



Identification of Suitable Areas for the Cultivation of *Oryza sativa* L. under Irrigation in the State of Campeche, Mexico

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Abstract

The federal and state governments of Campeche are proposing the implementation of the Campeche Plan, where one of its objectives is to promote rice production to support ejidatarios and farmers. In the state of Campeche, around 81,000 hectares were planted in 1980 and in 2023, according to SIAP, only 980 ha were planted in the P-V cycle and 290 ha in the O-I cycle, and 1530 ha were planted under irrigation in the P-V cycle and 4550 ha in the O-I cycle. A total of 8620 ha was planted in 2023; this area has been reduced year by year. If we compare it with that achieved in the 80's, it is due, among other aspects, to the fact that the area was mostly planted under rainfed conditions with high loss rates, low yields, low product prices, low profitability, in addition to the increase in rice imports from the United States, Vietnam and China, among others. If we consider that the history of rainfed crops generally led to economic losses, an important part of Plan Campeche is where the best conditions exist to produce high-potential rice with the help of irrigation to reduce the risk of drought losses, higher production and productivity, and to be profitable for the rice producer. In this study, three fundamental stages were considered to define the areas with potential: 1) identify altitude, temperature, luminosity and soil requirements for rice cultivation, 2) locate databases of agroclimatic conditions in the state of Campeche, and 3) process the data with QGIS Batioweiza 3.22.14 software. It was detected that in the state of Campeche there are only about 26,000 hectares under irrigation, most of which are planted with sugar cane, fruits and vegetables, so it would be necessary to propose a productive conversion process from rainfed to irrigation for 112,319 hectares, especially in the municipalities of Campeche, Champotón, Carmen, Palizada, Escár-

cega and Hopelchén.

Subject Areas

Agricultural Engineering

Keywords

Regionalization, GIS, Rice, Irrigation

1. Introduction

Rice (*Oryza sativa* L.) is the second most consumed cereal worldwide, after wheat, and plays a fundamental role in food security. In Mexico, rice is one of the most important food crops for Mexicans, behind only corn, beans and wheat, as it is an essential part of the basic food basket [1]. Despite its importance, its cultivation has suffered serious setbacks in recent years, and despite recent efforts, the production obtained in 1985 with 807,529 t has not been achieved, and has been declining steadily so that in 2023 only 259,099 t were produced [2].

In Mexico, rice is grown in twelve states, with Nayarit and Campeche accounting for the largest planted area, with 11,823 and 7350 hectares, respectively [2], representing 30% and 24% of national production. These areas were established mainly under rainfed conditions and, to a lesser extent, irrigated. Meanwhile, in the rest of the rice-producing states, the area under cultivation varied between 34 and 3935 hectares, which reflects a more limited production and, in many cases, oriented to local or regional consumption [2]. The current cultivated area does not reflect the rice self-sufficiency that Mexico experienced in the past, when production reached 498,000 tons and consumption was 436,000 tons. However, in the 2020/2021 cycle, a significant deficit in the supply of the domestic market was observed, with a national production of only 201,000 t, insufficient for a consumption of 960,000 t [3].

In view of this scenario, the Mexican government has incorporated in the National Development Plan (PND) 2025-2030 a specific strategy to boost rice production in the state of Campeche [4]. One of the main objectives of this strategy, called Plan Campeche, is to increase national rice production by strengthening local productive capacities, without compromising natural resources or encouraging deforestation. The plan promotes the use of sustainable agricultural practices aimed at improving grain quality, while contributing to the country's food security and sovereignty. According to Cobos-Mora *et al.* (2020) [5], rice is a highly adaptable crop, capable of establishing itself in diverse soil types and agroclimatic conditions. However, their productivity is closely linked to the use of appropriate technologies and improved varieties that guarantee economically viable yields. This need is accentuated in adverse agroecological environments, whose frequency and intensity have increased due to climate change and unsustainable

agricultural practices, factors that contribute significantly to yield declines and economic losses in producing areas.

Several studies have documented the positive impact of irrigation on rice cultivation, highlighting its role in increasing productivity. Hernaiz and Alvarado (2015) [6], reported that the application of irrigation favored greater plant height growth and reduced the incidence of weeds. Fonteh *et al.* (2013) [7] pointed out that the efficient use of irrigation should be promoted not only to optimize crop development, but also as a strategy to strengthen food security and mitigate the effects of climate change. In a complementary manner, Sévérin *et al.* (2014) [8] found that optimal rice development was achieved under irrigated conditions in soils with a clay content of 24%, which highlights the importance of considering edaphological characteristics when designing water management schemes. In this context, the objective of the present study was to identify areas in the state of Campeche that present the optimum conditions of climate, soil and altitude for the ideal development of rice cultivation under irrigation conditions.

2. Materials and Methods

2.1. Geographic Information and Map Algebra

A geographic information system and map algebra were used. Map algebra was a tool combining different territorial layers or variables in order to obtain alternative maps linked to specific characteristics of the territory [9]. In this case, map algebra was applied to locate the most suitable areas for rice production under irrigated conditions, with an ecological criterion combining climatic, soil, slope and altitude mapping. It was considered an ecological criterion combining, as a whole, the climatic, soil, slope and altitude cartography.

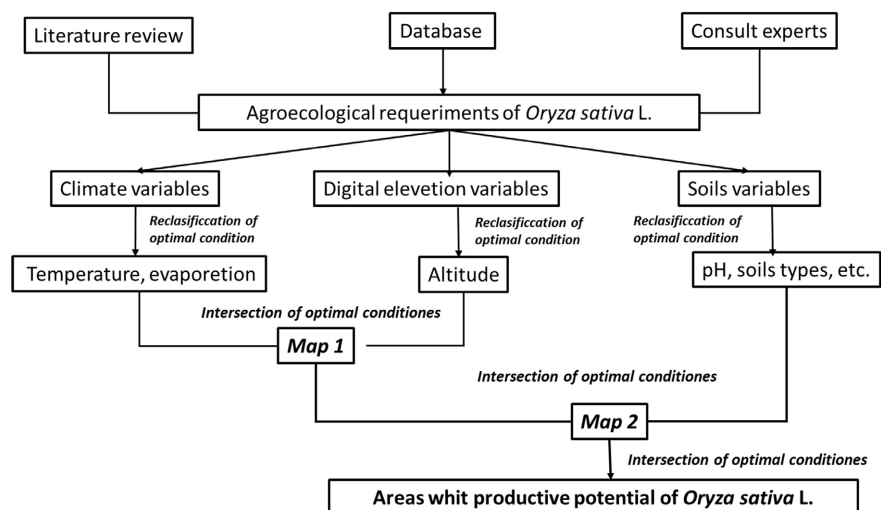


Figure 1. Methodological model used to determine productive potential.

With the help of symbols, the most suitable areas were distinguished as high potential ones, and the least suitable ones as unsuitable ones. In this study, three

fundamental stages (**Figure 1**) were considered to define the grade of potentiality: 1) To identify altitude, temperature, precipitation and soil requirements for rice cultivation; 2) locate databases of agro-climatic conditions for the state of Campeche; and 3) data processing. For the evaluation of the potential of rice cultivation in the state of Campeche, the main edaphoclimatic requirements of the species were taken into account. Regarding altitude, it was considered that rice can be established from sea level to 2,000 meters above sea level, although its optimum development is reached between 0 and 500 meters [10]. Regarding photoperiod, rice is a short-day plant, with a critical threshold of between 12 and 14 hours of light. However, this sensitivity varies among genotypes, and in the case of the most susceptible varieties, the critical photoperiod can be reduced to 10 hours [10]. In relation to temperature, the crop presents a tolerance range from 18 to 40°C. Each phenological stage has specific requirements for adequate development. For germination, temperatures between 18 and 40°C are required; for emergence and establishment, between 25 and 30°C; during bolting, between 25 and 31°C; at flowering, from 30 to 33°C; and for ripening, temperatures between 20 and 29°C [11].

In terms of soil requirements, rice prefers clay-loam or clay loam soils that are not calcareous and have poor drainage, conditions that favor crop management in flooded environments. The ideal soil pH varies according to its humidity condition: in dry soils a pH of 5.5 to 6.5 is considered optimum, while in flooded soils the ideal range is 7.0 to 7.2 [10]. In the state of Campeche, the soil types that meet these characteristics are mainly Vertisols and Gleysols, which represent the largest extensions with agricultural potential. To a lesser extent, there are also Luvisols, Nitisols and Fluvisols, which could be used under certain management conditions.

2.2. Determining Agroecological Needs for Rice

The variables used were the agro-climatic requirements of rice in Campeche [12], specifically average temperature, altitude, precipitation, light and soil (**Table 1**). Agro-climatic information was taken from bibliographic sources [12]-[14] and databases from **Ecocrop**, which identified more than two thousand plant species. The opinions of some rice experts were also considered. Database of agroclimatic and Geographic conditions of Mexico were also consulted. For soil conditions, the World Reference Base for Soil Resources [15] was considered in vector format [13] at a scale of 1:250,000. The tool used for the climatological data was **WorldClim** version 2.0 [16], specifically for average temperature and precipitation. From the National Institute of Statistics and Geography, the Digital Elevation Model with three-second data of altitude values was acquired [17]. From the **National Commission for the Knowledge and Use of Biodiversity**, through its **Geoportal**, the maps of slopes, mangroves, urban areas, water bodies and rural areas of Mexico were obtained, as well as the maps of protected natural areas in vector format with a resolution of 1:1,000,000 [18].

2.3. Database Processing

The procedure consisted on classifying the climatic and soil attributes required under rainfed conditions for rice. The vector format was used to perform analysis, interpolations, cuts and intersections. In this format data were obtained (entities associated with each attribute) with its own spatial characteristics and the geometry of the attribute. Map algebra refers to the set of techniques and procedures used in Geographic Information Systems (GIS) to obtain information derived from mathematical, logical or statistical operations applied on one or more layers of geospatial data, whether in raster and/or vector format. These operations, by combining attributes and spatial relationships, generate new thematic layers representing synthetic variables or modeled phenomena [19]. This vector data geometry was implemented through the intersection of the edaphic and climatic layers; and the mangrove, protected areas and urban and rural settlements were eliminated. All the information was processed and reclassified using the QGIS 3.22.14 Batioweiza software [20]. The potential zones were classified into **high potential zones**, areas that had irrigation and where all the agroclimatic variables considered combine to provide optimal crop conditions, and **zones in the process of conversion to irrigation**, which have all the optimal variables except for precipitation, so that auxiliary irrigation is required, and finally unsuitable zones, where all conditions are suboptimal or limiting for crop development, so that it is inappropriate to use these areas.

Table 1. Agroecological requirements of rice (*Oryza sativa* L.) under irrigation conditions and methodological model for estimating productive potential.

Variable	Unit	Optimal	Suboptimal	Not suitable
Average Annual Temperature	°C	25 - 30	20 - 25 30 - 35	Less than 20 Over 35
Altitude	<i>masl</i>	0 - 500	1500 - 2000	Over 2000
Soil	<i>Type</i>	Fluvisoles Luvisoles Nitisoiles Vertisoiles Gleysoles	Cambisoiles Phaeozems	Solonchaks Leptosoles Arenosoles Calcisoiles Regosoles
Texture	<i>Type</i>	Heavy to Medium	Medium	Heavy and Light
Depth	<i>m</i>	Over 1	0.5 to 1	Less than 0.5
pH	<i>Indicator</i>	6.5 to 7.0	5.5 to 6.5 7.0 to 7.5	< de 5.5 > de 7.5
Ligth hours per year	<i>Hours</i>	Over 3000	2500 a 3000	Less than 2500
Drainage	<i>Type</i>	Moderately Efficient	Efficient	Very efficient

3. Results

High Potential Areas

The identification and delimitation of areas with high potential for rice cultivation

under irrigation conditions are shown in **Figure 2**. In the state of Campeche, the rice area under irrigation conditions in 2023 was 6,080.00 hectares, of which 4,150.00 were planted in the Autumn-Winter cycle and 1,530.00 in the Spring-Summer cycle, in the municipalities of Carme, Escárcega, Hopelchén and Palizada.

In 11 of the 13 municipalities in the state of Campeche there are irrigated areas for a total of 25,332.00 hectares, which are not necessarily planted with rice, as they are mostly used for fruits and vegetables, therefore, areas with high irrigation potential would have to compete with crops such as tomatoes, habanero peppers, lemons, oranges, etc.

In the state of Campeche there are already antecedents that in the valleys of Edzná, Chunchintok and Yohaltún, the cultivation of rice under rainfed conditions, since rainfall was insufficient for its development, drought losses were frequent, even in regions where rainfall is more than 2,000 mm per year, as in the case of the Chunchintok, Edzná and Yohaltún valleys, 1000 mm per year, as in the case of the municipalities of Escárcega, Carmen and Palizada, also presented this problem, hence the need to convert rainfed areas to irrigation, which implies a process of identification and planning to incorporate them into production.

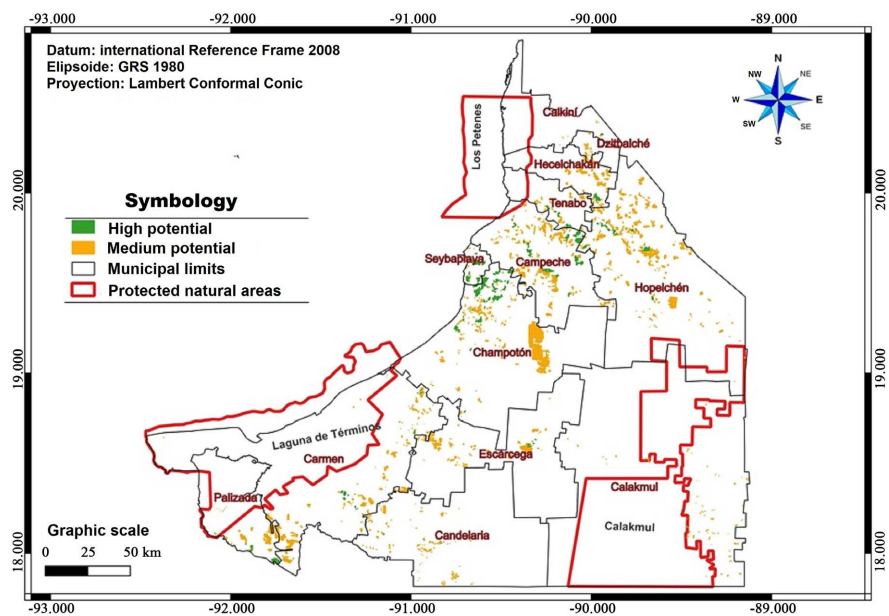


Figure 2. Identification and delimitation of areas with high potential for irrigated rice cultivation in the state of Campeche, Mexico.

The greatest possibilities to grow in surface area and have a greater probability of success in rice cultivation is through a process of productive reconversion in the areas open to cultivation under rainfed conditions to incorporate them to irrigation. According to the results of the study, these areas are located mainly in the municipalities of Hopelchén, Champotón, Campeche and Carmen, in these municipalities are located three regions that were important in the 70's as the

Edzná Valley, Yohaltún Valley and Chunchintok Valley. The municipalities of Hopelchén, Champotón, Campeche, Carmen, Escárcega and Palizada stand out for concentrating the largest areas with the potential to be converted to irrigated rice cultivation, with 32,313 ha in Hopelchén, 27,879 ha in Champotón, 17,069 ha in Campeche, 16,347 ha in Carmen, 10,695 ha in Escárcega and 8,016 ha in Palizada. Together, they total 112,319 ha, which positions them as strategic areas for the development of technified and sustainable agriculture. It should be noted that the municipalities of Carmen, Candelaria, Escárcega and Palizada are located in the river region, where the availability of surface water bodies represents a key opportunity for the use of irrigation systems. However, in these same municipalities there is average annual rainfall ranging between 1,000 and 2,200 mm, so the use of irrigation would be mainly auxiliary, with a relatively low environmental and energy impact (Figure 3). The municipality of Hopelchén concentrates the largest area with potential for rice cultivation in the state of Campeche, which is due to a combination of geographic, climatic and productive factors. This demarcation has a high proportion of rural areas and intense agricultural activity, conditions that favor agricultural expansion. The municipal territory is divided into two large regions: La Montaña and Los Chenes, of which La Montaña, located in the southern zone, covers approximately 200,000 hectares and represents the largest portion of the municipality.

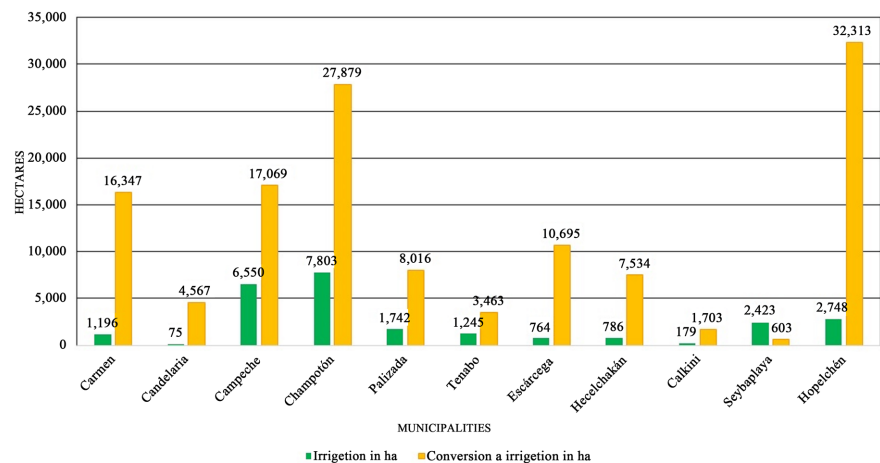


Figure 3. High-potential rice land with irrigation available and ready to be converted to irrigation.

Although it is classified as a high priority area for conservation because it is part of the buffer zone of the Calakmul Biosphere Reserve and the Mesoamerican-Mexico Biological Corridor [21], this region has agroecological characteristics that are favorable for agriculture under sustainable management. The sub-humid tropical climate of the municipality, with an average annual temperature of 26°C and an average annual rainfall of 1,050 mm, provides suitable conditions for rice cultivation [20]. In addition, La Montaña is more humid compared to the Los Chenes region, which increases its suitability for the establishment of irrigation

systems [22]. In terms of vegetation cover, La Montaña is dominated by medium sub evergreen and deciduous forest, while Los Chenes has predominantly low deciduous forest, which also influences the availability of soil and water for agricultural activities [21]. Together, these elements explain why Hopelchén constitutes a strategic zone with the greatest productive potential for rice cultivation in Campeche.

4. Discussion

Irrigation is defined as the system through which water is brought to the crops, capable of supplying the water needs of the plants, which are not covered by rainfall alone. This contribution can be made in order to increase the production of a plot of land, transforming rainfed agricultural areas into irrigated areas.

In the state of Campeche irrigated areas are limited and are generally occupied by other crops more profitable than rice and although it is one of the states where the average annual rainfall is between 400 and 2500 mm, in most of its territory rainfall fluctuates between 800 to 1500 mm, which is insufficient for its development in most of the entity, so necessarily if the state aims to be the leading producer of rice in the country, you should think about the conversion of rainfed areas to irrigation.

Rice cultivation is recognized as the largest consumer of water in agriculture worldwide [23], which poses serious challenges in regions where water resources are limited or under pressure. In the state of Campeche, water management in rice systems is mainly carried out through two modalities: gravity irrigation and rainfed cultivation. Rice grown under rainfed conditions tends to have significantly lower yields compared to that established under flood irrigation, particularly in agricultural cycles with limited rainfall [23].

The difference in productivity between irrigation systems is largely explained by the high sensitivity of rice to water availability during critical phenological stages. According to Nahar *et al.* (2018) [24], crop response to water stress can vary depending on the variety, presenting differences in the duration and synchrony of its phenological stages, whether early or late. Among the stages most vulnerable to drought are establishment after transplanting, tillering, initiation and development of the floral primordium, flowering and panicle filling, the latter being particularly sensitive until approximately two weeks before harvest [23]. Water stress in these phases significantly reduces the photosynthetic rate, which translates into lower biomass production and a reduction in the harvest index [25], directly affecting the final crop yield. In this context, the impacts of climate change represent an additional challenge, as an increase in the frequency and intensity of drought periods is expected, which could significantly increase the crop's water demands [26]. This scenario underscores the urgency of implementing efficient water management strategies and adapting rice production systems to more variable climatic conditions, in order to ensure their long-term sustainability and productivity. Faced with this problem, various irrigation systems for

rice cultivation have been evaluated, including conventional flooding, furrow irrigation with and without plastic mulching, and drip irrigation [27].

Among the different methods evaluated, drip irrigation has demonstrated higher water use efficiency (WUE), due to its ability to significantly reduce the volume of water applied compared to other irrigation systems [28]. Several international studies have explored alternatives to conventional irrigation with the objective of optimizing the use of water resources in rice cultivation. For example, in India, He *et al.*, (2013) [29] compared the traditional flood irrigation system with drip irrigation, observing favorable results in terms of reducing the volume of water used, without severely compromising crop development. These findings support the potential of drip irrigation as a viable strategy to improve water efficiency in contexts of water scarcity or rational water use [24]. There are seven main sub-basins in the state of Campeche, each with different edaphoclimatic characteristics that determine their suitability for rice cultivation. The Merida sub-basin, located to the north, has rainfall of less than 1000 mm per year and predominantly stony soils, with little usable agricultural area. In contrast, the Dzitbalché-Pustunich sub-basin, which covers part of the municipalities of Hopelchén and Campeche, has between 1000 and 1100 mm of annual precipitation and the presence of Vertisols, which are more favorable for cultivation. The Sabancuy-Sihochac and Champotón sub-basins, with rainfall of 1100 to 1150 mm and Vertisols and Gleysols soils, stand out in the municipality of Champotón. The San Isidro-Monclova sub-basin, which includes Escarcega and Candelaria, has Vertisols and Gleysols soils, bodies of water such as the Candelaria River and rainfall between 1500 and 2000 mm. Finally, the Chumpán and Bajo Usumacinta sub-basins (also known as the river region) have the highest precipitation values (2000 to 2200 mm per year) and Gleysols predominate, especially in the municipalities of Carmen and Palizada [30]. This last region is the most favorable for the conversion from rainfed to irrigation, given its abundance of water and soil conditions.

This study is based on the areas currently open to cultivation, according to information provided by Mexico's Agrifood and Fisheries Information Service (SIAP), and excludes those areas with agricultural potential that are located within Natural Protected Areas, in order to avoid negative impacts on these ecosystems. However, one of the main limitations is that future scenarios associated with climate change, such as temperature increase, variation in precipitation patterns or increase in the concentration of tropospheric ozone, among other factors, were not incorporated. These aspects represent an important line of research for future studies. Likewise, in the region of the rivers, in the south of the state, where there are areas of high potential or susceptible to conversion to irrigation, it is essential to consider sustainable and environmentally responsible agricultural technologies that avoid negative impacts on aquatic ecosystems, especially in the rivers that flow into the Laguna de Términos, in the municipalities of Carmen and Palizada.

5. Conclusions

The possibility of producing irrigated rice on large extensions of the current irrigation infrastructure is limited.

The productive conversion of rainfed areas to irrigation is required to produce rice in larger extensions than the current ones in the state of Campeche and with less risk of loss.

The state of Campeche has optimal soil, temperature, altitude and pH conditions, but not in terms of rainfall, so it is necessary to consider the aid of irrigation, since the areas of high potential under rainfed conditions are very limited.

For the conversion from rainfed to irrigation, it is necessary to have a plan that considers investment in irrigation infrastructure in the medium and long term in the valleys of Edzná, Yohaltún and Chunchintok.

Conflicts of Interest

The authors declare no conflicts of interest.

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