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Mapping Current and Future Chili Pepper (*Capsicum annuum*) Production Areas in the Municipality of Malanville (Benin) in the Context of Climate Change: The Contribution of GIS and MaxEnt Modeling

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Abstract

Chili pepper (*Capsicum annuum*) cultivation plays a significant role in the agricultural economy of the municipality of Malanville, one of the main vegetable-growing regions in northern Benin. However, the growing effects of climate change are raising concerns about the sustainability of this strategic sector. This study analyzes the contribution of Geographic Information Systems (GIS) and MaxEnt modeling to the current and prospective mapping of areas favorable for chili pepper production in the municipality of Malanville. The study is based on 35,283 chili pepper occurrence points derived from field surveys and the GBIF database, combined with bioclimatic and environmental variables. Future projections were made for the year 2050 based on the RCP 4.5 and RCP 8.5 climate scenarios. The model's performance was validated using the AUC and TSS indicators, whose respective values—greater than 0.90 and ranging from 0.77 to 0.84—attest to the robustness of the predictions. The results show that the minimum temperature of the coldest month (Bio6) and the annual temperature range (Bio7) are the main factors determining the current distribution of chili peppers. Under the RCP 8.5 scenario, average annual precipitation also becomes a determining factor. Areas currently classified as favorable and very favorable cover 52% of the municipal territory. By 2050, this proportion is projected to reach 53% under the RCP 4.5 scenario, indicating relatively stable production conditions. In contrast, under the RCP 8.5 scenario, favorable areas would drop

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to 38%, revealing the crop's high vulnerability to the intensification of climate change. Furthermore, producers identify climatic constraints as the main obstacle to production (55%), ahead of phytosanitary constraints (25%), technical constraints (15%), and financial constraints (5%). These results underscore the need to promote adaptation strategies based on controlled irrigation, climate-stress-tolerant varieties, sustainable management of natural resources, and the integration of geospatial tools into agricultural planning.

Keywords

Malanville, GIS, MaxEnt, Climate Change, Chili Pepper, Spatial Modeling, Adaptation

1. Introduction

The chili pepper (*Capsicum spp.*) is a vegetable plant belonging to the Solanaceae family, native to the Americas and found on every continent.

In Africa, and particularly in Benin, it is grown year-round but requires irrigation during the dry season [1]. For many years, chili pepper cultivation in Benin was primarily a traditional activity practiced by family farmers. Farmers grew chili peppers primarily for household consumption, with a portion sold at local markets. Over time, demand for chili peppers has increased in both domestic and international markets. This has encouraged farmers to shift toward larger-scale chili pepper cultivation to meet the growing demand [2]. Although they are now deeply rooted in African agriculture and food culture, chili peppers (*Capsicum spp.*) are an integral part of food systems in sub-Saharan Africa, where they serve as staple condiments, income-generating cash crops, and culturally significant ingredients in various culinary practices [3].

In Benin, chili peppers are among the most widely produced and consumed vegetable crops and undeniably hold a prominent place in households. Vegetable farmers, a segment of the agricultural community, cultivate large areas of land for chili pepper production in certain localities. In Beninese households, this plant ranks among the most commonly consumed vegetables. Chili peppers (*Capsicum spp.*) hold a prominent place and therefore remain one of the most widely produced crops nationwide. Accounting for 20% of total vegetable production during the 2022 - 2023 growing season, chili peppers are among the main vegetable crops produced in Benin. In recent years, national chili pepper production has shown an upward trend, rising from 38.434 metric tons in the 2010 - 2011 growing season to 133,412 metric tons in the 2022 - 2023 growing season. However, there was a slight decline (3%) in production during the most recent crop year [2]. The area planted with chili peppers has also shown an upward trend, rising from 23,564 hectares in the 2010 - 2011 crop year to 37.467 hectares in the 2022 - 2023 crop year. The annual chili pepper yield varied during the period under review (2010 to 2023), ranging from 1.631 metric tons per hectare to 4.175 metric tons per hectare, for an average yield of 2.995 metric tons per hectare. A significant portion of local production is processed through drying, generating substantial added value (ranging from 307 FCFA to 611 FCFA per kilogram) and offering a lucrative alternative during periods of high abundance. Dried chili peppers are one of the most profitable products. They are sold at border markets at minimum prices of approximately 3.246 FCFA per kilogram. This price rises sharply depending on seasonality and external demand, particularly from Nigeria [2].

In the municipality of Malanville, located in northern Benin, vegetable farming plays a strategic role, particularly the production of chili peppers (*Capsicum annuum*). Chili pepper cultivation plays a key role in the local economy of the municipality of Malanville. Located in one of Benin's main vegetable-growing regions, the municipality of Malanville benefits from favorable agroecological conditions. This allows for chili pepper production during both the rainy season and the off-season. According to the Ministry of Agriculture and Livestock, chili peppers are one of the main vegetable crops, alongside onions, tomatoes, and okra, in the municipality of Malanville. On average, each farmer cultivates up to 0.75 ha, which underscores the importance of this crop. According to statistics from the Ministry of Agriculture, Malanville ranks among the top five chili pepper-producing municipalities in Benin, with an estimated production of 6.047 metric tons, representing approximately 6.96% of national production. It ranks second behind Adjohoun. However, its production faces numerous constraints, both abiotic and biotic. Among the abiotic factors are the effects of climate change, with disruptions that negatively impact agricultural yields through soil degradation and loss of fertility, as well as the proliferation of insect pests and diseases [4]. Climate change threatens global food security by altering rainfall patterns and raising temperatures. In Benin, this phenomenon directly impacts rain-fed agriculture. Rising temperatures and rainfall variability lead to lower yields for major crops and reduce farmers' incomes; farmers are both drivers and "victims" of climate change [5]. In fact, in recent years, chili pepper production has faced a gradual decline in productivity in Benin's market gardening areas. Chili pepper production has remained nearly constant, rising from 133.412 metric tons in 2022 - 2023 to 134.120 metric tons during the 2023 - 2024 growing season, representing a 0.5% increase. Average chili pepper production over the past five years is 117.080 metric tons [6]. This situation has led to lower yields, declining farm incomes, and reduced food security for farming households. Despite its contribution to the local economy, the sector's performance remains limited by numerous technical, environmental, and organizational constraints [7] [8].

Furthermore, little research has been devoted to mapping and modeling the effects of climate change on vegetable-growing areas in Benin—particularly chili pepper production areas—by combining geographic information systems (GIS) with MaxEnt modeling. Existing studies in the recent literature have primarily focused on the determinants of vegetable growers' adoption of adaptation strategies in response to climate variability [9], on the impact of climate change on the incomes of farming households in Benin through the application of the Ricardian model [10], and the analysis of the effects of climate change on the dynamics of soybean (Glycine max) production zones in the Sudanese region of Benin [11]. However, knowledge remains limited regarding current and future changes in the suitability of regions for chili pepper production due to climate change. Yet the observed changes in climate parameters—notably rising temperatures, increasingly erratic rainfall, and more frequent episodes of drought and flooding—are gradually altering the agroecological conditions favorable to this crop. These changes affect not only agricultural yields but also the spatial distribution of areas suitable for chili pepper cultivation, with potential consequences for producers' incomes, food security, and local economic development [12].

In this context, Geographic Information Systems (GIS), combined with spatial modeling techniques, are particularly well-suited tools for analyzing, representing, and anticipating territorial dynamics related to climate change. They enable the integration and cross-referencing of climate, environmental, and agricultural data to identify the factors that influence the distribution of chili pepper cultivation and to simulate its future evolution under various climate scenarios. The municipality of Malanville is a particularly relevant study area due to its importance in national vegetable production. Renowned for chili pepper cultivation, it is one of the main agricultural regions in northern Benin. However, producers there face growing constraints related to climate variability, which could jeopardize the sustainability of production systems.

The research thus aims to analyze the contribution of GIS and MaxEnt modeling to the current and prospective mapping of areas suitable for chili pepper production in the municipality of Malanville. It seeks to identify the areas most vulnerable to climate change and the constraints associated with production, to anticipate future spatial shifts in this crop, and to propose adaptation strategies likely to strengthen the resilience of production systems and the sustainability of the sector.

2. Methodological Approach

2.1. Overview of the Study Area

The municipality of Malanville is located in northern Benin, in the Alibori Department. It lies between 11.5˚ and 12˚ north latitude and between 3˚22' and 3˚33' east longitude. It covers an area of 3278 km^2. The climate is of the Sudano-Sahelian type, with an average annual rainfall of 800 mm and high interannual variability. Temperatures range from 16˚C to 40˚C. The terrain is dominated by alluvial plains, which are favorable for agriculture. The river system is characterized by the Niger River, which irrigates all the land. The soils are mainly alluvial and sandy-clay, suitable for vegetable farming. **Figure 1** shows a map of the geographical location of the municipality of Malanville.

Despite the gradual development of commercial activities linked to its border location with Niger and Nigeria, agriculture remains the main sector of employment for the population. According to data from the RGPH-4, the "Agriculture, Fishing, and Hunting" sector still accounted for 77.1% of the municipality's labor force in 2013, with 13.753 farming households out of a farming population of

96.000, reflecting households' heavy reliance on agricultural activities. According to INTaD, the agricultural population is increasing in absolute terms, rising from 88,000 to approximately 140,000 - 150,000 people between 2002 and 2025. However, its relative share of the total population is gradually decreasing, from 72.7% to approximately 60–64%. This decline reflects a gradual diversification of the local economy toward trade, transportation, and services, even though agriculture remains the municipality's primary sector of activity [13].

Looking ahead, these demographic and agricultural trends are increasing pressure on arable land, water resources, and rural infrastructure. They justify the implementation of policies aimed at improving agricultural productivity, strengthening value chains, securing land tenure, and promoting climate-resilient agriculture in order to sustainably support the local economy [14].

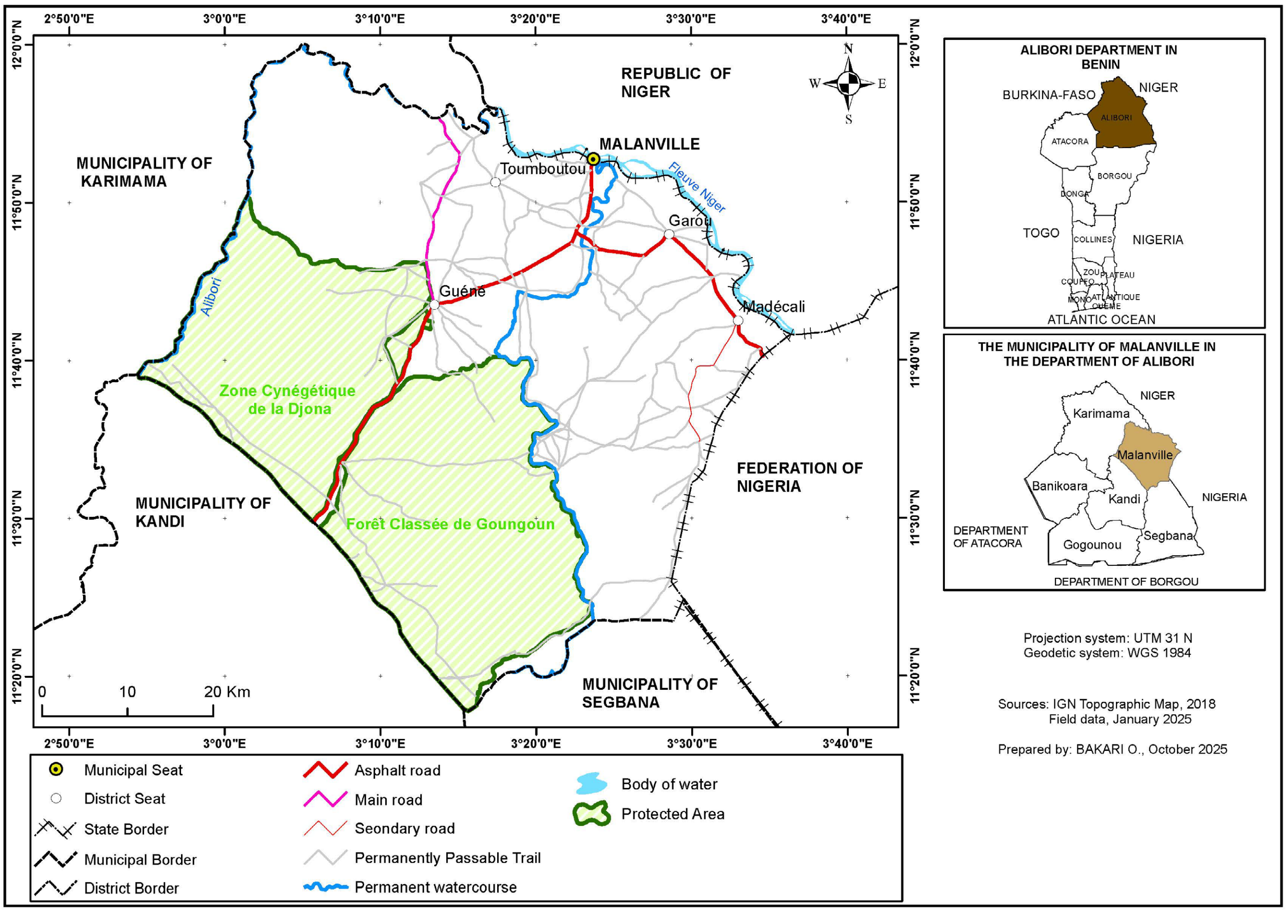

Figure 1. Geographic location of the municipality of Malanville.

2.2. Data Used

To map current chili pepper production areas, two categories of data were used, namely:

- ✓ 10.197 chili pepper occurrence points from the field data collection campaign conducted in April 2025;
- ✓ the average area planted (7.481.40 ha) with chili peppers over the past five

years, which was used to validate the identification of current favorable areas.

- ✓ To map future chili pepper production areas by 2050, three categories of data were used, namely:
- ✓ 25.086 occurrence points downloaded using the GBIF Occurrence extension via QGIS 3.22 software at the West African scale;
- ✓ Future bioclimatic variables (2050) available at https://webfiles.york.ac.uk/KITE/AfriClim. These were obtained using the regional model "AFRICLIM 3.0: high-resolution ensemble climate proj ections for Africa";
- ✓ Data on soil formations (https://www.fao.org/land-water/resources/tools/data-bases/hwsd/en?utm_source=chatgpt.com).

The resulting dataset was subjected to a correlation analysis to eliminate weakly correlated variables, as suggested by some authors [15]. This analysis was performed using the ENMTools 1.3 software.

Projections for the year 2050 were considered under two scenarios: climate conditions for an optimistic future (RCP 4.5) and climate conditions for a pessimistic future (RCP 8.5). The climate layers used have a resolution of 1 km by 30 arcseconds (corresponding to a grid resolution of approximately 1 km × 1 km). Data from the Shuttle Radar Topography Mission (https://earthexplorer.usgs.gov/?utm_source=chatgpt.com) were added to the bioclimatic data. **Table 1** presents the bioclimatic variables used.

Table 1. Bioclimatic variables used.

Variable	Description	**Units**	**Years**
Bioclimatic data	Summary variables		
	1. Temperature (tbio)		
BIO1	Average annual temperature	Cx10, Int16	2000 - 2050
BIO2	Average daytime temperature range	Cx10, Int16	2000 - 2050
BIO3	Isothermal	Cx10, Int16	2000 - 2050
BIO4	Temperature Seasonality	Cx10, Int16	2000 - 2050
BIO5	Maximum temperature of the hottest month	Cx10, Int16	2000 - 2050
BIO6	Minimum temperature of the coldest month	Cx10, Int16	2000 - 2050
BIO7	Annual temperature range	Cx10, Int16	2000 - 2050
BIO10	Average temperature of the warmest quarter	Cx10, Int16	2000 - 2050
BIO11	Average temperature of the coldest quarter	Cx10, Int16	2000 - 2050
PET	Potential evapotranspiration	mm, Uint16	2000 - 2050
	2. Moisture (mbio)		
BIO12	Average annual precipitation	mm, Uint16	2000 - 2050
BIO13	Precipitation in the wettest month	mm, Uint16	2000 - 2050
BIO14	Precipitation in the driest month	mm, Uint16	2000 - 2050

Continued

BIO15	Seasonality of precipitation	mm, Uint16	2000 - 2050
BIO16	Wettest quarter	mm, Uint16	2000 - 2050
BIO17	Driedest quarter in terms of precipitation	mm, Uint16	2000 - 2050
MI	Annual humidity index	x100, Uint16	2000 - 2050
MIMQ	Humid Quarter Humidity Index	x100, Uint16	2000 - 2050
MIAQ	Dry-Quarter Humidity Index	x100, Uint16	2000 - 2050
DM	Number of dry months	months, byte	2000 - 2050
LLDS	Duration of the longest dry season	months, byte	2000 - 2050

Source: [16].

2.3. Screening and Preparation of Occurrence Records

Prior to MaxEnt modeling, occurrence records obtained from field surveys and the Global Biodiversity Information Facility (GBIF) were subjected to a rigorous quality-control procedure to ensure data reliability and minimize potential sources of bias.

A total of 10,197 occurrence points were collected during field surveys conducted in April 2025 using the QField mobile application. Data collection covered all boroughs of the municipality of Malanville, with a sampling interval of approximately 1 km between observation points. Each occurrence point corresponded to an actively cultivated chili pepper (*Capsicum annuum*) production site identified and verified in situ. Geographic coordinates were checked for positional accuracy and consistency with known agricultural areas. Records with missing coordinates, duplicate locations, or obvious positioning errors were removed.

In addition, 25,086 occurrence records were downloaded from the Global Biodiversity Information Facility (GBIF) database at the West African scale using the GBIF Occurrence plugin in QGIS 3.40. Taxonomic screening was performed by retaining only records identified as *Capsicum annuum* and excluding records with unresolved or doubtful taxonomic status. The dataset was further cleaned by removing records with missing coordinates, duplicate geographic locations, erroneous coordinates, georeferencing inconsistencies, or invalid positions located outside the known distribution range of the species. To ensure temporal relevance, only records associated with documented and relatively recent observations were retained.

After cleaning, the field and GBIF datasets were merged into a single occurrence database. A second verification step was carried out to identify and remove duplicate records resulting from the integration of the two datasets.

To minimize spatial sampling bias and reduce the overrepresentation of densely sampled areas, spatial filtering (spatial thinning) was applied to the merged occurrence dataset prior to model calibration. This procedure retained only one occurrence point within a specified distance threshold, thereby reducing spatial autocorrelation and clustering effects. The resulting dataset provided a more balanced spatial representation of chili pepper occurrences and improved the robustness and predictive performance of the MaxEnt model.

The final validated occurrence database was subsequently used for habitat suitability modeling under current and future climate scenarios.

3. Methods for Mapping Current and Future Chili Pepper (*Capsicum annuum*) Production Areas

The two methods used are modeling the spatial entropy of chili peppers using MaxEnt and mapping their current and future production areas in the municipality of Malanville.

3.1. MaxEnt Modeling and Model Validation

The modeling of current chili pepper production areas using MaxEnt® 3.4 software was based on 10,197 observation points collected in the field in April 2025, the average planted area (7481.40 ha) during the last growing season, and various current environmental and climatic variables (average annual temperature, isotherm, maximum temperature of the hottest month, minimum temperature of the coldest month, average temperature of the coldest quarter, potential evapotranspiration) obtained from Météo Bénin. Note that 510 presence points (5%) were used for training and 197 for testing. A total of 10,197 points were used to determine the Maxent distribution (background points and presence points). The algorithm stopped after 500 iterations (5 seconds).

The modeling of future ranges by 2050 was performed using 35,283 chili pepper occurrence records (field data and GBIF data) and various future environmental and climatic variables, using the MaxEnt® 3.4 software (R. Phillips, *et al.*, 2005, p. 338). Note that for both the RCP 4.5 and RCP 8.5 scenarios, 1764 occurrence records (5%) were used for training, compared to 764 records for testing. The algorithm converged after 500 iterations in 6 seconds for the RCP 4.5 scenario and 500 iterations in 5 seconds for the RCP 8.5 scenario.

3.1.1. Jackknife Test and Receiver Operating Characteristic Curve (AUC or AUROC)

The Jackknife test was performed to determine the importance of the environmental variables when used individually. The Area Under the Curve (AUC) statistic was used to evaluate the model's performance, as was the True Skill Statistic (TSS). The model is considered high-performing if the AUC value is greater than 0.90; it is considered acceptable when $0.75 \le AUC \le 0.90$, and it is classified as poor if $AUC < 0.75$ [17]. In this case, the AUC value is greater than 0.90 in both scenarios (RCP4.5 and RCP8.5); therefore, the model performs very well.

A model is considered high-performing if the AUC value is greater than 0.90; it is considered acceptable when $0.75 \le AUC \le 0.90$, and it is considered poor if $AUC < 0.75$ [17]. Spatial block validation was performed, which is recommended to avoid spatial autocorrelation bias.

3.1.2. False Positives and False Negatives

We use the following abbreviations for the empirical measures: (a), the number of true presences; (b), the number of false presences (commission); (c), the number of false pseudo-absences (omission); and (d), the number of true pseudo-absences.

The commission error, or false positive rate (FPR), is a threshold-dependent measure of accuracy, defined as the proportion of areas falsely classified as areas of presence for the modeled species [18]. In general, the lower the false positive error, the higher the model's performance. When using pseudo-absences, this measure should be interpreted with caution. It is given by Formula [18]:

$$\text{FPR} = \frac{b}{b+d} \tag{1}$$

The omission error, or false negative rate (FNR), is a measure of accuracy defined as the proportion of areas falsely predicted as absence areas for the species (*i.e.*, the proportion of species occurrences misidentified by the models). It provides information on the model's discriminatory power and its tendency toward overfitting. In general, a low false negative rate indicates higher performance (better discrimination between areas favorable to the species and those that are not). Models with underfitting issues also have high false negative rates. It is given by Formula [18].

$$\text{FNR} = \frac{c}{c+a} \tag{2}$$

3.1.3. Sensitivity and Specificity

Sensitivity (Se), also known as the true presence rate, is the ratio of true presences to the sum of true presences and false absences, excluding false absences and true absences. It is the probability that the model correctly classifies a true presence.

$$\text{Se} = \frac{a}{a+c} \tag{3}$$

Specificity (Sp), also known as the true absence rate, is equal to 1 minus the false positive rate. It is also the ratio of true absences to the sum of true absences and false positives. It is the probability that the model correctly classifies a true absence.

$$\text{Sp} = 1 - \frac{b}{b+d} \tag{4}$$

3.1.4. True Skill Statistic (TSS)

The True Skill Statistic is a threshold-dependent measure of accuracy, widely used in medical diagnostic tests. It was introduced into the literature on species distribution models through the work of [18].

It is a measure of the model's ability to accurately detect true presences (sensitivity) and true absences (specificity). It ranges from −1 to 1, with a value close to 1 indicating high classification accuracy, while a value below 0 indicates classification no better than random. The TSS is given by the formula:

$$\text{TSS} = \frac{a}{a+c} - \frac{b}{b+d} \quad \text{Sensibilité} + \text{Spécificité} - 1 \tag{5}$$

A model with a TSS ≤ 0 indicates a random prediction, whereas a model with a TSS close to 1 (TSS > 0.5) has good predictive power [18]. The TSS for the present prediction is 0.84 for RCP 4.5 and 0.77 for RCP 8.5—both close to 1—which confirms that the model has good predictive power.

3.2. Spatial Distribution of Chili Pepper Production Areas

The modeling results were mapped using QGIS 3.22 software. The dynamics of chili pepper production areas under current and future climate conditions were analyzed. The crude probability distribution (pixel value) obtained from the model was used as a measure of the probability of chili pepper occurrence. A four-level categorization (very favorable, favorable, somewhat unfavorable, and very unfavorable) of this pixel value was performed to distinguish between current and future chili pepper production areas using the "Reclassify by Layer" tool in the QGIS 3.22 raster processing and analysis toolkit. For the purposes of this study, an area is considered very unfavorable for chili pepper cultivation when the pixel value is less than or equal to 0.03. If this pixel value is between 0.03 and 0.04, the area is considered somewhat unfavorable. Pixel values between 0.04 and 0.05 indicate a favorable area, while those greater than 0.05 are considered very favorable areas.

To determine the extent of the defined areas, the image file was converted to a vector file in shapefile format. A field named "area" was added to the attribute table, and the areas of each zone were calculated using the "Raster Calculator" tool from the QGIS 3.22 Raster Toolbox. Based on these areas, the proportion of the study area occupied by each category (very favorable, favorable, somewhat unfavorable, and very unfavorable) was calculated relative to the total area of the study area.

3.3. Data Collection and Processing Method for the Analysis of Constraints Related to Chili Pepper Production in the Municipality of Malanville

3.3.1. Data Collection Equipment and Tools

Several pieces of equipment and tools were used for data collection. These included:

- a GPS device to record the geographic coordinates of the households of the farmers surveyed;
- a survey form consisting of a questionnaire and an interview guide for officials at various levels, as well as an observation grid to gather the perspectives of the affected populations and stakeholders on current and future constraints on chili pepper production;
- an Excel spreadsheet for creating a database and processing the collected data.

3.3.2. Methodology for Collecting Socioeconomic Data

The various techniques used are:

- Six (06) focus groups using an interview guide to gather specific information from producers in order to better understand their views on the types of constraints affecting chili pepper production in the municipality of Malanville. Each focus group included at least 12 participants, including women;

- Twenty-five (25) face-to-face individual interviews conducted using a questionnaire were used to gather specific information directly from key informants, such as technical staff at City Hall, local authorities, officials from the Territorial Agricultural Development Agency (ATDA), and the head of UCOM-CVPC.

3.3.3. Method for Processing Socioeconomic Data

The Citation Rate (CR) was estimated based on [19]:

$$\mathrm{TC} = \frac{m}{N} \tag{6}$$

m: the number of people in the target group who cited a constraint;

N: the total number of people interviewed in the target group.

All of these analyses led to these results.

Figure 2 presents the research methodology flowchart.

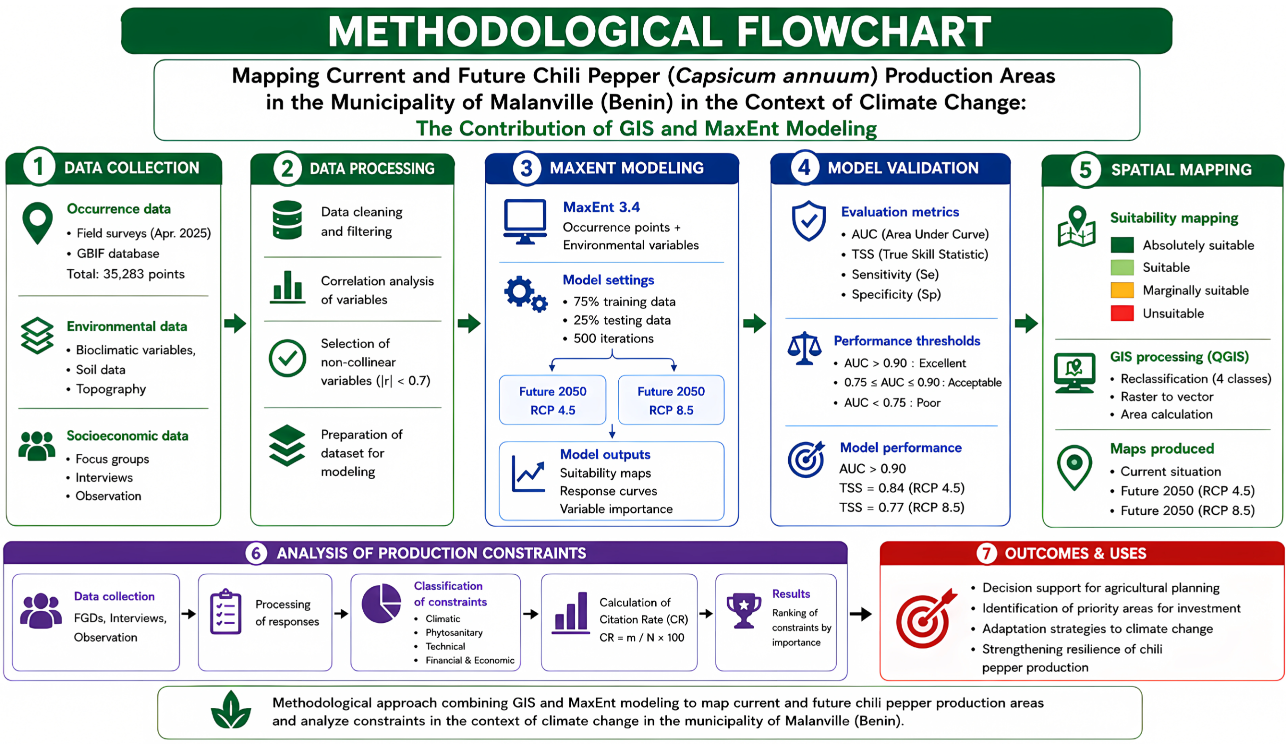

Figure 2. Research methodology flowchart.

4. Results

4.1. Mapping of Current and Future Chili Pepper (*Capsicum annuum*) Production Areas in the Municipality of Malanville

Figure 3 presents the Jackknife test on the contribution of variables to the mapping of current and future chili pepper production areas.

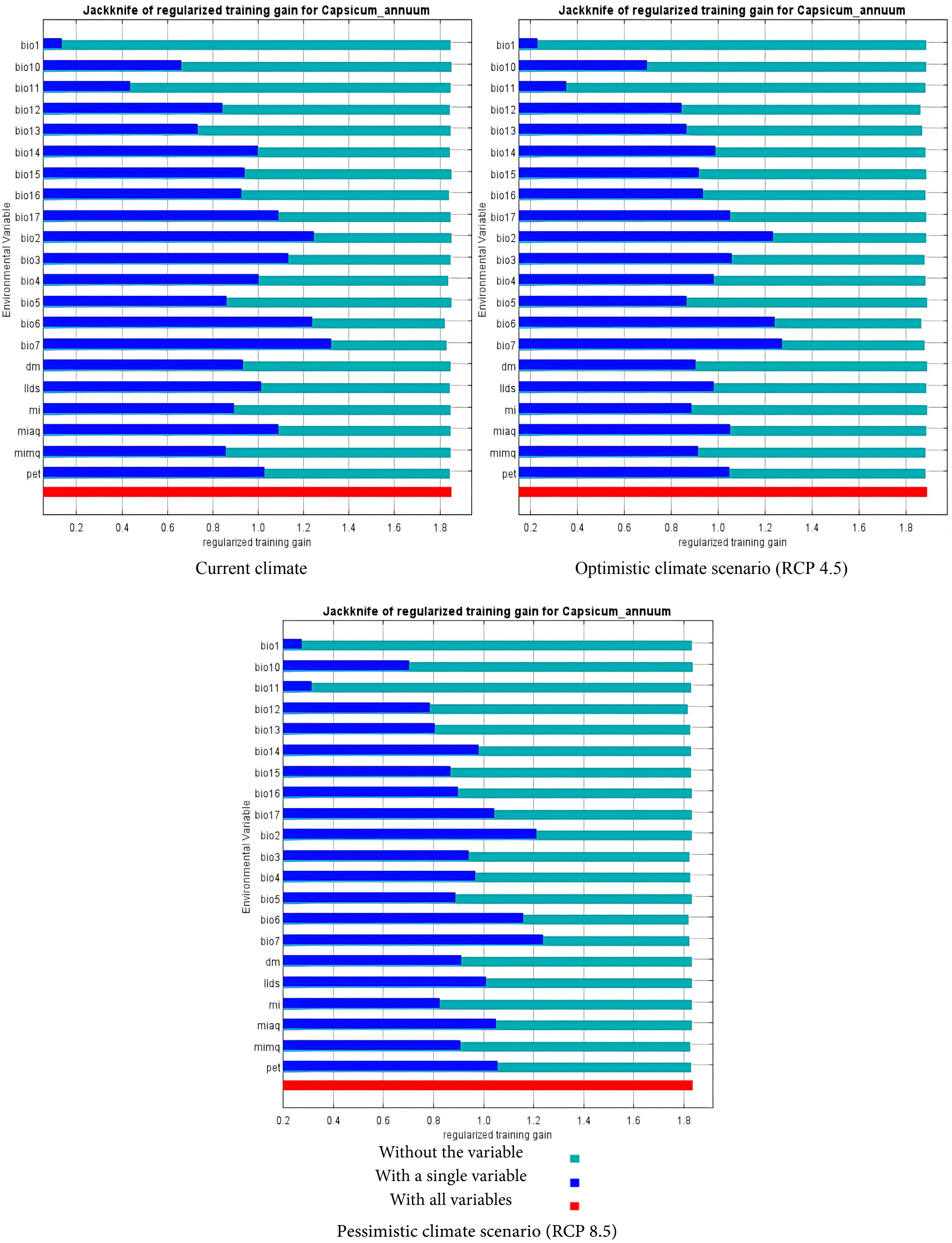

Figure 3. Jackknife test of current and future (2050) climate conditions.

Analysis of **Figure 3** shows that the current distribution of areas suitable for chili pepper cultivation in the municipality of Malanville is primarily influenced by temperature variables. The minimum temperature of the coldest month (Bio6) appears to be the most decisive factor, with a contribution of 38.8% and a permutation importance of 23.3%. This variable alone contains a large portion of the information needed to predict the distribution area of chili peppers. In contrast, the annual temperature range (Bio7), with a contribution of 28.1% and a permutation importance of 14.9%, is the variable whose omission results in the greatest decrease in model performance, underscoring its complementary role and its ability to provide information that is not redundant with respect to other environmental variables.

By 2050, under the optimistic RCP 4.5 climate scenario—characterized by a relative reduction in greenhouse gas emissions—the minimum temperature of the coldest month remains the most influential variable (38.5% contribution and 34.8% importance). The annual temperature range also retains a major role, with a contribution of 26.2% and an importance of 16.1%. These results reflect a certain stability in the climatic factors that influence chili pepper production, despite expected changes in the climate.

Under the pessimistic RCP 8.5 scenario, characterized by a significant increase in greenhouse gas emissions, the hierarchy of variables shifts slightly. The annual temperature range (Bio7) becomes the variable with the highest contribution (30.2%), while average annual precipitation (Bio12) emerges as the variable whose omission most significantly reduces the model's performance (23% contribution). This shift highlights the growing importance of water resources in maintaining conditions favorable to chili pepper cultivation in the context of accelerated global warming.

In general, the results show that the minimum temperature of the coldest month (Bio6) and the annual temperature range (Bio7) are the main climatic factors currently determining the distribution of chili peppers in the municipality of Malanville. By 2050, regardless of the climate trajectory considered, these temperature variables will continue to play a decisive role.

However, the increased average annual precipitation under the RCP 8.5 scenario reveals a growing sensitivity of chili pepper cultivation to variations in rainfall. This situation suggests that future adaptation strategies will need to incorporate both the management of extreme temperatures and the securing of access to water in order to maintain the productivity of vegetable farms.

4.2. Spatial Distribution of Current and Future Chili Pepper (*Capsicum annuum*) Production Areas in the Municipality of Malanville

Figure 4 shows the current chili pepper production areas in the municipality of Malanville.

An analysis of **Figure 4** shows that current climatic conditions offer relatively varied potential for chili pepper production in the municipality of Malanville. Favorable and very favorable areas together cover 52% of the municipality's territory, or approximately 1,702 km^2. Very favorable areas account for 25% of the municipality's total area (812 km^2) and are concentrated mainly in the northern part of the municipality as well as in the Goungoun Protected Forest. As for the favorable areas, they cover 27% of the total area (890 km^2) and are located notably in the northwest and south of the Guéné district, east of Madécali, and south of Toumboutou.

Conversely, areas classified as less favorable and very unfavorable account for 48% of the municipality's territory, or 1,576 km^2. They are primarily located in the central and southern parts of the municipality, particularly in the districts of Guéné and Madécali. This spatial distribution highlights the strong influence of local agroclimatic conditions on the suitability of land for chili pepper cultivation and suggests that production activities should be concentrated in the favorable and very favorable zones in order to optimize yields and farm profitability.

Overall, the results indicate that the municipality of Malanville has significant potential for chili pepper production, with more than half of its territory exhibiting favorable ecological conditions. This situation represents a major asset for the development of this vegetable crop, provided that appropriate strategies for natural resources, and adaptation to climate change are implemented.

An analysis of **Figure 5** shows that by 2050, according to the RCP 4.5 climate scenario, areas suitable for chili pepper cultivation will remain relatively extensive within the municipality of Malanville. Areas highly suitable for chili pepper cultivation will account for 28% of the municipality's total area, or approximately 923 km^2. These areas will be concentrated primarily in the districts of Tomboutou, Malanville, and Garou in the north, as well as in the southern part of the municipality, near the Goungoun Protected Forest. Areas favorables for chili pepper cultivation, meanwhile, will cover 25% of the territory (806 km^2) and will extend mainly south of the districts of Malanville, Tomboutou, and Guéné, as well as east of Madécali. This situation offers an opportunity to strengthen the resilience of the local vegetable farming sector by prioritizing agricultural investments in the areas of Tomboutou, Malanville, Garou, and the lands bordering the Goungoun Protected Forest.

Areas classified as "less favorable" and "very unfavorable" will account for 24% (783 km^2) and 23% (766 km^2), respectively, of the municipality's total area. These areas will be located primarily in the central, eastern, and western parts of the municipality, particularly in the neighborhoods of Guéné and Madécali. This underscores the need to implement targeted adaptation measures. These could include the development of water-efficient irrigation systems, the adoption of chili pepper varieties that are more tolerant to heat and water stress, the promotion of agroecological practices (mulching, agroforestry, sustainable soil management), and the strengthening of agroclimatic monitoring systems. These actions would help reduce producers' vulnerability to fluctuations in temperature and precipitation.

This spatial distribution reflects a slight increase in areas classified as "very favorable" compared to current conditions, suggesting that the RCP 4.5 scenario could maintain—or even locally improve—the agroclimatic conditions conducive to chili pepper production in the municipality of Malanville. Thus, nearly 53% of the municipal territory would remain favorable or very favorable for this crop by 2050.

Figure 5 shows the future chili pepper production areas in the municipality of Malanville by 2050 according to the RCP 4.5 scenario.

Figure 6 shows the future chili pepper production areas in the municipality of Malanville by 2050 according to the RCP 8.5 scenario.

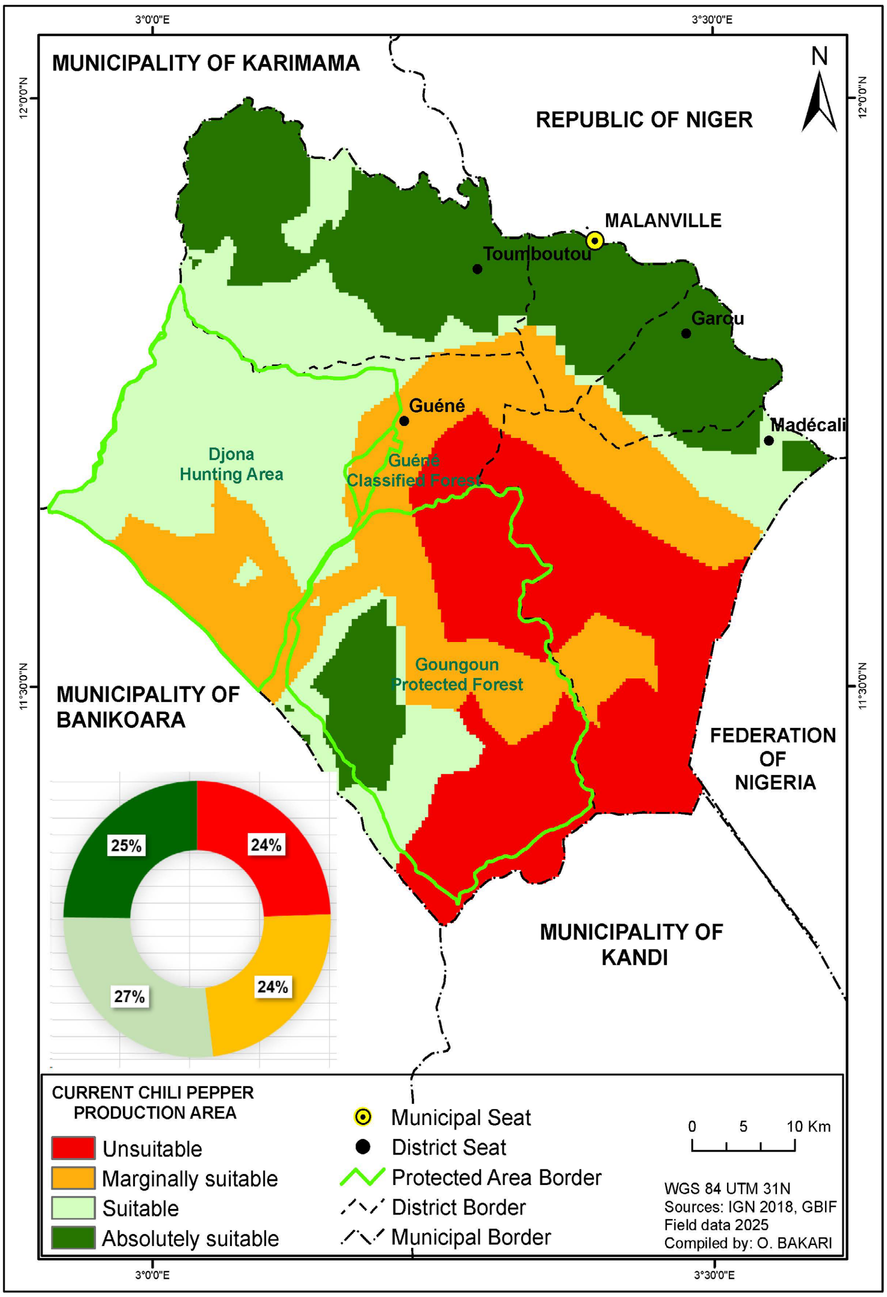

Figure 4. Location of current chili pepper production areas in the municipality of Malanville.

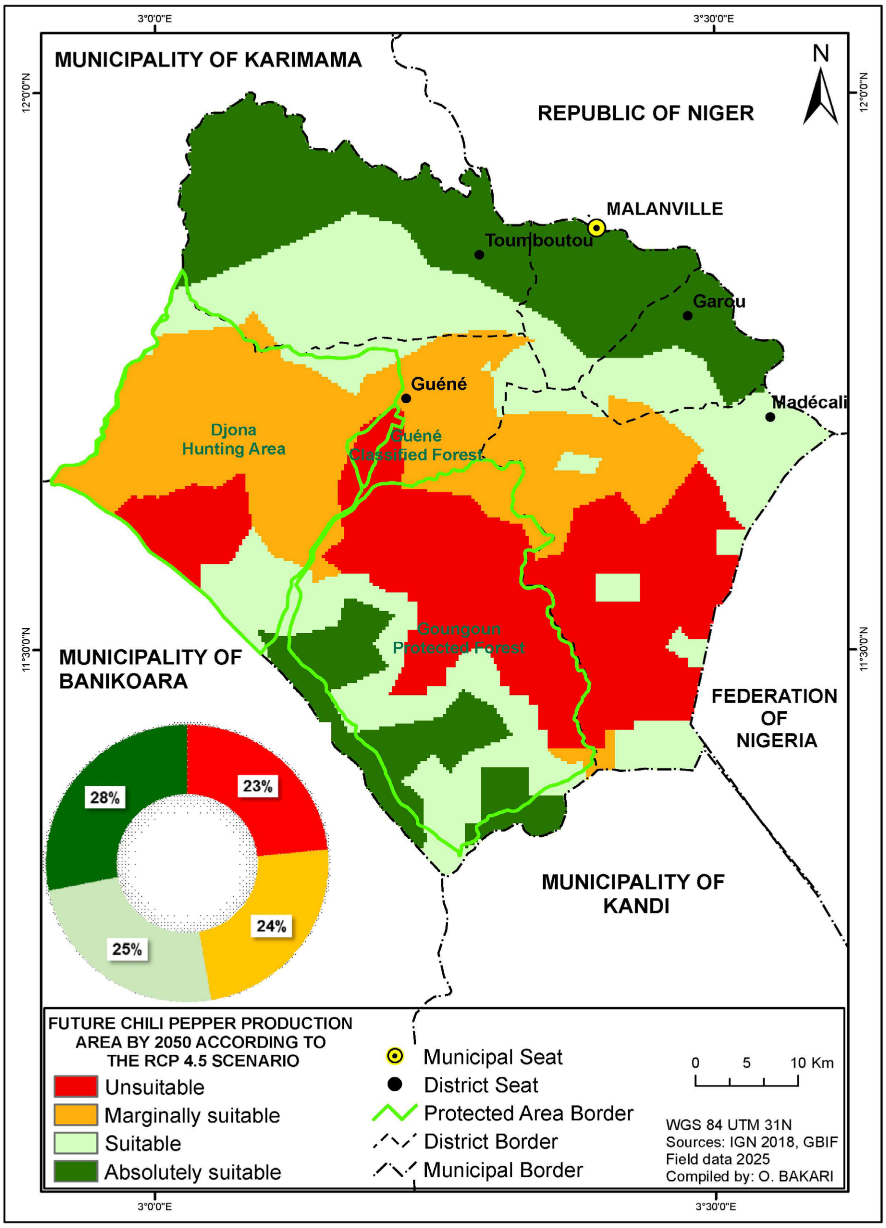

Figure 5. Location of future chili pepper production areas in the municipality of Malanville by 2050 according to RCP 4.5.

An analysis of **Figure 6** shows that by 2050, under the RCP 8.5 worst-case scenario—characterized by a sharp increase in greenhouse gas emissions—chili pepper production conditions will deteriorate significantly in the municipality of Malanville. Areas classified as very favorable will account for only 18% of the municipality's total area—approximately 602 km^2—compared to 25% under current conditions and 28% in the RCP 4.5 scenario. These areas will be concentrated mainly in the southern part of the municipality, particularly around the Goungoun Protected Forest. Favorable areas will cover 20% of the territory (646 km^2) and will be located mainly south of the districts of Malanville, Tomboutou, and Guéné, as well as east of Madécali.

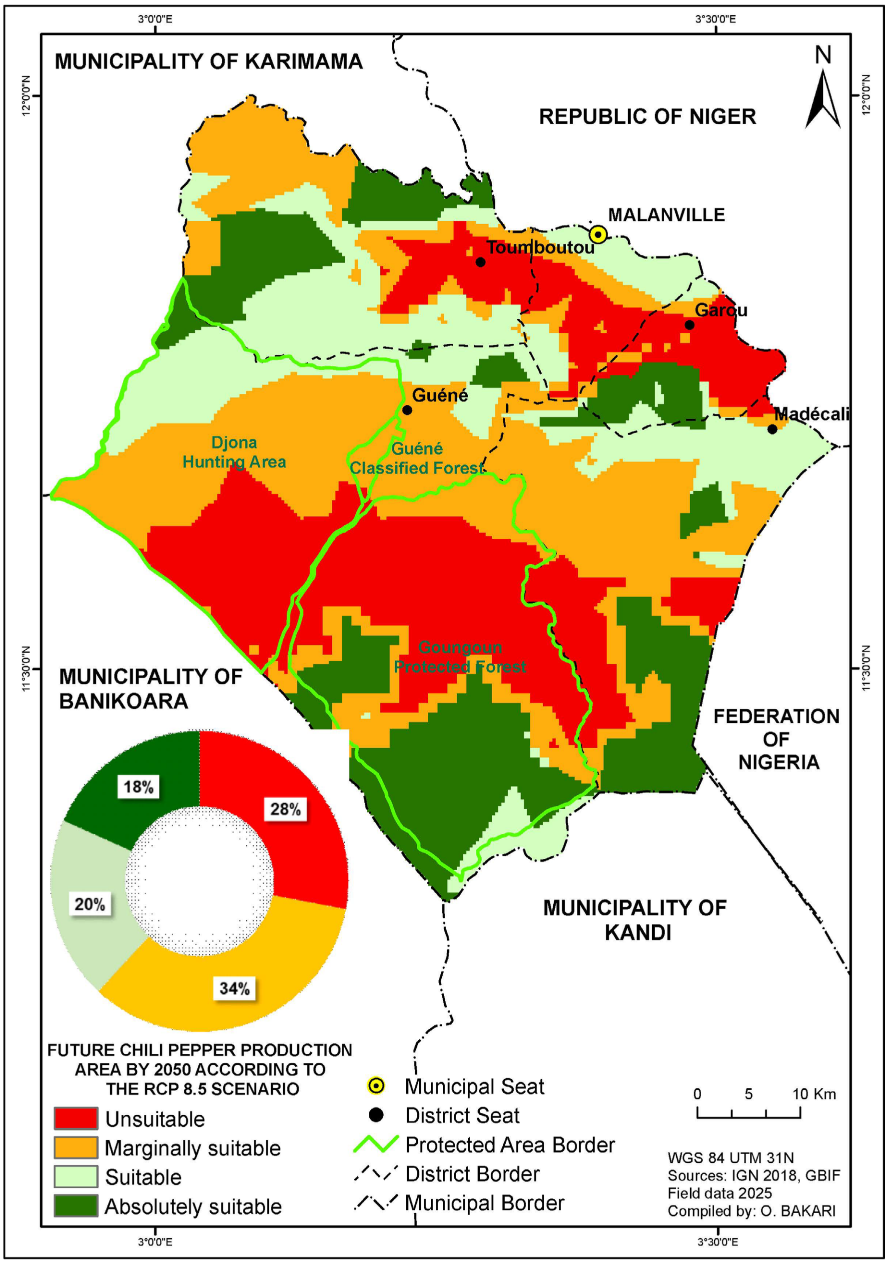

Figure 6. Location of future chili pepper production areas in the municipality of Malanville by 2050 according to RCP 8.5.

Conversely, areas deemed somewhat unfavorable and very unfavorable will account for 34% (1.113 km²) and 28% (916 km²) of the municipal territory, respectively—a total of 62% of the municipality's total area. These areas will extend mainly across central and northern Malanville, particularly in the neighborhoods of Guéné, Tomboutou, Garou, and Madécali. This trend reflects a significant decline in ecological conditions favorable to chili pepper cultivation, due to rising temperatures and changing rainfall patterns. Compared to the current situation, the proportion of favorable and very favorable areas would drop from 52% to just 38%, indicating that this crop is highly vulnerable to climate change.

Faced with this situation, producers will need to strengthen their adaptive capacity by adopting heat- and drought-resistant varieties, developing efficient irrigation systems, harvesting rainwater, and implementing soil and moisture conservation practices. Areas identified as favorable and very favorable should be considered strategic locations for sustaining future production.

Furthermore, this projection highlights the need to integrate climate and spatial data into local agricultural development policies. The prospective mapping obtained using GIS and MaxEnt modeling serves as a decision-support tool for anticipating climate risks, guiding agricultural investments, and planning sustainable land use. Without appropriate adaptation measures, the reduction in favorable areas could have a lasting impact on yields, farmers' incomes, and local food security.

4.3. Constraints Related to Chili Pepper Production in the Municipality of Malanville

Figure 7 presents the various types of constraints related to chili pepper production in the municipality of Malanville.

An analysis of Figure 7 shows that climatic constraints are the main factor limiting chili pepper production in the municipality of Malanville, according to 55% of the producers surveyed. These are followed by phytosanitary constraints (25%), technical constraints (15%), and financial and economic constraints (5%). This ranking reflects the chili pepper crop's heavy dependence on environmental conditions. Producers are particularly affected by erratic rainfall, droughts, floods, and high temperatures, which disrupt the plants' growth cycle and lead to lower yields.

Phytosanitary constraints rank second and are mainly linked to viral diseases and insect pest infestations that affect crop productivity and quality. Technical constraints, although less significant, include a lack of improved seeds, limited mastery of cultivation techniques, inadequate water management, and high post-harvest losses.

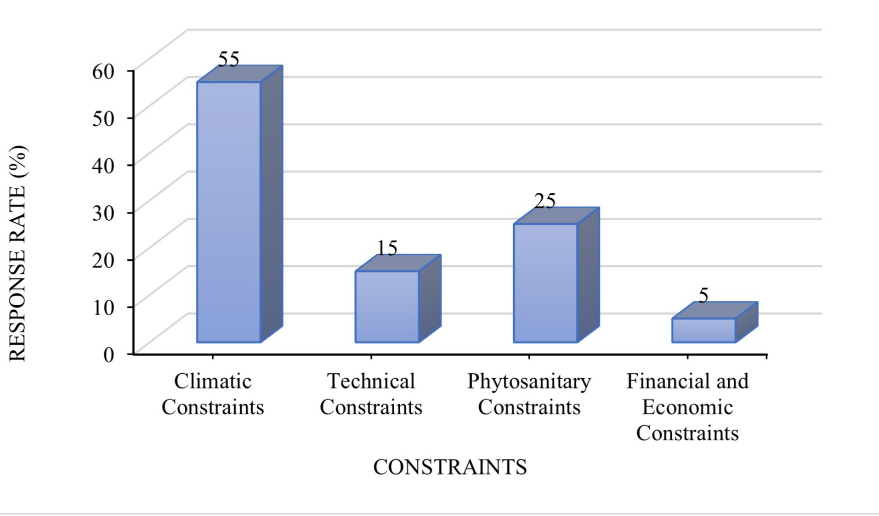

Figure 7. Classification of constraints related to chili pepper production.

Finally, financial and economic constraints—cited by a small proportion of producers—manifest as limited access to credit, high input costs, marketing difficulties, and low market value for chili peppers. These results show that sustainable improvement of the sector requires, first and foremost, measures to adapt to climate change, reinforced by better technical, phytosanitary, and economic support for producers.

5. Discussion

The results of this study highlight the decisive role of climatic variables in the current and future spatial distribution of chili pepper production areas in the municipality of Malanville. The use of the MaxEnt model, combined with GIS, made it possible to accurately identify areas of high agricultural suitability and their dynamics under the influence of climate change.

5.1. Influence of Current and Future Climate Variables on Chili Pepper Production

Analyses from the Jackknife test show that the minimum temperature of the coldest month (Bio6) and the annual temperature range (Bio7) are the main climatic factors currently determining the distribution of chili peppers in the municipality of Malanville. By 2050, regardless of the climate trajectory considered, these temperature variables will continue to play a decisive role. This result confirms the principles of the ecological niche defined by [20], according to which the distribution of a species depends heavily on abiotic conditions.

These results are consistent with those of [17], which showed that certain dominant climatic variables shape the distribution of plant species in West Africa. However, they differ from those of [11], where precipitation variables were more decisive for soybeans. This divergence can be explained by the specific ecophysiological requirements of each crop. Furthermore, several studies [21] [22] have demonstrated that temperature strongly influences crop productivity. However, temperature alone is insufficient to explain agricultural performance, as the intraseasonal distribution of rainfall plays a key role. Thus, in the case of chili peppers in Malanville, the dominance of thermal variables suggests that this crop is highly sensitive to temperature variations, a finding also confirmed by the work in [23] on global warming in West Africa.

5.2. Mapping of Current and Future Chili Pepper (Capsicum annuum) Production Areas in the Municipality of Malanville by 2050

Current climatic conditions present a relatively mixed picture for chili pepper production in the municipality of Malanville. Favorable and very favorable areas together cover 52% of the municipal territory, or approximately 1.702 km^2. Conversely, less favorable and very less favorable areas account for 48% of the municipal territory, or 1.576 km^2. This spatial distribution highlights the strong influence of local agroclimatic conditions on the suitability of land for chili pepper cultivation and suggests that production activities should be concentrated in favorable and very favorable zones to optimize yields and farm profitability. In the Sudanese region and the Sahelian zone of Mali, [24] demonstrated that, under current climatic conditions, favorable and very favorable areas for sorghum production account for 69% and 68%, respectively, of the study area. In contrast, [11] found that areas most suitable for soybean cultivation under current climatic conditions account for 22%.

By 2050, according to the RCP 4.5 climate scenario, areas favorable for chili pepper cultivation will remain relatively extensive, covering 53% of the territory of the municipality of Malanville. This spatial distribution reflects a slight increase in the area classified as very favorable compared to current conditions, suggesting that the RCP 4.5 scenario could maintain—or even improve locally—the agroclimatic conditions conducive to chili pepper production in the municipality of Malanville. In contrast, under the pessimistic RCP 8.5 scenario—characterized by a sharp increase in greenhouse gas emissions—chili pepper production conditions will deteriorate significantly in the municipality of Malanville, with a reduction in very favorable and favorable areas (38%) in favor of less favorable and very less favorable areas, which will account for 62% of the municipal land area. These results are consistent with the findings of [11] on soybeans in northern Benin, [17] on sorghum in Mali, and [25] on the spatial distribution modeling of Argania spinosa (L.) Skeels. Faced with this situation, producers will need to strengthen their adaptive capacities by adopting heat- and drought-resistant varieties, developing efficient irrigation systems, harvesting rainwater, and implementing soil and moisture conservation practices [9] [14] [26].

The observation that certain areas remain favorable despite climate change can be explained by the presence of local factors such as alluvial soils, proximity to the Niger River, and agricultural practices [27]. This is consistent with the conclusions of [9], which emphasize the importance of integrating local variables into regional climate models.

Furthermore, the results highlight the importance of integrating climate and spatial data into local agricultural development strategies to strengthen the resilience of production systems in the face of the effects of climate change. Prospective mapping using Geographic Information Systems (GIS) and the MaxEnt model makes it possible to identify areas likely to retain or lose their suitability for chili pepper production by 2050. This approach thus provides decision-makers, agricultural extension services, and producers with valuable information to anticipate climate risks, direct investments toward the most favorable areas, and promote sustainable agricultural land management [28].

The combined use of GIS and the MaxEnt model has proven particularly effective for the spatial analysis and prediction of chili pepper production areas. The results confirm that GIS is an indispensable decision-support tool for agricultural planning, anticipating the impacts of climate change, and optimizing production systems. They not only allow for the visualization of current and future spatial dynamics but also help guide adaptation strategies such as the relocation of cultivation areas, the diversification of crops, and the implementation of farming practices adapted to new climatic conditions [11] [29]. These conclusions are consistent with those of [30] and [31], which highlight the effectiveness of species distribution models in the sustainable management of natural resources and land-use planning in the face of environmental changes.

5.3. Constraints on Chili Pepper (*Capsicum annuum*) Production in the Municipality of Malanville

An analysis of the constraints related to chili pepper production reveals that climatic constraints are the primary limiting factor for chili pepper production in the municipality of Malanville, accounting for 55% of the responses collected from producers. These are followed by phytosanitary constraints (25%), technical constraints (15%), and, to a lesser extent, financial and economic constraints (5%). This predominance of climatic constraints can be explained by the high dependence of vegetable farming on weather conditions. Producers face irregular rainfall, droughts, heat waves, and floods, which directly affect plant growth, flowering, fruit set, and yields. These results corroborate those of [9], which showed that climate variability is one of the main determinants of the adaptation strategies developed by Beninese vegetable farmers. Similarly, [32] emphasizes that vegetable crops are particularly vulnerable to climate change due to their high-water requirements and sensitivity to temperature fluctuations.

Phytosanitary constraints ranked second, accounting for 25% of responses. These primarily concern viral diseases, insect pest attacks, and difficulties in managing farm health. These observations are consistent with the findings of [7], which highlighted the significant role of diseases and pests in reducing chili pepper yields in Benin. Technical constraints (15%) are linked to the limited use of improved seeds, poor mastery of cultivation techniques, irrigation difficulties, and post-harvest losses. Similar results were reported by [8], which emphasizes that the low level of technical guidance is a major obstacle to improving vegetable crop productivity. Finally, although financial and economic constraints account for only 5% of the responses, they remain significant. Lack of access to credit, the high cost of agricultural inputs, fluctuations in sales prices, and the absence of processing facilities limit producers' investment capacity and reduce their resilience to other constraints. These findings confirm the analyses in [7] and [33], which suggest that economic vulnerabilities amplify the effects of climate change on agricultural incomes.

6. Conclusions

This study demonstrates the relevance of combining Geographic Information Systems (GIS) and MaxEnt modeling as an effective framework for assessing the current and future spatial suitability of chili pepper (*Capsicum annuum*) production in the municipality of Malanville under changing climatic conditions. Beyond identifying suitable production zones, the approach provides a robust decision-support tool for anticipating climate-induced shifts in agricultural potential and supporting evidence-based territorial planning.

The findings contribute to the growing body of research on climate-smart agriculture in West Africa by showing that temperature-related variables, particularly the minimum temperature of the coldest month (Bio6) and the annual temperature range (Bio7), are key determinants of chili pepper suitability. The projected contraction of favorable production areas under the RCP 8.5 scenario further highlights the vulnerability of vegetable production systems to future climate change and underscores the urgency of strengthening adaptation measures.

From a practical perspective, the suitability maps generated can support policymakers, extension services, and development partners in targeting investments, prioritizing climate-resilient agricultural interventions, and promoting sustainable land-use planning. The results also provide valuable guidance for producers by identifying areas where future production opportunities are likely to persist and where adaptation efforts should be concentrated.

Despite these contributions, the study has some limitations. The modeling relied primarily on bioclimatic and environmental variables and did not explicitly incorporate socioeconomic factors, market accessibility, irrigation infrastructure, soil fertility dynamics, or farmers' adaptive capacities, all of which may influence the actual distribution and productivity of chili pepper cultivation. In addition, uncertainties associated with climate projections and species distribution modeling should be considered when interpreting future suitability patterns.

Future research should therefore integrate socioeconomic and institutional variables, explore additional climate scenarios and time horizons, and assess the effectiveness of specific adaptation strategies under projected climatic conditions. Combining GIS-based suitability analysis with economic and agronomic assessments would provide a more comprehensive understanding of the resilience and sustainability of chili pepper production systems in northern Benin.

Overall, this study confirms that climate change is likely to reshape the geography of chili pepper production in Malanville and demonstrates the potential of GIS and MaxEnt modeling to support proactive adaptation planning, enhance agricultural resilience, and contribute to sustainable rural development in the face of increasing climatic uncertainty.

Author Contributions

The authors confirm their contributions to the paper as follows: Study design: Mama Djaouga, Yaya Issifou Moumouni, and Osséni Bakari.

Data collection and data processing: Osséni Bakari; Yaya Issifou Moumouni.

Drafting of the manuscript: Mama Djaouga, Yaya Issifou Moumouni, and Osséni Bakari.

All authors reviewed the results and approved this version of the manuscript.

Availability of Data and Materials: The data will be made available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding this study.

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