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Determination of the main agricultural crops for the Metropolitan Puebla-Tlaxcala area using the Papadakis Methodology

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ABSTRACT

Objective: This study aimed to identify potential areas for establishing the main agricultural crops in the Puebla-Tlaxcala Metropolitan Area (ZMPT).

Design/methodology/approach: From April to June 2022, the classification process for identifying the main crops in the ZMPT was conducted. This process utilized monthly climatic data from the Mexican Institute of Water Technology (IMTA), analyzed through the Papadakis methodology (1970). Subsequently, the results were mapped using the Weighted Overlay (WO) tool in ArcGIS v.10.2.

Results: The Papadakis methodology identified 10 seasonal crop types, particularly for summer and winter. The WO tool categorized potential areas into five classes: optimal, highly suitable, acceptable, and unacceptable for the establishment of several crops.

Limitations on study/implications: This study has limitations due to incomplete and scarce databases and the complexity and cost associated with the software used. However, the implications for agriculture include the potential to enhance and diversify agricultural production by identifying optimal areas for establishment, especially in Urban-Periurban Agricultural areas (UPAs).

Findings/conclusions: This study successfully identified the main crops cultivated in the ZMPT and highlighted potential areas for their establishment. The generated cartographic information enables the strategic distribution of productive agricultural systems, particularly in UPAs, to adapt to regional climate fluctuations in the short, medium, and long term. Besides, an adequate distribution in the implementation of productive agricultural systems, particularly in UPAs, depending on fluctuations in the climatic conditions of the region.

Keywords: self-consumption, Climate change, Urban growth, Spatial modeling.

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INTRODUCTION

Natural resources such as soil, climate, vegetation, and topography, among others, collectively constitute the concept of land, which serves as the foundation for establishing agriculture in rural areas (FAO, 2023). Studying it as a landscape element is the result of environmental factors that work together; therefore, it requires an understanding of most of the biophysical characteristics (Delgado-Calvo-Flores, Sánchez Marañón & Delgado Calvo-Flores, 1987).

On the other hand, soil is the physical space where human activities take place. Besides being a landscape element, it enables food production and serves as a refuge, space, and habitat, providing various elements for survival (Burbano-Orjuela, 2016). This resource is considered the substrate that supports and supplies nutrients to plants, while also participating in the hydrological cycle by allowing water filtration into groundwater, among other ecosystem services (Montanarella, 2015).

In the early 1980s, human population growth led to a drastic increase in food supply and, consequently, agricultural production, promoting negative effects associated with changes in land use for poorly planned productive activities. This decrease in productive capacity created the international need to develop standard soil classification systems (IUSS & WRB, 2007).

To harness the productive potential of the soil, it is imperative to manage territories to make decisions that are not overly complex to interpret, even for specialists from other disciplines unrelated to soil science (Perucca & Kurtz, 2016). The physical, chemical, biological, economic, and social evaluation of the soil constitutes a solid tool for sustainable management based on its inherent potential and productive capacity (Miranda *et al.*, 2021). This approach offers the possibility of implementing rational and sustainable use of this resource (Vargas & Ponce de León, 2008), as both soil and climate are the most relevant environmental factors that seasonally determine crop production in different regions around the world, as exposed in various agrometeorological studies (Mehrdad, 2017). Additionally, FAO (2022) recommends that this evaluation should be approached in a multidisciplinary method, considering environmental, social, economic, and cultural factors that impact agricultural systems.

Therefore, currently, the challenge is to produce more food while impacting fewer natural resources, especially soil, in order to mitigate the devastating effects on agrobiodiversity. This is because there are only about 100 species of plants and animals worldwide that are of agricultural and livestock importance for food production, with between 12 and 15 of them sustaining global production. Crops like rice, wheat, corn, and potatoes provide over 60% of the calories consumed by humans (Alemán, 2019). Recently, various more precise techniques for planning, implementation, and data analysis have been developed to improve the accuracy of results, thus promoting the prevention of the loss of germplasm with the potential to increase agricultural system productivity (Storck, Steckling, Roversi & Lopes, 2008).

As a result, the classification of agricultural soils will depend largely on the characteristics and quality of their mappable unit in comparison to agroecological needs for sustainable soil management in the short, medium, and long term, while minimizing environmental degradation. In this context, the task of classifying, evaluating, analyzing, and identifying soils to determine their productive potential could be carried out using the Papadakis method, mapped through the WO tool within a Geographic Information System (GIS). However, no quantitative or qualitative developments have been made in this regard (Flores, 1997). Therefore, this study aimed to identify potential areas for the establishment of the main agricultural crops in the ZMPT.

MATERIALS AND METHODS

Study area

The ZMPT is located in the central part of Mexico, specifically in Puebla and Tlaxcala states, between the coordinates 18° 50' and 19° 25' N 97° 55' and 98° 40' W. It covers an approximate area of 2,204.34 Km^2. This area is composed of 38 municipalities, with 20 belonging to Tlaxcala and 18 to Puebla. It exhibits temperate, semi-cold, cold, and semi-humid climates, with annual precipitation ranging from 800 to 1500 mm. The average annual temperature varies between −2 °C and 18 °C (Periódico-Tlaxcala, 2013; Figure 1).

The information was collected from 18 weather stations owned by the IMTA, from which databases containing records of 20 years or more were obtained. These stations are distributed throughout the entire study area (Figure 2). The data from these stations were extracted using Eric III v.2 (IMTA, 2009), a tool that streamlined data retrieval from the National Historical Data Bank of the National Meteorological Service, stored within the CLICOM database of the same institution. To do this, the suitable stations distributed in the ZMPT were selected (Table 1).

To identify the main crops in the ZMPT, monthly average climate data, including the lowest, minimum, and maximum temperatures, precipitation, and vapor pressure from IMTA databases, were analyzed using the Papadakis method (1970). The climate classification required determining parameters such as winter and summer characteristics, temperature regimes, humidity, as well as climatic types, adaptability, and limitations for

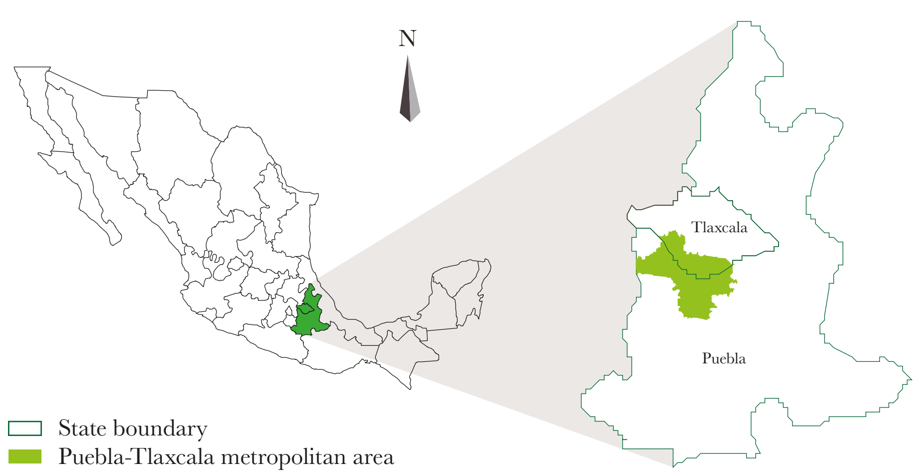

Figure 1. Location of the study area (ZMPT).
Source: Own elaboration with information from INEGI, 2021.

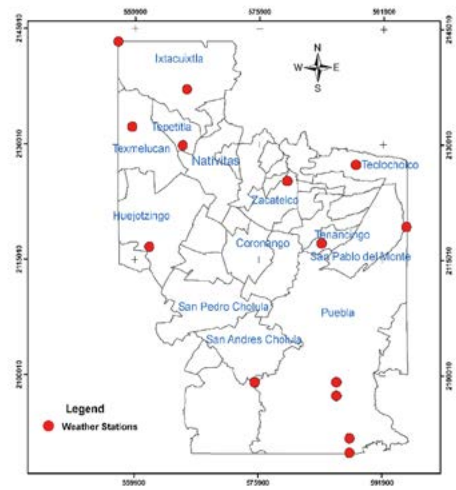

Figure 2. Distribution of IMTA meteorological stations in the ZMPT.
Source: Own elaboration using locations in the Mexican Republic. Scale: 1:50,000 from INEGI, 2018.

Table 1. Selected climate stations distributed across ZMPT, with records of 20 years or more.

Key	Initial year	Final year	Total Recorded years
21016	1943	2007	64
21023	1943	2006	63
21034	1943	2006	63
21035	1952	2006	54
21046	1925	1998	73
21164	1978	1996	18
21071	1954	2001	47
21148	1977	2003	26
21078	1961	2006	45
21089	1969	1990	21
21163	1978	2000	22
21214	1982	1995	13
29040	1974	2004	30
29041	1974	2005	31
29050	1980	2002	22
29056	1992	2002	10
29161	1990	2004	14
29169	1994	2002	8

important crops. This method comprised two phases: a) climate information analysis, involving the integration of the climatic system with crop requirements to ascertain their agricultural potential, and b) spatial analysis conducted through interpolation using the Spline tool of ArcGIS® (ESRI, Inc., 2019). This interpolation method estimates values through a mathematical function that minimizes the global curvature of the surface, resulting in a smooth area that accurately fits the input points.

With the interpolation product, WO was performed, which included a set of methods applied to determine the optimal locations for crop establishment through suitability modeling. In this technique, a common value scale was applied to various inputs that differed from each other to generate a comprehensive analysis. A weighting factor derived from the Papadakis classification was applied, taking into account factors such as relative humidity, precipitation, and extreme maximum and minimum temperatures.

RESULTS AND DISCUSSION

The results from the climate stations display the extreme values of precipitation, relative humidity, maximum temperature, and minimum and extreme temperatures in the ZMPT (Table 2).

Interpolation results provide an average approximation of the prevailing climate type in the ZMPT, from which maps of maximum, minimum, absolute average temperatures, precipitation, and relative humidity were obtained.

Data suggested the presence of average maximum temperatures ranging from 23.8-32.4 °C, which were located in the northern and central parts of Puebla, including San Martín Texmelucan, Huejotzingo, and Domingo Arenas. In contrast, values ranging from 18.6-23.8 °C were recorded in the eastern part of San Pedro Cholula, the western part of Puebla, San Andrés Cholula, San Miguel Xoxtla, Tetlatlahuca, San Jerónimo

Table 2. Extreme values were obtained from the IMTA climate stations in the ZMPT.

Station	Precipitation	Relative humidity	Maximum temperature	Minimum temperature	Extreme temperature
21016	143.5	69	29.3	6.20	2.1
21023	94.7	69.5	26.80	4.57	0.4
21034	185.1	69.5	26.46	0.91	−3.9
21035	195.6	69.5	26.46	4.88	1.24
21046	165.9	69.5	27.36	3.10	−0.78
21071	140.8	69.5	28.19	4.76	0.78
21078	126.1	69	28.16	3.97	−0.31
21089	70.6	69	26.34	−0.52	−6.75
21148	183.8	69.5	23.87	2.95	−0.21
21163	204.5	69.5	16.25	2.45	−2.5
21164	204.4	69.5	16.25	−0.57	−3.64
21214	160.9	69.5	19.97	0.68	−2.3
29040	129.9	69	27.60	1.6	−3.48
29041	133.9	69	26.02	0.63	0.62
29050	165.9	69	19.5	3.2	−0.11
29056	249.7	69.5	27.5	3.1	−0.37
29161	149.9	69	25	2.8	−0.68
29169	185.8	69	26.8	3.3	−0.22

Zacualpan, San Juan Huactzinco, San Lorenzo Axomanitla, Zacatelco, Coronango, and Cuautlancingo. Temperature ranges of 13.53-18.67 °C corresponded to San Pablo del Monte, Acuamanala de Miguel Hidalgo, Mazatecochco de María Morelos, Tenancingo, Santa Catarina Ayometla, Ixtacuixtla de Mariano Matamoros, Tepetitla de Lardizábal, Santa Ana Nopalucan, Tlaltenango, and Juan C. Bonilla. On the other hand, the threshold of 5.9-13.5 °C was concentrated in the central and western parts of Ocoyucan. The lowest temperatures of −6.1-5.9 °C were found in the eastern part of Puebla (Figure 3).

In contrast, the average minimum temperatures showed that ranges of 20.2-33.2 °C were distributed in the south of Ocoyucan and Puebla. Values of 12.10-20.2 °C were observed in the east of Ocoyucan, southeast, and central Puebla. Thresholds of 7.3-12.1 °C were located in the east of San Martin Texmelucan, Huejotzingo, Domingo Arenas, and the west of Puebla. On the other hand, values of 3.97-7.28 °C were present in Tepetitla de Lardizábal, Ixtacuixtla de Mariano Matamoros, Santa Ana Nopalucan, Nativitas, San Miguel Xoxtla, Tlaltenango, Juan C. Bonilla, San Gregorio Atzompa, Tenancingo, San Pablo del Monte, and others. Similarly, the ranges of −1.9-3.9 °C were distributed in the west of Ocoyucan (Figure 4).

On the other hand, the average minimum extreme temperatures were located in the center of Puebla and Ocoyucan. Thresholds between 11.9-21.5 °C were situated to the east of Ocoyucan and the south of Puebla. Values of 6.7-11.9°C were recognized to the west of Puebla, Amozoc, and the center of Ocoyucan. Ranges of 3.6-6.8 °C were focused in the center and east of Huejotzingo, San Martín Texmelucan, Nativitas, Tepetitla de Lardizábal, Tlaltenango, San Miguel Xoxtla, Santa Apolonia Teacalco, and others. Figures between −9.5-0.7 °C corresponded to the southeast of Puebla (Figure 5).

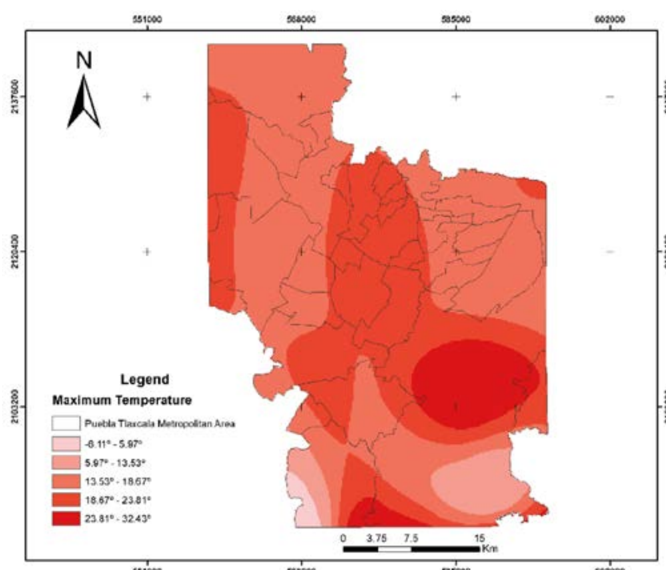

Figure 3. Cartographic results of the Spline interpolation method for average maximum temperature recorded in the municipalities of the ZMPT.
Source: Own elaboration with information from SMN and INEGI climate stations (INEGI, 2021).

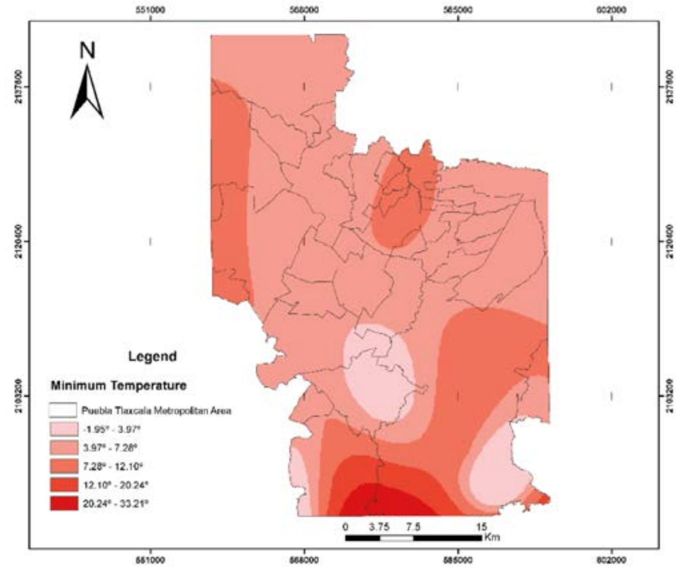

Figure 4. Cartographic results of the Spline interpolation method for average minimum temperatures recorded in the municipalities of the ZMPT.
Source: Own elaboration with information from SMN and INEGI climate stations (INEGI, 2021).

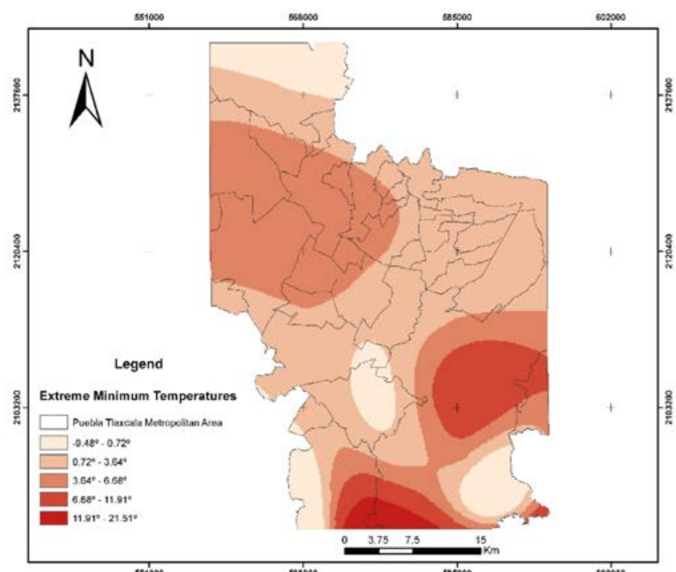

Figure 5. Cartographic results of the Spline interpolation method for average minimum extreme temperatures recorded in the municipalities of the ZMPT.
Source: Own elaboration with information from SMN and INEGI climate stations (INEGI, 2021).

On the other hand, average precipitation showed values between 98-137mm, which occurred in the west of Ocoyucan, southeast of San Andrés Cholula, Puebla, and Amozoc. Ranges of 73-98 mm were observed in the east of Tlaltenango, northwest of Puebla, Huejotzingo, Papalotla de Xicohtencatl, Santa Catarina Ayometla, Zacatelco, San Miguel Xoxtla, Coronango, Juan C. Bonilla, and others. Thresholds of 52-73mm were present in the northwest of Puebla, San Martin Texmelucan, east of Huejotzingo, southeast of

Puebla, Domingo Arenas, south of Ocoyucan, Ixtacuixtla de Mariano Matamoros, north of San Pablo del Monte, Santa Ana de Nopalucan, Santa Apolonia Teacalco, Nativitas, Tepeyanco, San Jerónimo Zacualpan, Tetlatlahuca. Parameters between 20-52 mm were recorded in the north of Ixtacuixtla de Mariano Matamoros, south of San Pablo del Monte, Mazatecochco. Similarly, values of 35-20 mm were reported in the center of Puebla and southeast of Ocoyucan (Figure 6).

Finally, average relative humidity ranges from 58.382% to 58.520% were located in the center of Huejotzingo, north of San Pablo del Monte, Papalotla de Xicohtencatl, Cuautlancingo, Santa Catarina Ayometla, and the south of Tlaltenango, Coronango, and Xicohtzinco. The range of 58.278-58.382% was observed in San Andrés Cholula, the center of Puebla, San Pablo del Monte, Nativitas, Tepetitla de Lardizábal, San Martin Texmelucan, Santa Ana Nopalucan, and more. Humidity thresholds between 58.140% and 58.278% were found in the south of Cuautlancingo, San Pedro Cholula, Tenancingo, the center of Huejotzingo, San Pablo del Monte, Papalotla de Xicohtencatl, Cuautlancingo, the south of Tlaltenango, Coronango, Santa Catarina Ayometla, and Xicohtzinco. Values between 57.9% and 58.1% were concentrated in the center of Huejotzingo, Ixtacuixtla de Mariano Matamoros, north of San Pablo del Monte, Papalotla de Xicohtencatl, Cuautlancingo, Santa Catarina Ayometla, Tlaltenango, Coronango, and Xicohtzinco. Humidity scales from 57.8% to 57.9% dominated the south of Ixtacuixtla de Mariano Matamoros, the north of Zacatelco, Huejotzingo, the east of San Jerónimo Zacualpan, Teolocholco, Santa Ana Nopalucan, Tepetitla de Lardizábal, Nativitas, San Martin Texmelucan, Tepeyanco, Santa Apolonia Teacalco, and more (Figure 7).

The results from Papadakis highlighted the main crops with productive potential that adapted to the prevailing climatic conditions in the ZMPT (Table 3).

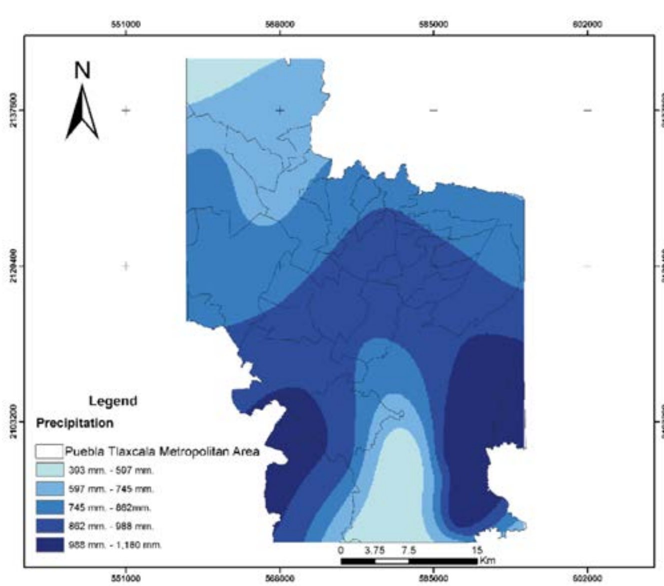

Figure 6. Cartographic results of the Spline interpolation method for average precipitation recorded in the municipalities of the ZMPT.
Source: Own elaboration with information from SMN and INEGI climate stations (INEGI, 2021).

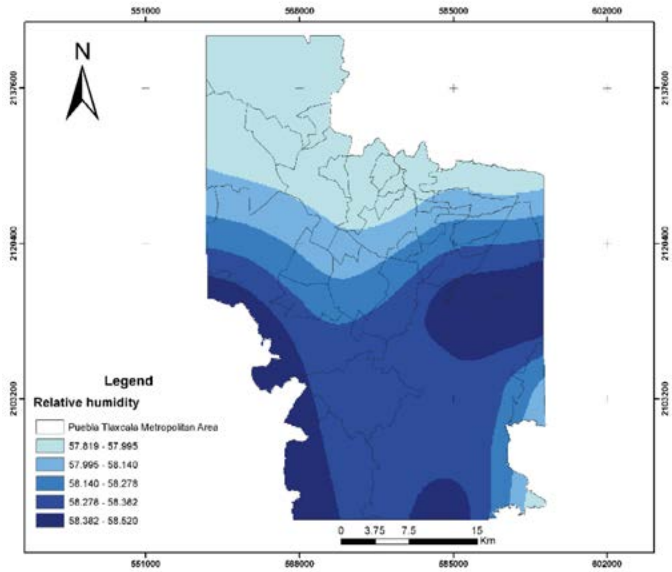

Figure 7. Cartographic results of the Spline interpolation method for average relative humidity recorded in the municipalities of the ZMPT.
Source: Own elaboration with information from SMN and INEGI climate stations (INEGI, 2021).

Table 3. Papadakis results, emphasizing the main crops with productive potential adapted to the recorded climatic conditions in ZMPT.

Key	Possible crops	Annual Precipitation (mm)	Annual Max. Temperature	Annual Min. Temperature	Annual Extreme Temperature
21106	Summer cereals: maize, sorghum, millet, rice.	724.3	29.3	6.20	2.1
21023	Winter cereals: wheat, oats, barley, rye.	464	26.80	4.57	0.4
21034	Summer cereals: maize, sorghum, millet, rice.	899.4	26.46	0.91	−3.9
21035	Summer cereals: maize, sorghum, millet, rice.	960.5	26.46	4.88	1.24
21046	Summer cereals: maize, sorghum, millet, rice.	827	27.36	3.10	−0.78
21071	Winter cereals: wheat, oats, barley, rye.	1400.9	28.19	4.76	0.78
21078	Summer cereals: maize, sorghum, millet, rice.	766.2	28.16	3.97	−0.31
21089	Summer cereals: maize, sorghum, millet, rice.	439.5	26.34	−0.52	−6.75
21148	Summer cereals: maize, sorghum, millet, rice.	830.4	23.87	2.95	−0.21
21163	Summer cereals: maize, sorghum, millet, rice.	876.7	16.25	2.45	−2.5
21164	Sugar beet and potato.	1026.9	16.25	−0.57	−3.64
21214	Winter cereals: wheat, oats, barley, rye.	891.6	19.97	0.68	−2.3
29040	Winter cereals: wheat, oats, barley, rye.	684.4	27.60	1.6	−3.48
29041	Summer cereals: maize, sorghum, millet, rice.	696.1	26.02	0.63	0.62
29050	Summer cereals: maize, sorghum, millet, rice.	802.8	19.5	3.2	−0.11
29056	Summer cereals: maize, sorghum, millet, rice.	955.8	27.5	3.1	−0.37
29161	Summer cereals: maize, sorghum, millet, rice.	780.3	25	2.8	−0.68
29169	Summer cereals: maize, sorghum, millet, rice.	885.0	26.8	3.3	−0.22

Similarly, the Papadakis results obtained suggested some management recommendations for the crops with productive potential identified in this study for the ZMPT (Table 4).

The results of the WO displayed the optimal locations for establishing certain crops with productive potential in the ZMPT. This location was successfully mapped, allowing the identification of five categories (optimal, very suitable, suitable, acceptable, and unacceptable) of soil suitability or potential for these crops.

The information generated through the WO indicated that summer cereals had an Optimal Potential in two municipalities, while Very Suitable was present in 12 municipalities. Suitable was located in nine municipalities, and Acceptable was also registered in eight (Figure 8).

For winter cereals, the Optimal Potential was recorded in 11 municipalities, Very Suitable in more than 11 municipalities, and Acceptable in only one (Figure 9).

For Sugar Beet, the Optimal Potential was observed in one municipality, Very Suitable in 12 municipalities, Suitable in 28 municipalities, and Acceptable in only one (Figure 10).

Regarding potatoes, the Optimal Potential was located in eight municipalities, and Suitable in more than 22 municipalities (Figure 11).

Likewise, the results of the SP allowed the estimation of the total areas by category for the establishment of productive potential crops in the ZMPT (Table 5).

Table 4. Papadakis results highlighting some management recommendations for the main crops with productive potential adapted to the recorded climatic conditions in ZMPT.

Key	Crops	Description
21106 21046 21078 21148 21163 29040 29041 29056 29161 29169	Summer cereals: maize, sorghum, millet, rice.	The cool nights in these climates make them favorable for summer cereals, which are grown during the frost-free season. This type of climate is most suitable for maize.
21023 21034 21035 21071 21089 21214	Winter cereals: wheat, oats, barley, rye.	Winter cereals (wheat, oats, barley, rye) can be sown in both spring and autumn, but in many subdivisions, irrigation is required. In some cases, even spring-sown crops require irrigation, and with proper irrigation and fertilization, good yields can be obtained.
21164	Sugar beet and potato	Potatoes are frequently damaged by frost but are still cultivated; irrigation is essential. For cryophilic grasses, irrigation is necessary, and legumes require either irrigation or the selection of suitable species, as their yields are considerably limited. Sugar beets can be grown using varieties that do not easily flower and are frost-resistant.
29050	Potato, Sugar beet	Potatoes yield well, but depending on the climate and planting time, irrigation is usually required. Sugar beets can grow well, but their production could be costly.

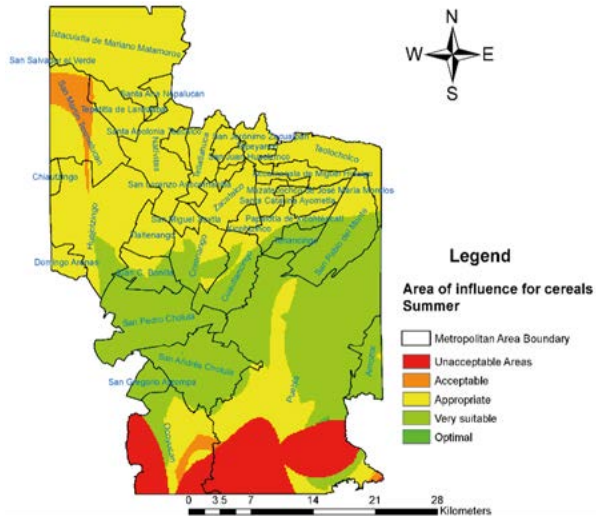

Figure 8. Cartographic results of the Weighted Overlay (WO), showing the optimal locations for establishing productive potential summer cereals based on the five categories of soil suitability or potential in municipalities of the ZMPT.

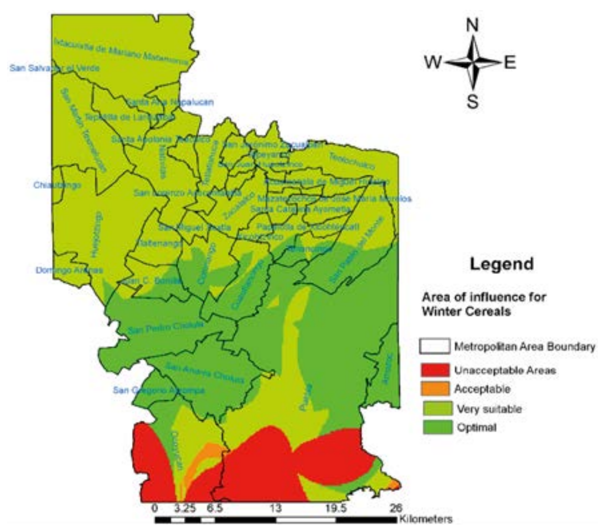

Figure 9. Cartographic results of the Weighted Overlay (WO), showing the optimal locations for establishing productive potential winter cereals based on the five categories of soil suitability or potential in municipalities of the ZMPT.

On the other hand, some authors (Velasco, 2010; Bautista-Capetillo, 2017; Mehrdad, 2017; Mendoza-Cariño *et al.*, 2021) conducted various studies on agroclimatic zoning using the Papadakis method to identify areas with potential for crops, focusing on specific climatic conditions in each area. These studies were based on climatic records collected over periods of at least 10 years or more, using information from 25 to 133 stations. The aim of these studies was to improve production in the study areas. In the case of the provinces of Kermanshah and Hamadán in Iran, characterized by their semi-arid and dry climate, the possibility of rainfed crops, specifically winter crops such as wheat, oats, citrus, cotton,

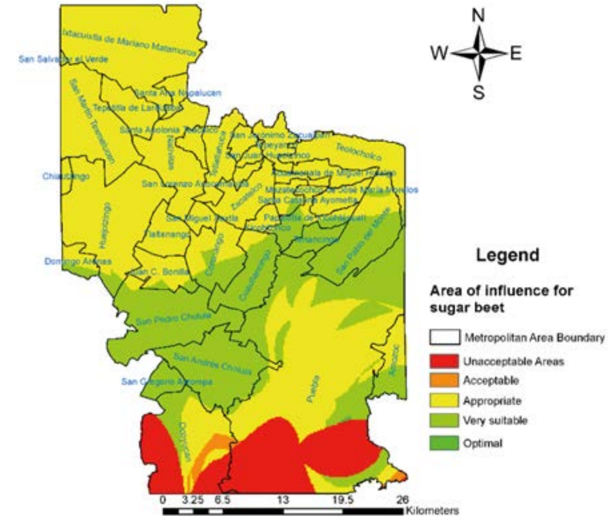

Figure 10. Cartographic results of the Weighted Overlay (WO) showing the optimal locations for establishing productive potential sugar beet based on the five categories of soil suitability or potential in municipalities of the ZMPT.

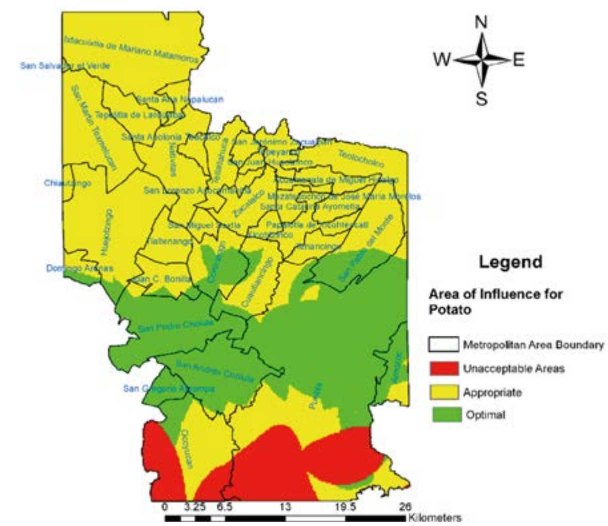

Figure 11. Cartographic results of the Weighted Overlay (WO) showing the optimal locations for establishing productive potential potatoes based on the five categories of soil suitability or potential in municipalities of the ZMPT.

Table 5. Results of the Weighted Overlay (WO) displaying the total areas by category for the establishment of productive potential crops in the ZMPT.

Type of crops	Unacceptable Areas ha.	Acceptable Areas ha.	Suitable Areas ha.	Very Suitable Areas ha.	Optimal Areas ha.
Winter cereals	138.88	9.9	829.35	481.86	0
Summer cereals	138.88	35.53	760.30	524.77	0.51
Sugar Beet	138.88	10.39	892.09	418.21	0.42
Potato	138.88	0	885.32	435.79	0

and others, was identified. Meanwhile, in Nayarit state, Mexico, areas with potential for summer crops, including rice, corn, millet, sorghum, as well as bananas and sugarcane, were identified. For the semi-arid zone of Zacatecas, Mexico, areas suitable for maize, beans, and soybean crops were identified. It is important to note that these studies covered large geographical areas and were mainly conducted at the state level in Mexico.

In this way, these studies align with the present research in managing some crops, particularly wheat, oats, rice, corn, sorghum, potatoes, and soybeans. However, the present study succeeded in identifying areas with productive potential for some crops such as rye, barley, and potatoes in the ZMPT using the Papadakis method and WO. For the first time in this region of Mexico, it was demonstrated that sustainable crop management is possible. This allows for the implementation of UPA systems to diversify agricultural production in areas seemingly unsuitable for it. These findings were mapped in a Geographic Information System (GIS), suggesting that the recommendations generated from our results for these crops are more precise and robust. It was possible to determine the months with the highest precipitation, crucial for rainfed agriculture in the study area.

Furthermore, this study differs from previous research because it focused on zoning urban and periurban areas, which is essential for food production in resource-limited settings. It enabled the identification of optimal zones for specific crops based on their productive potential, primarily driven by climatic factors. Additionally, the number of weather stations considered in this study is a distinguishing factor. While we used a smaller number of weather stations, we had more extensive data records over the years. Despite the differences in the number of stations and years, the trends identified in this study appear to be equally robust because we focused on the ZMPT, particularly in urban and periurban areas. The recommendations for crop establishment can contribute to producing what is needed for self-consumption and even for sale on relatively smaller land areas than those evaluated by other authors. This is a significant contribution because this study generated fundamental information that can enhance food security in this specific region of Mexico.

It is important to highlight that these mentioned studies share some similarities with the approach of this study. Their focus was on identifying climatic groups, primarily considering temperature, unlike the current study, which concentrated on identifying potential areas for agricultural crops based on climatic aspects.

CONCLUSIONS

Potential areas for the establishment of certain agriculturally productive crops in the ZMPT were successfully identified. The Papadakis methodology, along with WO and its cartographic projection in GIS, constitutes a set of tools with significant potential to promote good practices in UPA systems in relatively small land areas. This allowed us to determine the appropriate months for crop establishment, particularly in rainfed systems. As a result, this will foster sustainable agriculture that contributes to local food security through self-consumption and the generation of some economic development through the commercialization of these crops in local and regional markets.

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