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Spatialization and Zoning of Agro-Climatic Constraints in the Department of Zou in Southeast Benin (West Africa)

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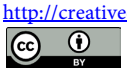


Abstract

In the Zou department of southeastern Benin, agriculture remains highly dependent on rainfall and seasonal water dynamics. Interannual variability in precipitation, water deficits, excess humidity, and irregularities in the agricultural season constitute major constraints on production systems. This study analyzes the spatial distribution and zoning of agro-climatic constraints in the Zou department, with the aim of identifying the most vulnerable areas and better guiding agricultural adaptation strategies. The study is based on the analysis of climate data on rainfall, temperature, and potential evapotranspiration for the period 1993-2022, supplemented by agricultural statistics on yields, cultivated areas, and production of five major crops: maize, cassava, tomato, cowpea, and groundnut. Field surveys conducted with producers allowed for the integration of local perceptions of climate constraints and adaptation practices developed at the farm level. The analysis relied on rainfall anomalies, water balance, the relationship between water and crops, and constraint mapping to arrive at an agro-climatic zoning of the territory. The results show a high degree of irregularity in rainfall patterns in the Zou department, marked by alternating years of deficit, normal rainfall, and surplus rainfall. Deficient years, characterized by low precipitation and periods of drought, disrupt the agricultural calendar and particularly affect crops sensitive to water stress. Conversely, surplus years increase the risks of flooding, soil saturation, and crop degradation in the most exposed areas. Analysis of the water balance highlights a pre-wet period from March to May, a wet period from June to September, and a post-wet phase from October to November, with direct impacts on water availability for crops. The results also reveal a spatial differentiation of constraints, with some areas more exposed to water deficit, others to excess water, and intermediate areas where vulnerability depends on the intra-seasonal distribution of

rainfall. This study highlights the value of spatial analysis and agro-climatic zoning as decision-making tools for agricultural planning in the Zou department. It underscores the need to adapt cropping calendars, promote water management practices, and strengthen local resilience strategies to sustainably improve agricultural productivity in the face of climate variability.

Keywords

Benin, Zou Department, Agro-Climatic Constraints, Zoning

1. Introduction

The spatialization and zoning of agro-climatic constraints aim to analyze and map the geographical variations in climatic and environmental conditions that influence agriculture. By delineating specific zones according to criteria such as temperature, rainfall, and soil quality, these approaches allow for a better understanding of the agricultural challenges and opportunities specific to each region (DGEC, 2022: p. 33). They thus offer valuable tools for optimizing agricultural practices, improving yields, and adapting to climate change, providing a solid basis for decision-making and strategic planning in the agricultural sector. Understanding hydrological processes is crucial for better management of agricultural activities in the Agbado River basin (Vissoh et al., 2023: p. 220). In some regions, the gradual changes in temperature and rainfall, along with the increasing frequency of extreme weather events, are expected to lead to crop losses, livestock deaths, and other losses of production assets, thereby threatening not only food production but also access to, stability of, and utilization of food resources (UNDP, 2014: p. 72). The geographical basis of this type of agricultural production leads some producers to cultivate soils and lowlands with prolonged humidity due to their fertility, which is essential for good agricultural production (Souberou et al., 2018: p. 137). According to Ahossin et al. (2023: p. 79), producers develop adaptation measures based on beliefs and empirical knowledge, as well as suggestions from rural extension services. Consequently, farming communities have retained a strong memory of the negative impacts of climate on agriculture. They possess proverbs and songs that clearly reflect the importance of weather and climate for agricultural activities (FAO, 2012: p. 5). By combining these approaches, researchers and practitioners can gain an integrated understanding of agro-climatic challenges at different spatial scales. This approach is essential for developing sustainable agricultural solutions and implementing appropriate policies in the study area, which is bordered to the north by the Collines department, to the south by the Atlantique and Ouémé departments, to the east by the Plateau department, and to the west by the Couffo department and the Republic of Togo. The Zou department extends between longitudes 1˚39'20" East and 2˚30'50" East, and latitudes 6˚57' North and 7˚31'20" North, as shown in **Figure 1**.

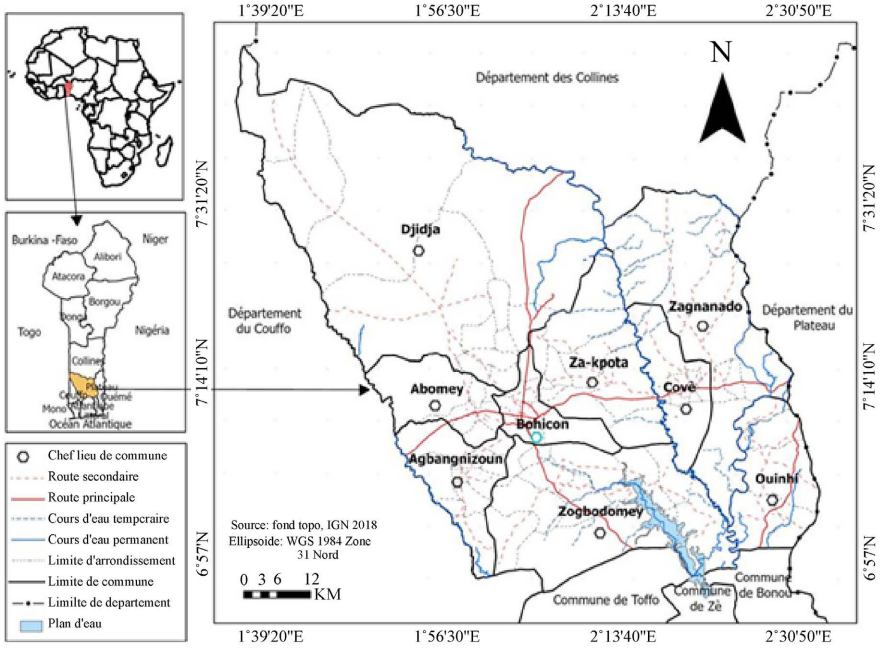


Figure 1. Geographical location of the study area.

The department covers an area of approximately 5,243 km^2 and includes nine communes: Abomey, Agbangnizoun, Bohicon, Covè, Djidja, Ouinhi, Zagnanado, Za-Kpota, and Zogbodomey.

Physically, the Zou region lies in a transitional zone between the sub-equatorial environments of the south and the more continental tropical regions of central Benin (Ekpangbo, 2006). It features a moderately undulating plateau topography, with elevations generally ranging from 200 to 300 meters. The climate is characterized by alternating wet and dry seasons, which strongly influence agricultural activities. Annual rainfall generally varies between 900 and 1,200 mm, with a seasonal distribution that determines the length of the growing season, the planting calendar, and water availability for crops. Agriculture is the dominant activity for the population and relies primarily on rain-fed farming systems, making farms particularly vulnerable to climatic irregularities, water deficits, excesses, and disruptions to the seasonal cycle.

The choice of the Zou department as a study area is justified by its agricultural importance, the diversity of its production systems, its sensitivity to hydroclimatic hazards and the interest of a spatial approach to agro-climatic constraints at the scale of a territory strongly dependent on rainfall.

2. Materials and Methods

2.1. Nature and Sources of the Data Used

The data used in this study are of several types. They consist primarily of climatological statistics relating to rainfall, temperature, and evapotranspiration over the period 1993-2022. These were extracted from the files of Meteo-Benin (2023). Agricultural statistics, particularly those relating to total production, yields, and

cultivated areas for maize, tomato, cowpea, cassava, and groundnut crops, over the period from 1996 to 2018. This data was obtained from the Ministry of Agriculture, Livestock and Fisheries (MAEP), and qualitative information was gathered during socio-anthropological investigations. This data was used to analyze climatic constraints (such as drought and excessive humidity) and agro-climatic constraints (such as water reserves for crops).

2.1.1. Documentary Research

The literature review constituted the first phase of data collection. It consisted of consulting books, scientific articles, dissertations, technical reports, institutional documents, and statistical databases related to climate variability, rainfed agriculture, agro-climatic constraints, and spatial approaches in tropical environments. This research primarily involved the documentation centers of the Faculty of Humanities and Social Sciences (FASHS), the National Institute of Statistics and Technological Development (INSTAD), Meteo-Benin, the Benin Environment Agency (ABE), the Federation of Agricultural Sciences (FSA), and the internet. This step allowed us to define the research question, select the analytical indicators, and guide the collection of field data.

2.1.2. Field Investigations

Field investigations were conducted in the communes of the Zou department with agricultural producers and resource persons. They aimed to complement statistical information with direct observations and qualitative data relating to the concrete manifestations of agro-climatic constraints, disruptions to the agricultural calendar, the most affected crops, areas exposed to excess or insufficient water, and local responses to these hazards.

☑ Sampling

The method of Schwartz (1995) was used to determine the sample size for this study. $X = Z\alpha^2 \times pq/i^2$, where x = sample size, $Z\alpha = 1.96$ (reduced deviation corresponding to a 5% α risk), p = n/N, where p = proportion of households in each locality (n) relative to the number of agricultural households in the research area (N) to which it is located, q = 1 − p, and i = 5%. The total number of agricultural households is 13,410, with a total agricultural population of 233,542. Thus, p = n/N = 46,708/233,542 = 0.20, or 17%, with n = 46,708 and N = 233,542. I^2 = random error rate = 5% = 0.05. $X = (1.96)^2 \times 0.20\ (1 - 0.20)/0.05^2 = 245.86$. Therefore, the total number of households surveyed is 246.

☑ Data collection techniques and tools

Several data collection tools are used; these include:

- The observation grid made it possible to record the findings during direct observation in the field;
- The interview guide and questionnaire sheets were sent to resource persons and target groups in order to collect information to achieve the objectives;
- a camera for taking pictures of producers in their various activities, in the fields.

In order to obtain as much reliable data and information as possible, several

techniques were implemented. These include:

Direct observation allows us to understand production systems;

- The active participatory research method (PARM) involves first focusing on the daily realities of the producers being surveyed. Its objective is to collect information related to the set objectives;
- The focus group technique, direct interviews, etc., allowed us to supplement the information gathered from each farmer. It also helped to confirm the accuracy of the information collected in the targeted localities of the Zou department.

2.2. Data Processing and Results Analysis

Data processing and results analysis constitute the final step in the methodological approach used.

It involves cross-referencing and grouping information obtained from documentation. After being manually reviewed, the survey forms were coded and then processed using Excel. This software was used to aggregate monthly and then annual data in order to create tables and graphs.

They also allowed for the calculation of average rainfall, agricultural statistics (areas and yields), and the standard deviation for calculating anomalies. The different formulas involved in the processing and analysis are:

- Average monthly and annual rainfall:

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{n} x_i$$

With N = the total number of individuals; $\overline{X}$ = the mean of the series to be considered; and x_i = the category of the characteristic being studied. This allows us to characterize the average climatic state and to develop some dispersion indices.

- Reduced centered anomalies, through data analysis, allowed for the evaluation of monthly and interannual variation in rainfall and temperature in Bohicon. The distribution of wet and dry years is based on the Lamb index (1882), used by Seydou (2020: p. 81), which represents the deviation from the mean normalized by the standard deviation.

$$X = \frac{x_i - \overline{x}}{\sigma}$$

where X represents the average annual cumulative rainfall obtained per station for year i; $\overline{x}$ and σ represents, respectively, the mean and standard deviation of the series considered. According to this index, a year is considered normal if its index is between −1 and 1. It is considered wet if its index is greater than 1 and dry when its index is below −1.

➢ **Analysis of Climatic Constraints**

Rainfall Evolution: The analysis of rainfall amounts made it possible to identify periods of drought and humidity in the Zou department. These periods were determined by a study of rainfall variations over the years, identifying years with deficits and surpluses;

Water Balance: Comparison between precipitation and evapotranspiration made

it possible to characterize pre-wet, wet, and post-wet periods, indicating favorable or unfavorable times for agriculture.

➢ **Analysis of Agro-Climatic Constraints**

Water Deficit and Crop Water Requirements: The study focused on local crops such as maize, tomato, cowpea, cassava, and peanut. The relationship between water availability and the specific needs of these crops was analyzed;

Influence of Rainfall Variations on Agricultural Yields: Yields were compared to rainfall to understand the impact of climate variations on agricultural production.

➢ **Spatialization of Agro-Climatic Constraints**

Constraint Mapping: Climatic and agro-climatic data were spatially represented to visualize the geographical distribution of constraints in the Zou department. This step made it possible to identify the areas most affected by climatic constraints, such as droughts or excessive rainfall.

➢ **Zoning of Agro-Climatic Constraints**

Delineation of Homogeneous Zones: Based on the results of the spatial analysis, the zoning consisted of grouping areas with similar constraints. This made it possible to establish distinct climatic zones with tailored recommendations for each zone in terms of agricultural practices.

3. Results

Climatic and agro-climatic constraints in the Zou department are outlined here.

3.1. Climatic and Agro-Climatic Constraints in the Department of Zou

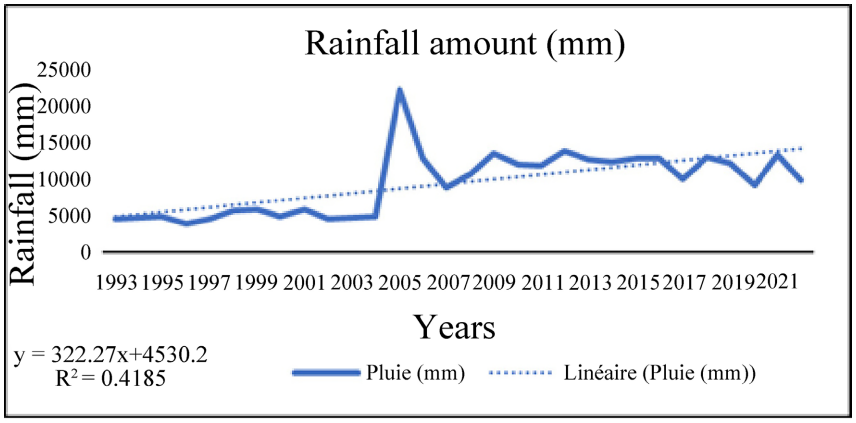
The climate balance, the agro-climatic balance, and the water-crop relationship served as the basis for analyzing climatic and agro-climatic constraints in the Zou department. This analysis led to their spatial distribution and zoning.

3.1.1. Climate Constraints in the Zou Department

Analysis of rainfall patterns and climate balances allowed for the identification of climatic constraints in the study area. Figure 2 shows the evolution of rainfall amounts from 1993 to 2022 in the Zou department.

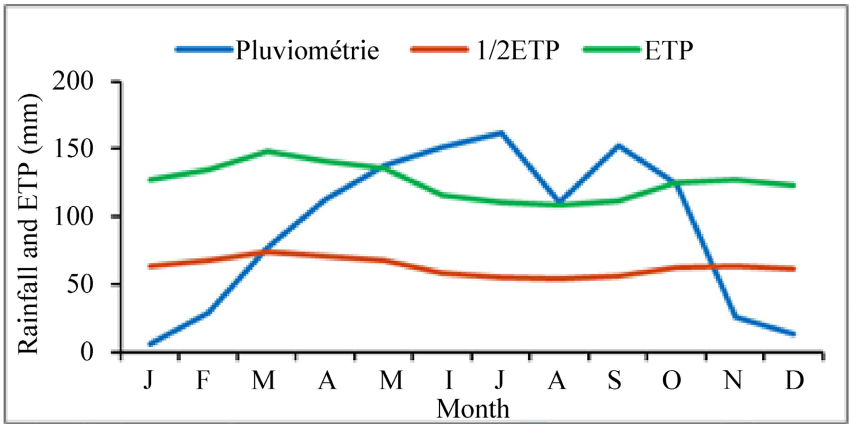
Analysis of Figure 2 shows that rainfall in the study area is highly variable, with alternating years of deficit, normal rainfall, and surplus rainfall, despite a slight overall upward trend (slope = 3.9888). The average annual rainfall is 1109.16 mm. Deficient years favor certain crops with low water requirements, while surplus years increase the risk of flooding but can improve agricultural yields. Normal years are generally favorable when rainfall is well distributed in time and space.

Analysis of Figure 3 shows that the pre-wet period extends from March to May. During this time, rainfall is less than the potential evapotranspiration in the Zou department. The wet period (active vegetation season) covers June, July, August, and September. This period represents the time when rainfall is generally greater than potential evapotranspiration. Furthermore, the post-wet period, from October to November, marks the point at which rainfall falls below potential evapotranspiration.



Sources: Meteo-Benin (2023), data processing, 2024.

Figure 2. Evolution of rainfall amounts in the Zou department.



Sources: Meteo-Benin (2023), data processing, 2024.

Figure 3. Water balance between rainfall and evapotranspiration (ETP) from 1993 to 2022.

This climate, conducive to polyculture, allows two agricultural seasons a year, and exuberant vegetation, which is now heavily affected by demographic pressure.

3.1.2. Agro-Climatic Constraints in the Department of Zou

Analysis of the climate balance reveals significant interannual variability in water conditions. In 1993, the dry season extended until the end of the second ten-day period of April, with a late replenishment of available water reserves and a near-total absence of runoff. This situation resulted in insufficient water for crops, making the agricultural calendar difficult to manage and yields very low. Conversely, in 1999, available water reserves were replenished as early as the second ten-day period of May and remained stable until the end of October, promoting longer periods of runoff and better water availability for crops. Despite a brief rainfall decrease in August, water reserves were sufficient to support second-season crops, reflecting overall more favorable agricultural conditions than in 1993. **Figure 2** illustrates the effect of agro-climatic constraints on maize cultivation.

Observation of **Plate 1** shows the state of the cornfield (1.1) cultivated by farmer

Comlan, subjected to late and irregular rains, and that (1.2) of farmer Koboudé, devastated by floods. The crops are subject to several agro-climatic constraints that are the root cause of the low yields.

Photographs taken by the author, August 2024.

Plate 1. Maize cultivation is subject to agro-climatic constraints in the Zou department.

3.2. Water-Crop Relationship and Other Agro-Climatic Parameters

This concerns the water deficit and water needs of crops and other agro-climatic parameters of agricultural production in the Zou department.

3.2.1. Water Deficit and Water Needs of Crops

The crops considered in this study are maize, tomato, cowpeas, cassava, and peanuts.

Analysis of **Figures 4(a)-(d)** highlights significant interannual variability in rainfall, marked by rainfall peaks around 2004-2007, followed by a gradual decline. Despite these fluctuations, yields of cassava, tomato, cowpea, and groundnut remain relatively stable, reflecting the low sensitivity of these crops to rainfall variations. This stability is explained by their adaptability as well as the influence of other factors such as soil fertility, cultivation practices, and water management techniques. In contrast, maize appears more dependent on rainfall conditions: periods of moderate rainfall generally correspond to improved yields, while rainfall deficits are accompanied by a decrease in production. Episodes of excessive rainfall do not necessarily lead to increased yields and can even have adverse effects, notably through soil waterlogging or flooding. Overall, these results show that rainfall, while important, does not alone explain agricultural performance (MAEP, 2019). Crop yields also depend on the agronomic characteristics specific to each species, production practices, and soil conditions. Thus, moderate rainfall, well distributed over time, remains the most favorable condition for ensuring sustainable agricultural production and better yields.

3.2.2. Other Agro-Climatic Parameters of Agricultural Production in the Zou Department

This involves solar radiation, air temperature, wind, and air conditions.

Sources: Benin Meteorological Service, Agricultural Statistics, Data Processing 2024.

Figure 4. Evolution of agricultural yields and rainfall patterns.

1) Solar Radiation and Temperature

For the five crops considered in this study—maize, cowpeas, peanuts, tomatoes, and cassava—soil temperatures are favorable year-round because, according to Boko (1988), "average soil temperatures in Benin are favorable to all tropical crops throughout the year." Therefore, the crops in the Zou department exhibit excellent conditions for cultivation, temperature, and irrigation. However, plants do not thrive on averages but rather on the specific, successive temperatures they experience. Each plant is characterized by the sum of daily temperatures recorded during the growing season. This value is called "degree days."

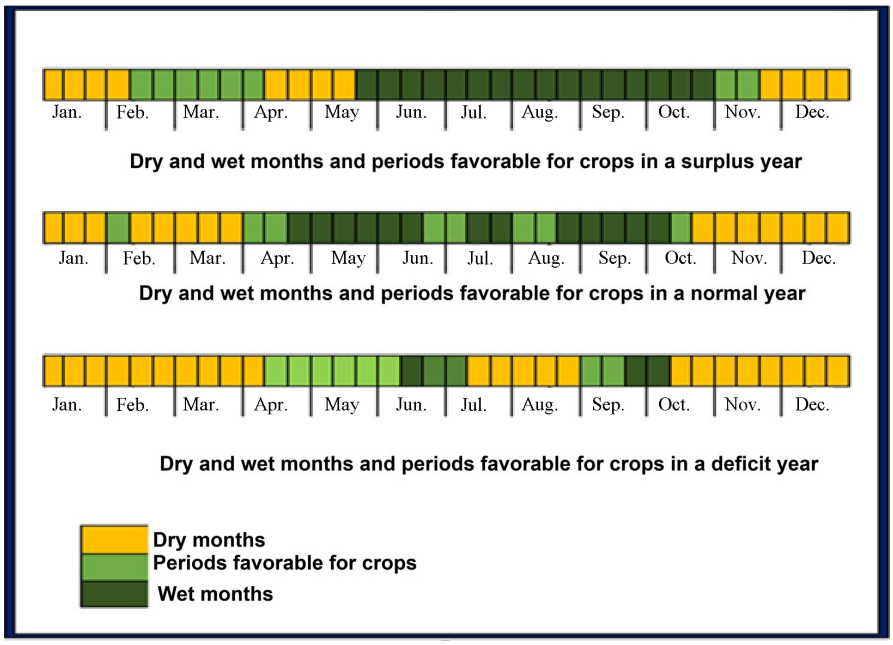
2) Wind and Air

Wind plays a crucial role in gas exchange between the soil, plants, and the atmosphere by promoting air renewal. In the study area, potential evapotranspiration, which represents the maximum amount of water lost by the soil (evaporation) and plants (transpiration), generally increases with wind speed. Therefore, increased wind speed promotes evaporation and transpiration, potentially increasing crop water requirements, particularly during periods of low water availability. Furthermore, air also influences plant growth through its thermal characteristics and dynamics. However, due to the lack of specific data on these

parameters in this study, it was not possible to assess their impact on the selected crops.

3.3. Climatic Seasons and Growing Periods

Figure 5, obtained using climate balances established with climate data from the synoptic station in Bohicon, represents the seasons and periods.



Sources: Benin Meteorological Service, Agricultural Statistics, Data Processing 2024.

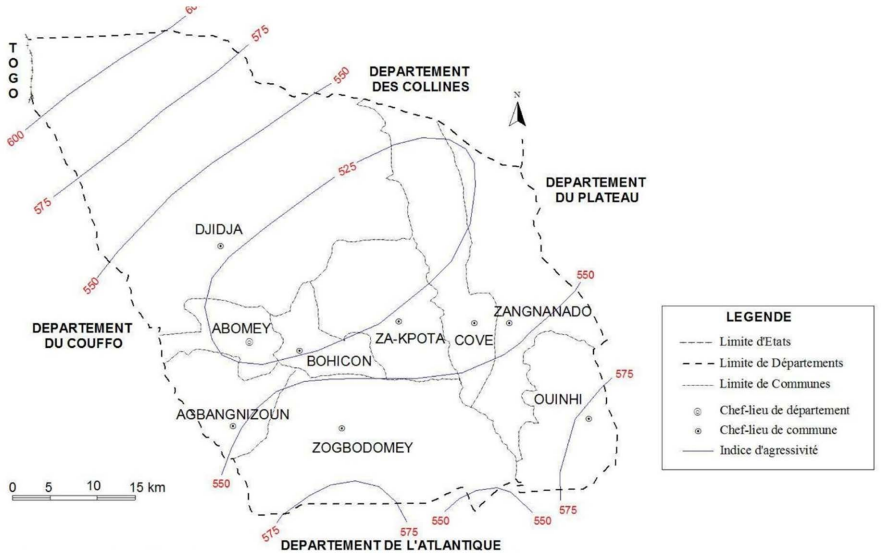
Figure 5. Dry months, wet months, and periods favorable to crops in the Zou.

Analysis of the figure shows that the duration of dry, wet, and crop-friendly periods varies according to the type of climatic year. Years with above-average rainfall have the longest wet season and the most favorable growing conditions, while years with below-average rainfall are characterized by a long dry season and a reduction in periods suitable for agricultural production. Normal years occupy an intermediate position, with generally favorable water conditions when rainfall is well distributed.

3.4. Spatialization and Zoning of Agro-Climatic Constraints

Figure 6 shows the zoning of annual climatic aggressiveness indices in the different localities of the Zou department.

Analysis of this map shows that climatic severity in the Zou department exhibits a contrasting spatial distribution. The highest values (600) are observed in the northwest, particularly around Djidja, then gradually decrease towards the center and southeast, where they reach 550. This distribution reflects a decreasing gradient of climatic severity from the northwest to the southeast, highlighting varying levels of vulnerability across the municipalities.

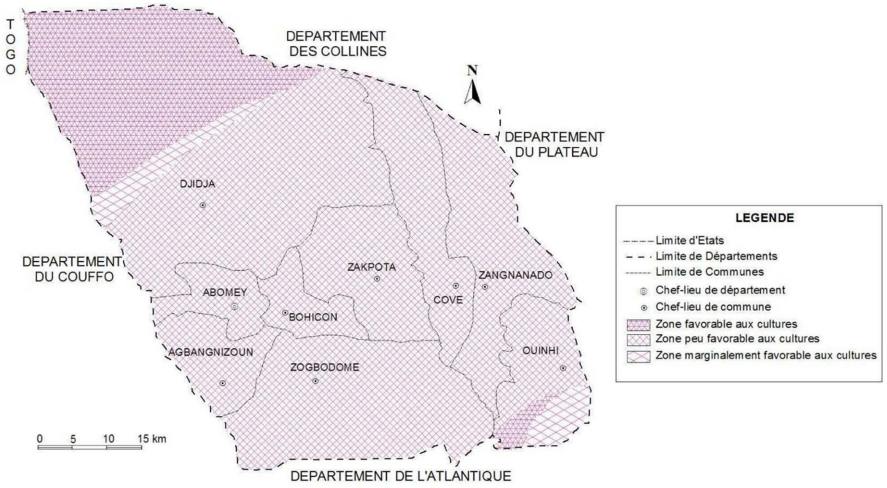


Sources: Benin Meteorological Service, Agricultural Statistics, Data Processing 2024.

Figure 6. Hint of an aggressive climate annual in the Zou.

3.4.1. Spatialization of Agro-Climatic Constraints

Figure 7 shows the spatial distribution of agro-climatic constraints in the different localities of the Zou department.



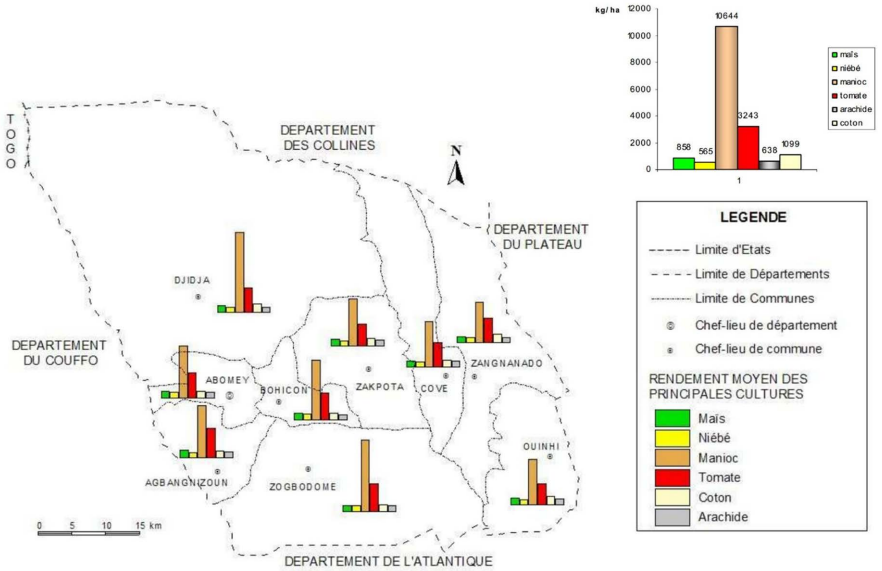
Sources: Benin Meteorological Service, Agricultural Statistics, Data Processing 2024.

Figure 7. Influence of the agro-climatic constraints on the Zou.

Analysis of this map shows that the Zou department is largely classified as an area favorable to agriculture, covering most of its municipalities. A highly favorable zone is located in the northwest, particularly around the municipality of Djidja, while a marginally favorable zone appears in the far southeast. This distribution reflects varying agricultural capabilities depending on agro-climatic conditions, with higher production potential in the northwest than in the southeast of the department.

3.4.2. Zoning of Agro-Climatic Constraints

Figure 8 shows the spatial distribution of average yields of the main targeted crops in the different localities of the Zou department.



Sources: Agricultural Statistics, Data Processing 2024.

Figure 8. Yield average of the main crops in the Zou.

Analysis of this map reveals a contrasting spatial distribution of average yields for the main crops in the Zou department. Cassava has the highest yields across all communes, followed by tomatoes, while maize, cowpeas, cotton, and peanuts show relatively lower production. The communes of Djidja, Covè, and Zogbodomey stand out with generally higher agricultural yields, reflecting more favorable agro-ecological conditions for production.

4. Discussion

The results show that climate variability is a major factor in agricultural vulnerability in the Zou department. The alternation of deficit, normal, and surplus years alters water availability and influences the course of agricultural seasons. Our results obtained on the water balance reveal that rainfall distribution is more crucial than annual rainfall for meeting crop needs. This aligns with the findings of Seydou (2020: p. 121), who demonstrated that yields react differently to climatic fluctuations: cassava, cowpeas, tomatoes, and peanuts appear relatively resilient, while maize is more sensitive to rainfall variations. The various results obtained on the correlation between agriculture and the determining factors of its development corroborate the findings of Ahossin, Wokou, and Yabi (2023: p. 60), who demonstrated that agricultural performance also depends on soil characteristics, farming practices, access to inputs, and seed quality. Furthermore, the results of this research have highlighted that in the Zou department, agricultural production (particularly maize and cotton) is hampered by soil depletion and shorter fallow peri-

ods. Therefore, Integrated Soil Fertility Management (ISFM) is essential, combining organic amendments and specific mineral fertilizers to restore essential nutrients. The spatial analysis of these constraints reveals territorial contrasts in vulnerability, justifying appropriate agro-climatic zoning. This zoning serves as a decision-making tool to guide crop calendars, crop selection, and adaptation strategies (Vissin, 2007: p. 215). Despite some limitations related to data availability, this study provides useful insights for strengthening the resilience of production systems to climate change in the Zou department.

5. Conclusion

This study analyzed the spatial distribution and zoning of agro-climatic constraints in the Zou department, highlighting the relationships between climate variability, water availability, and the performance of major crops. The results show that the department is characterized by high rainfall variability, marked by alternating years of deficit, normal, and surplus rainfall, which directly influences agricultural production conditions. Water deficits, droughts, and excessive rainfall constitute the main constraints affecting crops, with varying impacts depending on their water requirements.

Analysis of the water balance identified favorable and unfavorable periods for agricultural activities, demonstrating that the temporal distribution of rainfall is as important as its quantity. The study also showed that cassava, tomato, cowpea, and groundnut exhibit greater resilience to rainfall fluctuations, while maize remains more sensitive to variations in water availability. However, agricultural yields also depend on other factors such as soil quality, farming practices, inputs, and production techniques.

One of the main contributions of this research lies in the creation of an agro-climatic zoning map that highlights areas with varying degrees of exposure to water deficit, excess humidity, and flood risk. This zoning map provides a valuable decision-making tool for guiding crop selection, adapting agricultural calendars, improving water management, and strengthening producers' adaptation strategies to climate change.

Despite limitations related to the availability of certain climate and agricultural data, this study provides a useful scientific basis for agricultural and land-use planning in the Zou department. It recommends strengthening climate information systems, promoting resilient agricultural practices, improving the sustainable management of water and soil resources, and continuing research that integrates soil and socio-economic dimensions with future climate projections to support sustainable and resilient agriculture.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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