different costs over the time horizon considered: the cost of sampling and possibly one or more C1 costs and one or more C2 costs. Adding these together gives the total cost of this trajectory. By repeating the generation of such trajectories a large number of times (in practice 100,000 times) over a time horizon H, we deduce the average cost of these trajectories, which is nothing other than the mathematical expectation of the cost as a function of the numerical values chosen for each of the parameters.

This method therefore involves two intertwined random elements: the onset of the disease and whether it is detected or not. The two main parameters we adjust here are N, the size of each sample, and T, the time between two sampling events. The other parameters depend on the type of problem we are dealing with. We have not carried out a precise econometric study of the value of these parameters, so the results presented here are of qualitative interest only.

Figure 7 uses 2100 (i.e. 30 × 70) parameters sets, with the possibility of the disease occurring over 100 time steps. Therefore, 21 billion (30 × 70 × 100 × 100,000) draws of pseudo-random numbers are required to simulate the possible onset of the disease. A problem related to the recycling of these numbers could arise: the number generator used is the one presented in Terreaux (2000), which does not present this risk.

4.2. The Various Parameters of the Model

The parameters considered here, together with the numerical values adopted, are presented in Table 1. It should be remembered that the values are arbitrary and must be adapted for their quantitative application to a specific situation.

Table 1. Parameter values for numerical simulations.

Parameter	Symbol	Numerical value
herd size	y	8.000
cost if disease is detected by testing	C1	30.000 €
cost if disease is detected by symptoms	C2	300.000 €
cost of sampling and testing one animal		20 €
“entry cost” of sampling (see text)		150 €
time step		1 day
calculation horizon	H	100 days
probability of disease occurrence at each time step	p	0.0005
prevalence leading to symptomatic detection	P_{max}	40 %
pathology evolution coefficient	δ	1.6
duration of quarantine	Q	20 days
number of individuals per sample	N	variable to be optimized
time between two sampling events	T	variable to be optimized

The cost of a sampling event is defined by its “entry cost” (i.e. the fixed cost whatever the sample size N) plus the sample size N multiplied by the “cost of sampling and testing an animal.”

4.3. Sampling: Optimal Size as a Function of the Number of Days Between Two Sampling Events

We have two variables, N and T, whose values we can choose, and which will determine the total cost (sampling, testing, culling, and dissemination to other farms) of controlling the disease. Our objective is:

$$\min_{N,T}\left(Overallcost\right) \tag{2}$$

If T is fixed, this leads to a value of N that allows this minimum to be achieved. We show N as a function of T in Figure 5.

On this graph, the slight decrease observed when T = 9 is not significant; it is due to the still low number of trajectories generated, which is still 100,000 for each set of parameters N and T. Increasing this number would eliminate this artifact and make the surface shown in Figure 7 “smoother.”

Note that the minimum cost for a period T greater than 7 days corresponds to a sample size greater than 60, i.e. that obtained with a prevalence assumption of 5% and a desired accuracy of 95% for a single sampling event (see Terreaux, 2022).

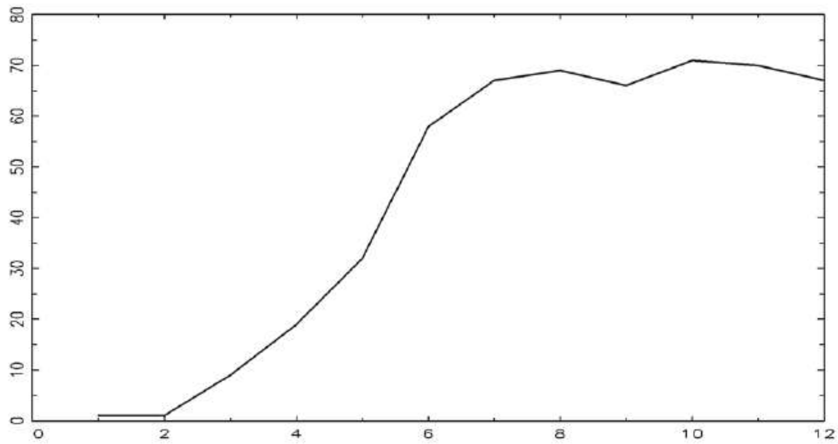

Figure 5. N (sample size, y-axis) as a function of T (sampling periodicity in days, x-axis) to minimize total cost.

Example: To minimize the total cost (cost of testing + cost of euthanasia if positive + impact of spreading the disease if not detected in time), if we sample every 4 days (x-axis = 4), the number of animals to be tested (sample size) is 19 (y-axis = 19).

Another example: If T = 5, then N = 32; beyond 11 days, the optimum for the chosen parameter values is around 70.

4.4. Minimum Cost as a Function of Sampling Periodicity

We now show the evolution of this minimum cost (i.e. by adjusting N, the sample size, as much as possible) as a function of sampling periodicity. Figure 6 shows that, beyond T = 3, the total cost increases with the sampling periodicity. The minimum cost is obtained for T = 3 and corresponds (see Figure 5) to a sample size of N = 9.

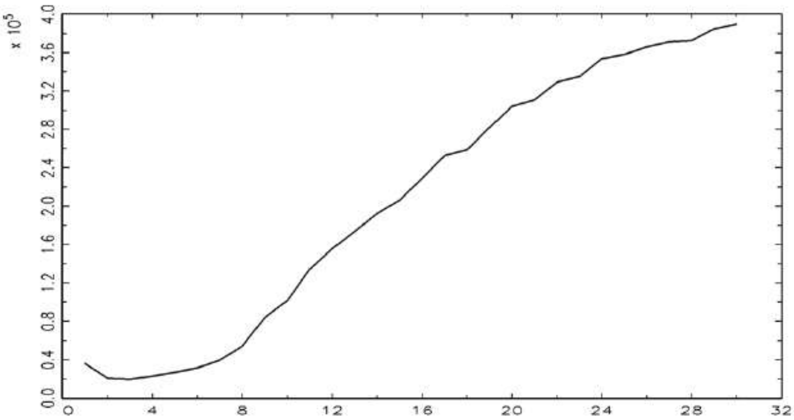

Figure 6. Evolution of total cost (y-axis, in €) as a function of sampling periodicity T (in days).

Beyond three days, the higher the sampling periodicity T, the higher the cost.

The minimum corresponds to sampling every 3 days, which, according to Figure 5, corresponds to 9 animals tested every 3 days with these data.

4.5. Cost as a Function of Periodicity and Sample Size

The evolution of the total cost as a function of N and T is shown below in a three-dimensional perspective graph.

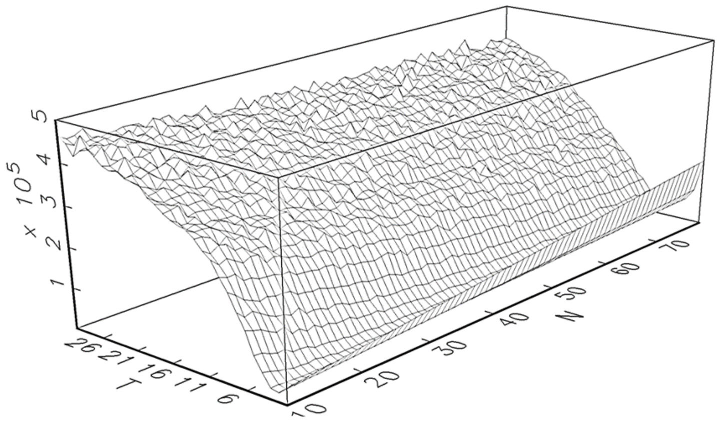

Figure 7. Evolution of total cost (z-axis, in €) as a function of sampling periodicity (T, in days) and sample size (N).

Note that the z-axis scale starts from zero: an error in the numerical values assigned to N or T can be costly, potentially multiplying the total cost of the disease by much more than 5.

5. Conclusion

In practical terms, the results of this research show how it is possible to significantly reduce the costs associated with pathology by replacing a single sampling to test for its presence on the farm with successive samplings of smaller size: We have shown here that instead of carrying out a single sampling (T → ∝), or a small number of samplings (T large), it may be more interesting to carry out regular sampling events of smaller size (fewer animals or plants tested each time). In this case, a trade-off between sampling periodicity and sample size has to be made. Optimal values depend on the estimation of the different parameters, and therefore on the animal or plant disease under investigation and in particular the economic conditions and the stakes of the agricultural production in question, the fixed and variable costs of sampling, the probability of the pathology appearing on the farm and, if present, its dynamics. Monte Carlo methods have proved their worth here, making it possible to calculate numerically and illustrate graphically the economic benefits of choosing the right sampling parameters.

The scientific breakthrough lies in the fact that, in the sampling problem addressed here, we take into account both the costs and benefits associated with earlier detection of the pathology and the fact that sampling is not carried out once and for all to find out whether the disease is present on the farm, but is repeated periodically over time. Its characteristics—sampling frequency and size—are determined by a multidisciplinary approach (economics, epidemiology, probability calculation, Monte Carlo modeling). Further work could take into account the fact that the interest of each individual farmer is not the same as that of the farmers as a whole, nor that of the processing and marketing chain, nor that of the State (see Terreaux, 2017, on a similar issue in beekeeping, or Terreaux, 2023, on plumpox virus for some fruit orchards). In certain cases, this could make it possible to replace regulatory constraints with incentive instruments, in everyone's interest.

Moreover, following Giral-Barajas et al. (2023), our model could be extended to multistage epidemiological dynamics, when, for some diseases, it is possible to distinguish different clinical stages. Another development of our work on sampling could be to take into account the possibility of vaccinating, or at least reducing the incidence of the pathology on, for example, part of the herds or orchards susceptible to the disease; this would make our results more precise when this possibility is real (see the extension of epidemiological models in this regard in Ramponi & Tessitore, 2024).

Another line of research would be to extend our work with an economic objective to farms made up of different herds, orchards, or more generally different subsets when the prevalence of pathology differs from one subset to another (see an example of such a situation in Clement et al., 2023). Still, another area of research could be to combine the costs studied here with those of biosecurity measures, bearing in mind that these measures may be taken by the farmer in his own interest, with an externality effect on the spread of the pathology to other farmers (see Hennessy & Rault, 2023). Finally, coming back to sampling, it would be useful to be able to take into account the possibility, when it occurs, of false positives and false negatives when testing individuals for the presence of the pathology (see Vasiliauskaite et al., 2021).

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Agricultural & Rural Studies

Article

Repopulating and Rewilding a Historical Agricultural Landscape: 2030–2100 Transition

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Abstract: Spain is at the forefront of organic agriculture in Europe and entering carbon farming but is facing rural depopulation, draughts, soil erosion and pervasive glyphosate pollution in water. These are factors affecting the rural ecosystem, which is simulated here as a 4-species Lotka-Volterra model from 2030 through 2100. The role of interstitial permaculture (IP) in solving for land fragmentation and loss of local agricultural knowledge and practices, is explored. Landscape ecology, and especially the role of hedgerows in bocage and *dehesa* landscapes give credence to IP as a form of agroforestry. The Lotka-Volterra simulation captures the high interconnectedness of species in the local agroecosystem. The simulation also provides insight into the limits of a viable transition to sustainable agriculture: reforestation is fostered by the inflow of permaculturists, but wolves cannot by themselves stem the tide of boar growth. Rather, human intervention throughout Europe seems to be required. Eventually, the model manages to bring boar, wolf and human populations to a certain balance, oscillating near the carrying capacity of the system, but tree populations keep well below carrying capacity, suggesting more reforestation efforts. The ecobenefits resulting from the ecosystem's evolution fostered by permaculture were found to be in terms of soil protection hence soil organic carbon sequestration. A striking suggestion of the model regarding herbivory is that boar meat should be consumed by humans, a practice in the area during the Holocene, and supported by new research in Europe.

Keywords: permaculture; Lotka-Volterra; depopulation; rewilding; carrying capacity; soil protection

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1. Introduction

Sustainable agriculture has a pivotal role to play in solving global change issues; not only must it reduce its water consumption and pollution, its carbon footprint, and its role in critical global soil erosion (Evans et al., 2020). It must also contribute to natural land cover recovery, rewilding, and the provision of safe food and employment.

Locally, climate change, and especially increased frequency and severity of droughts is hitting the agricultural area of Salas de los Infantes, in the historical heartland of Spain, a country viewed as a climate change laboratory for Europe (Agrospecials, 2023). Salas is surrounded by five Natura 2000 European Union protected areas (Figure 1). The area also belongs to the ageing and "deserted Spain": it has lost population for 50 years to the large industrial cities of Bilbao, Madrid and Barcelona.

By 1980, the remaining agriculturalists had embraced Green Revolution agrochemicals and machinery, and more recently, fast-growth monoculture woodland. And so, in this hilly region, erosion is high and glyphosate water pollution is, per official accounts, omnipresent (Subdirección General de Protección de las Aguas y Gestión de Riesgos, 2023).

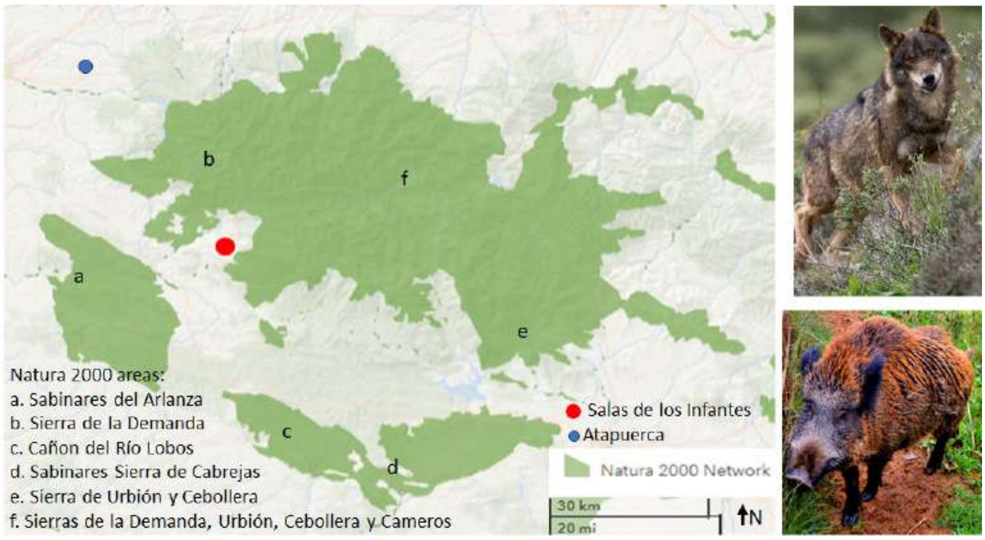

Figure 1. Feasibility of rewilding. Salas is located within a set of nature reserves of European importance. Human presence dates back to 1.3 million years BP in Atapuerca. Sierra de la Demanda is also among the top ten Spanish areas for observing wolf (*Canis lupus* signatus) and its potential role in controlling boar (*Sus scrofa*) population.
Sources: Anthiro 57, 2016; European Environment Agency, 2021; Tudela de Duero, 2016.

A bifurcation needs to take place in areas like Salas. Business-as-usual would turn the area into an extractive economy area. Already, depopulation is seen, in the long game of mining and the energy sector, as an opportunity: decommissioned nuclear power plants in the province are never really shelved for good (Caubilla, 2022) and uranium is present in Salas (Sánchez & López, 2021) so prospection could be revived. Windpower turbines already straddle the region. Contrariwise, sustainable agriculture can revert depopulation and produce healthy foodstuff in a manner appropriate to local climate, protect the local pharmacopeia heritage knowledge, protect soil and water resources, and combine heritage landscapes and practices and current landscape ecology to protect crops from frost, wind desiccation, excess solar irradiance and temperature, herbivory, and excess evapotranspiration.

1.1. Theoretical Underpinnings

Permaculture and ecology ascribe a prominent role to systems theory, as expounded by Bertalanffy in 1934. This theory guides the integration of elements, such as plants, animals, and humans, to enhance the resilience of the whole system. The theory also emphasizes the integration and adaptation of subsystems: landscape ecology, functional diversity (primary producers, herbivores, predators, human stewards), and resilience to disturbances.

In terms of scientific method, the trophic network and IP are modules that are described and simulated. In the simulation, modularity means there is no limit to the number of interconnected subsystems (species) nor a limit to the number of functions and parameters that relate any two species. An account of the system limits imposed by interconnectedness can be given by sensitivity analysis. The modular object-oriented method befits the system theoretic approach and a problem-solving definition of science, as proposed by Herbert Simon in the 1980s.

1.2. Interstitial Permaculture, Rewilding and Repopulation

Permaculture is a set of sustainable production techniques for food security, ecosystem restoration, and social revitalization that integrates plants, animals, and humans into healthy coupled human and natural systems (CHANS). Permaculture creates productive synergies conducive to developing community-driven economies (Ferguson & Lovell, 2019) and enhances the ability of CHANS to self-sustain by improving soil, supporting wildlife and conserving water (Hirschfeld & Van Acker, 2021).

In turn, IP is permaculture in underutilized, neglected or unused rural spaces: it has a potential for non-confrontational land use change. Initially transforming urban unused spaces into productive ecosystems, efforts are being made into applying new technologies to enhance sustainability (Concepcion et al., 2021). By fostering local food production, IP helps communities become more resilient by reducing their vulnerability to external food supply shocks. IP also promotes carbon farming, stormwater management, and soil regeneration, which are vital for improving environmental health.

Permaculture and rewilding are complementary approaches to ecological restoration and sustainability: while IP mimics natural ecosystems, rewilding focuses on allowing nature to restore itself by minimizing human intervention. Both prioritize biodiversity, trophic networks in balance, and long-term sustainability. IP however tries to minimize the cultivated area, maximize yearlong nutritional output, use belowground automated fertigation, use natural succession to develop hedgerow protection against desiccating and eroding winds, frost, excess solar irradiation and evapotranspiration, runoff erosion, use water harvesting, renewables, vegetation waste and humanure biorefinery. IP also benefits from reforestation in the form of green corridors and waterholes for pollinators and seed dispersers. By striving for nutritional self-sufficiency and the use of a local pharmacopeia, IP fosters the recovery of heritage agricultural knowledge.

To understand future land use, and IP as a non-confrontational driver of land use change, one must look back at how land use change and tenure upheavals are historically concomitant: While medieval land use change was driven by wheat and wine production, the *dehesa* silvopasture tried to prevent conversion to extensive cereal culture; the *dehesa* also benefitted the *Mesta* guild and transhumant merino sheep. Commons date back to before the 16th century Castille *Comuneros* rebellion. The challenge to commons by competition for land by nobility and clergy is just as old. Thereafter, commons and clergy lands were challenged by the liberal push for private property, extensive agriculture and husbandry under 19th century monarchic and republican rule. Under the 20th century republic, cooperative and union movements became a force (Beltrán Tapia, 2012) repressed by Francoist rebellion against the republic. The incarceration, execution, and exile of cooperativists and unionized rural workers, and the eviction of their families, jumpstarted a rural exodus to urban industries. Under Franco, afforestation with tree diversity loss took place under the aegis of a state corporation. In a way, Salas has historically been interstitial, being less intensively and extensively cultivated than the area surrounding Burgos, the provincial capital. In future, agricultural and ecological policies are likely to retain a degree of past tenure and land use ideological conflicts. Arguably, the forces behind future sustainability embrace the use of commons.

In turn, land use has altered interactions between species and will continue to do so in future. Evidence of a Medieval Climatic Optimum has been inferred from recorded wheat production increases, ensuing population rise, and deforestation. This led to forest protection under the late 15th century and early 16th century rulers. This protection contrasted with the long-lasting clergy opinion in Western countries against wolf and a host of other animals. Hunting and forest disturbances have taken their toll too. The Spanish wolf meta-population has declined, local wolf populations are becoming disconnected, inbreeding and breeding with dogs seem on the rise, despite some evidence of genetic flows from across the Pyrenees. As to the ongoing wild boar surge, it is a byproduct of wolf decline (about a third of wolf diet includes boar, particularly piglets) and boar feeding on irrigated maize, wheat and potato. Boars also heavily rely on energy-rich acorns, especially during fall and winter. This, and trampling, affects acorn survival, germination and the number of seedlings. Wolf depredation on livestock occurs in remote locales. Recently, wolf hunting was banned in Spain to comply with European Union rules, but some EU parliament members and the incumbent EU Commission President might try to reverse said rules. In 2024, the EU Nature Restoration law was enacted, with specific member States obligations regarding reforestation. Again, ideological viewpoints are likely to clash in future.

Significance of This Study

Owing to the rewilding trend, any rural repopulation effort should account for its net impact on the other species (and here, its impact on wolf reintroduction, reforestation and boar control). This account hinged firstly on a simulation of trophic dynamics. And secondly, on a demonstration that humans can be stewards of a trophic network; this amounted to showing IP as a solution to one problem: how humans can help nature so nature can help them.

1.3. Goals

This paper deals with future agricultural landscapes and the ecological matrix in which they occur. Formalization and implementation of a model for a rural ecosystem was necessary as multiple connections (in a simplified trophic network, Figure 3) preclude intuitive predictions of action (or policy) outcomes. The policies of repopulation and rewilding were at stake here. Therefore, the goals were to represent trophic network dynamics as a mathematical model of populations that responded to a matrix of relationships between species. The model needed to identify the limits within which the species operate and transition from unsustainable to sustainable states (from 2030 through 2100), supported by IP.

2. Method

A dynamic model of the 2030–2100 transition to a sustainable agroecosystem was grounded on feasibility elements, so firstly, a locally relevant form of sustainable agriculture was characterized (IP) to solve for today's land ownership fragmentation. Secondly, historically important agricultural practices (*hacenderas*, village shepherd and shepherd guilds) and landscape elements (e.g., commons: *eras*, *ejido*, *dehesa*, and also bocage and hedgerows) were identified as local accumulated knowledge and accepted practices. Thirdly, the nature-rural population matrix was formalized (as a 4-species Lotka-Volterra logistic/sinusoidal growth). A sensitivity analysis helped understand the interconnections in the ecosystem (Supplementary Materials). The Python code for this model is available at https://github.com/EmmanuelCastillo87/Sus-Scrofa/tree/main. Fourthly, the results showed some of the limits of rewilding and human repopulation, as well as practices adjuvant in seeking ecological balance. And fifthly, the ecobenefits of IP were identified.

3. Results

3.1. Interstitial Permaculture

Land fragmentation was identified as a factor in land disuse. IP would take advantage of marginal lands that have not been subjected to land concentration (Figure 2), and still harbour highly valuable bocage landscapes (Figure 3). The value of bocage stems from being a tight network of hedgerows able to regulate temperature and solar irradiance and thus reduce evapotranspiration, frost, and wind desiccation. Hedgerows can also halt herbivory and the progress of pathogens through the landscape. As to permaculture, i.e., permanently producing agriculture with a high degree of produce diversity and high nutritional quality and food safety, it seems a requirement to attract younger generations with evolving nutritional preferences (discussed below).

Figure 2. Cadastral map, Salas area. Land ownership fragmentation (small size, dispersion and shared ownership) suited to IP in bocage landscapes. Dispersion among vicinities suggested different ecotopes hence exposures to weather, herbivory and pathogens.

Table 1. Typical fragmentation of one property into plots located in different vicinities. The names of the vicinities depict ecological features.

Vicinity	Area (m^2)
Cerro (hill)	549
Valle (combe)	717
Mese (harvest or grain or masiega - herbaceous plants)	1,135
Ladera (hillside)	59
Ladera (hillside, shaded green plot in Figure 2)	245
Moje (small boundary stone)	1,357
Corzas (female roe deer, Capreolus capreolus, in a sheltered valley)	1,094

Remnant bocage plots persist, and even tractor-tilled plots preserved scattered trees in 2023, suggestive of *dehesa* landscapes that mixed trees and other uses (Figure 3). *Dehesa* (from Latin *defensa*, defense) mixed other uses with trees to avoid clear cutting. Bocage is a succession of faster, then slower growth trees. Among the latter *Pinus sylvestris* and *Quercus pirenaica* are the most abundant in the study area. In IP, fast growth berry shrubs should be added. Beyond the bocage, native wild herbaceous species (such as *Carex camposii*) should be protected for their value. Permaculture is best taken care of by the whole household so dwellings should be incorporated into the bocage landscape.

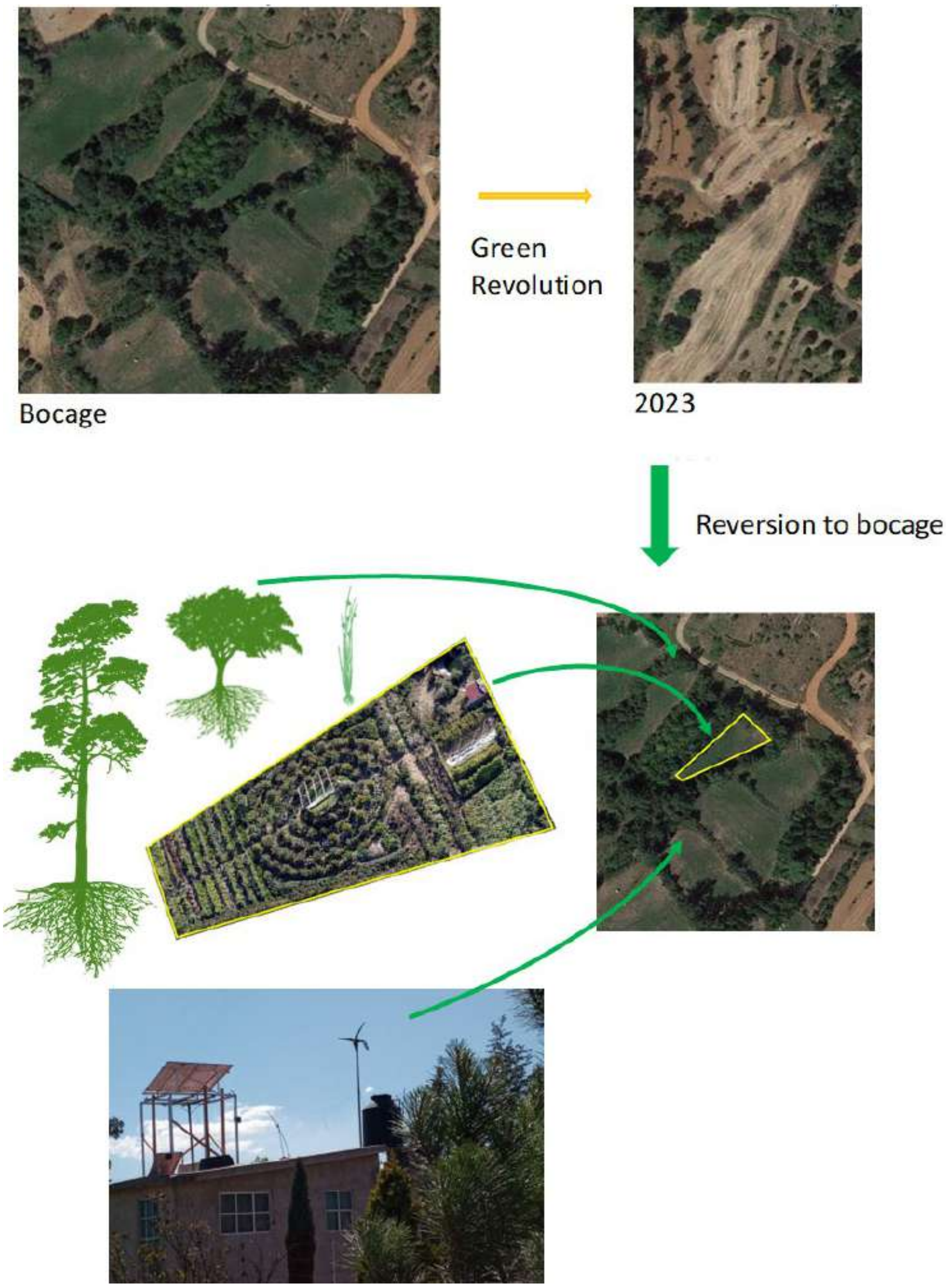

Figure 3. Historically important agricultural practices and landscape elements.
Sources: Alôsnys, 2016; Instituto Geográfico Nacional and Google ©2023. Solar roof atop a live-in lab: © de las Heras and Islas-Espinoza.

3.2. Trophic Model of the Rural Ecosystem

A key result of trying to bring humans and nature closer together, as they once were before the 1980s in the study area, was the formalization of the repopulation-rewilding link. The formal expression took the shape of a logistic curve, used for over a century in statistics, demography, ecology, microbiology and now, artificial intelligence. The curve depicts growth up to the limits of a system (Figure 4). After reaching the limit of the system, all present species, if behaving like natural populations, should oscillate sinusoidally around the limit for each species imposed by the whole system (Figure 5). The number of *Quercus* trees that bear acorns was included in the trophic model. Wolf had a role in controlling boar, and humans had an impact on tree, boar and wolf populations. An interaction matrix was an additive element to the logistic-sinusoidal Lotka-Volterra model. Of note is the amplitude parameter A which could be interpreted as (non-random) variation rather than a single-valued limit to the growth of a population.

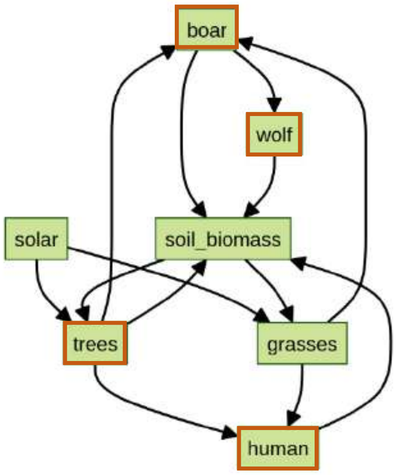

Figure 4. Trophic network. The boxes outlined in red were explicitly modelled. Acorn was the part of the trees that was factored in.

The Lotka-Volterra model was:

$$P_{i,t+1} = P_{i,t}(1+r_i)\left(1-\frac{P_{i,t}}{K_i(1+A\sin(\frac{\pi}{4}t))}\right)+\sum\frac{\alpha_{ij}P_{j,t}P_{i,t}}{K_i} \quad (1)$$

r_i is the population intrinsic growth rate.
$P_{i,t}$ is the current population.
K_i is the carrying capacity.
A is the amplitude (height) of the sinusoidal variation near K_i (the base model used the values in Tables 2 and 3).

Table 2. Lotka-Volterra base model, values of parameters.

	r	**P_0**	**K**	**A**
Acorn	0.015	31,300	122,000	0.1
Boar	0.5	300	6,000	0.1
Wolf	0.4	4	12	0.15
Human	0.106	1,900	28,500	0.05

Table 3. Lotka-Volterra base model, interaction matrix (α_{ij}). Column species j controlled row species i (each j individual had an ij controlling effect which was multiplied by the i and j populations).

	Acorn	**Boar**	**Wolf**	**Human**
Acorn	0	−0.1	0	−0.1
Boar	0	0	−1	−0.9
Wolf	0	0	0	0.00039
Human	0	0	0	0

The limits of the trophic network were given by the interplay of the parameters r, P_0, K and A. The model showed that gradual reforestation could accompany an increase in human population (Figure 5). Also, reforestation needed to be higher than just bocage. But boar could not be controlled solely by wolf, as wolf population was limited by wolf large range for enough prey to exist; and wolf could only grow to a level that avoided conflicts with husbandry. Even large wolf growth rates could not match the dynamics of boar which suggested that the natural landscape and agricultural plots were feeding boar, and that human consumption of boar should be factored in.

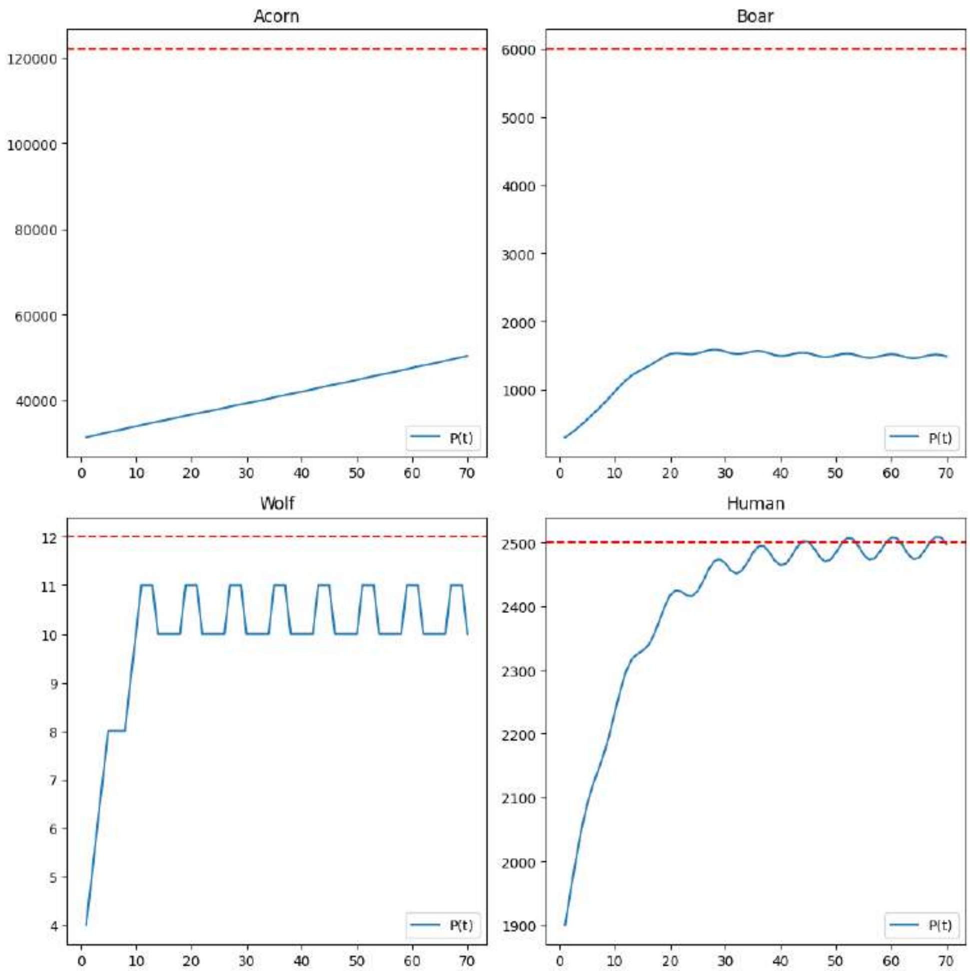

Figure 5. The human repopulation – rewilding base model. “Acorn” stands for trees producing acorns, which are among the most energy-rich boar feeds. Boar in turn was central in this trophic network, as it fed on acorn and fed wolf. Humans participated in reforestation and wood consumption, wolf reintroduction and boar consumption.

The Lotka-Volterra model showed an increase in acorn-bearing trees from 31 thousand to 50 thousand. At a reforestation density of 1000 trees per square kilometer, this was a 19 km^2 reforestation. Reforestation, in addition to its direct carbon sequestration, had an indirect contribution via its role in erosion control. The reduction of soil erosion ensuing reforestation was 0.12 t/ha/yr soil C sequestration (FAO, 2024) despite 2.2 t/ha/yr soil loss (Comunidad Autónoma de Castilla y León, 2012).

But the model also highlighted the difficulty in reaching the tree carrying capacity, due to the pressure exerted by boar and humans. Boar in this model was successfully controlled by human pressure. Wolf pressure on boar however was very limited due to the small predator population. Boar ended the transition at less than a third of the population predicted by its current trend.

Trophic Model Sensitivity Analysis (21st Century Scenarios)

Qualitatively, the simulations produced variants of two scenarios: Sustainable repopulation and rewilding, and Extractive rural world. The upshot is that human growth up to carrying capacity and pressure on boar would allow for reforestation, with wolf a necessary predator whose functional role in the ecosystem is thwarted by humans. Under Sustainable repopulation and rewilding (the reference model, Figure 5), boars were controlled well below their possible maximum population, humans grew from 2030 through 2050, but the timber industry limited reforestation. In the Extractive rural world, continued human depopulation prompted a continued boar surge.

3.3. Interstitial Permaculture and Rewilding Benefits

When the permaculture and ecological strands of this study are brought together, it appears that repopulation and rewilding can be mutually beneficial. Benefits for every invested Euro are 4-38 Euro (Directorate-General for Environment, 2024). The values in the Lotka-Volterra model parameters determined the ecobenefits of permaculturists (Table 4). Human repopulation (from 1,900 to 2,500 dwellers in 70 years), if driven by in-migration or immigration of interstitial permaculturists contributed only a small additional ecological footprint, compensated for by improved practices and ecobenefits. Job generation (based on 2 permaculturists per permaculture and 2 dependents, for a total increase of 600 persons) was 300 jobs. This occurred at carrying capacity level and, in an ageing rural hinterland, was a valuable increase.

Table 4. Interstitial permaculture and rewilding benefits.

Rural change	Solutions to agricultural issues	Solutions to global change issues
Human repopulation	Stable job generation by permaculture. Recovery of local knowledge, practices and commons.	Stewardship of abandoned land. Local knowledge added to global scientific assets.
Bocage reforestation	Reduction of soil erosion. Regulation of evapotranspiration in the plots.	Mitigation of solar radiation forcing. Hedgerows as obstacles to herbivory and pathogens reduce the need for agrochemicals.
Interstitial permaculture	Increased nutritional density and innocuity of foodstuff. Recovery and protection of wild and cultivable medicinal and edible plants.	Carbon farming. Local production reduces the carbon footprint of foodstuff transportation.
Wolf reintroduction	Control of wild boar and zoonoses. Control of boar herbivory impact on cereal production. Ecotourism.	Change in the framing of predator issues in the press and political discourses.

4. Discussion

This study departed from studies on the limits of Earth's life support system and instead tried to pinpoint the limits of a viable space at a scale where models are actionable. Rural issues are multifarious and highly interconnected. This makes agricultural and rural policy outcomes difficult to predict. Calls for agriculture planning seem to be on the rise, but mostly rely on data repositories without mentioning that actionable models of dynamics and high interconnectedness are lacking.

Globally and locally, sustainable agriculture could help solve its own environmental footprint, while agroforestry can help in carbon sequestration via protection of soils (against erosion brought about Green Revolution mechanical and chemical technologies). This approach to agriculture is termed Carbon Farming and is embedded in the 2023 official Spanish policy approved by the European Union for its new Common Agricultural Policy (Directorate-General for Agriculture and Rural Development, 2023; McDonald et al., 2021). Salas has the second lowest soil loss in the Burgos province (Comunidad Autónoma de Castilla y León, 2012) and IP, agroforestry and reforestation could accrue revenue in the Carbon Farming certification schemes now developing. Caution is warranted however, regarding carbon schemes which could derive into monoculture afforestation with fast-growth species. This would derail the transition to sustainable agriculture. Recent research shows that permaculture enhances soil carbon content and biodiversity (Reiff et al., 2024).

Locally, human repopulation was found to rely on an IP embedded in the local trophic network. In this network, the largest trees and mammals were accounted for (save for cattle). The most striking suggestion of the simplified trophic network was that boar consumption by humans was likely needed to compensate for agricultural losses attributable to boar and because boar meat is more sustainably produced than pig meat; both meats are indistinguishable genetically and in taste (Machácková et al., 2021; Sales & Kotrba, 2013; Strazdiņa et al., 2013). The history of boar and pig consumption by humans in Atapuerca, a few kilometers from Salas, spans the Holocene (Galindo-Pellicena et al., 2024). Another justification for boar control are zoonoses; they have prompted a European reaction, and in the Castilla y León community and Salas, the enactment of an order to augment hunting pressure on boar (Boletín Oficial de Castilla y León, 2024).

The ongoing nutrition transition with lessened environmental impacts in Spain includes the noticeable increase in consumption of vegetables and diminution of meat consumption, especially among younger generations (Lantern, 2021). Concomitantly, Spain is the European leader in organic agriculture (Agrospecials, 2023).

Policies and Simulation of Rural Future

It is a sobering fact that policies are fraught with side-effects and non-coordination (especially between agricultural and ecological policies), which call for simulations prior to discussion and implementation. Based on the insights gained from documenting the feasibility of IP and the simulated future trophic network, the following recommendations emerged:

1. Sustainable land use management policies are crucial in degraded regions.
2. Forest and land policies aimed at increasing connectivity and biodiversity through reforestation programs align with IP.
3. Wild boar population control: Effective management strategies include reducing food availability, selective culling of younger wild boar, and controlling access to feeding sites. These methods have been tested in peri-urban areas to manage populations and can be adapted to rural areas. Promoting humane culling would largely improve the quality and market value of wild boar meat. Culling piglets is more efficient than culling adults as fewer boar-years are spent impacting environment and crops.
4. Wolf reintroduction: Integrating a keystone predator into land use management helps naturally control wild boar populations. Policies should incentivize farmers to maintain free-ranging livestock systems that coexist with wolves, as these systems contribute to ecological balance while minimizing human-wolf conflicts.
5. Permaculture and human repopulation: This could be supported by regional policies focused on sustainable land and water management, fertigation plans and automation that aim to balance environmental and economic goals. Policies incentivizing sustainable agricultural practices, like rotational grazing and reforestation, could create jobs and attract people to rural areas while improving the ecological health of the region.
6. Subsidize sustainable agriculture preferentially. Sustainable agriculture requires land not to be chronically overused, not overpopulating terroirs, integration in the larger ecosystem, no debt-financed Green Revolution technologies and non-exploitative use of labor. Subsidies should favor technologies such as: no tillage, rotation, waste recycling, use of renewables, biological control, automated belowground fertigation, hedgerows, participation in carbon farming.

Specific policies with a potential for supporting IP include:

(1) Zoning regulations that encourage the repurposing of vacant land for permaculture projects. Flexible zoning can allow for community agriculture.
(2) Subsidies, such as grants or tax breaks, for individuals, cooperatives and communities engaging in permaculture practices on interstitial land for ecological restoration.
(3) Community Engagement and Support in permaculture through educational and training programs can enhance social cohesion, knowledge preservation and healthy ecosystems. Ongoing intergenerational attitude shifts are best fostered via educational programs.
(4) Research policies, agricultural extension and citizen science should evolve into collaborative inquiry with permaculturalists and live-in laboratories.
(5) Public awareness campaigns and partnerships between local governments and grassroots organizations are critical to supporting IP.

Supplementary Materials: The following supporting information can be downloaded at: https://zenodo.org/doi/10.5281/zenodo.13740794, Sensitivity analysis.

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Article

Financial Analysis and Cost Implications of Implementing an Agroforestry System in Brazil

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Abstract: Agroforestry Systems (AFS) integrate agricultural and forest production, providing ecosystem environmental services. They are considered important tools for addressing problems caused by modern agricultural development. Despite their proven environmental and productive benefits, more studies are needed to support the viability and adoption of AFS by rural producers. This study accounts for the primary costs of implementing 1 hectare of a biodiverse AFS in Brazil. The results show that the acquisition of seedlings and propagules constitutes the highest costs, with avocado seedlings being the most expensive. Operational costs, particularly grading and the purchase of inputs, also represent significant expenses. Future research should focus on tracking the evolution of implementation costs, substituting expensive external supplies, and optimizing operational times for area preparation. These efforts will enhance the design and viability of AFS, addressing local producer needs and ensuring profitable maintenance.

Keywords: sustainable agriculture; financial viability; implementation costs; agricultural development; operational costs

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1. Introduction

The model of agricultural development adopted in Brazil through the Green Revolution, consisting of the use of technological packages linked to petrochemical and mining products, allowed the country to improve its position in the global scenario as an exporter of agricultural commodities and fostered internal industrial growth (Nehring, 2022). Since 1960, the technological revolution has led to significant transformations in almost every economic sector, including agriculture. This has resulted in profound changes in the social and territorial division of agricultural work, with the primary goal being to boost productivity and lower production costs through the utilization of machinery, chemical additives, and biotechnological inputs provided by the industry (Martinelli et al., 2010; Oyvat, 2016).

However, some consequences have emerged, such as social impacts on agrarian structure, environmental issues, and income concentration, exacerbating the agrarian and urban crises (Martinelli et al., 2010; Oyvat, 2016). The adoption of modern machinery in Brazilian farming reduced the need for labor, leading to an increase in rural exodus (Nehring, 2022). Large areas of natural vegetation were converted into agricultural land, leading to increased soil compaction, salinization, and desertification. Soil and water were also contaminated by agrochemicals (Pingali, 2012). There was a significant increase in pressure on areas suitable for this agriculture model, leading to social and environmental conflicts (Paulino, 2014).

Given the serious environmental and social impacts generated, there's hope to ensure that future generations continue to have access to natural resources vital to life and production (Nehring, 2022; Pingali, 2012; Srivastav, 2020). The Agroforestry Systems (AFS) adopt less aggressive production practices, playing an important role in this scenario (Angelotti et al., 2015; Gomez-Zavaglia et al., 2020; Ollinaho & Kröger, 2021; Sacramento et al., 2013). The AFS refers to a combination of land use systems and technologies that incorporate at least one perennial plant species into crop and/or animal husbandry within the same management unit, taking into account their spatial arrangement and chronology (Nair et al., 2021). AFS vary widely according to the purpose of establishment and in the spatial arrangement and they can use native plants, animals, and crops interleaved with trees (Rosa-Schleich et al., 2019). In this area, different species coexist and are planted and managed according to their specific requirements. The primary objective is to optimize biomass production, efficient use of space, light and nutrients, and produce agricultural and non-agricultural goods essential for human life and to ecosystem services (Haggar et al., 2019; Santos et al., 2019).

Comparing the performance of different systems requires an understanding of production costs. Technical coefficients for AFSs must consider labor, supply inputs, seedlings, and seeds necessary for implementation, as well as the management of the cultivation area for each species (Arco-Verde & Amaro, 2021). This allows for a cost projection specific to each species, leading to more accurate analyses, especially as AFSs consists of multiple plant species.

In order to promote AFSs as a replicable tool to distinct groups of producers, it is necessary to create management tools (Bowman & Zilberman, 2013). These might include cost estimates for area implementation, production forecasts and revenue projections, enabling efficient planting and management for achieving necessary profitability and socioeconomic improvements. Therefore, it is crucial to conduct studies that outline the costs of AFS implantation. The complexity of having multiple species within the reproductive system requires special attention to production dynamics. This is important not just for on-site management, but also for accurate financial projections, including initial expenditures such as supplies, seeds, seedlings, and labor costs. This data is fundamental to assist in the management of cultivated areas, as it takes into account the costs farmers will incur during implementation. Therefore, the purpose of this paper is to present and discuss the main costs of implementing one hectare of a biodiverse Agroforestry System in Brazil. To achieve this, we adhered to the steps outlined in Figure 1.

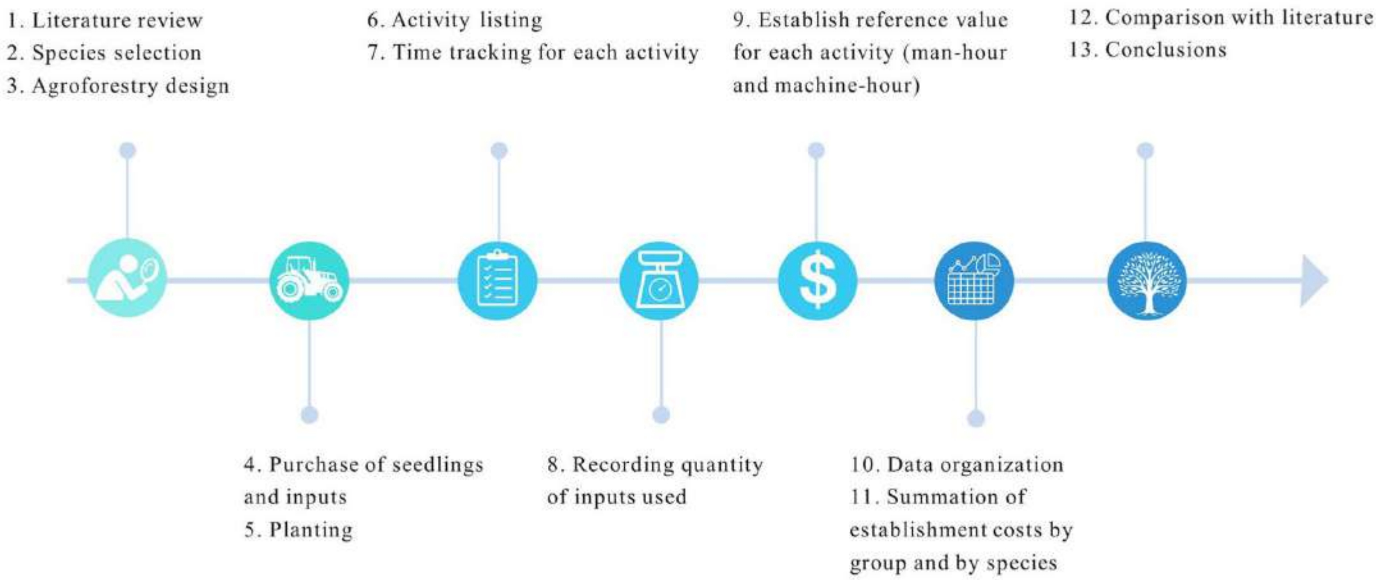

Figure 1. Key steps for evaluating the costs of implementing a biodiverse Agroforestry System in Brazil.

Literature Review

The adoption of AFS can bring a series of benefits and advantages to farmers, both economically and ecologically. Properties can experience economic advantages due to the diversity of production (Jezeer et al., 2018), increased productivity (Rezende et al., 2021) and the promotion of a green economy in which environmental services provided might be compensated. The soil will be protected as it benefits from reduced water and nutrient loss, as well as decreased erosion processes (Fahad et al., 2022). This also leads to an increase in fauna abundance, possibly attracting more predators to control herbivorous insects and more pollinators to aid in fruit formation (Marsden et al., 2020).

Ecologically, trees offer protection for vegetation, enhance biological pest control (Moura et al., 2021), reduce humidity loss, and mitigate wind impact (Anjos et al., 2022). The arrangement of the landscape surrounding cultivated areas has an impact on pollinator diversity. It offers new nesting possibilities and food resources throughout the year, subsequently, enhancing productivity, including fruits and seeds (Coutinho et al., 2020; Hipólito et al., 2018; Torezan-Silingardi et al., 2021). Furthermore, AFS demonstrated a more favorable assessment of environmental services compared to full-sun systems (de Melo Virginio Filho et al., 2021). Moreover, diversified practices like AFS offer significantly greater biodiversity and related ecosystem services, such as pest and weed control, soil health, nutrient and water management and carbon sequestration compared to non-diversified farming (Hübner et al., 2021). Multiple factors demonstrate the benefits of AFS in agriculture. AFSs offer significant environmental advantages by promoting the sustainable use of natural resources while reducing the need for external inputs (Froufe et al., 2020). This leads to increased food security and cost savings for producers. As a result, agroforest ecosystems tend to be more resilient in the face of economic and environmental challenges compared to conventional systems, particularly for small and medium-scale family farmers (Rosa-Schleich et al., 2019).

Despite studies showing that AFSs may be economically, socially, and ecologically viable (Rasmussen et al., 2024), they are not widely adopted (Do & Whitney, 2020). The increased biodiversity within AFS production complicates cultivation, requiring knowledge of the species, how to incorporate them into the production space, their growth habits, nutritional needs, and ecological factors (Sagastuy & Krause, 2019). It is important to have prior knowledge about the benefits and drawbacks that certain species may bring to financial gains and the cultivation area when grown in association with other plants. With this preliminary understanding, revenue can be generated by cultivating agricultural species that provide quick economic returns and intercropping them with timber species that yield financial returns in the long term (Sagastuy & Krause, 2019).

Farmers need to have a good understanding of the farming process and the design model for the areas to be cultivated and managed. This knowledge allows for making interventions that are beneficial in the long term and lead to profitable farming systems (Valencia et al., 2015; van der Wolf et al., 2019). Even though not just the concept and background are important, the role transition to achieve an established AFS must be taken into account (Ollinaho & Kröger, 2021). Associated with this knowledge are the financial aspects of the system. Not only crop yield, but also labor costs, price premiums for product quality, and additional income streams and costs of inputs are main factors that influence overall profitability (de Melo Virginio Filho et al., 2021). Diverse agricultural practices, such as AFSs, have been shown to potentially result in higher and more consistent yields, improved profitability, and reduced long-term risks. However, according to Rosa-Schleich et al. (2019), the ecological benefits for farmers were found to only partially outweigh the economic costs in the short term.

Sagastuy and Krause (2019) identified the three most commonly mentioned reasons why conventional agriculture farmers are hesitant to shift to agroforestry practices: uncertainty about whether the system will work, concerns about potential reduction in yield of the main agricultural crop, and a lack of models and knowledge in the region. This demonstrates the necessity of economic feasibility studies before implementing agroforest projects (Martinelli et al., 2019).

The absence of economic and financial indicators tailored to the needs of agroforestry production in agriculture can hinder adoption. Therefore, utilizing modeling tools and economic indicators can help identify the most suitable species configuration with the potential for both fast and long-term economic returns. This process can improve understanding of the market and help in accurately selecting crops. Studies have shown that diversified farming systems are just as profitable as simplified farming systems, with higher total costs, gross income and profits (net income or gross margin) in diversified systems compared to simplified ones. The benefit-cost ratio was found to be equivalent in both types of farming systems (Hübner et al., 2021).

There is strong evidence to suggest that AFSs are not only feasible but also economically advantageous compared to simplified farming systems in various situations (de Melo Virginio Filho et al., 2021). The benefit-cost ratio was found to be higher in diversified systems utilizing agroforestry (Hübner et al., 2021). Estimates show that household income generated from agroforestry was approximately three times higher than the income generated from conventional farming (Abbas et al., 2021).

The complexity of integrating multiple species into diverse systems also reflects in the complexity of evaluating positive financial indicators. Financial indicators in AFS do not always guarantee long-term success (Paul et al., 2017). Palma et al. (2020) conducted a study within an organic ADS and found that despite positive initial indicators during the evaluation period, the field results did not meet expectations. They discovered that high density of perennial species and improper allocation negatively affected production. Additionally, the high plant density and the number of trees in the system significantly increased overall costs and energy inputs (Tabal et al., 2021).

Costs in a diverse planting system can depend on a range of factors. From an overall perspective, it is possible to identify that labor availability and costs are concerns among researchers and practitioners. Before establishing an AFS, it is important to consider production cost and its economic feasibility (Martinelli et al., 2019). The choice of planting method, whether manual, semi-mechanized, or fully mechanized, labor availability (de Morais et al., 2023; Huang et al., 2023), input costs, and subsidies are all factors that impact the total cost. Studies conducted in various regions have shown that labor costs increased in diversified farming systems, but so did gross incomes, leading to farm profits equivalent to those in simplified systems (Hübner et al., 2021).

Those findings are similar as seen in other studies, such as Bentes-Gama et al. (2005) that discovered that labor represented over 50% of total costs, with the highest proportion occurring during land preparation. Armando et al. (2002) reported that the highest expenses were related to inputs, materials, and services (56.86%), followed by labor (43.14%). In a study by Pauletto et al. (2018), it was found that labor costs for cleaning and preparing the cultivation area accounted for 38 to 45% of the total resources invested in the crop. The labor demand in an AFS is influenced by several factors, including species composition and productive objective. AFSs designed for vegetable production, for example, require greater work intensity and more workers (Palma et al., 2020). Thus, the cost assessment of a complex production system depends on factors such as area size, plant quantity, technological level, labor availability, and crop focus (Grahmann et al., 2024; Tabal et al., 2021).

2. Methodology

2.1. Studied Area: Region and Rural Property Profiles

The study was conducted at the rural property "Sítio São Francisco" (23°09'53.50"S and 49°32'51.13"W) in the municipality of Timburi, São Paulo State, Brazil, from September 2021 to March 2022. We assessed the establishment of a one hectare diverse AFS using a variety of fruit and timber species. The area is predominantly covered by vegetation from the Atlantic Forest biome. Timburi town has a population of 2,647 people and a strong presence of family farming in its agricultural sector (Instituto Brasileiro de Geografia e Estatística, 2021). This has inspired the property owners to introduce agroforestry prototypes in the region. The rural property under analysis is actively working on projects aimed at developing and producing AFSs with the vision of setting a precedent for the region. It's worth noting that the municipality falls within the environmental preservation area of the state of São Paulo, designated by State Decree No. 20,960 dated June 8, 1983.

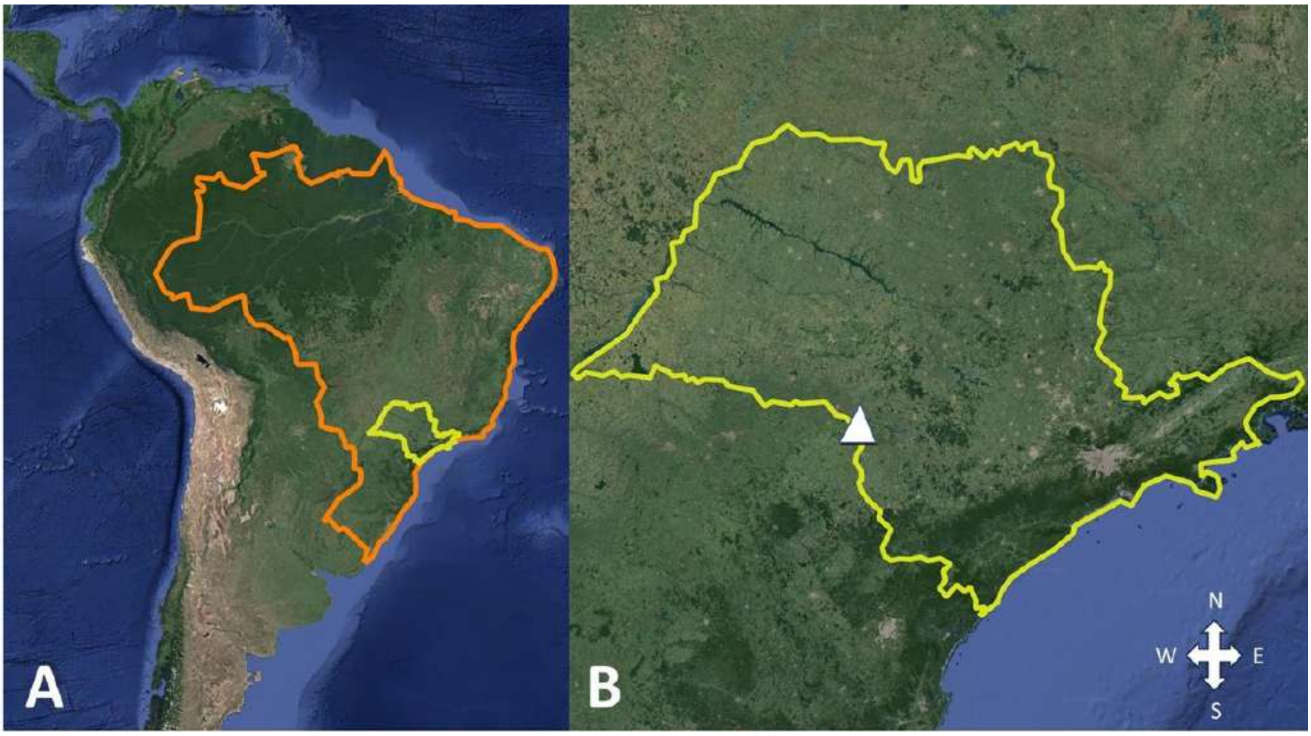

Figure 2. Study area. The São Paulo state (yellow) is located in the Southeastern part of Brazil (orange) (A). The Sítio São Francisco is situated in the city of Timburi (B), indicated by the white triangle.
Source: Google Earth.

2.2. Plant Species

The plant species used for the intercropped AFS were spaced in rows 4 meters apart from each other. The conventional avocado planting logic (8×6m) was used, with other species planted in between the free spaces. The exotic Avocado (*Persea americana*, Lauraceae) was the main crop on the property. Hass, Quintal, and Margarida were the three avocado varieties planted as a strategy for diversification and to synchronize pollen exchange among them (Gaurha et al., 2024). The dwarf banana (*Musa paradisiaca*, Musaceae) is an exotic invasive plant with medium to low stature (2.0 to 3.5 m) and was planted in all rows. This banana variety is considered cold-tolerant and moderately tolerant to nematodes, while also showing good potential for productivity (Quénéhervé et al., 2012). Pink pepper (*Schinus terebinthifolia*, Anacardiaceae) is a small-sized species native to the coastal restingas in Brazil. It was planted in rows interspersed between the rows of forestry species (African mahogany and pink jequitibá) for commercial purposes. This is because its seeds are used as a spice, and also serve as a species for pruning of its branches and leaves for fruit harvesting, which returns material to the soil after fruit separation (Wilkomm et al, 2024). Pink jequitibá (*Cariniana legalis*, Lecythidaceae) is a native tree species of the Atlantic Forest. It is being considered in this design for increasing diversity and producing long-cycle timber (Ribeiro et al., 2022). African mahogany (*Khaya grandifoliola*, Meliaceae) was chosen as a medium-cycle timber species. This exotic species has good wood quality and market value (Ferraz Filho et al., 2021), and it is more tolerant to tip borer than Brazilian mahogany. The species that had the highest number of planted seedlings in the area was the pink pepper, while the species with the lowest quantity was the pink jequitibá. As part of a strategy for biological nitrogen fixation and biomass production to cover the planting rows, four species were sown as cover crops: sunn hemp (*Crotalaria juncea*, Fabaceae), an exotic species, pigeon pea (*Cajanus cajan*, Fabaceae), jack bean (*Canavalia ensiformis*, Fabaceae), and forage radish (*Raphanus sativus*, Brassicaceae). The cover crop species were sown in the inter-row spaces only after planting the forestry and fruit species. Among the planted species, only sunn hemp is considered by the Horus Institute as an invasive species (Instituto Hórus, 2022).

2.3. Cost Calculations

This study accounts for the primary costs of implementing one hectare of a biodiverse AFS in Brazil, and the methodology used was based mainly on Araújo (2020). First, all the activities carried out to effectively characterize their operation and performance needed to be listed. For the application of the methodology, the establishment costs of the systems were divided into individual costs per species and collective costs. This separation resembles what happens at the field level, where some operations and supply inputs are used throughout, and others are specific to a given species. For example, the amount of hydrogel used per species or the time spent digging avocado planting holes is larger than the holes required for the forestry species.

The data was directly assigned to the activities performed by the producer based on the time spent and the cost generated for each activity. This process was applied to all system activities, including area preparation and planting. Reference values, taken as premises, accounted for the prices associated with establishing the studied AFS, as presented in Table 1. To determine costs, a base salary of R$1,200.00 per month in 2022 was established, with taxes set at 90% of this amount. The total is then divided by the average number of hours worked per month to calculate the hourly wage paid to each worker. The “hour/machine” figure represents the average regional rate for one hour of work with rented machinery, as provided by the owners.

Table 1. Individual costs on AFS implementation date expressed in Brazilian reais (R$), and after conversion to US dollars (US$) according to the exchange rate on the date of each publication.

Cost description	Individual cost (R$)	Exchange rate	Individual cost (US$)
Hour/person	12.7	4.73	2.68
Hour/machine	200.00	4.73	42.28
Hour/semi-mechanized labor	15.20	4.73	3.21
Salary	1,200.00	4.73	253.7
Taxes	0.90	4.73	0.19
Total labor costs/month	2,280.00	4.73	482.03

The resources used for carrying out the activities were documented in the field records. The costs associated with the activities and the total amount of resources used for specific tasks for each species were calculated periodically. For example, the quantity of hydrogel applied in plant holes varied for each plant species as shown in Table 2, as well as the amount of seedlings used per hectare, as shown in Table 3.

Table 2. Hydrogel amount (Kg) used per seedling of each species.

Species	Kg
Avocado (Plastic bag)	0.007
Pink pepper (Seedling tray)	0.003
Dwarf banana (Plastic bag)	0.003
African mahogany (Seedling tray)	0.003
Pink jequitiba (Seedling tray)	0.003

Table 3. Number of plants per species per hectare based on the proposed design.

Species	Plants/ Hectare
Pink pepper (*Schinus terebinthifolia*)	1,000
Dwarf banana (*Musa spp.)*	667
Avocado (*Persea americana*)	208
African mahogany (*Khaya senegalensis*)	156
Pink jequitiba (*Cariniana legalis*)	52

To calculate the identification costs for each species and the total cost of implementing the AFS, we categorized the inputs and activities into operational costs, supply costs, and seedlings and propagule costs. The total costs are the sum of these three categories. Each category has further subdivisions and descriptions of the items within it. For instance, in the operating costs we include the expenses related to cleaning and preparing the planting area. If the activity was not carried out in the entire area, the description includes the name of the species for which it was done. This approach was also used for the other groups, which allows for the allocation of costs for each species at the end.

2.4. Agroforest System Implementation Methodology

The label "semi-mechanized" is used because machinery and implements are used for site preparation and supply input distribution, while manual labor is used for the remaining operations. The sequence of operations for site preparation was determined based on the area's history, soil chemical and physical analysis, the experience of the technicians, and the availability of machinery and labor. Soil preparation was done using a Massey Ferguson tractor (4×4, 80hp) with a 16-disc drag harrow (Figure 3A). Then, lime and gypsum inputs were evenly distributed with new harrowing for better incorporation (Figure 3B). After that, our chosen organic fertilizer, the chicken manure, was spread in the planting rows using a lime spreader before row preparation (Figure 3C). Afterwards, a Forest Subsoiler SR with a fertilizer distribution box was used to prepare the planting rows (Figure 3D). Cover crop seeds were then sown in the spaces between the rows, and wood shavings were spread to cover the soil (Figure 3E). Then, holes were dug manually (Figure 3F), hydrogel was distributed, and seedlings were planted (Figure 3G).

Figure 3. Preparation of a biodiverse agroforestry system in Timburi city, Brazil. Soil tillage (A); soil amendment (B); distribution of chicken manure (C); subsoiling of planting rows (D); distribution of wood shavings to cover planting rows after sowing green manure seeds (E); manual digging of planting holes for the placement of seedlings rows (F); planting of seedlings (G).

3. Results

The total amount spent per hectare after totaling all product categories was R$28,164.60, equivalent to $5,954.46 (Table 4). The cost breakdown shows the percentage of each category relative to the total cost. It indicates that the purchase of supplies represents the lowest cost at 19%, followed by operation costs at 24%, and the most expensive being the acquisition and care of seedlings and propagules at 57%. The expenses for operations and the purchase of agricultural supplies (Table 5) were lower than the expenses incurred for the purchase of seedlings and propagules (Table 6).

Table 4. Total costs per component implanted in one hectare of biodiverse AFS in Timburi, SP, in Brazilian reais (R$), after conversion to US dollars (US$) according to the exchange rate on the date of each publication, and in percentage (%).

Group	Individual cost (R$)	Exchange rate	Individual cost (US$)	Percentage (%)
Supply Cost	5,350.49	4.73	1,131.18	19
Operational Cost	6,780.5	4.73	1,433.51	24
Seedling and Propagule Cost	16,033.60	4.73	3,389.77	57
TOTAL COST/HECTARE	28,164.60	4.73	5,954.46	100

Table 5. Operations performed during area preparation (AP) and planting (Pl), including required materials, unit considered as hour/machine (H/M) or hour/person (H/P), time spent during operation, and final cost of each process in Brazilian reais (R$) and US dollars ($), considering the exchange rate of 4.73.

	Performed Operation	Material	Unit	Time (hour)	Total Cost (R$)	Total Cost (US$)
AP	Area cleaning	Chainsaw	H/P	8.0	121.60	25.71
	Grading	80 hp Tractor (36" Disc Harrow)	H/M	8.0	1,600.00	338.27
	Liming operation	FertiMax DCA 5.8 Lime Spreader	H/M	4.0	800.00	169.13
	Assistance in liming operation	Marispan Front Bucket	H/M	0.6	120.00	25.37
	Row preparation	Forest Subsoiler SR	H/M	4.0	800.00	169.13
	Distribution of manure in the rows	FertiMax DCA 5.8 Lime Spreader	H/M	4.0	800.00	169.13
	Assistance in manure distribution	Marispan Front Bucket	H/M	0.6	120.00	25.37
	Distribution of wood shavings in the rows	FertiMax DCA 5.8 Lime Spreader	H/M	4.0	800.00	169.13
	Assistance in wood shaving distribution in the rows	Marispan Front Bucket	H/M	0.6	120.00	25.37
Pl	Opening of avocado planting holes (Plastic bag)	Manual Shovel	H/P	12.5	158.08	33.42
	Opening of pink pepper planting holes (Seedling tray)	Manual Shovel	H/P	16.0	202.67	42.85
	Opening of dwarf banana planting holes (Plastic bag)	Manual Shovel	H/P	10.7	135.18	28.58
	Opening of African mahogany planting holes (Seedling tray)	Manual Shovel	H/P	2.5	31.62	6.68
	Opening of Pink jequitiba planting holes (Seedling tray)	Manual Shovel	H/P	0.8	10.54	2.23
	Distribution of seedlings	Wheelbarrow	H/P	10.0	126.67	26.78
	Hydrogel distribution – Avocado planting hole	Bucket	H/P	2.1	26.35	5.57
	Hydrogel distribution – Pink pepper planting hole	Bucket	H/P	5.0	63.33	13.39
	Hydrogel distribution – Dwarf banana planting hole	Bucket	H/P	3.3	42.24	8.93
	Hydrogel distribution – African mahogany planting hole	Bucket	H/P	0.8	9.88	2.09
	Hydrogel distribution – Pink Jequitibá planting hole	Bucket	H/P	0.3	3.29	0.7
	Planting of avocado seedlings	-	H/P	10.4	131.73	27.85
	Planting of pink pepper seedlings	-	H/P	16.0	202.67	42.85
	Planting of dwarf banana seedlings	-	H/P	10.7	135.18	28.58
	Planting of African mahogany seedlings	-	H/P	2.5	31.62	6.68
	Planting of Pink Jequitibá seedlings	-	H/P	0.8	10.54	2.23
	Protection of avocado seedlings	Aluminum Protector	H/P	5.0	63.33	13.39
	Staking of seedlings	Bamboo	H/P	5.0	63.33	13.39
	Seeding of cover crops in the inter-rows	Raffia bags	H/P	4.0	50.67	10.71
		TOTAL			6,780.51	1,433.51

Table 6. Supply investments used, considering each quantity in kilograms (Kg), the price per unit and delivery cost in Brazilian reais, and final cost of each supply in Brazilian reais (R$) and US dollars ($), based on an exchange rate of 4.73.

Supply	Unit	Quantity (Kg)	Price per unit + delivery (R$)	Total Cost (R$)	Total Cost (US$)
Limestone	Ton	1.5	250.00	372.00	79.28
Gypsum	Ton	0.3	200.00	60.00	12.68
Reactive Natural Phosphate (29% P205)	Ton	0.4	780.00	312.00	65.96
Hydrogel for Avocado planting hole	Kg	1.4	33.00	45.30	9.58
Hydrogel for Pink Pepper planting hole	Kg	3.3	33.00	108.90	23.02
Hydrogel for Dwarf Banana planting hole	Kg	2.2	33.00	72.64	15.35
Hydrogel for African Mahogany planting hole	Kg	0.5	33.00	16.99	3.59
Hydrogel for Pink Jequitibá planting hole	Kg	0.2	33.00	5.66	1.2
Chicken Manure (1.2% Nitrogen)	Ton	5.0	150.00	750.00	158.56
Wood shavings	M³	50.0	70.00	3,500.00	739.96
Aluminum Protector for Grafted Seedlings	Unit	208.0	0.50	104.00	21.99
			TOTAL	5,347.49	1,131.18

Table 7. Seedling and propagule cost breakdown per species, considering each quantity in kilograms (Kg), the price per unit, delivery cost and nursery cost in Brazilian reais, and final cost of each item in Brazilian reais (R$) and US dollars ($), based on an exchange rate of 4.73.

Seedling and Propagule	Unit	Quantity (Kg)	Price per unit + delivery + nursery (R$)	Total Cost (R$)	Total Cost (US$)
Pink pepper	Seedling	1,000	2.50	2,750.00	581.40
Dwarf banana	Seedling	667	4.00	2,934.80	620.47
Avocado	Seedling	208	35.00	8,008.00	1,693.02
African mahogany	Seedling	156	5.00	858.00	181.40
Pink Jequitibá	Seedling	52	3.00	171.60	36.28
Sun hemp	Kg	20	17.90	393.80	83.26
Pigeon pea	Kg	20	15.90	349.80	73.95
Jack bean	Kg	20	15.90	349.80	73.95
Forage radish	Kg	20	9.90	217.80	46.05
			TOTAL	16,033.60	3,389.77

The operational cost of each work stage varied, with grading being the most expensive, followed by liming, row preparation, and distribution of wood shavings in the rows (Figure 4). The highest costs for supply inputs were for wood shavings, followed by manure, limestone, and phosphate (Figure 5). The most expensive seedlings and propagules were grafted avocado seedlings, followed by dwarf banana and pink pepper seedlings (Figure 6). Avocado had the highest implementation cost in this AFS design, followed by pink pepper and dwarf banana (Figure 7).

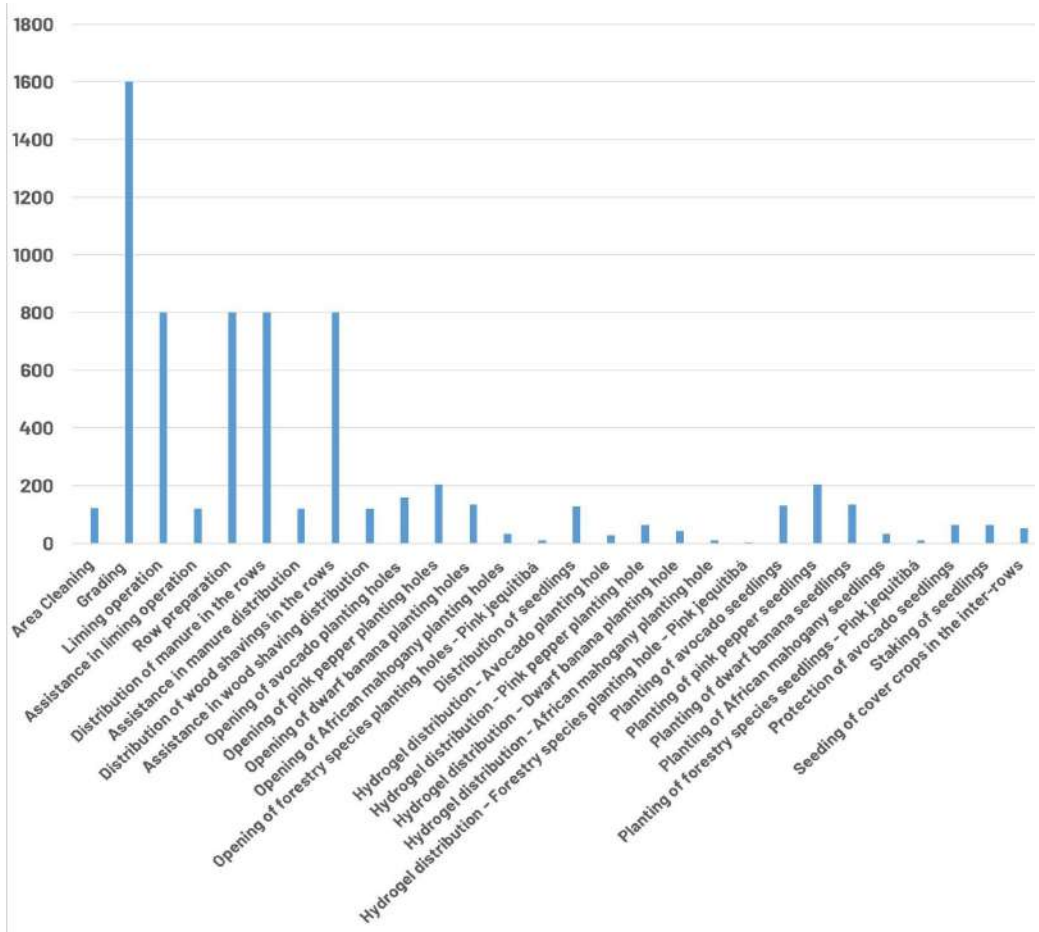

Figure 4. Investment (R$) within operating groups.

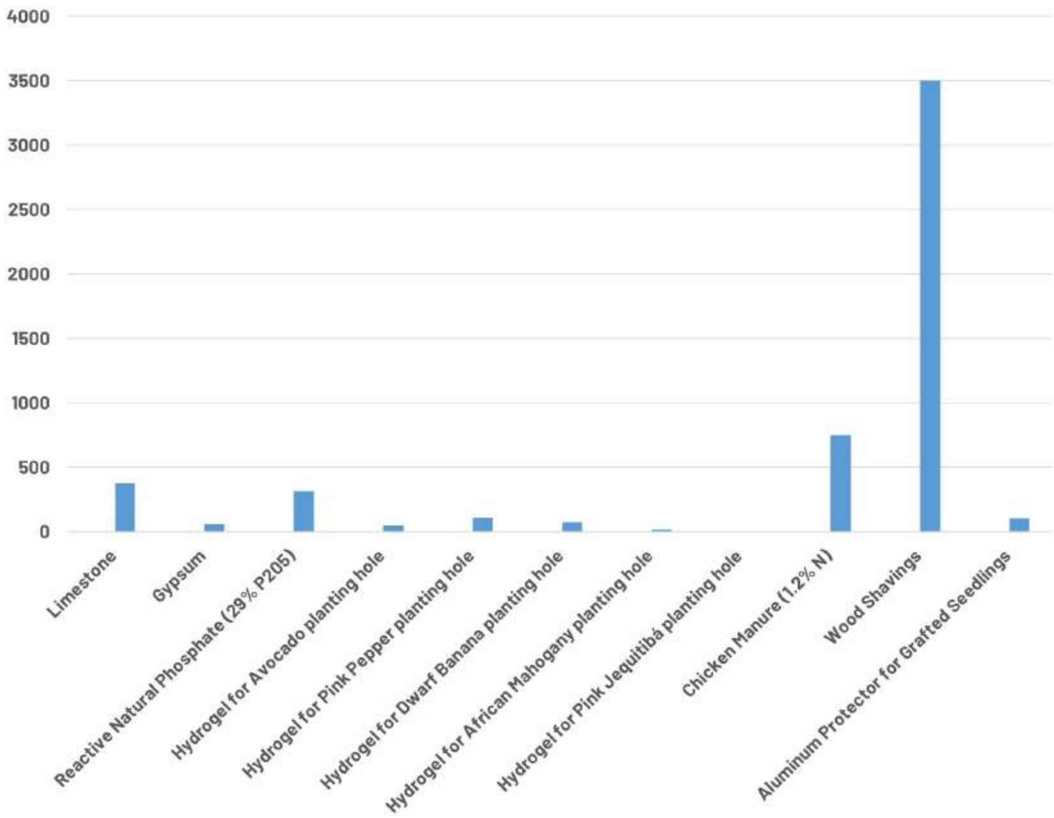

Figure 5. Investment (R$) within the supplies group.

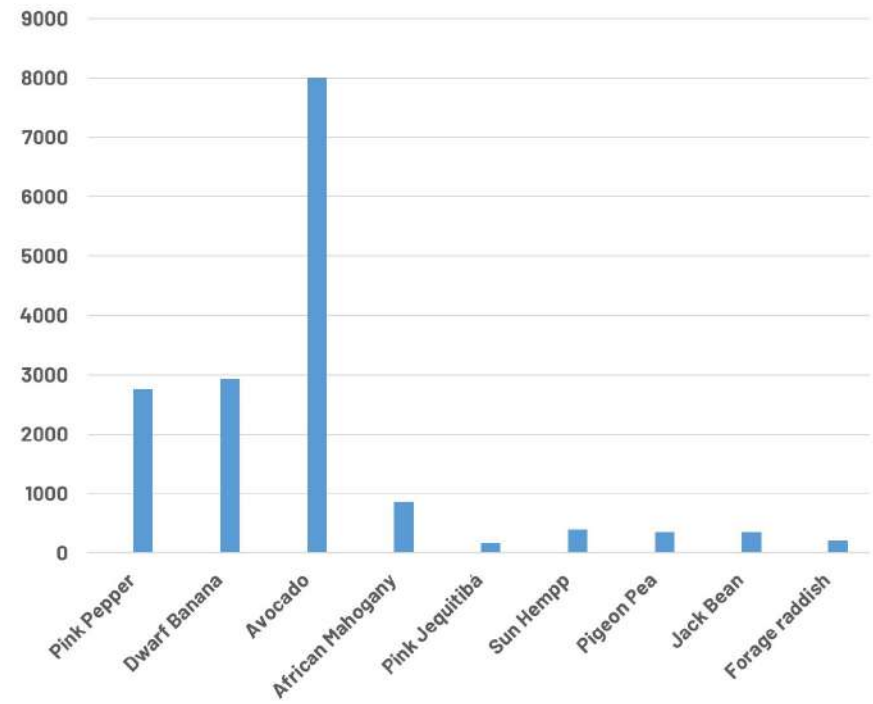

Figure 6. Investment (R$) in the purchase of seedlings and propagules.

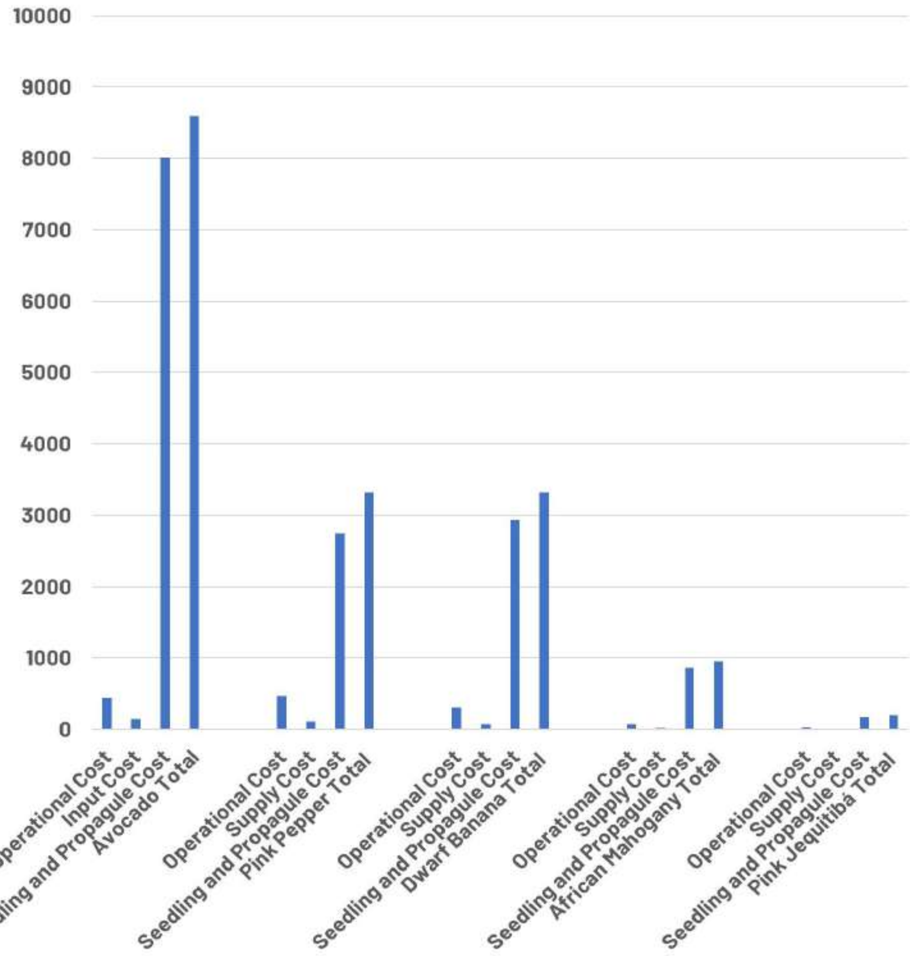

Figure 7. Total investment (R$) per species after the implementation of the agroforest system.

4. Discussion

The implementation costs for one hectare of a diverse AFS varied between the present study and those presented in the scientific literature. The costs observed at "Sítio São Francisco" in Brazil from September 2021 to March 2022 were significantly lower than the costs reported by Oliveira et al. (2017), as shown in Table 8. However, they were higher than the costs reported by Bentes-Gama et al. (2005), as well as the costs reported by Pauletto et al. (2018) for a semi-mechanized AFS and a mechanized AFS. However, when we convert the Brazilian reais to US dollars, the total investment required to implement one hectare of the diverse AFS we investigated was similar to the values found by Bentes-Gama et al. (2005), and the comparisons with the other studies were as previously. The implementation costs of an AFS reflect the complexity of these systems. They can be planned in different ways with varied species compositions and methods, in areas with very distinct original vegetation and characteristics. All these factors influence the overall implementation costs.

Table 8. Comparison of the total implementation costs for one hectare of AFS obtained by several authors in Brazilian reais (R$), and after conversion to US dollars (US$) according to the exchange rate on the date of each publication.

Reference	Total cost (R$)	Exchange rate	Total cost (US$)
Oliveira et al. (2017)	40,499.20	3,15	12,856.89
Oliveira et al. (2024)*	28,164.60	4,73	5,954.46
Bentes-Gama et al. (2005)	20,333.80	3,5	5,809.70
Pauletto et al. (2018): Semi-mechanized AFS	8,115.58	3,7	2,193.40
Pauletto et al. (2018): Mechanized AFS	6,191.48	3,7	1,673.37

* This present study

The cost study for implementing one hectare of diverse AFS showed that purchasing seedlings and propagules was the most expensive component, representing more than half of the total costs (57%) (Table 4). This finding is consistent with the results of Moraes et al. (2013), who allocated a very similar percentage (59.1%) of their costs to purchasing seedlings in the first year of implementing an AFS with coffee as the main crop. This occurred despite three distinct differences between these studies: the species of cultivated plants, the number of site preparation operations, and the types and quantities of inputs used, such as fertilizers, manure, and hydrogel. Consequently, the purchase of seedlings and propagules accounted for a very high percentage of the total expenses in our study, similar to the findings of Moraes et al. (2013). A comparable observation was made by Neves et al. (2014), where the purchase of seedlings and propagules represented 38.2% of the total costs for implementation. The decisive factor for seed costs assuming this importance in the evaluated studies, including the present one, was the high added value that fruit seedlings have in the market compared to forestry species. Therefore, the decision-making process to include species with high added value must consider that the investment in this group will be high at the time of implementation.

The purchase of avocado seedlings within this expense group represented 49.9% of the costs. This can be explained by the acquisition price of grafted seedlings, which require greater care to produce, and by a 10% increase in the final price of the seedling, reflecting the care in the waiting nursery. Our results are corroborated by Mouco et al. (2012), who analyzed the production costs of avocados and concluded that expenses with seedlings were the most significant among all the implantation costs analyzed. These significant seedling implementation costs can be reduced if farmers produce them themselves. However, it is worth noting that this process may be hindered by the need for technical knowledge, as exemplified by the production of grafted seedlings of clonal avocado varieties. The physiological and sanitary quality of the seedlings at the time of planting, among other factors, influences the future productive quality of these plants. Therefore, a technical and economic assessment should be made to determine whether in-house production is viable for reducing costs.

The second most expensive set of costs was the operational cost, which includes all mechanized, semi-mechanized, and manual operations, accounting for 24% of the total cost of implementing the diverse AFS. Of this, 18.68% corresponds to site preparation, while labor concentrated in planting operations accounted for only 5.32% of the total costs. Within the operational costs, site preparation was significantly more expensive than planting, despite requiring fewer hours of machinery used (34 hours in total) compared to planting hours (118 hours; Table 2). The cost of machinery per hour is substantially higher than the cost of labor per hour, resulting in 78% of operational costs being allocated to site preparation and 22% to planting. It is noteworthy that the cost of machinery per hour includes the costs of the machinery operator. Grading was the most expensive soil preparation operation, accounting for 30% of the total, which can be explained by the number of machinery hours required for this efficient preparation, as two gradings were performed, totaling 8 machine hours.

Similar values to ours were found by Palma et al. (2020), with 21% allocated to labor. However, higher values were reported by other authors, as cited below. Pauletto et al. (2018) compared the implementation costs of mechanized and semi-mechanized AFSs, finding that the amount spent on cleaning and preparing the cultivation area consumed between 38 to 45% of the total resources invested in the crop. Armando et al. (2002) found that the implementation of an AFS accounted for 43.14% of labor costs. Bentes-Gama et al. (2005) assessed the production and investment risk of AFSs and found that labor participation was higher in site preparation, corresponding to more than 50% of the total costs. Our results can be explained by the exclusive use of mechanized and semi-mechanized operations during our site preparation, consequently reducing the labor participation in terms of hours of work required. These data highlight the importance of considering that, due to the much higher cost of machinery per hour compared to labor per hour, mechanized AFSs can reduce the need for manual labor but not necessarily the overall costs.

However, costs will vary over time in the years following implementation. Neves et al. (2014) reported that labor costs constituted 80.1% in the first year of maintenance, decreasing to 63.5% by the fourth year. This variation indicates that the relative importance of input costs in implementation and their evolution over time will depend directly on the system type, desired production goals, and management intensity. The same considerations apply to labor, requiring early planning for management practices required by each cop to assess their suitability for the local context. This assessment is crucial for determining whether the system can achieve its intended objectives over time, whether they involve reducing external inputs or labor.

AFSs can be designed to reduce the need for labor over time. Palma et al. (2020) observed that in the first four years of their study on AFSs, labor was intense due to vegetable production. However, as the system matured and shading increased, which was less conductive to vegetable growth, labor requirements significantly decreased. Neves et al. (2014) noted that in the initial year of implementation, labor costs were lower compared to expenditures on inputs and seedlings. However, by the second year, labor costs become predominant due to tasks such as area cleaning, which decreased in the following years, thereby reducing labor needs. This reduction can be attributed to ground cover that minimizes weed growth and improves environmental balance.

The cost of inputs in our study represented the smallest proportion of total costs, accounting for only 19%. This percentage is lower than reported by Armando et al (2002), who found it to be 56.86%, and by Palma et al. (2020), who reported 79%. However, our values were higher than those found by Neves et al. (2014), who reported only about 10% for inputs. While comparing percentages among cost groups depends on their proportional relationship with other groups, it provides insight into how each cost group evolves over time.

Our most costly input was wood shavings, used for immediate soil cover in planting rows. However, the cost of acquiring these shavings combined with delivery fees proved to be financially burdensome, accounting for 65% of the total input costs. An alternative utilized by other AFSs involves using locally sourced vegetative cover, such as grasses, banana stems, pruning residues, and wood (Paula et al., 2015). Therefore, considering on-site production of vegetative material as an alternative to purchasing organic material for soil cover aligns with ecological management principles and can potentially reduce implementation costs.

Among the five species planted, our study found that avocado required the highest total investment per species for establishment. When considering costs in dollars, we observe similar expenditures across the three studies (Table 9), despite variations in study specifics: as our study planted 208 avocado seedlings per hectare, Partichelli et al. (2018) focused on monoculture with 100 avocado seedlings per hectare, and Mouco et al. (2012) planted 250 avocado seedlings per hectare. The slight cost variation between the cited authors and our study results from differences in seedling acquisition costs, labor rates per hour, machinery use per hour, and the number of avocado seedlings planted per hectare, all contributing to the overall cost structure.

Table 9. Comparison of the avocado total implementation costs for one hectare of AFS obtained by several authors in Brazilian reais (R$), and after conversion to US dollars (US$) according to the exchange rate on the date of each publication.

Reference	Total cost (R$)	Exchange rate	Total cost (US$)
Oliveira et al. (2024)*	8,600.13	4.73	1,818.21
Partichelli et al. (2018)	6,683.90	3.5	1,909.68
Mouco et al. (2012)	6,400.00	3.7	1,729.73

* This present study

Alves et al. (2020) investigated the economic viability of AFS focusing on fruit production and observed that commercial fruits are crucial for achieving financial viability. This underscores that, despite the high initial investment required to establish fruit trees within the system, they are strategically necessary for ensuring financial viability, enhancing food security, and bolstering economic and environmental resilience.

Biodiverse AFSs that integrate multiple species in diverse configurations demonstrate potential for financial viability by offering a variety of products, thereby enabling multiple income streams at different times (Oliveira et al., 2017). This supports our approach of maximizing species with commercial value. However, when planning such diversification, it is important to assess whether these species interact antagonistically or synergistically, necessitating ongoing monitoring of AFS evolution and potential management practices like pruning to ensure optimal plant growth.

Thus, it is important to note that despite our gross cost for implementing 1 hectare being higher than that found for monoculture crops, this cost per plant becomes more economical when divided by the number of individuals planted, regardless of the species. We planted a total of 2,083 individuals per hectare including fruit trees, service plants, and timber species, with a total cost of R$28.164,60, resulting in an average implementation cost of R$13.52 ($2.86) per plant. This average cost is significantly lower than that reported for each avocado seedling monoculture by Mouco et al. (2012): R$25.60 ($6.92), as well as by Partichelli et al. (2018): R$66.83 ($19.09).

Moreover, the perceived high implementation cost of an agroforestry system focused on avocado production, such as ours, might seem significant when not considering the quantity of individuals from other species. However, dividing our costs by all individuals planted in the system, as advocated by El Serafy's theory (1989, as cited in de Queiroz et al., 2020), results in a considerable cost reduction. This theory asserts that every available natural asset should be viewed as a permanent source of income. Therefore, even species with long cycles that may not yield immediate commercial returns provide valuable environmental benefits within the planting area. These include nutrient recycling, deeper water uptake that enhances moisture retention, reduced susceptibility to diseases through increased biodiversity, improved light capture, heightened photosynthesis rates, and enhanced soil fertility. These environmental services are essential components of a sustainable planting area.

Ultimately, AFSs should always be designed with a comprehensive approach that includes analyzing the implementation costs of the chosen design, as well as considering social and environmental aspects, local food security, input efficiency, and environmental enhancement (Arco-Verde & Amaro, 2014). Taking a systemic approach to these various aspects related to integrated production systems such as AFSs ensures multiple advantages and benefits. These can be optimized when aligned with a thorough study of implementation costs.

5. Conclusions

When investigating the primary implementation costs of a biodiverse agroforestry system in Brazil comprising five different main species, we found that the most substantial expense was for seedlings and propagules, followed by operational costs, and finally supply inputs. Avocado, chosen for its high economic value, incurred the highest implementation costs due to the expense of purchasing seedlings and the intensive care required for planting them. The significant market value of avocado fruits justifies these initial costs. Moreover, integrating seedling production on farms could potentially reduce acquisition costs, considering both technical and economic factors. Despite high machinery costs, this approach may be feasible in areas with limited labor availability. Contrary to current literature, labor costs in this study accounted for only 5.32% of total expenses. Tailoring the design to fit farmers' circumstances can lead to systems that demand different levels of labor and other management inputs. Furthermore, harrowing operations and the acquisition of wood shavings were identified as the most expensive within their respective categories. While input costs remained relatively low, optimizing the use of locally produced organic materials for row coverings could further reduce expenses. Overall, spreading total costs per unit across the total number of seedlings helps to dilute the expenses of establishing an agroforestry system. Each species planted in this study was selected for specific ecological or economic benefits, underscoring their crucial roles within the agroforestry system and facilitating this cost dilution.

The present investigation was limited to the period of the agroforestry system implementation. We suggest that further studies include the evolution of costs through ongoing monitoring, considering not only the initial implementation costs but also the costs incurred during the development of the agroforestry systems over the years, including the replacement of species. This approach could enhance the financial analysis with the new inputs and the production data from the mature, enabling more complex analyses and addressing many other questions related to agroforestry systems. Future studies can detail the implementation costs of AFSs in distinct countries, considering different species and other requirements. Such studies are essential for the successful application of these systems at the field level and for designing them more efficiently by practitioners according to the specific needs of each farmer. Ultimately, the potential social and environmental benefits of agroforestry systems make them an excellent alternative for sustainable food production, balancing conservation and productivity while supporting family farming. We also emphasize to policymakers the relevance of promoting greater adoption of agroforestry systems among farmers worldwide. Public subsidies and subsidized rural credit can facilitate the establishment of these systems.

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Agricultural & Rural Studies

Article

The Impact of Typhoons on Agricultural Productivity—Evidence from Coastal Regions of China

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Abstract: The impact of natural disasters on agricultural production has garnered global attention. This study takes typhoons as an example, employing their movement paths to construct a difference-in-differences (DID) model and combining survey data from Rural Fixed Observation Spots to estimate changes in agricultural productivity from coastal regions of China, including Guangdong, Fujian, and Zhejiang provinces. This study finds that typhoons significantly deteriorate local agricultural productivity. Specifically, the planting income per mu and planting income per capita of rural households have decreased by 11% and 14%, respectively, while agricultural total factor productivity (TFP) has dropped by 3.7%. The decline in productivity can be attributed to two channels. Firstly, typhoons directly damage crops, leading to reduced total output. Secondly, in anticipation of typhoons, rural households increase asset input but reduce labor input and intermediate goods, resulting in the misallocation of agricultural inputs, which further diminishes productivity. The cost-benefit analysis indicates that to compensate for 20% of the negative impact of typhoons on agricultural productivity, local financial funds ranging from 3.4 million to 20 million yuan are required. Therefore, it is imperative for the Chinese government to strengthen the natural disaster warning system and improve farmland water conservancy infrastructure to mitigate the misallocation of agricultural inputs by rural households.

Keywords: agricultural productivity; agricultural inputs allocation; natural disasters; typhoons

1. Introduction

Agricultural productivity is a fundamental indicator of the quality of agricultural development. Improving agricultural productivity not only enhances agricultural competitiveness but also significantly promotes economic structural transformation (Cao & Birchenall, 2013; Gollin et al., 2021; Lewis, 1954; Ranis & Fei, 1961). According to the classic Cobb-Douglas production function, agricultural productivity is influenced by asset inputs (Cui, 2023), labor inputs (Shi, 2018), land use (Chari et al., 2021), technological progress (Kantor & Whalley, 2019), and institutional changes (Lin, 1992). In addition to these traditional factors, numerous studies have identified natural disasters, such as extreme temperatures, floods, and droughts induced by climate change, as significant disruptors of agricultural production, leading to severe losses in productivity (Burke & Emerick, 2016; Chen & Gong, 2021; Chen & Chen, 2018; Lesk et al., 2016).

Natural disasters exacerbated by climate change are becoming increasingly frequent. Typhoons are among the natural disasters with the highest frequency and most severe global impacts. Previous research has documented their adverse effects on economic growth (Cavallo et al., 2013; Deryugina et al., 2018; Elliott et al., 2015; Strobl, 2011), industrial production (Elliott et al., 2019), residents' wealth (Kahn, 2005; Pugatch, 2019), and education levels (Lin et al., 2021). In the context of agricultural production, typhoons disrupt the supply of agricultural products and induce abnormal fluctuations in market prices (Bao et al., 2023; Gagnon & López-Salido, 2020; Kinnucan, 2016).

China's coastal areas, particularly those located on the northwest side of the Pacific, are frequently affected by typhoons (Lin et al., 2021). Typhoons can significantly impact agricultural productivity through two primary mechanisms. Firstly, the strong winds and heavy rainfall associated with typhoons can cause crop lodging and farmland flooding, directly damaging crops and reducing production efficiency. Secondly, rural households often adjust their production inputs to mitigate the impact of typhoons, leading to input distortions that indirectly diminish agricultural productivity. This study constructs a difference-in-differences (DID) model to evaluate the impact of typhoons on agricultural productivity. The findings suggest that typhoons notably impair local agricultural productivity. Specifically, planting income per mu and planting income per capita of

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rural households have decreased by 11% and 14%, respectively, while agricultural total factor productivity (TFP) has declined by 3.7%. Moreover, the impact of typhoons on agricultural productivity varies significantly with the geographical characteristics of the village, including the organizational capacity represented by the density of village cadres and the land transfer ratio. Mechanism analysis reveals that both the direct destruction of crops by typhoons and the distortion of input allocation by rural households are the main channels of deteriorating agricultural productivity.

This study contributes to literature in several aspects. Firstly, by utilizing the exogeneity of typhoon paths, it effectively reduces the estimation bias of natural disasters on agricultural productivity. This allows for the precise delineation of treatment and control groups, enabling accurate estimation of the impact on agricultural productivity (Angrist & Pischke, 2009). This methodology not only enhances our understanding of the specific effects of typhoons but also provides insights into the broader implications of related natural disasters, such as earthquakes, droughts, and floods. Secondly, this study confirms the sudden impact of environmental changes on agricultural productivity. While Burke & Emerick (2016) and Chen & Gong (2021) have focused on the long-term effects of climate change on agricultural farming adaptability and productivity, this study specifically investigates the short-term impact of typhoons. It emphasizes the inadequate coping mechanisms of farmers and underscores the importance of government intervention. Thirdly, the mechanism analysis demonstrates how typhoons alter rural households' behavior and, consequently, reduce agricultural productivity. While numerous studies have assessed the impact of natural disasters on agricultural production (Chen & Chen, 2018; Lesk et al., 2016), few have delved into the intermediate mechanisms driving farmers' responses. By deeply exploring the behavioral mechanisms of farmers when facing typhoon impacts, this study provides valuable insights into how government agencies can guide farmers to mitigate the adverse effects of natural disasters and implement effective agricultural production.

2. Research Background and Methods

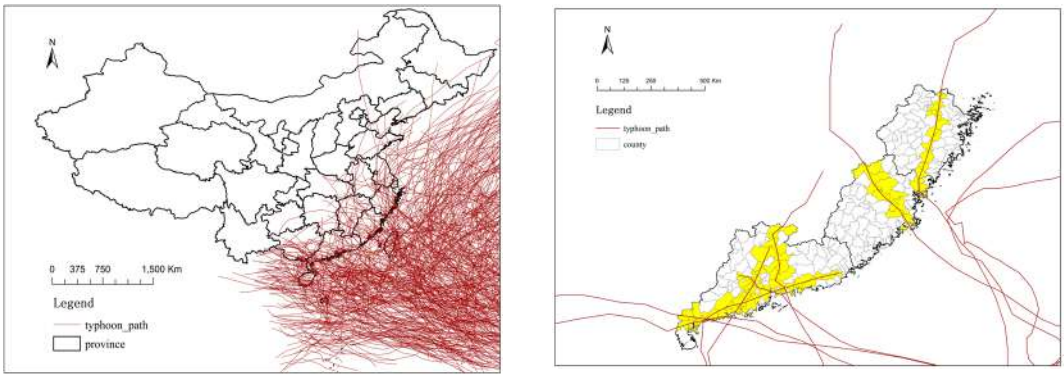
2.1. Research Background: Typhoons in Coastal Regions of China

China frequently experiences typhoons, with an average of 7.4 typhoons of magnitude 8 or above on the Beaufort scale annually (Lin et al., 2021). The main affected areas are coastal provinces such as Guangdong, Fujian, Hainan, Zhejiang, and Guangxi. From 1993 to 2006, the average annual economic losses from typhoons in Zhejiang reached 7.73 billion yuan, while Fujian, Guangdong, and Hainan experienced losses of 3.14 billion, 2.06 billion, and 1.11 billion yuan, respectively (Zhang et al., 2009).

During the period of our study, typhoons had a significant impact on agricultural production in China's coastal areas for several reasons. Firstly, the typhoon warning and monitoring system was not fully established until the 1980s (Wen, 2004). Secondly, the time and location of typhoon landfall are difficult to predict (Lin et al., 2021), making it difficult for local farmers to make corresponding adjustments to agricultural production. Thirdly, many people in these areas make their livings from agriculture, which is particularly vulnerable to typhoons (Xu et al., 2005). Finally, inadequate infrastructure exacerbates the impact of typhoons. Prior to the 1980s, many dams in China were poorly constructed and unable to effectively protect against flooding caused by typhoons. (Jia-bi & Dong-ya, 2009). These factors pose serious threats to agricultural production in coastal regions.

This study proposes the following mechanisms to explain how typhoons lead to significant declines in agricultural productivity. First, the direct mechanism involves the destruction of crops due to the strong winds and heavy rains associated with typhoons, resulting in immediate agricultural losses. Second, the indirect mechanism involves pre-landfall adjustments by rural households aimed at mitigating typhoon damage. These adjustments often disrupt optimal decision-making regarding the allocation of agricultural inputs, leading to misallocation and, consequently, a decline in agricultural productivity. Adamopoulos et al. (2022) attribute the stagnation in China's agricultural productivity from 1993 to 2002 to the misallocation of agricultural inputs due to land policy constraints. Similarly, Chen and Gong (2021) show that the ability of rural households to adjust production inputs flexibly significantly reduces the negative impact of extreme temperatures on agricultural productivity. These studies highlight the importance of input allocation in determining agricultural productivity, making the "typhoon shock—factor allocation distortion—agricultural productivity decline" mechanism a plausible explanation.

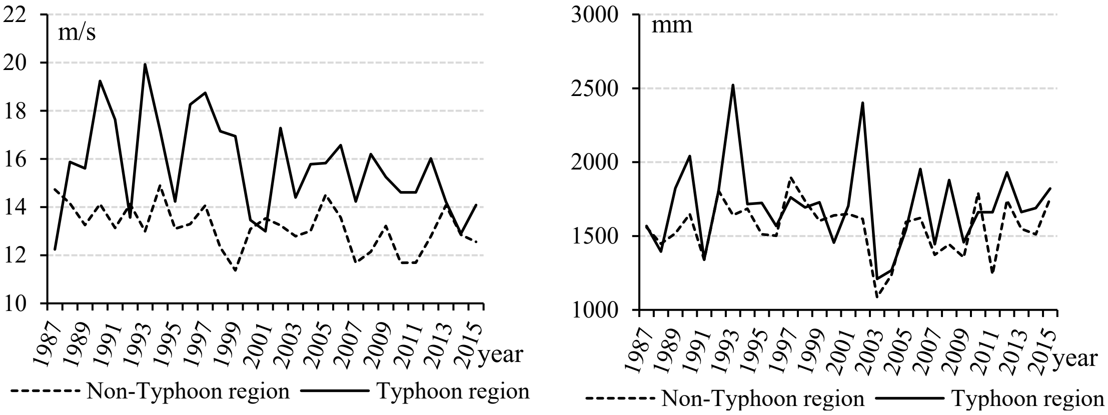
Figure 1 (a) illustrates the movement paths of typhoons in the Northwest Pacific from 1986 to 2015, highlighting the frequency with which China's coastal areas were affected. I obtained agricultural production data for the coastal provinces of Guangdong, Fujian, and Zhejiang from the Rural Fixed Observation Spot of the Chinese Ministry of Agriculture. Figure 1 (b) shows the intersection area of the typhoon track and the sample counties; the shaded area indicates a higher degree of impact and the non-shaded area indicates a lower degree of impact. Since typhoon movement is a natural phenomenon, I categorize the shaded areas as the treatment group and the unshaded areas as the control group. Then I compare the agricultural productivity gap between these two groups before and after the typhoons' landfall to accurately estimate the impact of typhoons.



(**a**) (**b**)

Figure 1: (**a**) Typhoons landed in China (1986−2015); (**b**) Typhoons landed in coastal counties (2008).

In addition, Figures 2 (a) and (b) illustrate the average maximum wind speed and average rainfall in sample counties, distinguishing between areas affected by typhoons and those that are not. On average, the annual maximum wind speed in non-typhoon areas is generally below 14 meters per second, whereas it can reach 16 meters per second or even 20 meters per second in typhoon-affected areas. Such increases in wind speed can easily cause crops to fall or even be destroyed. The average annual rainfall in typhoon-affected areas is significantly higher than in non-typhoon areas. The heavy rains not only directly damage the soil where crops grow but also frequently trigger floods that can completely destroy farmland. To mitigate the negative impacts of typhoons and reduce agricultural losses, rural households often take temporary measures such as dredging ditches, reinforcing crops, and expediting harvests before the typhoon makes landfall. These remedial actions can have a notable impact on the allocation of agricultural inputs and production, leading to deviations in agricultural productivity from normal status.



(**a**) (**b**)

Figure 2: (**a**) Typhoon and average wind speed; (**b**) Typhoon and average rainfall.

2.2. Model Setting and Data Description

I employ a standard two-way fixed effects (TWFE) regression model to estimate the influence of typhoons on agricultural productivity:

$$Y_{ict} = \alpha + \beta Typhoon_{ct} + \gamma \mathbf{X} + \theta_i + \delta_t + \varepsilon_{ict} \tag{1}$$

Here, Y_{ict} represents the agricultural productivity of rural households i in region c during year t , measured by crop production. $Typhoon_{ct}$ is an indicator variable that takes the value of 1 if region c was affected by a typhoon in year t, and otherwise 0. As shown in Figure 1 (b), if the area intersects with the typhoon track in a given year, $Typhoon_{ct}$ equals 1; otherwise, it equals 0. This setting is similar to Bao et al. (2023). $\mathbf{X}$ denotes the control variables, including the fixed assets (*FAS*) of rural households, labor working days (*WDY*) in planting, land size (*LSZ*), and intermediate inputs (*INP*) in planting. Except for $Typhoon_{ct}$, which is a dummy variable, other variables are in logarithmic form. θ_i represents the rural household fixed effect, δ_t is the year fixed effect, and ε_{ict} is the random disturbance term.

The data sources are as follows. First, agricultural productivity indicators are from the Rural Fixed Observation Spots sample survey conducted by the Agricultural Economic Research Center of the Ministry of Agriculture and Rural Affairs of China. This survey covers 11 provinces, including Shanxi, Jilin, Zhejiang, Fujian, Jiangxi, Henan, Hubei, Hunan, Guangdong, Sichuan, and Gansu, providing a comprehensive sample distribution. Coastal areas including Guangdong, Fujian, and Zhejiang are selected as the study samples. Second, typhoon data is from the China Meteorological Administration's Tropical Cyclone Data Center. This dataset includes the position and intensity of tropical cyclones in the Northwest Pacific (including the South China Sea, north of the equator, and west of longitude 180°E) every 6 hours since 1949. By using the typhoon's longitude and latitude, I adopt ArcGIS software to map the typhoon paths and identify the affected areas within the sample data.

Table 1. Descriptive statistics.

	Variables	Variable description	Count	Mean	SD	Min	Max
dependent variables	*Ln(NINC_PM)*	*NINC_PM* = net income of planting/sown area	28490	5.68	1.23	0	9.01
	Ln(NINC_PC)	*NINC_PC* = net income of planting/labor force	28490	5.84	1.30	0	9.87
	Ln(TFP)	total factor productivity of planting	28490	2.76	0.86	1.26	7.29
independent variables	*Typhoon*	landed = 1 ； otherwise = 0	28490	0.17	0.37	0	1
	Max_wind	m/s	28490	13.36	3.43	8.08	30.95
	Ave_rain	mm	28490	1.58	0.31	1.04	2.49
	Ln(AFE)	agricultural fiscal expenditure (10 million yuan)	11517	0.89	0.54	0.24	2.70
baseline control variables	*Ln(FAS)*	original value of productive fixed assets(yuan)	28490	6.97	1.50	3.71	11.67
	Ln(WDY)	labor input of planting (day)	28490	1.36	0.50	0.26	3
	Ln(LSZ)	cultivated land area (mu)	28490	4.87	0.77	1.10	5.88
	Ln(INP)	operating expenses of planting (yuan)	28490	6.56	1.21	3.43	12.72
village control variables	*Ln(VPOP)*	population size	28262	7.70	0.75	6.16	8.90
	Log(VLSZ_PC)	land size per capita(mu/per_capita)	28029	0.77	0.31	0.23	2.22
	Log(VFAS_PC)	fixed assets per capita(yuan/per_capita)	27924	2.41	1.09	0.49	6.24
	VR_Sex	sex ratio	28262	1.04	0.08	0.82	1.21
	VP_Lab	proportion of labor force	28101	0.54	0.09	0.34	1.18
climate control variables	*D_Sun*	sunshine duration (100 days/year)	28490	1.76	0.17	1.17	2.24
	Max_tem	maximum temperature (celsius)	28490	37.58	1.33	33.47	43.20
	Min_tem	minimum temperature (celsius)	28490	−0.72	3.95	−13.94	8.29
	Ave_tem	average temperature (celsius)	28490	19.73	2.03	15.48	24.38
other dependent variables	*Ln(GOTP_PM)*	*GOTP_PM* = grain output/sown area	28490	5.63	1.18	0	7.51
	Ln(GOTP_PC)	*GOTP_PC* = grain output/labor force	28490	5.47	1.29	0	7.21
	Ln(GTFP)	total factor productivity of grain production	28490	3.95	1.33	−3.09	5.12
	Cap_dist	capital distortion (refer to Appendix)	28490	0.05	0.22	0	3.76
	Lab_dist	labor distortion (refer to Appendix)	28476	1.87	2.94	0	17.16
	Total_dist	total input distortion (refer to Appendix)	28476	0.99	0.37	0	2.13

The dependent variables include the average net income per mu of planting (*NINC_PM*), the average net income per capita of planting (*NINC_PC*), and the total factor productivity (*TFP*) of planting. *NINC_PM* is calculated by dividing the total net income from family planting by the sown area, while *NINC_PC* is obtained by dividing the total net income from family planting by the household labor force. *TFP* is estimated by using the Cobb-Douglas production function (Cao & Birchenall, 2013; Lin, 1992). The core independent variable is whether a rural household in a county was affected by a typhoon. For robustness checks, annual maximum wind speed and annual average rainfall are also considered, with data sourced from the national meteorological science data sharing platform. Among the control variables, fixed assets (*FAS*) are measured by the original value of productive fixed assets owned by rural households, labor input is measured by working days (*WDY*) in planting, land size (*LSZ*) represents the area of land managed by rural households, and intermediate inputs (*INP*) are quantified by the operating expenses of planting. To address potential issues with missing variables, village-level, and climate control variables are included in the regression model. To mitigate the impact of extreme outliers, all continuous variables are winsorized at the 1% level, and observations with only one occurrence or abnormal samples with zero dependent variables in 1993 are excluded. Descriptive statistics for the main variables are presented in Table 1.

3. Benchmark Regression Results

3.1. Baseline Regression

In the baseline regression analysis, I utilize the intersection of the typhoon path with specific areas as the criterion for determining typhoon landfall and subsequently examine its impact on agricultural productivity. The estimation results presented in Table 2 confirm that typhoon shocks have a significant negative effect on agricultural productivity. Specifically, models (1−2) demonstrate that in areas affected by the typhoon, the average net income per mu and net income per capita of rural households decreased by 11% and 13.9%, respectively. These results are statistically significant at the 1% level. Model (3) substitutes the dependent variable with the total factor productivity (*TFP*) of crop production and finds that the *TFP* growth rate in planting decreased by 3.72% significantly after the typhoon landed. Even after adding control variables for inputs such as assets, labor, land, and intermediate goods of rural households in models (4−6), the conclusions remain unchanged.

Table 2. Regression results of typhoon impact on agricultural productivity.

Variable	Model(1) *Ln(NINC_PM)*	Model(2) *Ln(NINC_PC)*	Model(3) *Ln(TFP)*	Model(4) *Ln(NINC_PM)*	Model(5) *Ln(NINC_PC)*	Model(6) *Ln(TFP)*
Typhoon	−0.110***	−0.139***	−0.0372***	−0.102***	−0.115***	−0.0375***
	(0.0157)	(0.0171)	(0.00731)	(0.0158)	(0.0163)	(0.00735)
Ln(FAS)	-	-	-	−0.000620	−0.0299***	−0.00251
	-	-	-	(0.00735)	(0.00765)	(0.00409)
Ln(WDY)	-	-	-	0.222***	0.380***	0.0254**
	-	-	-	(0.0197)	(0.0193)	(0.0125)
Ln(LSZ)	-	-	-	−0.274***	0.398***	0.0364**
	-	-	-	(0.0336)	(0.0332)	(0.0174)
Ln(INP)	-	-	-	0.0753***	0.191***	−0.0274***
	-	-	-	(0.0151)	(0.0146)	(0.00975)
Household Fixed_effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed_effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	28,490	28,490	28,490	28,490	28,490	28,490
R^2	0.528	0.525	0.798	0.538	0.594	0.798

Notes: *NINC_PM*-net income per mu; *NINC_PC*- net income per capita; *TFP*- total factor productivity of planting; *FAS*- fixed assets; *WDY*- working days; *LSZ*-land size; *INP*-intermediate inputs. *** p<0.01,** p<0.05,* p<0.1; Standard errors clustered at the household level are in parentheses.

3.2. Endogeneity Discussion

The occurrence of typhoons is a natural phenomenon and cannot be controlled by humans. Therefore, typhoons exhibit strict exogeneity. Despite this, completely eliminating endogeneity problems in econometric regression analysis remains challenging. There are three main sources of endogeneity in econometric models: omitted variables, measurement error, and reverse causality.

First, concerning reverse causality, the formation and movement of typhoons are influenced by temperature, atmospheric pressure, and the Earth's rotation. Agricultural productivity cannot affect these factors, thereby the issue of reverse causation is eliminated.

Secondly, although I have controlled for variables related to rural household agricultural inputs in the baseline regression, omitted variables may still exist. For instance, villages with larger populations may possess stronger organizational capabilities in responding to typhoons, which could impact agricultural productivity. Moreover, villages with larger land areas per capita are more likely to engage in large-scale agricultural operations and enhance productivity. However, larger agricultural land sizes also experience more severe impacts from typhoons, resulting in greater declines in productivity. To minimize the influence of related factors, Models (1–3) in Table 3 include additional control variables at the village level, such as population size, land size per capita, fixed assets per capita, sex ratio, and labor force proportion. Following this adjustment, the core regression results remain unchanged. Furthermore, climate change affects both the frequency and intensity of typhoons and directly impacts agricultural production. Models (4–6) introduce regional-level control variables like annual sunshine duration, maximum temperature, minimum temperature, and average temperature. The fundamental regression results remain robust after considering these variables.

Table 3. Consider omitted variables.

Variable	**Model(1)** ***Ln(NINC_PM)***	**Model(2)** ***Ln(NINC_PC)***	**Model(3)** ***Ln(TFP)***	**Model(4)** ***Ln(NINC_PM)***	**Model(5)** ***Ln(NINC_PC)***	**Model(6)** ***Ln(TFP)***
Typhoon	−0.134***	−0.144***	−0.0360***	−0.122***	−0.128***	−0.0323***
	(0.0162)	(0.0167)	(0.00759)	(0.0163)	(0.0168)	(0.00772)
Add village control variables						
Ln(VPOP)	0.300**	0.356***	0.0668	0.232**	0.279**	0.0566
	(0.122)	(0.125)	(0.0670)	(0.118)	(0.122)	(0.0665)
Log(VLSZ_PC)	−0.214***	−0.190***	−0.0975***	−0.186***	−0.158***	−0.0957***
	(0.0293)	(0.0351)	(0.0285)	(0.0297)	(0.0353)	(0.0280)
Log(VFAS_PC)	−0.00252	−0.0239**	−0.00344	−0.00826	−0.0288**	−0.00484
	(0.0111)	(0.0112)	(0.00589)	(0.0111)	(0.0113)	(0.00593)
VR_Sex	0.0477	−0.134	−0.186**	0.0813	−0.0997	−0.186**
	(0.128)	(0.137)	(0.0756)	(0.128)	(0.136)	(0.0750)
VP_Lab	−0.518***	0.116	−0.0432	−0.459***	0.154	−0.0386
	(0.137)	(0.137)	(0.0848)	(0.139)	(0.137)	(0.0843)
Add climate control variables						
D_Sun	-	-	-	−0.0465	0.0450	−0.141***
	-	-	-	(0.0816)	(0.0817)	(0.0360)
Max_tem	-	-	-	−0.00241	−0.00823	−0.000566
	-	-	-	(0.00862)	(0.00801)	(0.00378)
Min_tem	-	-	-	−0.0579***	−0.0701***	−0.0208***
	-	-	-	(0.00764)	(0.00755)	(0.00328)
Ave_tem	-	-	-	0.134***	0.129***	0.0158
	-	-	-	(0.0327)	(0.0360)	(0.0192)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Household Fixed_effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed_effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	27,846	27,846	27,846	27,846	27,846	27,846
R^2	0.543	0.599	0.798	0.544	0.601	0.799

Notes: Control variables include baseline control variables in Table 1. *VPOP*-population size in village level; *VLSZ_PC*-land size per capita in village level; *VFAS_PC*-fixed assets per capita in village level; VR_Sex-sex ratio in village level; *VP_Lab*-labor force proportion in village level; *D_Sun*-annual sunshine duration; *Max_tem*-maximum temperature; *Min_tem*-minimum temperature; *Ave_tem*-average temperature

Finally, concerning measurement error, while I accurately determine the affected areas based on historical typhoon paths, the assumption of homogeneity in assigning the impact of typhoons to the treatment group each year introduces some discrepancies. This is because typhoon intensity varies from year to year. The impact of typhoons primarily stems from strong winds and heavy rains. Therefore, I substitute the independent variables with other weather variables to analyze the impact of typhoons. Models (1–3) in Table 4 demonstrate that as the maximum wind speed increases, the average net income per mu, net income per capita, and total factor productivity of planting decline more significantly. Similarly, Models (4–6) use annual average rainfall as the independent variable and reveal that in areas with higher rainfall, agricultural productivity is notably lower. Thus, replacing other typhoon-related weather variables does not substantially alter the baseline regression results of this study.

Table 4. Consider measurement error.

Variable	Model(1) *Ln(NINC_PM)*	Model(2) *Ln(NINC_PC)*	Model(3) *Ln(TFP)*	Model(4) *Ln(NINC_PM)*	Model(5) *Ln(NINC_PC)*	Model(6) *Ln(TFP)*
Max_wind	−0.0233***	−0.0204***	−0.0102***	-	-	-
	(0.00235)	(0.00237)	(0.00108)	-	-	-
Ave_rain	-	-	-	−0.376***	−0.335***	−0.170***
	-	-	-	(0.0288)	(0.0289)	(0.0135)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Household Fixed_effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed_effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	27,846	27,846	27,846	27,846	27,846	27,846
R^2	0.545	0.601	0.799	0.547	0.602	0.800

Note: Control variables include baseline control variables, village control variables, and climate control variables in Table 1.

3.3. Robustness Test

To assess the robustness of the baseline regression model, I perform supplementary tests. Initially, I modified the indicators of agricultural productivity. Models (1–3) in Table 5 substitute the dependent variables with grain output per mu (*GOTP_PM*), grain output per capita (*GOTP_PC*), and estimated grain total factor productivity (*GTFP*) to mitigate the effects of crop price fluctuations on planting net income indicators. The regression outcomes reveal that typhoons notably decrease agricultural productivity, as evidenced by grain production, aligning with the baseline regression results.

Table 5. Robustness check.

Variable	Model(1)	Model(2)	Model(3)
	Change the indicators of agricultural productivity		
	Ln(GOTP_PM)	*Ln(GOTP_PC)*	*Ln(GTFP)*
Typhoon	−0.0830***	−0.0303**	−0.0493***
	(0.0163)	(0.0127)	(0.0151)
Control Variables	Yes	Yes	Yes
Household Fixed_effects	Yes	Yes	Yes
Year Fixed_effects	Yes	Yes	Yes
Observations	27,846	27,846	27,846
R^2	0.613	0.768	0.723

Notes: Control variables include baseline control variables, village control variables, and climate control variables in Table 1. *GOTP_PM*-grain output per mu; *GOTP_PC*--grain output per capita; *GTFP*- total factor productivity of grain production.

Secondly, to mitigate the influence of migration and farmland abandonment on agricultural production, Models (1–2) in Table 6 exclude samples with zero planting income for that year and re-run the regression. The findings demonstrate that the adverse impact of typhoons on agricultural productivity remains significant. Thirdly Models (3–5) exclude the sample from the year 1999, which includes specific abnormal observations. The regression outcomes suggest that the detrimental effect of typhoons endures.

Table 6. Robustness check.

Variable	Model(1)	Model(2)	Model(3)	Model(4)	Model(5)
	Eliminate samples with zero output		Eliminate abnormal year 1999		
	Ln(NINC_PM)	*Ln(NINC_PC)*	*Ln(NINC_PM)*	*Ln(NINC_PC)*	*Ln(TFP)*
Typhoon	−0.0625***	−0.0682***	−0.0728***	−0.0780***	−0.0141*
	(0.0119)	(0.0121)	(0.0151)	(0.0155)	(0.00762)
Control Variables	Yes	Yes	Yes	Yes	Yes
Household Fixed_effects	Yes	Yes	Yes	Yes	Yes
Year Fixed_effects	Yes	Yes	Yes	Yes	Yes
Observations	27,527	27,527	26,946	26,946	26,946
R^2	0.679	0.727	0.586	0.641	0.813

Notes: Control variables include baseline control variables, village control variables, and climate control variables in Table 1.

Finally, I exclude the impact of other policies. Before the implementation of the rural tax and fee exemption reform, rural households were required to pay agricultural taxes and fees, which significantly affected their farming enthusiasm. Additionally, the land transfer rate plays a crucial role in promoting the efficient concentration of farmland and forming large-scale agricultural operations, directly impacting productivity. Models (1–3) in Table 7 include variables for tax and fee burden of rural households and land transfer rate to control for the impact of rural tax policies and land transfer policies. The regression results do not change significantly.

To eliminate the interference from policies that vary over time at the provincial level, such as the household contract responsibility system and family planning system gradually implemented by each province, Models (4–6) include the interaction term of province and year. After controlling for these effects, the regression coefficient is slightly reduced but remains negative and significant.

Table 7. Exclude the impact of other policies.

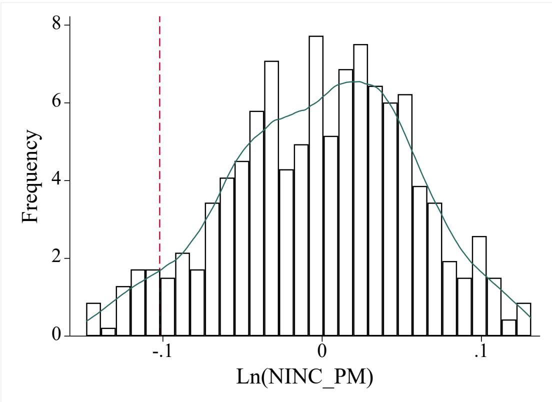
Variable	Model(1)	Model(2)	Model(3)	Model(4)	Model(5)	Model(6)
	Ln(NINC_PM)	*Ln(NINC_PC)*	*Ln(TFP)*	*Ln(NINC_PM)*	*Ln(NINC_PC)*	*Ln(TFP)*
Typhoon	−0.122***	−0.129***	−0.0324***	−0.112***	−0.0990***	−0.0121
	(0.0163)	(0.0168)	(0.00772)	(0.0188)	(0.0194)	(0.00890)
Agri_tax	−0.000398	−0.140**	−0.106***	−0.00556	−0.162**	−0.108**
	(0.0865)	(0.0636)	(0.0387)	(0.0955)	(0.0765)	(0.0427)
Agri_fee	0.0490	0.0337	0.0237	0.0249	0.00764	0.0197
	(0.0383)	(0.0386)	(0.0155)	(0.0365)	(0.0424)	(0.0151)
Land_tf	−0.0588	0.0446	−0.0210	−0.0545	0.0355	−0.0329
	(0.0405)	(0.0438)	(0.0274)	(0.0393)	(0.0421)	(0.0259)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Household Fixed_effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed_effects	Yes	Yes	Yes	Yes	Yes	Yes
Year×Prov Fixed_effects	No	No	No	Yes	Yes	Yes
Observations	27,846	27,846	27,846	27,846	27,846	27,846
R^2	0.544	0.601	0.799	0.562	0.617	0.810

Notes: Control variables include baseline control variables, village control variables, and climate control variables in Table 1. *Agri_tax*-agricultural tax burden; *Agri_fee*-agricultural fee burden; *Land_tf*-land transfer rate

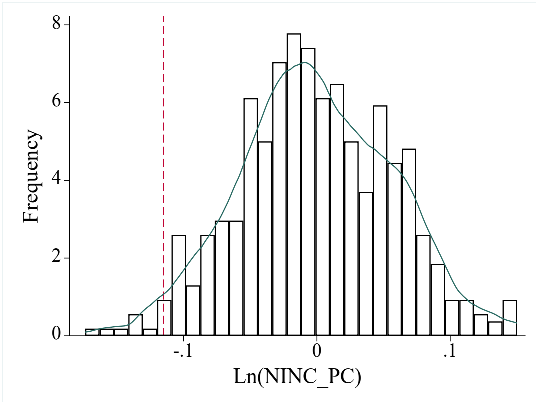
3.4. Permutation Test

The exogeneity of the typhoon movement path is crucial to ensure that the baseline regression estimate is unbiased. To verify this assumption, I conducted a permutation test. Initially, during our study period, the total number of typhoons hitting each region was 136. So I randomly selected 136 samples from the regional panel data as the treatment group and assigned a value of 1 to the simulated typhoon variable; otherwise, the value was 0 for the control group. Subsequently, I re-estimate the coefficients according to regression equation (1). This process is repeated 500 times to obtain the distribution of the estimated coefficients for different productivity indicators. Finally, I conduct a comparative analysis with the regression results from Models (4–6) in Table 2.

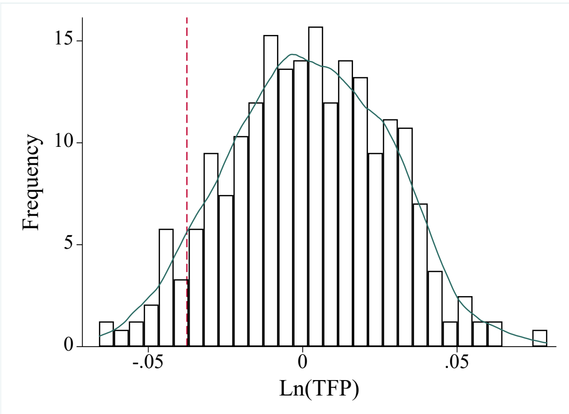
Figures 3 (a), 3 (b), and 3 (c) display the distribution of estimated coefficients for the simulated impact of typhoons on net income per unit of planting, net income per capita of planting, and total factor productivity of planting, respectively. The simulated false coefficients are distributed approximately normally around zero, while the true values of the baseline regression, indicated by the dotted line, are situated at the periphery of the false coefficient distribution. This confirms that the treatment effect of typhoon impacts on agricultural productivity in the baseline regression does not encompass the influences of other unobservable variables.



(**a**)



(**b**)



(c)

Figure 3: (**a**) Simulated typhoon and *Ln*(*NINC_PM*); (**b**) Simulated typhoon and *Ln*(*NINC_PC*); **(c)** Simulated typhoon and *Ln*(TFP).

3.5. Heterogeneity Analysis

The characteristics of villages and rural households can either worsen or alleviate the impact of typhoons. I employ the following regression model to examine the heterogeneous effects from three perspectives: village geographical environment, rural organizational capabilities, and land transfer level:

$$Y_{ict} = \alpha + \beta Typhoon_{ct} \times Z_{(i)ct} + \delta Typhoon_{ct} + \varphi Z_{(i)ct} + \gamma \boldsymbol{X} + \theta_i + \delta_t + \varepsilon_{ict} \tag{2}$$

Here, $Z_{(i)ct}$ represents the characteristics of the village or rural household, including whether the village is located in a plain area (*Plain*), village cadre density (*Cdensity*), and the proportion of rural household contracted land in the total cultivated land (*Tsland*). The remaining variables are consistent with the baseline regression.

Models (1–3) in Table 8 demonstrate that villages situated in plain areas exacerbate the negative effects of typhoons on agricultural productivity compared to those in hills and mountains. This is due to their proximity to the sea, leading to higher typhoon intensity. Moreover, plain areas are more susceptible to post-typhoon disasters like flooding.

Table 8. Heterogeneity analysis.

	Model(1)	**Model(2)**	**Model(3)**
		Geographical heterogeneity	
	Ln(NINC_PM)	***Ln(NINC_PC)***	***Ln(TFP)***
Typhoon	−0.186***	−0.181***	−0.0552***
×Plain	(0.0445)	(0.0442)	(0.0165)
Typhoon	−0.0837***	−0.0719***	−0.00530
	(0.0206)	(0.0215)	(0.00997)
Plain	0.686***	0.756***	0.300***
	(0.0819)	(0.0817)	(0.0265)
Observations	27,846	27,846	27,846
R^2	0.565	0.620	0.811
	Model (4)	**Model (5)**	**Model (6)**
		Organizational capability heterogeneity	
	Ln(NINC_PM)	***Ln(NINC_PC)***	***Ln(TFP)***
Typhoon	0.0953**	0.102**	0.0180
×Cdensity	(0.0444)	(0.0429)	(0.0214)
Typhoon	−0.141***	−0.130***	−0.0180*
	(0.0227)	(0.0230)	(0.0106)
Cdensity	0.198***	0.249***	0.0646
	(0.0592)	(0.0565)	(0.0440)
Observations	27,846	27,846	27,846
R^2	0.562	0.618	0.810
	Model (7)	**Model (8)**	**Model (9)**
		Land transfer heterogeneity	
	Ln(NINC_PM)	***Ln(NINC_PC)***	***Ln(TFP)***
Typhoon	0.0824	0.111*	0.0842***
×Tsland	(0.0620)	(0.0590)	(0.0299)
Typhoon	−0.125***	−0.117***	−0.0261***
	(0.0221)	(0.0219)	(0.00935)
Tsland	−0.0722*	0.0128	−0.0503*
	(0.0410)	(0.0434)	(0.0269)
Observations	27,846	27,846	27,846
R^2	0.562	0.617	0.810
Control Variables	Yes	Yes	Yes
Household Fixed_effects	Yes	Yes	Yes
Year Fixed_effects	Yes	Yes	Yes

Notes: Control variables include baseline control variables, village control variables, and climate control variables in Table 1. *Plain*-Whether the village is located in a plain area; *Cdensity*-Village cadre density; *Tsland*-The proportion of rural household contracted land in the total cultivated land.

Second, models (4–6) demonstrate that as the proportion of cadres in the village increases, the negative impact of typhoons is significantly weakened. This is due to the influential role of grassroots organizations in mitigating the effects of disasters. Village cadres can promptly convey information from higher-level governments about typhoon warnings and preventive measures, then help farmers take effective measures to reduce the serious impact of typhoons on agricultural production. Finally, models (7–9) show that when rural households hold a higher share of transferred land from others, the negative effect of typhoons on planting productivity is reduced. The implementation of policies such as the "Rural Land Contract Law of the People's Republic of China" legally guarantees the stability of farmland, which can improve the scale of agricultural land and agricultural productivity (Chari et al., 2021). Rural households with a higher share of transferred land may be more skilled in agricultural production and have more flexible and effective measures to withstand the negative impact of typhoons.

4. Mechanism Analysis

4.1. Direct Mechanism

The direct impacts of typhoons on agricultural production are usually reflected in the destruction of production conditions, crop damage, and even labor casualties. Therefore, it is essential to investigate how typhoons directly decrease crop yield due to their strong winds or heavy rains. Models (1–2) in Table 9 indicate that typhoons did not significantly affect the sown area of planting or the number of family laborers. In other words, rural households' enthusiasm for agricultural farming remains strong despite the typhoons. The reason is that the agricultural planting period is generally at the turn of spring and summer, and typhoons mostly occur in summer and autumn. Therefore, farmers in coastal areas are unlikely to change their agricultural production plans due to subsequent typhoons. Moreover, the stable number of household laborers suggests that the typhoon-related casualties in our study are not severe. Therefore, the decrease in output cannot be solely attributed to a reduced labor force.

Second, Model (3) in Table 9 demonstrates that using the total net income from planting as a measurement indicator, typhoons significantly reduced agricultural productivity. Given that the decline in planting enthusiasm and the decrease in laborers are not core factors contributing to agricultural productivity loss, the substantial decrease in the net income from planting confirms the direct influence of typhoons on agricultural output.

Table 9. Verification of direct mechanism.

	Model(1)	**Model(2)**	**Model(3)**
	Ln(Sown)	***Ln(Labor)***	***Ln(Nincome)***
Typhoon	0.00466	0.00720	−0.103***
	(0.00952)	(0.00474)	(0.0203)
Control Variables	Yes	Yes	Yes
Household Fixed_effects	Yes	Yes	Yes
Year Fixed_effects	Yes	Yes	Yes
Year×Prov Fixed_effects	Yes	Yes	Yes
Observations	27,782	27,813	27,846
R^2	0.603	0.547	0.610

Notes: Control variables include baseline control variables, village control variables, and climate control variables in Table 1. *Sown*-Sown area of planting; *Labor*-The number of rural household labor force; *Nincome*-Net income of planting.

4.2. Indirect Mechanism

When faced with typhoons, rural households will make adjustments in agricultural input allocation to minimize potential losses. However, these adjustments are often unexpected and unintentional, which can lead to a relative distortion in input allocation and a negative deviation in agricultural productivity.

First, I examine the impact of typhoons on rural households' agricultural input decisions. The dependent variable of the baseline regression model is replaced with the agricultural inputs of rural households. Models (1–4) in Table 10 indicate that typhoons do not have a significant impact on the scale of land cultivated by rural households. However, rural households notably increase their investment in fixed assets while reducing labor time and intermediate inputs. The land cultivated by rural households is allocated based on the "rural land contract management system" and acquired through land transfers from other rural households. Therefore, the scale of land farming is not directly influenced by the occurrence of typhoons.

Additionally, rural households need to reinforce crops or clear farmland drainage to mitigate the impact of typhoons. The implementation of such measures necessitates investment in fixed assets like windproof brackets, iron and wood farm tools, and drainage machinery, which accounts for the rise in fixed assets. Conversely, the adverse weather conditions caused by typhoons impede rural households' engagement in on-site farming. The destruction of farmland also complicates planting, while crop damage decreases the demand for intermediate inputs. Models (5–7), which analyze agricultural inputs per mu as the dependent variable, demonstrate similar behavioral patterns among rural households.

Table 10. Changes in agricultural inputs.

	Model(1) *Ln(LSZ)*	**Model(2)** *Ln(FAS)*	**Model(3)** *Ln(WDY)*	**Model(4)** *Ln(INP)*	**Model(5)** *Ln(FAS_PM)*	**Model(6)** *Ln(WDY_PM)*	**Model(7)** *Ln(INP_PM)*
Typhoon	−0.0113	0.0581***	−0.0453***	−0.0684***	0.0856***	−0.0424***	−0.0708***
	(0.00767)	(0.0218)	(0.0115)	(0.0167)	(0.0240)	(0.0115)	(0.0154)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household Fixed_effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed_effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year×Prov Fixed_effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	27,846	27,846	27,846	27,846	27,846	27,846	27,846
R^2	0.672	0.633	0.633	0.681	0.657	0.499	0.700

Notes: Control variables include village control variables and climate control variables in Table 1. *FAS_PM*-original value of productive fixed assets per mu; *WDY_PM*-labor input of planting per mu; *INP_PM*-operating expenses of planting per mu.

In general, the arrival of typhoons prompts rural households to temporarily adjust their agricultural inputs by substituting labor and intermediate inputs with fixed assets. Further discussion is needed to determine whether this adjustment in agricultural inputs leads to misallocation. To assess whether typhoons distort the input allocation of rural households, I first calculate the distortion index of agricultural production and then analyze it as the dependent variable in the baseline regression.

Table 11. Agricultural input distortions.

	Model(1) *Cap_dist*	**Model(2)** *Lab_dist*	**Model(3)** *Total_dist*
Typhoon	0.00920**	0.141***	0.0130**
	(0.00445)	(0.0404)	(0.00598)
Control Variables	Yes	Yes	Yes
Household Fixed_effects	Yes	Yes	Yes
Year Fixed_effects	Yes	Yes	Yes
Year×Prov Fixed_effects	Yes	Yes	Yes
Observations	27,846	27,833	27,833
R^2	0.470	0.635	0.677

Notes: Control variables include baseline control variables, village control variables, and climate control variables in Table 1. The calculation process of *Cap_dist, Lab_dist,* and *Total_dist* can be referred to in Appendix.

Models (1–2) in Table 11 demonstrate that typhoons significantly increased the degree of distortion in rural households' capital investment and exacerbated the distortion in labor input. The rise in investment in fixed assets and the decline in labor input caused by the typhoon led to a deviation in the capital and labor inputs from the typical endowment of rural households. This unexpected adjustment in factor inputs creates distortions, with labor distortions exceeding capital distortions. This is attributed to the fact that capital investment has traditionally played a minor role in China's agricultural production, which relies more heavily on labor and intermediate goods. Since the capital stock of agricultural production is low and the capital fluctuation range is limited, the impact of capital distortion is relatively small; on the contrary, since agricultural production mainly relies on labor input, the typhoon has caused a reduction in agricultural working days and the phenomenon of labor idleness has become more obvious, which has a greater impact on input distortion. Combining the distortions in capital and labor inputs, Model (3) shows that the overall distortion in rural households' input allocation worsened due to typhoon impacts. I conclude that the involuntary substitution of fixed assets for labor in the aftermath of a typhoon is a key factor contributing to the distortion of overall input allocation. Thus, the hypothesis of "typhoon impact—distortion of input allocation—decline in agricultural productivity" proposed in the theoretical analysis of this study is fully supported by empirical evidence.

5. Cost-Benefit Analysis

Through the above analysis, we understand that typhoons significantly reduce agricultural productivity. An important question is whether the government's financial investment in agriculture can mitigate this negative impact. Model (1) in Table 12 uses "expenses for agriculture, forestry, water, and electricity" (*AFE*) from the "Financial Statistics of Prefectures, Cities, and Counties Nationwide" for the years 1993 to 2007 as a proxy for local government's agricultural fiscal expenditures. These models include interaction terms between the typhoon variable and *AFE* to assess their effects.

Model (1) indicates that local government's agricultural fiscal expenditures effectively mitigate the decline in agricultural productivity, as measured by the net income per mu of planting. Specifically, if the government were to double its agricultural fiscal expenditure, the local net income loss per mu could be reduced by 18.5%. With an average agricultural fiscal expenditure of 19.47 million yuan per year in the sample, an increase of approximately 20 million yuan in local government expenditures would offset nearly 20% of the drop in agricultural productivity caused by typhoons. This represents the estimated lower limit of the efficiency of government agricultural fiscal expenditures in suppressing typhoon-related agricultural losses.

Furthermore, data from 2003 to 2006 reveal that local government "water conservancy and meteorological expenditures" account for about 17% of the total "agriculture, forestry, water, and electricity expenses." Therefore, if the positive effect of government fiscal expenditure on reducing agricultural productivity decline is attributed solely to water conservancy and meteorological construction, then an increase of 3.4 million yuan in these expenditures could counteract nearly 20% of the decline in agricultural productivity caused by typhoons. This estimate provides the upper limit of the efficiency of government agricultural fiscal expenditures in mitigating typhoon-related impacts.

Table 12. Cost-Benefit analysis of agricultural production expenditures.

	Model(1) ***Ln(NINC_PM)***
Typhoon×Ln(AFE)	0.185***
	(0.0594)
Ln(AFE)	−0.0259
	(0.0969)
Typhoon	−0.270***
	(0.0626)
Control Variables	Yes
Household Fixed_effects	Yes
Year Fixed_effects	Yes
Year×Prov Fixed_effects	Yes
Observations	10,971
R^2	0.396

Notes: Control variables include baseline control variables, village control variables, and climate control variables in Table 1. "Expenses for agriculture, forestry, water and electricity" were only disclosed from 1993 to 2002. This study uses the sum of "agricultural expenditures," "forestry expenditures," and "water conservancy and meteorological expenditures" as proxy indicators from 2003 to 2006. In 2007, this study uses "agriculture, forestry, and water expenditure" as a proxy indicator.

6. Conclusions

The threat of natural disasters to rural development has garnered attention from governments worldwide. This study focuses on coastal typhoons, identifying the affected treatment group and the unaffected control group based on their unique movement paths. Using a difference-in-differences (DID) model and survey data from the Rural Fixed Observation Spot of the Chinese Ministry of Agriculture, this study finds that typhoons significantly reduce the agricultural productivity of local rural households. Specifically, the average income per mu and per capita from planting decreases by 11% and 14%, respectively, while agricultural total factor productivity falls by approximately 3.7%. This provides quantitative evidence of the adverse effects of typhoons on agricultural production.

The mechanism through which typhoons exacerbate the decline in agricultural productivity operates through several channels. First, typhoons directly damage crops, reducing total output. Second, in anticipation of the typhoon, rural households significantly increase asset investment in agricultural production while reducing labor input and intermediate goods. This adjustment leads to a distortion in the allocation of agricultural inputs, further diminishing productivity. The adverse impact of typhoons is more pronounced in plain areas, whereas strengthening rural organizational capabilities and improving land circulation can substantially mitigate the negative effects. This implies that policies should enhance farmland and water conservancy infrastructure, consolidate the strength of rural grassroots organizations, and expand land circulation channels.

Finally, a cost-benefit analysis indicates that reducing the negative impact of typhoons on agricultural productivity by 20% within the context of China requires local financial support for agriculture amounting to approximately 3.4 million to 20 million yuan. This provides a reference for other developing countries in planning financial investments for typhoon prevention and control. To optimize the use of financial resources, future improvements should focus on streamlining spending processes, updating assessment systems, and developing disaster prevention strategies tailored to local conditions.

However, this study has the following limitations: First, this study focuses solely on the impact of typhoons in China's coastal regions, neglecting indirect consequences like supply chain disruptions and market fluctuations in inland areas resulting from shortages of agricultural products. Second, due to the lack of detailed data, this study has only conducted a preliminary examination of the effectiveness of government financial support for disaster prevention and has not yet proposed a comprehensive and practical improvement plan. These limitations highlight the need for additional research in the future.

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Appendix

Calculating the Distortion of Agricultural Inputs in Rural Households

Assume rural households use capital (K), labor (L), land (T), and intermediate goods (M) for agricultural production, following a Cobb-Douglas production function. Let total factor productivity be denoted as A, and output as Y:

$$Y_{it} = A_{it} K_{it}^{\alpha} L_{it}^{\beta} T_{it}^{\gamma} M_{it}^{\delta} \tag{A1}$$

In Equation A1, i represents the rural household and t represents the year, with the return to scale of the production function remaining unchanged ($\alpha + \beta + \gamma + \delta = 1$). The rural household's profit maximization problem is:

$$\max \left\{ P_{it} Y_{it} - (1+\tau_{Kit}) K_{it} P_{Kit} - (1+\tau_{Lit}) L_{it} P_{Lit} - P_{Tit} T_{it} - P_{Mit} M_{it} \right\} \tag{A2}$$

Due to the lack of detailed information on the prices of various agricultural inputs (P_{it}), I use the total income from agricultural production ($P_{it} Y_{it}$) directly. Hsieh and Klenow (2009) discussed productivity due to irrational allocation of capital and labor inputs under distorted factor prices. They assumed P_{Kit} and P_{Lit} represent the market prices of capital and labor, while $(1 + \tau_{Kit}) P_{Kit}$ and $(1 + \tau_{Lit}) P_{Lit}$ denote the distorted prices faced by enterprises, with τ_{Kit} and τ_{Lit} represent the degrees of distortion for capital and labor inputs, respectively.

This study focuses on the impact of typhoon disasters on rural households' adjustment of fixed assets or labor input, regardless of distorted input factor prices. This adjustment is reflected in the distortion of capital input $(1+\tau_{Kit})K_{it}$ and labor input $(1+\tau_{Lit})L_{it}$. I define the distortion of agricultural input as the total cost of inputs: $(1+\tau_{Kit})K_{it}P_{Kit}$ and $(1+\tau_{Lit})L_{it}P_{Lit}$. Here, τ_{Kit} and τ_{Lit} indicate the distortion of capital and labor factors, respectively. The calculation of the distortion index is similar to previous literature.

Assuming land is used free of charge ($P_{Tit}=0$) and given the difficulty of obtaining data of intermediate inputs, I calculate only the distortions in capital and labor inputs. Based on the profit maximization conditions derived from Equations A1 and A2, we have:

$$\alpha P_{it}Y_{it} = (1+\tau_{Kit})P_{Kit}K_{it} \tag{A3}$$

$$\beta P_{it}Y_{it} = (1+\tau_{Lit})P_{Lit}L_{it} \tag{A4}$$

Thus, capital and labor input distortions can be expressed as:

$$1+\tau_{Kit} = \frac{\alpha P_{it}Y_{it}}{P_{Kit}K_{it}} \tag{A5}$$

$$1+\tau_{Lit} = \frac{\beta P_{it}Y_{it}}{P_{Lit}L_{it}} \tag{A6}$$

The overall factor distortion index for rural households can be defined as:

$$dist_{it} = (1+\tau_{Kit})^{\alpha}(1+\tau_{Lit})^{\beta} \tag{A7}$$

To measure capital and labor distortion, I utilize the following data: $P_{it}Y_{it}$ as the total income of agricultural planting; $P_{Kit}K_{it}$ as the original value of productive fixed assets; L_{it} as the number of days rural households worked in planting each year; and P_{Lit} as the opportunity cost of labor, estimated from the average income of migrant workers at the county level. All monetary values (P_{Lit}, $P_{it}Y_{it}$, $P_{Kit}K_{it}$ and P_{Lit}) are adjusted for inflation (with 1986 as the base year). Finally, α and β represent the output elasticity of capital and labor in the Cobb-Douglas production function as follows:

$$lnY_{it} = \alpha lnK_{it} + \beta lnL_{it} + \gamma lnT_{it} + \delta lnM_{it} + i\_fe + t\_fe + \varepsilon_{it} \tag{A8}$$

This regression model is used to estimate the coefficients for capital and labor inputs (α and β) and determine the degree of distortion in agricultural inputs ($dist_{it}$).

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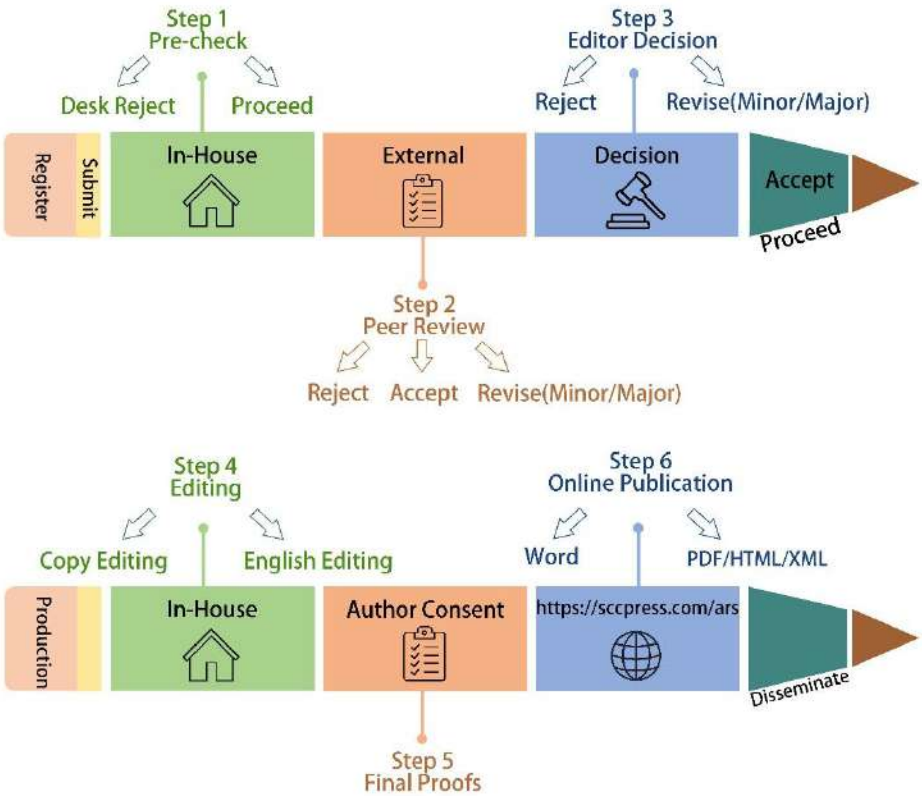

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