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Assessing the Impact of Climate Change Adaptation Practices on Honey Production among Beekeepers in Senegal

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Abstract

In Africa, climate change and the degradation of natural resources increase the vulnerability of beekeeping production systems and threaten their productivity. While the adoption of adaptation practices can help enhance productivity, their effects remain poorly documented in West Africa. This study assesses the impact of climate change adaptation practices on honey production per hive in Casamance, Senegal. Data were collected from 215 beekeepers in Lower, Middle, and Upper Casamance. Descriptive statistics and an Endogenous Switching Regression (ESR) model were used to analyze adoption rates, their determinants, and their effects on honey production. Results show that 58% of beekeepers are men and 42% are women, with the majority having less than ten years of experience and practicing beekeeping as a secondary activity; 63% own their hives. Reforestation with melliferous species is the most widely adopted practice (67.91%), followed by the use of modern hives with wax foundation frames (65.58%) and supplementary bee feeding (62.33%). Adoption of these practices is significantly associated with higher honey production per hive, by about 25%, 208%, and 16%, respectively (relative to the counterfactual without adoption). Adoption of practices and honey production are also associated with agro-ecological zone, beekeeping production system, marital status, and education level. These findings highlight the economic potential of climate change adaptation strategies and underscore the need to promote interventions that foster more productive, resilient, and sustainable beekeeping in Casamance.

Keywords

Climate Change, Adaptation Strategies, Beekeeping, Productivity, Adoption, Impact, Senegal

1. Introduction

Beekeeping provides livelihoods, income, and food for millions of vulnerable people in rural areas [1]-[3]. It also plays a major role in preserving biodiversity, improving agricultural yields, and enhancing food security in Africa [4] [5]. In Senegal, beekeeping contributes 7.4% of the national Gross Domestic Product (GDP), supports income diversification, and improves food security, especially in rural areas [6]. At the national level, annual national honey and beeswax production are estimated at 10,000 tons and 2300 tons, respectively [7]. However, beekeeping remains precarious because it is vulnerable to climate change and the degradation of natural resources. Studies have demonstrated a reduction in the quantity of honey produced per hive as a result of climate change and environmental degradation [8] [9]. Indeed, climate-related changes in temperature and precipitation can disrupt plant phenology and alter the availability of nectar and pollen, leading to periods of nutritional stress for colonies [10] [11]. Similarly, [12] show that short-term weather conditions can influence bee–plant interactions and, consequently, honey production. A recent review on honey production in Africa highlights that deforestation, habitat degradation, and climate change constitute major constraints for beekeeping productivity [5]. These factors can affect the availability and dynamics of floral resources, modify foraging activity, and alter bee–plant interactions [11] [12]. In response, several environmental, ecosystem-based, technological, and feeding adaptation practices have been promoted to strengthen the resilience of beekeeping farms to climate change and natural resource degradation [5] [13]-[16]. For example, such adaptation practices have been widely implemented in Casamance, Senegal, in recent years by government services, NGOs, and beekeepers' associations. These include restoration and preservation through reforestation with melliferous species, modernization of hives to better control production conditions, and mitigation through supplementary feeding to temporarily compensate for deficits in natural food resources, namely nectar and pollen [14] [17]. However, few studies have evaluated the impact of beekeepers' adoption of these adaptation practices on honey productivity. Existing studies focus more on the effects of climate change on beekeeping, beekeepers' perceptions of climate change, and the characterization of adaptation practices and beekeeping farms [18]-[20]. The present study thus contributes to filling this knowledge gap.

2. Materials and Methods

2.1. Sampling and Data Collection

The study was conducted in Casamance, southern Senegal (**Figure 1**). Casamance benefits from the humidest climate in Senegal, with annual rainfall generally ranging from 900 mm to over 1200 mm, while temperatures remain relatively high due to continental conditions [21]-[23]. The area has substantial forest and mangrove resources favorable to beekeeping development [24] [25]. This zone provides more than 70% of the country's national honey production [6]. Beekeeping constitutes a secondary economic activity for rural populations alongside agriculture,

pastoral livestock farming, and forestry [24] [26]. However, beekeepers in the area face several constraints, including climate change and the degradation of natural resources through deforestation and bushfires, which affect the availability of floral resources and colony development conditions, thereby compromising the productivity and sustainability of beekeeping activities [14] [27].

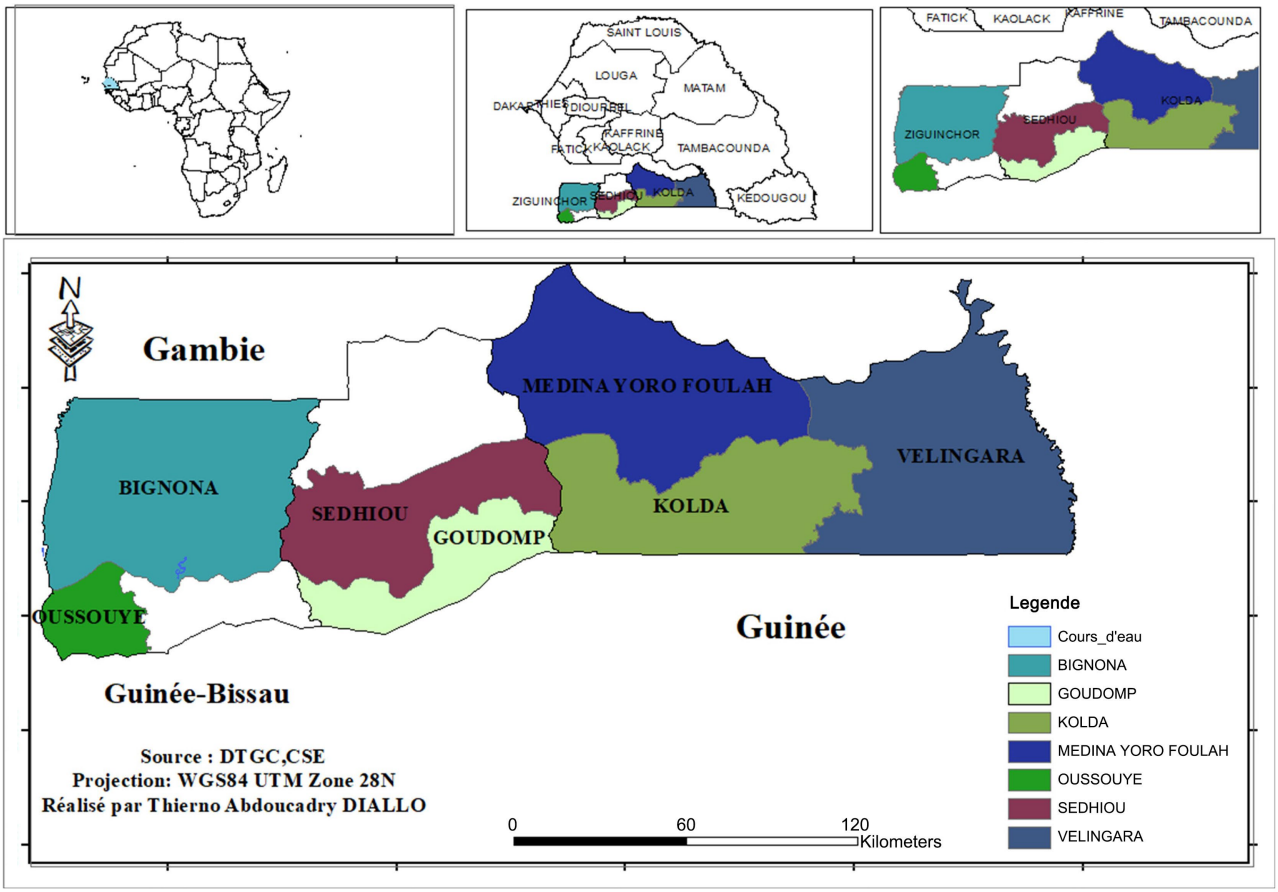

Figure 1. Location of the study area.

Data were collected using a semi-structured questionnaire developed on the KoboToolbox platform (version 2.024.05), deployed on the KoboCollect application (version 2023.2.4), and administered to beekeepers by trained enumerators. The survey was conducted in three agro-ecological zones of Casamance: Lower, Middle, and Upper Casamance. The database of the Casamance Agro-Food Cooperative (CAC/Miel) served as the sampling frame for identifying beekeepers. The total sample size was then determined using [28] formula (1):

$$n = \frac{Z^2 pqN}{e^2 (N-1) + Z^2 pq} \quad (1)$$

where:

n = required sample size; p = 0.5 (50% reliability of the population); $q = 1 - p = 0.5$; N = 487 (total number of targeted beekeepers); Z = 1.96 (standard error corresponding to a 95% confidence interval); e = 0.05 (tolerated margin of error).

2.2. Variable Definition and Descriptive Statistics

The study focuses on evaluating three climate change adaptation practices that have been promoted in the area to strengthen beekeepers' resilience. These are: 1) reforestation with melliferous species, 2) supplementary feeding of bees, and 3) use of modern hives with frames and wax foundation sheets. These three adaptation practices are defined here as adoption variables (treatment variables), each taking the value 1 if the beekeeper adopts the practice and 0 otherwise. The study also uses the quantity of honey harvested per hive (expressed in liters) as the outcome variable. Finally, the explanatory or control variables are the socio-demographic, technical, and economic characteristics of the beekeepers. Table 1 presents the variables and their descriptions.

Honey production was self-reported by beekeepers for the 2024-2025 campaign and was not independently verified (e.g., by weighing); it may therefore be subject to recall and measurement error. Honey quantity per hive is calculated as the total volume harvested divided by the number of hives harvested, so that the estimates refer to yield per harvested hive, not per hive owned.

Table 1. Variable definitions.

Variables		Description
Adoption variables	Reforestation	1 = adoption (beekeeper practices reforestation); 0 = non-adoption
	Bee feeding	1 = adoption (beekeeper provides supplementary feed); 0 = non-adoption
	Improved hive	1 = adoption (uses modern hive with frames and wax foundation); 0 = otherwise
Outcome variable	Honey quantity per hive (L)	Honey harvested per hive (liters) during the 2024-2025 campaign, self-reported by the beekeeper (total volume harvested divided by the number of hives harvested)
Explanatory variables	Socio-demographic & economic	Age, sex, marital status, ethnicity, religion, agro-ecological zone, farming system, main activities (beekeeping training is used as the excluded instrument, see Section 2.3.2)

2.3. Econometric Approach and Estimation

2.3.1. Decision to Adopt a Climate Change Adaptation Practice

The decision to adopt a climate change adaptation practice is binary. Beekeepers decide whether or not to adopt an adaptation practice based on a set of observable factors. We model the adoption of an adaptation practice within a random utility framework. In this context, the beekeeper's decision mainly rests on a comparison of expected utilities (U_{Pi} and U_{Ni}). Let the difference between expected utilities be represented by U_{ti}^{*}; then beekeeper i will adopt a climate change adaptation practice if:

$$UT_i^{*} = U_{Pi} - U_{Ni} > 0$$

However, this difference is not directly observable but can be specified as a

function of observable factors within a latent variable model, as follows:

$$UT_i^* = \beta X_i + \vartheta_i \text{ with } M_i = \begin{cases} 1 & \text{if } UT_i^* > 0 \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where UT_i^* is a latent utility indicator associated with the binary decision M_i, equal to 1 if beekeeper *i* adopts an adaptation practice and 0 otherwise; β represents the vector of unknown parameters to be estimated; X_i corresponds to socio-demographic and economic characteristics (sex, age, education level, marital status, ethnicity, agro-ecological zone, type of beekeeping, etc.); and ϑ_i is the error term. The probability that a beekeeper adopts a climate change adaptation practice can be specified as follows:

$$P_r(M_i = 1) = P_r\left(UT_i^* > 0\right) = P_r\left(\vartheta_i > -\beta X_i\right) = 1 - F\left(\beta X_i\right) \quad (3)$$

where F is the cumulative distribution function of ϑ_i and other elements are as defined above. Without loss of generality, we assume that the outcome variable vector (quantity of honey produced per hive) is a linear function of the independent variables X_i and an indicator variable for adoption of a climate change adaptation practice, so that the outcome equation can be specified as:

$$Y_i = \varphi X_i + \gamma M_i + \varepsilon_i \quad (4)$$

where Y_i is the outcome variable (quantity of honey produced per hive); X_i is a vector of explanatory variables; M_i represents adoption of a climate change adaptation practice; φ and γ are parameters to be estimated; and ε_i is the error term.

To obtain consistent and unbiased results, we must control for observable and unobservable characteristics that determine adoption of a climate change adaptation practice, as these characteristics may be correlated with the outcome variable. In our non-experimental data, households' observable and unobservable characteristics may be associated with both adoption of an adaptation practice and the outcome variable (quantity of honey produced per hive). Quasi-experimental methods, such as Propensity Score Matching (PSM) and Inverse Probability Weighting Regression Adjustment, can account for selection bias. However, they only consider observable characteristics and ignore unobservable factors such as adaptive abilities, preferences, and risk aversion. To account for both observed and unobserved factors in this context, we employ the Endogenous Switching Regression (ESR) model of [29]. For adopters and non-adopters of a climate change adaptation practice, this model uses full information maximum likelihood to jointly estimate a selection equation and two outcome equations.

2.3.2. Endogenous Switching Regression (ESR) Approach

The ESR approach is a one-step procedure that first estimates the factors influencing beekeepers' decision to adopt a climate change adaptation practice, then analyzes the factors influencing the outcome variable, namely the quantity of honey produced per hive [29]. This method accounts for selection bias induced by observable and unobservable factors, yielding precise and reliable parameter

estimates. The ESR model is a powerful tool for estimating treatment effects in situations where individuals' self-selection into treatment groups is a concern, and it is widely used in economics, public policy, and social sciences (e.g., [30]-[34]). The model is described below as comprising two regime equations, one for beekeepers adopting a climate change adaptation practice and another for non-adopters, with the selection function M_i determining the regime to which each belongs:

$$\text{Regime 1}: Y_{Pi} = \varphi_P Z_i + \varepsilon_{Pi} \text{ if } M_i = 1 \tag{5a}$$

$$\text{Regime 2}: Y_{Ni} = \varphi_N Z_i + \varepsilon_{Ni} \text{ if } M_i = 0 \tag{5b}$$

where Y_{Pi} and Y_{Ni} represent the outcome variables (quantity of honey produced per hive) for beekeepers adopting a climate change adaptation practice (regime 1) and non-adopters (regime 2), respectively; Z_i is a vector of observable factors determining the outcome variables; φ_P and φ_N are unknown parameters to be estimated; and ε_{Pi} and ε_{Ni} are error terms. Consequently, the error terms of Equations (2), (5a), and (5b) are assumed to follow a trivariate normal distribution with zero mean and non-singular covariance matrix, represented as:

$$\operatorname{cov}\left(\varepsilon_P, \varepsilon_N, \vartheta_i\right) = \begin{bmatrix} \sigma_P^2 & \sigma_{PN} & \sigma_{P\vartheta} \\ \sigma_{NP} & \sigma_N^2 & \sigma_{N\vartheta} \\ \sigma_{\vartheta P} & \sigma_{\vartheta N} & \sigma_\vartheta^2 \end{bmatrix} \tag{6}$$

where σ_P^2 = variance of ε_P, σ_N^2 = variance of ε_N, σ_ϑ^2 = variance of ϑ_i, σ_{NP} = covariance between ε_P and ε_N, $\sigma_{N\vartheta}$ = covariance between ε_P and ϑ, and $\sigma_{N\vartheta}$ = covariance between ε_N and ϑ. Following Greene (2018), we assume $\sigma_\vartheta^2 = 1$, since ϑ in the selection equation is identifiable only up to a scale factor.

For the ESR model to be properly identified, some variables in the regime equations may be common to those in the selection equation, but at least one variable must appear in the selection equation without appearing in the regime equations. To be considered a valid selection instrumental variable, this variable must satisfy three conditions: relevance, exclusion restriction, and exogeneity. In this framework, we use whether the beekeeper receives beekeeping training as an instrumental variable. Beekeeping training is expected to be relevant because training programs in Casamance (e.g., CasaMiel, ApiClimat) were designed to promote improved practices [14]; it is significantly associated with the adoption of each practice (**Table A1**). However, training may also directly affect honey production by improving colony management (e.g., swarm control, hive inspection, harvest timing), independently of the three practices studied. The exclusion restriction and exogeneity are therefore assumptions rather than established facts: training is assumed not to directly affect the quantity of honey produced per hive, nor to be correlated with unobserved factors affecting it. The validity of the selection instrument was assessed using the falsification test proposed by [31], applied separately to each practice. Training is significantly associated with adoption of reforestation ($p = 0.003$), supplementary feeding ($p = 0.026$) and modern hives ($p < 0.001$) (**Ta-**

ble A1), but is not significantly associated with honey quantity per hive among non-adopters of any of these practices (p = 0.628, 0.318 and 0.108, respectively; Table A2). These tests have limited statistical power given the subsample sizes (n = 69 - 81) and wide confidence intervals, and a non-significant association does not by itself establish the validity of the instrument. Moreover, because adoption of the three practices is largely joint (Section 3.2), the falsification regressions are run practice by practice and do not isolate beekeepers who adopted none of the practices. The estimated effects are therefore interpreted as associations that account for selection on observed and, under the instrument's assumptions, unobserved factors, rather than as definitive causal effects. The ESR model, as described above, accounts for the systematic difference observed between adopters and non-adopters. The inverse Mills ratios for adopters and non-adopters are calculated jointly with the corresponding covariance components, $\sigma_{P\vartheta}$ and $\sigma_{N\vartheta}$. To account for unobserved factors, these components are incorporated into Equations (5a) and (5b) after estimating the selection Equation (2), as follows:

$$Y_{Pi} = \varphi_P Z_i + \sigma_{P\vartheta}\lambda_{Pi} + \varepsilon_{Pi} \text{ if } M_i = 1 \quad (7a)$$

$$Y_{Ni} = \varphi_N Z_i + \sigma_{N\vartheta}\lambda_{Ni} + \varepsilon_{Ni} \text{ if } M_i = 0 \quad (7b)$$

In Equations (7a) and (7b), the inverse Mills ratios Y_{Pi} and Y_{Ni}, evaluated at δX_i, are used to account for selection bias resulting from unobserved factors, which leads to heteroskedasticity of standard errors (Following), a more appropriate approach to estimating the ESR model is to use the Full Information Maximum Likelihood (FIML) method, which jointly estimates the selection and outcome equations and generates the correlation coefficients $\rho_{P\vartheta}$ and $\rho_{N\vartheta}$ associated with the error terms of the selection and outcome equations. The significance of the coefficients $\rho_{P\vartheta}$ or $\rho_{N\vartheta}$ would confirm the presence of selection bias [29].

2.3.3. Estimation of Average Treatment Effects of Adopting an Adaptation Practice

The ESR model can be used to further evaluate the effect of adopting an adaptation practice on the outcome variable (quantity of honey produced per hive), in addition to estimating the effects of observed factors on the outcome variable in the adoption and non-adoption regimes of a climate change adaptation practice. To determine the average treatment effect on the treated (ATT), we compare the expected outcomes of adopters with those of the counterfactual situation in which these same beekeepers would not have adopted. Specifically, the expected outcomes for beekeepers who adopted (observed) and those who did not adopt (counterfactual) are expressed as follows:

$$E\left(Y_{Pi} \mid M = 1\right) = \varphi_P Z_i + \sigma_{P\vartheta}\lambda_{Pi} \quad (8a)$$

$$E\left(Y_{Ni} \mid M = 1\right) = \varphi_N Z_i + \sigma_{N\vartheta}\lambda_{Pi} \quad (8b)$$

Finally, the ATT associated with adopting a climate change adaptation practice is calculated as the difference between Equations (8a) and (8b), and is expressed as:

$$\text{ATT} = E\left(Y_{Pi} \mid M = 1\right) - E\left(Y_{Ni} \mid M = 1\right) = Z_i\left(\varphi_P - \varphi_N\right) + \lambda_{Pi}\left(\sigma_{P\vartheta} - \sigma_{N\vartheta}\right) \quad (9)$$

$$\text{ATU} = E\left(Y_{Pi} \mid M = 0\right) - E\left(Y_{Ni} \mid M = 0\right) = Z_i\left(\varphi_P - \varphi_N\right) + \lambda_{Ni}\left(\sigma_{P\vartheta} - \sigma_{N\vartheta}\right) \quad (10)$$

In the results, the percentage change is computed as the treatment effect divided by the expected outcome in the absence of adoption (the counterfactual outcome for the ATT, and the observed outcome of non-adopters for the ATU).

3. Results

3.1. Socio-Demographic Characteristics

Analysis of Table 2 highlights several socio-demographic and economic characteristics of the surveyed population. Men represent 58.6% of respondents, compared to 41.4% women. More than half of the beekeepers (53.49%) are aged over 41 years. The majority are married (85.12%), while 37.21% of respondents have no formal schooling. Ethnically, the Peulh constitute the majority group (52.56%), followed by the Diola (32.09%), Mandingues (11.63%), and Balantes (3.26%). The surveyed population is also predominantly Muslim (87.44%). Beekeeping represents the main economic activity for only 26.98% of respondents. More than half (60.93%) have practiced beekeeping for less than ten years and have joined an organization. Likewise, the analysis reveals a predominance of modern beekeeping systems, which concern 65.12% of respondents. Also, 63.72% of beekeepers report owning hives. Among the different types of hives used, Langstroth hives are the most frequently cited (86.51%), followed by "Coro" hives (58.14%), Vauthier (52.56%), and Kenyan (37.21%).

Table 2. Socio-economic profiles of beekeepers.

Parameter	Category	Percentage (%)
Sex	Male	58.6
	Female	41.4
Age	21 - 35	24.19
	36 - 40	22.33
	>41	53.49
Marital status	Single	14.88
	Married	85.12
Education level	Quranic	46.51
	Primary	18.60
	Middle & Secondary	24.19
	University	10.70
Ethnicity	Diola	32.09
	Peulh	52.56
	Others	14.88
Religion	Muslim	87.44
	Christian	12.56

Continued

Beekeeping as main activity	Yes	26.98
	No	73.02
Experience in beekeeping	<10 years	60.93
	>10 years	39.07
Member of association	Yes	90.70
	No	9.30
Technical training in beekeeping	Yes	79.07
	No	20.93
Hive ownership	Yes	63.72
	No	36.28
Types of hives owned	Kenyan	37.21
	Vauthier	52.56
	Coro	58.14
	Langstroth	86.51
	Others	5.12

3.2. Adoption of Climate Change Adaptation Practices

Results in Table 3 show that all three practices are relatively widely adopted. Reforestation with melliferous species has the highest adoption rate (67.91%), followed by the use of modern hives with wax foundation frames (65.58%) and supplementary bee feeding (62.33%).

Table 3. Adoption rates of climate change adaptation practices.

Adaptation Practice	Adopters (n)	Non-adopters (n)	Adoption Rate (%)
Reforestation with melliferous species	146	69	67.91
Supplementary bee feeding	134	81	62.33
Modern hives with wax foundation frames	141	74	65.58

Adoption of the three practices is largely joint: 43.72% of beekeepers adopt all three practices, 20.93% adopt two, 22.79% adopt only one, and only 12.56% adopt none (Table 4).

Table 4. Number of adaptation practices adopted simultaneously.

Number of practices adopted	n	%
None	27	12.56
One practice	49	22.79
Two practices	45	20.93
All three practices	94	43.72
Total	215	100.00

3.3. Impact of Adoption of Climate Change Adaptation Practices on Honey Quantity Produced per Hive

Results in Table 5 show that beekeepers adopting reforestation with melliferous species increase the quantity of honey harvested per hive by 25.32% at the 1% significance level, compared to their counterfactual situation. For non-adopting beekeepers, the evaluation shows they would have increased honey production per hive by 4.05% if they had adopted reforestation compared to their current situation, but the difference is not statistically significant. Also, results reveal that beekeepers adopting supplementary bee feeding increased their honey production per hive by 16.34% at the 1% significance level, compared to the situation if they had not adopted. Similarly, non-adopting beekeepers would have potentially increased their harvested honey quantity per hive by 6.41%, significant at the 10% level, if they had adopted. Finally, beekeepers who adopted improved hives with wax foundation frames show the largest effect among the three practices studied, with an increase in harvested honey quantity per hive of 207.94% at the 1% significance level, compared to their counterfactual situation. Also, among non-adopters, their honey quantity per hive would have potentially increased by 13.58%, statistically significant at the 1% level, if they had adopted.

Percentage changes are computed relative to the outcome expected without adoption (the counterfactual for adopters; the observed outcome for non-adopters). The very large effect for modern hives is driven by a low counterfactual (5.04 L per hive).

Table 5. Impact of adoption of adaptation practices on honey quantity produced per hive.

Variables	Parameters	Adopters	Non-adopters	Treatment effects	t-value	Variation (%)
Honey quantity per hive (L)	Reforestation with melliferous species					
	ATT	14.75 (0.13)	11.77 (0.27)	2.98 (0.31)	9.87*	25.32
	ATU	14.38 (0.21)	13.83 (0.31)	0.56 (0.43)	1.29	4.05
	Supplementary bee feeding					
	ATT	15.46 (0.17)	13.28 (0.27)	2.17 (0.32)	6.57*	16.34
	ATU	13.62 (0.23)	12.8 (0.37)	0.82 (0.44)	1.84***	6.41
	Improved hives with wax foundation frames					
	ATT	15.52 (0.14)	5.04 (0.45)	10.48 (0.47)	22.30*	207.94
	ATU	14.05 (0.23)	12.37 (0.33)	1.68 (0.42)	4*	13.58

ATT: Average Treatment Effect on Treated; ATU: Average Treatment Effect on Untreated; *, **, *** significance levels of 1%, 5% and 10%, respectively; The values in parentheses are the standard deviations.

3.4. Determinants of Adoption of Adaptation Practices and Honey Quantity

Results presented in Table 6 indicate that, apart from reforestation, other varia-

bles influence the quantity of honey harvested. Indeed, among beekeepers who adopted reforestation, religion is positively and significantly associated with the quantity of honey harvested ($\beta = 3.617$; p = 0.005), while sex and age show negative effects, significant at the 10% level ($\beta = -1.403$; p = 0.079) and 10% ($\beta = -0.884$; p = 0.098), respectively. These results suggest that among adopters, the quantity of honey harvested tends to decrease with age and among individuals in the male sex category. Among non-adopters of reforestation, the farming system exerts a negative and highly significant effect on the quantity of honey harvested ($\beta = -1.485$; p < 0.001), while belonging to Middle Casamance is associated with a decrease in production at the 10% level ($\beta = -2.405$; p = 0.067). Regarding adoption determinants, belonging to Upper Casamance is positively and strongly associated with adoption of reforestation ($\beta = 1.463$; p < 0.001), whereas other variables do not show a statistically significant effect.

Table 6. Other factors influencing adoption of adaptation practices and honey production.

Variables	Reforestation			Supplementary bee feeding			Improved hives with wax foundation frames		
	Decisive adoption	Factors affecting honey production		Decisive adoption	Factors affecting honey production		Decisive adoption	Factors affecting honey production	
		Adopters	Non-adopters		Adopters	Non-adopters		Adopters	Non-adopters
Sex	0.19	−1.40***	2.09***	−0.04	0.09	0.96	−0.31	−0.15	1.44
Age	−0.00	−0.88***	−0.78	−0.01	−0.66	−5.70	0.09	−1.23**	−0.19
Marital status	−0.06	0.06	0.15	0.07	0.47	−0.91	0.09	−0.21	−0.58
Religion	0.24	3.61***	−0.58	−0.48	3.77***	−2.53	−1.37**	1.78	7.57
Education level	0.08	0.15	0.06	0.00	0.47	0.03	0.18**	0.37	−0.54
Beekeeping system	−0.43	0.14	−1.48*	0.11**	0.03	−1.37*	−0.49	0.09	−0.49
Lower Casamance	1.46*	1.79	2.40***	Ref	Ref	Ref	0.03	0.16	4.12**
Moyenne Casamance	0.00	−0.38	0.91	−0.28	0.81	−1.60	1.29	1.48	−4.01
Upper Casamance	Ref	Ref	Ref	−1.10**	0.10	−1.51	Ref	Ref	Ref

*, **, *** significance levels of 1%, 5% and 10%, respectively; The values in parentheses are the standard deviation.

For beekeepers who adopted supplementary bee feeding, religion exerts a positive and statistically significant effect on the quantity of honey harvested ($\beta = 3.772$; p = 0.006). In contrast, sex, age, marital status, education level, agro-ecological zone, and farming system have no significant influence. In the non-adopter regime, the farming system appears as a negative and highly significant determinant of honey production ($\beta = -1.370$; p < 0.001), while other variables are not statistically significant. Factors significantly influencing the adoption of bee feeding are belonging to the Middle Casamance zone, which is negatively associated with adoption ($\beta = -1.103$; p = 0.001) and the improved beekeeping farming system, which is positively associated with adoption ($\beta = 0.118$; p = 0.031).

Finally, regarding beekeepers who adopted modern hives with wax foundation frames, age has a negative and statistically significant effect on the quantity of honey harvested ($\beta = -1.231$; p = 0.032), suggesting that an increase in age is associated with a decrease in honey production in this regime. In contrast, sex, agro-ecological zone, marital status, education level, religion, and farming system do not show a statistically significant association with the quantity of honey harvested among adopters. In the non-adopter regime, belonging to Lower Casamance exerts a positive and significant effect on the quantity of honey harvested ($\beta = 4.123$; p = 0.038), indicating that beekeepers in this zone have, ceteris paribus, higher production than those in the reference zone, while other variables are not statistically significant. Variables that significantly increase the probability of adopting modern hives with wax foundation frames are belonging to Upper Casamance ($\beta = 1.289$; p = 0.036) and education level ($\beta = 0.186$; p = 0.035), whereas religion is negatively associated with the probability of adopting this technology ($\beta = -1.380$; p = 0.001).

4. Discussion

4.1. Beekeeper Profiles

The study highlights a predominantly male and relatively older beekeeping population, with low youth involvement, a trend also observed in Senegal by [35] and [36]. This situation could be explained by financial constraints limiting young people's access to modern equipment [37] as well as the labor-intensive nature of traditional beekeeping [38]. The male predominance, combined with sociocultural specificities and conditions of traditional beekeeping practice, contrasts, however, with some studies conducted in Ethiopia and Rwanda, where women's participation is greater [39]-[41].

The low education level of a significant portion of beekeepers may constitute a constraint to accessing information and adopting innovations [42] [43]. However, the high proportion of beekeepers who received technical training and belong to professional organizations is an asset for modernizing the sector. Beekeeping remains mainly a secondary activity, complementary to agriculture, consistent with observations by [36] in Senegal. Results also reveal a gradual transition toward modern beekeeping systems, with a predominance of Langstroth hives. This evolution could be linked to their advantages in colony management and honey harvesting [44].

4.2. Uptake of Climate Change Adaptation Practices

Results show relatively high adoption of the three climate change adaptation practices studied among Casamance beekeepers. This may reflect beekeeping's particular vulnerability to environmental variation, since bee activity and honey production depend closely on interactions among colonies, vegetation, and weather conditions [4] [12]. A recent systematic review confirms that temperature, precipitation, and wind can affect several dimensions of bee biology and that climate

change can alter beekeeping production conditions [11].

Reforestation with melliferous species is the practice with the highest adoption rate (67.91%). This high adoption can be explained by the productive, ecological, and adaptive nature of this practice. Planting melliferous species enriches or restores floral resources around apiaries and can thus help secure nectar and pollen sources necessary for bee feeding; it is therefore generally promoted as a climate change adaptation strategy by development support actors and adopted by beekeepers [4] [8] [11] [12] [45]. The second most adopted practice is the use of modern hives with wax foundation frames, at 65.58%. This relatively high proportion indicates an appreciable level of modernization of the studied beekeeping systems. This can be explained by the fact that movable-frame hives with wax foundation offer several advantages over other hives, including the ability to inspect colonies, monitor brood development, control swarming, manipulate combs without destroying colony structure, and facilitate harvesting operations, thus contributing to more controlled management and improved production efficiency, justifying their adoption by beekeepers in areas where they are introduced [45]-[47]. The third practice, supplementary bee feeding, is adopted by 62.33% of beekeepers. Although it has the lowest adoption rate among the three practices studied, its frequency remains significant. This adoption level can be explained by the need to support colonies during periods of floral scarcity, when natural nectar and pollen resources become insufficient. This interpretation is strongly corroborated by [48], in a review on artificial bee feeding, showing that supplementary diets can help compensate for nutritional deficits when natural resources are insufficient, particularly during scarcity periods.

4.3. Determinants of Adoption of Climate Change Adaptation Practices

Results on adoption determinants show that factors associated with the decision to adopt differ according to the practice considered. This heterogeneity is consistent with the agricultural innovation literature, according to which technology adoption depends simultaneously on producer characteristics, resources, institutional environment, perceptions, and technology-specific characteristics.

For reforestation with melliferous species, belonging to Upper Casamance is positively and strongly associated with the probability of adoption ($\beta = 1.463$; $p < 0.001$), while other variables do not show a statistically significant effect. This result highlights the importance of the territorial dimension in the decision to invest in restoring plant resources. The positive effect of Upper Casamance could reflect inter-zonal differences in land availability, vegetation cover, pressure on natural resources, availability of melliferous species, or perceived exposure to climate variability effects. When floral resources decline or become more irregular, producers may be more inclined to invest in practices that restore or secure these resources. [49] notably identifies habitat degradation, declining melliferous resources, and climate change effects among environmental factors likely to influence the adop-

tion of beekeeping technologies and practices in sub-Saharan Africa.

For supplementary bee feeding, belonging to Middle Casamance is negatively and significantly associated with adoption compared to Upper Casamance ($\beta = -1.103$; $p = 0.001$). This spatial difference may be linked to characteristics of beekeeping systems and periods of floral resource availability, which are greater in the Sédhiou region compared to the Kolda region, which is more vulnerable to climate change, but also to the fact that modern beekeeping practices have been more disseminated in the Kolda region than in the Sédhiou region, where traditional beekeeping is more practiced.

For supplementary bee feeding, belonging to Middle Casamance is negatively and significantly associated with adoption compared to Upper Casamance ($\beta = -1.103$; $p = 0.001$). This spatial difference could be explained, at least in part, by agro-ecological, rainfall, and floristic contrasts between the two zones. Indeed, works on melliferous plants of Casamance show that floral resources available to bees vary according to territories. An ethnobotanical study conducted in the departments of Ziguinchor, Kolda, and Sédhiou identified 61 melliferous plant species belonging to 30 families, with differences in species composition and availability according to zones [50]. The authors notably highlight the importance of trees and shrubs in constituting the region's melliferous resources. Climatic differences between Kolda and Sédhiou may also contribute to explaining observed adoption gaps. Available data indicate that both regions belong to the Sudan-Guinean zone but present differences in rainfall and ecological conditions.[50] report an average annual rainfall of about 883 mm in Kolda versus about 1000 mm in Sédhiou, while other recent climate data indicate relatively close average precipitation levels but interannual variability likely to affect floral resource availability. Now, nectar and pollen availability is highly dependent on weather conditions and plant phenology. Variations in temperature and precipitation can modify flowering periods and cause periods of food deficit for colonies [11] [12]. In this context, the adoption difference between Upper and Middle Casamance could reflect differentiated adaptation strategies according to the local environment. Indeed, when natural floral resources are relatively available and regular, beekeepers may be less inclined to resort to supplementary feeding. Conversely, when food deficit periods are more frequent or longer, supplementation may become a more important management strategy. This hypothesis is consistent with recent work showing that climate change and floral resource disruptions can increase colonies' dependence on management interventions aimed at reducing nutritional stress [10] [11]. Finally, another explanation could be linked to differentiated dissemination of beekeeping innovations between Kolda and Sédhiou. FAO indicates that the CasaMiel and, more recently, ApiClimat initiatives have sought to strengthen the technical capacities of Casamance beekeepers, notably through the dissemination of climate-smart production techniques, use of modern equipment, and integration of climate information into beekeeping practices [14]. This hypothesis is all the more plausible since the literature on adoption of beekeeping technolo-

gies in sub-Saharan Africa shows that access to training, extension services, producer organizations, and modern technologies constitutes an important determinant of adoption [47] [49].

The improved beekeeping farming system is also positively associated with adoption of supplementary feeding ($\beta = 0.118$; $p = 0.031$). This result is particularly interesting as it suggests complementarity between innovations. Beekeepers who have already adopted an improved management system may be more willing to adopt other practices intended to improve colony performance. This association can be explained by a higher level of technical knowledge, greater perception of the economic benefits of innovation, or a stronger commercial orientation. [49] review indeed shows that experience, education, perception of benefits, access to information, and exposure to extension services constitute important factors in the adoption of beekeeping technologies in sub-Saharan Africa.

This hypothesis of technological complementarity is particularly relevant in the study area, as a beekeeper who already uses improved equipment may, for example, be more attentive to colony nutrition and more willing to invest in supplementary feeding. Literature also shows that beekeeping technologies are rarely adopted in isolation: movable-frame hives are often associated with improved colony management, technical training, use of appropriate equipment, and improved harvesting and processing operations [47] [49] [51]. This result also aligns with work conducted in Ethiopia. [52] shows that adoption of improved hives in the Kaffa, Sheka, and Bench-Maji zones depends on several institutional, socio-economic, and technological factors.

The positive effect of belonging to Upper Casamance on adoption of modern hives further suggests that territorial and institutional conditions can also favor innovation dissemination. Observed differences between zones may reflect differentiated access to producer organizations, development projects, extension services, equipment, or markets. In several African countries, membership in beekeeping cooperatives and associations is associated with higher adoption of modern technologies, notably because these organizations facilitate access to information, training, financing, and markets [47] show that access to credit and extension services constitutes a significant determinant of improved hive adoption in Tanzania. Similarly, [49] review indicates that producer organizations, advisory services, credit mechanisms, and training programs play an important role in the dissemination of beekeeping technologies in sub-Saharan Africa. In contrast, religion is negatively associated with the probability of adopting modern hives ($\beta = -1.380$; $p = 0.001$). This result should be interpreted with caution. Work on beekeeping in Africa shows that sociocultural factors can indeed influence attitudes toward innovations and that their influence may vary according to contexts [49] [51].

4.4. Impact of Adoption of Adaptation Practices on Honey Quantity Produced

Results show that adoption of reforestation is associated with a positive and sta-

tistically significant increase in the quantity of honey produced per hive. This result suggests that reforestation constitutes a particularly effective adaptation strategy to support beekeeping productivity in a context of climate variability. This result is consistent with recent work showing that honey bee colony productivity depends strongly on the availability, diversity, and continuity of floral resources, enabling bees to have food resources such as nectar and pollen and a microclimate favorable to foraging [5] [53]-[55]. Also, work by [56], conducted at large scale in Kenya, shows that climatic conditions, notably temperature and precipitation, influence colony losses and their productivity and that certain beekeeping management practices such as reforestation can help reduce the negative consequences of these environmental constraints on production. In the specific context of Casamance, this relationship is particularly important. The region constitutes one of Senegal's main beekeeping basins, but its honey production faces the effects of climate variability and environmental degradation, causing disruption of flowering periods and reduction in the availability of melliferous resources necessary for colonies [12] [14] [57]. FAO also emphasizes that Casamance beekeepers face changing climatic conditions that affect beekeeping production and necessitate the adoption of more climate-adapted production practices [14] [57].

Regarding supplementary bee feeding, counterfactual analysis results highlight a positive and statistically significant association between adopting this practice and the quantity of honey produced. This result suggests that supplementary feeding can help maintain colonies' productive performance when natural food resources become insufficient in this climate change context. This interpretation is consistent with recent work showing that the availability of supplementary foods such as water, sugared water, and food residues constitutes an essential determinant of colony development and their capacity to produce honey [11] [12]. Recent experiments conducted by [58] show that food supplementation can improve colony development and certain indicators of their strength during periods of reduced natural resource availability. Similarly, [59] report improved productive performance of colonies receiving different types of supplementary foods in the Ethiopian context. The result obtained in the present study is also consistent with work by [60], showing that nutritional supplementation positively influences brood development, colony population growth, and honey production. These results suggest that the effect of supplementary feeding on production is not only linked to a direct food supply but also to its influence on colony demographic dynamics. A colony with sufficient food resources can maintain a larger bee population and thus an increased capacity to exploit available floral resources and store nectar transformed into honey [60].

Finally, the use of improved hives equipped with movable frames and wax foundation shows the largest effect on harvested honey quantity among the three adaptation practices studied. Among adopting beekeepers, average observed production reaches 15.52 L per hive, compared to only 5.04 L per hive in the counterfactual non-adoption scenario. The estimated ATT of 10.48 L per hive thus cor-

responds to a 207.94% increase relative to the counterfactual (a large relative effect driven by a low counterfactual production of 5.04 L per hive) and is statistically significant at the 1% level. This result indicates that adoption of an improved hive system is strongly associated with improved colony productivity. It is consistent with beekeeping literature showing that modern colony management technologies can improve management conditions, facilitate monitoring of bee populations, and increase harvesting efficiency [5]. Several mechanisms can explain the magnitude of this effect. Unlike traditional fixed-comb hives, movable-frame hives allow the beekeeper to more easily inspect the colony, control brood development, monitor food reserves, and intervene more quickly in case of problems. Movable frames also allow combs to be moved without destroying the structure built by the bees, which reduces colony disturbances and facilitates more rational resource management. These characteristics constitute important advantages of modern hives over traditional systems [5] [45]. The use of wax foundation can also contribute to improving productivity by providing colonies with a standardized construction structure. Wax foundation facilitates comb construction orientation and allows bees to devote a greater part of their energy to other colony functions, notably brood rearing, nectar collection, and honey storage. Frame standardization also facilitates apiary management and harvesting operations. In modern systems, frames can be removed and replaced without destroying the colony, which allows preserving a significant part of the hive's biological and material capital [14] [45]. These results are particularly important in the climate change context. Temperature and rainfall variations can affect floral resource availability and increase stress on colonies [11] [12]. In this context, an improved hive can strengthen the beekeeper's capacity to adapt colony management to changing environmental conditions [5].

5. Conclusion

This study aimed to evaluate climate change adaptation strategies adopted by Casamance beekeepers and their impact on the quantity of honey produced per hive. Results show that adoption of climate change adaptation practices constitutes an important lever for improving beekeeping productivity in Casamance. Reforestation with melliferous species, use of modern hives, and supplementary bee feeding are significantly associated with higher honey production per hive, confirming the economic interest of these strategies in a context of climate change and natural resource degradation. However, their adoption remains influenced by beekeeper characteristics and their production systems, notably agro-ecological zone and education level. These results thus underscore the need to strengthen technical support, training, and access to equipment to favor wider dissemination of these practices. Promoting reforestation with melliferous species, improving access to modern hives, and developing adapted colony feeding strategies could thus contribute to sustainably strengthening the productivity, resilience, and sustainability of beekeeping in Casamance.

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Author Contributions

Conceptualization: S.D. and T.A.D.; methodology: S.D. and T.A.D.; software: X.X.; validation: S.D. and T.A.D.; formal analysis: L.D. and F.G.; research: T.A.D.; data management: T.A.D.; writing—first draft: T.A.D.; writing—revision and proofreading: S.D., L.D., and F.G.; visualization: S.N.; supervision: T.A.D.; project management: S.D. All authors have read and approved the published version of the manuscript.

Conflicts of Interest

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

References

[1] Dossou, S.A.R., Adanguidi, J., Aoudji, A.K.N. and Gbedomon, R.C. (2022) Promotion of Beekeeping: Insights from an Empirical Analysis of Three Honey Value Chains in Benin. *Natural Resources Forum*, **46**, 39-59. https://doi.org/10.1111/1477-8947.12238

[2] Hecklé, R. (2018) Beekeeping Adoption: A Case Study of Three Smallholder Farming Communities in Baringo County, Kenya. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, 119, 1-11.

[3] Hinton, J., Schouten, C., Austin, A. and Lloyd, D. (2019) An Overview of Rural Development and Small-Scale Beekeeping in Fiji. *Bee World*, **97**, 39-44. https://doi.org/10.1080/0005772x.2019.1698104

[4] Frazier, M., Muli, E. and Patch, H. (2024) Ecology and Management of African Honey Bees (*Apis mellifera* L.). *Annual Review of Entomology*, **69**, 439-453. https://doi.org/10.1146/annurev-ento-020823-095359

[5] Tadele, E., Worku, D., Muluneh, T., Ayana, Y. and Melese, A. (2025) Comprehensive Review on Improved Honey Production: Techniques, Challenges, Opportunities, and Future Prospects in Africa. *Frontiers in Bee Science*, **3**, Article ID: 1588416. https://doi.org/10.3389/frbee.2025.1588416

[6] Kanouté, P.A. (2012) La démarche de qualité liée à l'origine du miel de Casamance, Sénégal. Organisation des Nations Unies pour l'alimentation et l'agriculture (FAO), 30 p.

[7] Diedhiou, E.N.Y., Ndiaye, L., Diatta, K., Badji, M., Charabil, M.M. and Manga, E. (2026) Analyse technico-économique de la filière apicole en basse Casamance (Sud du Sénégal): Analyse technico-économique du secteur apicole dans les bas-fonds de Casamance (Sud du Sénégal). *Revue Internationale des Sciences Biologiques et Chimiques*, **20**, 1507-1520. https://doi.org/10.4314/ijbcs.v20i3.31

[8] FAO, IZSLT, Apimondia and CAAS (2021) Good Beekeeping Practices for Sustainable Apiculture (FAO Animal Production and Health Guidelines No. 25). https://doi.org/10.4060/cb5353en

[9] Fondation Énergies pour le Monde (2024) SENAPI: Développement du secteur apicole comme activité génératrice de revenus au Sénégal. https://fondem.ong/senapi/

[10] Quaresma, A., Baveco, J.M., Brodschneider, R., Buddendorf, W.B., Carreck, N.L., Gratzer, K., *et al.* (2025) Honey Bee Food Resources under Threat from Climate Change. *Nature Communications*, **17**, Article No. 1331. https://doi.org/10.1038/s41467-025-68085-6

[11] Zapata-Hernández, G., Gajardo-Rojas, M., Calderón-Seguel, M., Muñoz, A.A., Yáñez, K.P., Requier, F., *et al.* (2024) Advances and Knowledge Gaps on Climate Change Impacts on Honey Bees and Beekeeping: A Systematic Review. *Global Change Biology*, **30**, e17219. https://doi.org/10.1111/gcb.17219

[12] Vincze, C., Leelőssy, Á., Zajácz, E. and Mészáros, R. (2024) A Review of Short-Term Weather Impacts on Honey Production. *International Journal of Biometeorology*, **69**, 303-317. https://doi.org/10.1007/s00484-024-02824-0

[13] Ukamaka, D.M. and Eberechukwu, N.L. (2018) Indigenous Climate Change Adaptation Strategies Used by Honey Producers in Rural Communities of Enugu State, Nigeria. *Journal of Agricultural Extension*, **22**, 180-192. https://doi.org/10.4314/jae.v22i2.16

[14] Meisch, S.P., Bremer, S.R., Dunn-Sigouin, E. and Hempel, M. (2026) Adapting the Social Practice of Beekeeping to a Changing Climate. *Ambio*, **55**, 2139-2153. https://doi.org/10.1007/s13280-026-02354-6

[15] Gajardo-Rojas, M., Muñoz, A.A., Barichivich, J., Klock-Barría, K., Gayo, E.M., Fontúrbel, F.E., *et al.* (2022) Declining Honey Production and Beekeeper Adaptation to Climate Change in Chile. *Progress in Physical Geography: Earth and Environment*, **46**, 737-756. https://doi.org/10.1177/03091333221093757

[16] Kaiser-Bunbury, C.N., Mougal, J., Whittington, A.E., Valentin, T., Gabriel, R., Olesen, J.M., *et al.* (2017) Ecosystem Restoration Strengthens Pollination Network Resilience and Function. *Nature*, **542**, 223-227. https://doi.org/10.1038/nature21071

[17] FAO (2021) Cooler Hives Help Bees Adapt to Climate Change. FAO Climate Change. https://www.fao.org/climate-change/news/news-detail/Cooler-hives-help-bees-adapt-to-climate-change-/en

[18] Armand Paraïso, A., Sossou, A., Iz-Haquou, D., Nérice Yegbemey, R. and Sanni, A. (2012) Perceptions and Adaptations of Beekeepers and Honey Hunters to Climate Change: The Case of the Communes of Natitingou and Tanguieta in Northwest of Benin. *African Crop Science Journal*, **20**, 523-532.

[19] Gbetibouo, G.A. (2009) Understanding Farmers' Perceptions and Adaptations to Climate Change and Variability: The Case of the Limpopo Basin, South Africa (IFPRI Discussion Paper 849). International Food Policy Research Institute. https://hdl.handle.net/10568/21662

[20] Vercelli, M., Novelli, S., Ferrazzi, P., Lentini, G. and Ferracini, C. (2021) A Qualitative Analysis of Beekeepers' Perceptions and Farm Management Adaptations to the Impact of Climate Change on Honey Bees. *Insects*, **12**, Article No. 228. https://doi.org/10.3390/insects12030228

[21] Cormier-Salem, M.-C. (1992) Gestion et évolution des espaces aquatiques: La Casamance (Collection Études et thèses). ORSTOM, 583 p. https://www.documentation.ird.fr/hor/fdi:35619

[22] Ndiaye, S., Charahabil, M.M. and Diatta, M. (2021) Caractéristiques des Plantations D'anacardiers (*Anacardium occidentale* L.) et Déterminants Économiques des Exploitations en Casamance. *VertigO*, **21**, Article No. 14881.

https://doi.org/10.4000/vertigo.28723

[23] Paré, I. (1981) Évolution économique de la Casamance (1880-1930). Mémoire de maîtrise. Université de Dakar, 130 p.

[24] Manga, I. (2003) Crise agricole dans une vallée de Casamance: Le bassin de Goudomp (Senegal). University of Rouen, 73 p. https://www.memoireonline.com/12/06/306/m_crise-agricole-dans-une-vallee-de-casamance-goudomp0.html

[25] Sané, T., Mbaye, I. (2007) État des lieux et étude diagnostique de l'environnement de la casamance. *Annales de la Faculté des Lettres et Sciences Humaines*, No. 37, 129-147.

[26] Sané, T., Benga, A., Sall, O. (2010) La casamance face aux changements climatiques : enjeux et perspectives. *Acte du XXIIIe Colloque de l'Association Internationnale de Climatologie*, Rennes, 1-4 September 2010, 559-564.

[27] Sy, M.S., Savard, M., Diatta, D., Diarra, C., Manga, É., Sinitambirivoutin, M., Mbodj, A., Badiane-Ndour, N.Y., Diagne, M.L., Drieux, É., *et al.* (2022) Apiculture et changements climatiques: Construire une filière résiliente. 60. https://openknowledge.fao.org/items/350f6d8d-cb04-4ad5-b460-7f39c70344b9

[28] Kothari, C.R. (2004) Research Methodology: Methods and Techniques. New Age International, 401. https://qnamuni.dspace.vn/bitstream/QNA/1934/1/1.%20Research_methodology_methods_and_techniq.pdf

[29] Lokshin, M. and Sajaia, Z. (2004) Maximum Likelihood Estimation of Endogenous Switching Regression Models. *The Stata Journal*: *Promoting Communications on Statistics and Stata*, **4**, 282-289. https://doi.org/10.1177/1536867x0400400306

[30] Kumar, S. and Sidana, B.K. (2018) Farmers' Perceptions and Adaptation Strategies to Climate Change in Punjab Agriculture. *The Indian Journal of Agricultural Sciences*, **88**, 1573-1581. https://doi.org/10.56093/ijas.v88i10.84226

[31] Di Falco, S., Veronesi, M. and Yesuf, M. (2011) Does Adaptation to Climate Change Provide Food Security? A Micro-Perspective from Ethiopia. *American Journal of Agricultural Economics*, **93**, 829-846. https://doi.org/10.1093/ajae/aar006

[32] Kassie, G.T., Martin, W. and Tokgoz, S. (2022) Analysis of the Impacts of Agricultural Incentives on the Performance of Agricultural Value Chains (IFPRI Discussion Paper No. 2127). International Food Policy Research Institute (IFPRI).

[33] Arouna, A., Aboudou, R. and Ndindeng, S.A. (2023) The Adoption and Impacts of Improved Parboiling Technology for Rice Value Chain Upgrading on the Livelihood of Women Rice Parboilers in Benin. *Frontiers in Sustainable Food Systems*, **7**, Article ID: 1066418. https://doi.org/10.3389/fsufs.2023.1066418

[34] Antwi, K. (2024) Merging Adoption of Natural Climate Solutions in Agriculture with Climatic and Non-Climatic Risks within an (Intra)gendered Framework. *Scientific Reports*, **14**, Article No. 11672. https://doi.org/10.1038/s41598-024-60469-w

[35] Barry, F., Seck, D., Faye, O., Mbahin, N., Diawara, I., Camara, B., *et al.* (2018) Diagnostic apicole dans quatre bassins de production au Sénégal: Analyse des opportunités et des faiblesses. *International Journal of Biological and Chemical Sciences*, **12**, 1186-1198.

[36] Diouf, M. (2002) La filière apicole au Senegal. PhD Thesis, École Inter-États des Sciences et Médecine Vétérinaires (EISMV)/Université Cheikh Anta Diop de Dakar (UCAD). https://beep.ird.fr/collect/eismv/index/assoc/TD02-4.dir/TD02-4.pdf

[37] Kouassi, D.F., Ouattara, D., Coulibaly, S. and N'guessan, K.E. (2019) La cueillette, la

production et la commercialisation du miel dans le Département de Katiola (Centre-Nord, Côte d'Ivoire). *International Journal of Biological and Chemical Sciences*, **12**, 2212-2225. https://doi.org/10.4314/ijbcs.v12i5.22

[38] Paterson, P.D. (2008) L'apiculture. Éditions Quæ, CTA, Presses agronomiques de Gembloux. 160 p. https://doi.org/10.35690/978-2-7592-0678-0

[39] Abera, A., Yakob, H. and Yasin, G. (2016) Assessment of Production System and Constraints of Bee Keeping Practices in Damot Gale Woreda, Wolaita Zone, Southern Ethiopia. *Journal of Biology, Agriculture and Healthcare*, **6**, 7-13.

[40] Gebretsadik, T. and Negash, D. (2016) Honeybee Production System, Challenges and Opportunities in Selected Districts of Gedeo Zone, Southern Nation, Nationalities and Peoples Regional State, Ethiopia. *International Journal of Research—Granthaalayah*, **4**, 49-63. https://doi.org/10.29121/granthaalayah.v4.i4.2016.2754

[41] Niyonsenga, S. and Mwiza, W. (2017) Enabling Policies and Legal Framework to Support the Growth of Honey Industry in Sub-Saharan Africa: A Case of Rwanda. *Bulletin of Animal Health and Production in Africa*, **64**, 275-277.

[42] Ahouandjinou, S.T.B., Yedomonhan, H., Adomou, A.C., Tossou, M.G. and Akoegninou, A. (2016) Caractéristiques techniques et importance socio-économique de l'apiculture au Nord-Ouest du Bénin: Cas de la commune de Cobly. *International Journal of Biological and Chemical Sciences*, **10**, 1350-1369. https://doi.org/10.4314/ijbcs.v10i3.35

[43] Tchoumboue, J., Tchouamo, I.R., Pinta, J.Y. and Njia, M.N. (2001) Caractéristiques socio-économiques et techniques de l'apiculture dans les hautes terres de l'ouest du Cameroun. *Tropicultura*, **19**, 141-146.

[44] Berhe, A., Asale, A. and Yewhalaw, D. (2016) Community Perception on Beekeeping Practices, Management, and Constraints in Termaber and Basona Werena Districts, Central Ethiopia. *Advances in Agriculture*, **2016**, Article ID: 4106043. https://doi.org/10.1155/2016/4106043

[45] Bradbear, N. (2009) Bees and Their Role in Forest Livelihoods: A Guide to the Services Provided by Bees and the Sustainable Harvesting, Processing and Marketing of Their Products. Food and Agriculture Organization of the United Nations, 192. https://www.fao.org/4/i0842e/i0842e00.htm

[46] Delena, M.F. and Kayamo, S.E. (2021) Beekeeping Opportunities, Challenges and Technology Adoption in Gedeo Zone, Southern Ethiopia. *Journal of Apicultural Research*, **63**, 456-461. https://doi.org/10.1080/00218839.2021.1961429

[47] Kuboja, N.M., Isinika, A.C. and Kilima, F.T.M. (2020) Adoption and Impacts of Improved Beehive Technologies in the Miombo Woodland of Tanzania. *African Journal of Science, Technology, Innovation and Development*, **13**, 157-166. https://doi.org/10.1080/20421338.2020.1815943

[48] Kartik, A.R. and Singh, G. (2024) Artificial Diet Supplementation: A Review for Sustainable Approach to Boost Honeybee Health. *Journal of Scientific & Industrial Research*, **83**, 914-933.

[49] Kashumba, F.M. (2025) Determinants of the Intervened Beekeeping Technological Adoption in Sub-Saharan Africa: A Systematic Review. *Cogent Food & Agriculture*, **11**, Article ID: 2568752. https://doi.org/10.1080/23311932.2025.2568752

[50] Diatta, K., Diatta, W., Fall, A.D., Dieng, S.I.m., Mbaye, A.I. and Bassène, E. (2020) Contribution to the Knowledge of Melliferous Plants: Ethno Apicultural Survey with Beekeepers in the District of Ziguinchor, Kolda and Sedhiou (Senegal). *Journal of Medicinal Botany*, **4**, 1-5.

[51] Amulen, D.R., D'Haese, M., Ahikiriza, E., Agea, J.G., Jacobs, F.J., de Graaf, D.C., *et al.* (2017) The Buzz about Bees and Poverty Alleviation: Identifying Drivers and Barriers of Beekeeping in Sub-Saharan Africa. *PLOS ONE*, **12**, e0172820. https://doi.org/10.1371/journal.pone.0172820

[52] Tarekegn, K., Assefa, A. and Gebre, E. (2018) Adoption of Improved Beehive Technology in Ethiopia: Evidence from Kaffa, Sheka and Benchmaji Zones. *International Journal of Food and Agricultural Economics*, **6**, 87-100.

[53] Cannizzaro, C., Keller, A., Wilson, R.S., Elliott, B., Newis, R., Ovah, R., *et al.* (2022) Forest Landscapes Increase Diversity of Honeybee Diets in the Tropics. *Forest Ecology and Management*, **504**, Article ID: 119869. https://doi.org/10.1016/j.foreco.2021.119869

[54] Chege, M., Wambua, M.B., Kilonzo, W.J., Subramanian, S. and Nganso, B.T. (2025) Seasonal and Landscape-Driven Variations in Forage Resources of *Apis mellifera Scutellata*: Implications for Pollination Sustainability and Colony Health in Taita Taveta County, Kenya. *Ecology and Evolution*, **15**, e71613. https://doi.org/10.1002/ece3.71613

[55] Ruticumugambi, J.A., De Smedt, P., Verbeeck, H., Kaplin, B.A., Gatesi, J., Ndoli, A., *et al.* (2025) Local-Scale Tree Cover Modulates Pollination Services and Crop Yield in Tropical Agroforestry Landscapes, Rwanda. *Landscape Ecology*, **40**, Article No. 182. https://doi.org/10.1007/s10980-025-02108-x

[56] Sibaja Leyton, M., Lattorff, H.M.G., Kiatoko, N. and Requier, F. (2025) Climate Effects on Honey Bees Can Be Mitigated by Beekeeping Management in Kenya. *Journal of Environmental Management*, **374**, Article ID: 123879. https://doi.org/10.1016/j.jenvman.2024.123879

[57] FAO (2026) Building Climate Resilience through People, Pollinators and Ecosystems. SAGA 2 Program. https://www.fao.org/in-action/saga/news-and-events/news/news-detail/building-climate-resilience-through-people--pollinators-and-ecosystems/en

[58] Sultana, N., Reza, M.E., Alam, M.N., Siddiquee, M.N.A., Islam, M.S., Rahman, M.A., *et al.* (2024) Evaluating the Efficiency of Supplementary Feeding as a Management Strategy for Enhancing Honeybee (*Apis mellifera* L.) Colony Growth and Productivity. *Frontiers in Bee Science*, **2**, Article ID: 1386799. https://doi.org/10.3389/frbee.2024.1386799

[59] Amera, W.A., Mersso, B.T., Sisay, T.A., Arega, A.B. and Alene, A.T. (2024) Effect of Various Supplements on Productive Performance of Honey Bees, in the South Wollo Zone, Ethiopia. *PLOS ONE*, **19**, e0303579. https://doi.org/10.1371/journal.pone.0303579

[60] Hailemariam, W.A., C.A, M. and Mokolopi, B.G. (2026) Effects of Nutritional Supplementation on Honey Bee *Apis mellifera* L. Brood Development, Colony Population Growth, and Honey Yield in Central Ethiopia. *Frontiers in Bee Science*, **4**, Article ID: 1813470. https://doi.org/10.3389/frbee.2026.1813470

Appendix

Table A1. Relevance of the instrument (probit; dependent variable: adoption of each practice; independent variable of interest: beekeeping training).

Practice	Coef.	SE	z	p	LR χ^2 (p)	*n*
Reforestation	0.277	0.093	2.99	0.003	18.28 (0.011)	215
Supplementary feeding	0.204	0.092	2.22	0.026	9.04 (0.250)	215
Modern hives	0.440	0.097	4.51	<0.001	34.81 (<0.001)	215

Table A2. Falsification test (OLS; dependent variable: honey quantity per hive, L; non-adopters of each practice).

Practice	Coef. (training)	SE	p	95% CI	*n*
Reforestation	−0.309	0.634	0.628	[−1.576; 0.958]	69
Supplementary feeding	−0.495	0.492	0.318	[−1.475; 0.486]	81
Modern hives	−0.712	0.437	0.108	[−1.585; 0.160]	74