An index of environmental and cultural suitability for the cultivation of climate-resilient castor bean in rainfed low-productivity common lands in Mexico

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Highlights

- *In Mexico, the ejido is a unique land ownership and management system where users have access to common or individual (parcelled) land.*
- *According to our environmental productivity index, 114,300 ha of ejido land in Coahuila, México, were very suitable for castor bean cultivation.*
- *This index was complemented with a cultural component gauging the people's perception and willingness to introduce castor bean as a new crop.*
- *808,524 ha (12.4%) of ejido land were very suitable for castor bean cultivation according to the cultural component of our index.*
- *Differences in land tenure most strongly influence the willingness of the ejido people to cultivate castor beans.*

Abstract

Castor bean plants yield commercially important oilseeds with multiple uses; they are characterised by tolerance to drought and adaptation to marginal soils in arid and semi-arid regions. In northern Mexico, a large amount of arid land is categorised as *ejidos*: a system of mixed land ownership managed under a specific legal system, where land users have access to common or individual (parcelled) land. This work aimed to examine the suitability of castor bean cultivation on unused marginal land in ejido land. To determine the environmental suitability of the ejido lands of Coahuila, Mexico, we adapted a land productivity index (PI) from an existing method; it consisted of a set of biophysical indicators (edaphic factors, climate, and topography) adapted to castor bean cultivation. We then complemented this index with a *cultural component*, assessing the ethnobotanical knowledge of the people, their willingness to implement a new crop type, and the type and current use of the land. As a result, we found that 114,300 ha of ejido land (1.76% of the total) were very suitable for castor bean cultivation according to the environmental-PI and that 808,524 ha of ejido land (12.4% of the total) was very suitable according to the cultural-PI. We also hypothesised that the willingness of *ejidatarios* to cultivate castor beans was related to their degree of knowledge about the plant and the land available for its cultivation; however, their willingness was mostly related to differences in land tenure: *ejidatarios* who own parcelled land were more interested in obtaining benefits from the land through the implementation of novel crops, compared to those who only have access to common land.

Introduction

The Castor bean (*Ricinus communis* L.) is a species native to Ethiopia, Africa. However, it has been introduced to tropical, arid, and temperate zones of the world (Kiran and Vara Prasad, 2017).

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Castor bean's economic potential has aroused interest because more than 500 uses for it are known thanks to the properties of its oil seed (Severino *et al.*, 2012; Salihu, *et al.*, 2014; de França-Silva *et al.*, 2015). Many authors report oil seed content ranging from 35 to 55% of seed weight (Ogunniyi, 2006; Kallamadi *et al.*, 2015; Carrino *et al.*, 2020).

Castor beans' current global production depends mainly on four countries (India, China, Brazil, and Mozambique) and does not cover the growing demand of the world market (Severino *et al*., 2012; FAOSTAT, 2021). However, in 2021, in Mexico, one ton of castor bean seed was above $450 US; therefore, its cultivation is economically attractive for producers (SIACON, 2021).

Castor bean plant can grow in all types of soils, but it develops better in soils with a proper balance of moisture retention and drainage, such as sandy loam with a pH of 6 to 7.3 (Salihu *et al.*, 2014). Also, castor bean plants can grow at altitudes ranging from sea level up to 2500 m above sea level; however, the optimum altitude ranges from 0 to 1800 m above sea level (INIFAP, 2012; Carrino *et al.*, 2020). Castor bean plants can survive in a wide range of biophysical conditions, including marginal lands with strongly saline soils (unsuitable for more sensitive food crops), with annual rainfall ranging from 250 to 4250 mm. Castor bean has a great capacity to adapt to arid and semi-arid zones due to its tolerance for water deficit (Sausen and Rosa, 2010; Falasca, 2012; Carrino *et al.*, 2020; Patanè *et al.*, 2019). For this reason, several studies consider castor bean an attractive alternative crop for rural areas in northern Mexico (INIFAP, 2012; SAGARPA, 2017).

Castor bean seed yield is variable: seed yields of 350-700 kg/ha have been reported under adverse environmental conditions, and a maximum of 1250 kg/ha of seed has been reported under favourable conditions (Mazzani, 2007; Leite *et al.*, 2015). On the other hand, crop diversification helps reduce the negative impacts of climate change and improves the performance of agroecosystems in marginal areas that are more vulnerable to climate impact (McCord *et al.*, 2015; Hufnagel *et al.*, 2020). Castor bean is also a viable alternative for small farmers to reduce the vulnerability of their land to climate variations: castor bean could increase economic stability, reduce financial risk, stabilise income, and increase the choice of agricultural practices (McCord *et al.*, 2015; Makate *et al*., 2016; Adjimoti and Kawdzo, 2018). However, the willingness of small farmers to adopt new crops may be limited by a lack of knowledge of novel plants or cultivation techniques, the uncertainty of commercial aspects (profitability, customers), and differences in land tenure.

It is essential to identify and quantify land surfaces with favourable conditions for cultivating castor bean. Furthermore, land evaluation studies determine the degree of environmental suitability for specific use in a given territorial unit, which constitutes a basis for planning and managing possible territory uses (FAO, 2003). To achieve this objective, the Instituto Nacional de Tecnología Agropecuaria de Argentina (INTAA) developed the productivity index (PI). This index is based on the USDA – LCC (Land Capability Classification) soil evaluation system and the system developed by Klingebiel and Montgomery in 1961 and adopted by the FAO in 1970 (Morales-Poclava *et al.*, 2015). The PI provides a numerical assessment of the land's productive capacity for certain crops within a particular region.

Commonly-used methods to determine environmental suitability for crops are limited to the analysis of edaphic and climatic variables, rarely considering topographical and social features of the locality (Gingold *et al.*, 2012; Gardner *et al.*, 2021). However, social features are crucial because people make the decisions for managing ecosystems and lands, seeking how to optimise the benefits in the provision of goods and services. In the case of Mexico, the lack of attention to social factors, such as demographics, land tenure, governance, and social policy, has negatively impacted the rates of land use change and biodiversity loss (Challenger *et al.*, 2009).

Knowledge of the society's perception towards a novel crop (and people's willingness to adopt it) is essential, especially in Mexico, because there is a type of land ownership that is unique in the world called *ejido*. The ejido is a legal entity with its own assets, which is constitutionally recognised in article 27 of the Constitución Política de los Estados Unidos Mexicanos. The ejido is composed of three elements: i) an assembly of *ejidatarios* (people of the ejido), ii) the ejido commissioner, and iii) the surveillance council. The assembly of *ejidatarios* is, in turn, divided into *ejidatarios* (people with individual parcels and/or communal lands and who have a certificate of agrarian rights issued by the competent authority), possessors (people who live on the ejido with individual parcels without a certificate of agrarian and communal lands) and *avecindados* (people who may live on the ejido, but have no rights to the land). Ejido land is divided into communal land, individual parcels, and urban areas (Ley Agraria, 2018; Hoogesteger and Rivara, 2020).

In Mexico, ejido land is present in the 32 states of the country. The ejido surface of Mexico consists of 101.9 million hectares and represents 50% of the territory (Beraud Macías *et al*., 2018). For example, in the state of Coahuila, there are 6,507,087 ha of ejido land, divided into 2,438,489 ha of parcelled land and 4,068,598 ha of common-use land (Morett-Sánchez and Cosío-Ruiz, 2017; RAN, 2019). The ejido lands are mostly used as pasture and idle land (83.7%), with the remainder utilised for fodder, agro-industrial products, and vegetable agriculture (Morett-Sánchez and Cosío-Ruiz, 2017; de Ita, 2019; SIACON, 2021). It is worth mentioning that the lack of water has caused people to sell or stop using their land; for this reason, castor beans could be an alternative crop to increase the use of rural land.

In recent years, research related to the agriculture of castor beans in Mexico has started to develop (Armendáriz-Velázquez, 2012; SAGARPA, 2015; Isaza *et al.*, 2017; Buendía-Tamariz *et al.*, 2018; Peña-Uribe *et al.*, 2021). However, there are no studies that integrate the social perception for the planning of agricultural land uses in ejidos. This study aimed to adapt the PI developed by the Instituto Nacional de Tecnología Agropecuaria de Argentina (INTAA) to the cultivation of castor beans in the ejido land of Coahuila. We called this new metric the *environmental productivity index* (EPI) and then complemented it by assessing additional cultural components: the willingness of *ejidatarios* to introduce castor bean as a new crop, their perception towards it, and the type and current use of land. We hypothesized that the willingness of the *ejidatarios* to cultivate castor beans is related to their degree of knowledge of the plant and the land available for its cultivation.

Materials and Methods

Study area

The state of Coahuila de Zaragoza is in the northeast of Mexico (Figure 1). With 151,563 km^2, this state ranks third by area in Mexico, falling below Chihuahua and Sonora (INEGI, 2017). Coahuila is officially composed of five Socioeconomic Regions: Carbonífera region, Laguna region, Sureste region, Centro-Desierto region, and Norte region (SEMA, 2016). The predominant climate of Coahuila is arid (49%) and semi-arid (46%), with only 5% being considered sub-humid temperate. The average annual temperature ranges from 18 to 22°C (INEGI, 2017).

Information processing

Biophysical requirements to cultivate castor bean were obtained from the literature and were complemented with data obtained from 12 sites where invasive castor bean was found. To determine the EPI of the ejido lands of Coahuila, edaphic (edaphic-PI), climatic (climatic-PI), topographic (topographic-PI), and social (cultural-PI) properties were used (Equation 1). Values from 0 to 10 were assigned to each of these variables, which were weighted in each component of the productivity indices. These variables were categorised into five land suitability classes: not suitable (0), low (3), medium (5), high (<5 and ≥ 9), and very high (10), according to the FAO method, 1970.

$$EPI = (\text{Edaphic} - \text{PI}) + (\text{Climatic} - \text{PI}) + (\text{Topographic} - \text{PI}) + (\text{Cultural} - \text{PI}) \qquad (1)$$

Edaphic-productivity index

The edaphic-PI (Equation 2) was calculated using the INTAA methodology (Morales-Poclava *et al.*, 2015). The variables that were included in this index are drainage (D), effective depth (ED), surface texture (ST), subsurface texture (SB), pH, electrical conductivity (EC), organic matter (OM), and stoniness (S). These data are available in the historical archive of the national soil inventory of INEGI (2013). The ranges for each variable of the chemical properties and their corresponding index are shown in Table 1. The criteria used to establish the index of each of the variables corresponding to the physical properties used in the IP-Edaphic are presented in Table 2.

$$\text{Edaphic} - \text{PI} = D + ED + ST + SB + pH + EC + OM + S \qquad (2)$$

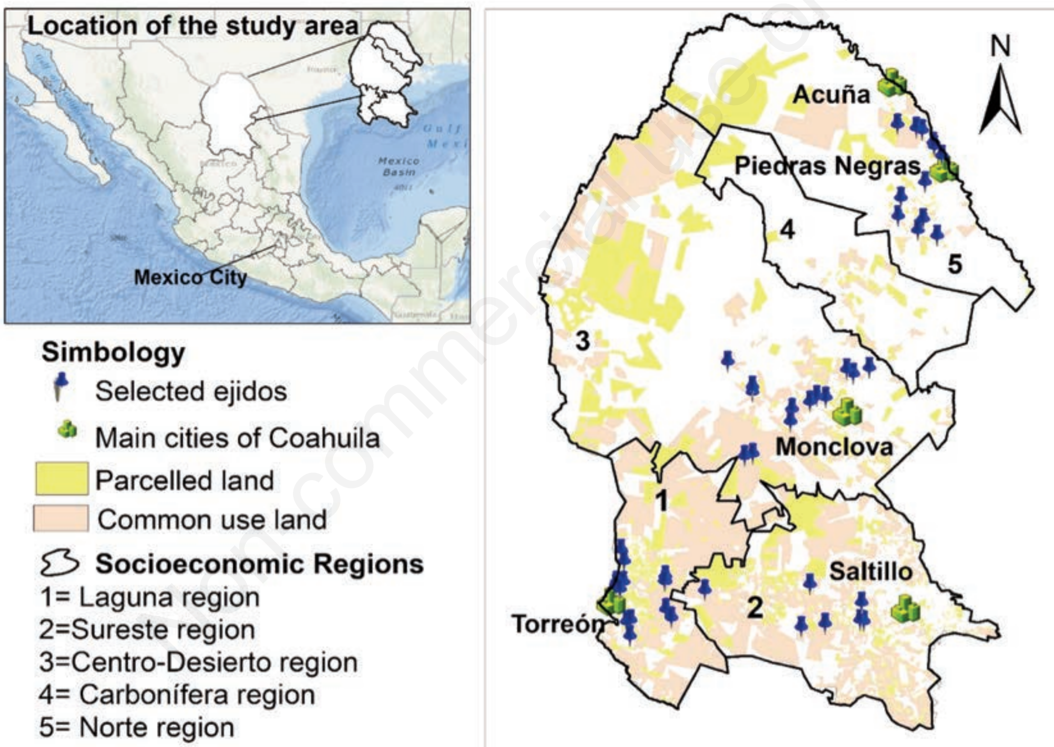

Figure 1. Coahuila State is divided by socioeconomic regions. Main cities, ejido lands of common use and parcels are shown.

Table 1. Chemical properties used to obtain the Edaphic-PI of castor bean cultivation.

Category	Organic matter (%)	Index	pH	Index	EC (dSm^{-1})	Index
Absence	0	0	5.6-6.5	5	0-2	10
Weak	0.2-1	5	6.6 a 7.5	10	2.4	5
Moderate	1-2	7	7.6-8.5	9	4-12	3
Strong	2-4	9	8.5- 9	3	>12	0
Very strong	4.1-5	10	9.1	0		

EC, Electrical conductivity. Sources: Martínez and Montenegro, 2008; Salihu *et al.*, 2014; FAO, 1994; Severino *et al.*, 2012; Carrino *et al.*, 2020.

Topographic-productivity index

The slope and altitude are essential for the agronomic management of castor beans. Altitude influences its development and fruiting; in addition, there is a direct relationship between altitude and oil content in castor bean seeds (Raya-Pérez *et al.*, 2016). We used QGIS software and the PLUGIN SRTM (NASA, 2017) to download the digital elevation model of Coahuila with a resolution of 30 m, to obtain slope and altitude information. Finally, the variables were categorised according to their suitability for the cultivation of castor beans (Table 3).

Climatic-productivity index

Castor beans can grow wild and be grown between 40°N and 40°S (Falasca, 2012). Water is the most important factor for castor bean cultivation. However, its cultivation is not recommended in areas with rainfall over 1500 mm/year because excessive rain stimulates vegetative growth and prolongs fruiting (Salihu *et al.*, 2014). To obtain the climatic-PI, data from the Servicio Meteorológico Nacional were used. A data quality analysis was performed using the Méndez and Magaña (2010) method. Finally, precipitation was classified according to its suitability for castor bean cultivation (Table 4).

Cultural-productivity index

Semi-structured interviews were conducted from February 2018 to June 2019 using the directed sampling method. People who were considered key informants of the ejidos (Ejido Commissioners and people from ejidos dedicated to agriculture or livestock) were selected (Ley Agraria, 2018). The interviews were conducted to gauge the existing knowledge of the *ejidatarios* concerning castor bean cultivation, their current use of the ejido lands, and the differences in land tenure. The influence that their answers may have on their willingness to adopt the castor bean as an alternative crop was analysed using the Kruskal-Wallis test.

Sampling sites

The study area was stratified into the socioeconomic regions of the state of Coahuila (SEMA, 2016). The ejidos to be surveyed were selected according to the following criteria: ejido lands greater than 1000 ha with agricultural use and ejidos close to places where researchers from the project *Potencialidades de la higuerilla como cultivo alternativo en el norte de México para la mitigación y adaptación al cambio climático (Key: 19010-ECI-60)* indicated via GPS that wild castor bean plants were found. The Carbonífera region was ruled out because it has a smaller area of ejido land.

Using the previous criteria, 46 ejidos of Coahuila were selected (5.1% of the total), from which 27 people from the Centro-Desierto region, 20 people from the Norte region, 15 people from the Sureste region, and 27 people from the Laguna region were interviewed. Finally, the results of the surveys were analysed using a descriptive analysis technique with the dynamic table function in Microsoft Excel® (2013).

To verify the influence of the variables collected in the survey on the willingness of the people from ejidos to cultivate castor beans, statistical analyses were conducted. First, data normality was checked with the Kolmogorov-Smirnov test. This test rejected the hypothesis of data normality, so non-parametric Kruskal-Wallis and Mann-Whitney tests were applied (Tables 5 and 6). The analyses were carried out using the statistical software SPSS ver. 25.0 (IBM, Armonk, NY, USA). The level of statistical significance was set to α=0.05. Based on the statistical analysis of the surveys, the Cultural-PI was formulated (Table 7).

Table 2. Physical properties used to obtain the edaphic-productivity index of castor bean cultivation.

Physical properties	Category	Index	Source
Drainage	Zero-drainage	0	Salihu *et al.* (2014); Samayoa (2007)
	Very poorly drained	3	
	Poorly drained	3	
	Moderately drained	5	
	Drained	10	
	Excessively drained	3	
Surface horizon texture and subsurface horizon texturel	Sandy	5	FAO (1994)
	Loamy sand	5	
	Sandy loam	10	
	Loam	10	
	Silt loam	10	
	Silt	5	
	Sandy clay loam	10	
	Clay loam	10	
	Silty clay loam	5	
	Sandy clay	9	
	Clay	5	
	Silty-clay	5	
Stoniness	No stoniness	10	Espinosa *et al.* (2013)
	Slightly stony	9	
	Stony	5	
	Strongly stony	3	
Effective depth	>100 cm	10	Portillo *et al.* (2017)
	75-99	9	
	50-74	7	
	40-49	5	
	<40	0	

Table 3. Slope and altitude ranges used to obtain the topographic-productivity index of castor bean cultivation.

Slope (%)	Category	Altitude (m above sea level)
<2 and >45	Not suitable	>3000
25-45	Low	2500-3000
15-25	Medium	1800-2500
10-15	High	1500-1800
2-10	Very high	0-1500

Sources: Samayoa (2007); González *et al.* (2011); Espinosa *et al.* (2015).

Table 4. Precipitation ranges used to obtain the climatic-productivity index of castor bean cultivation.

Precipitation (mm)	Category
<200	Not suitable
200-350	Low
350-1000	Very high

Sources: Falasca *et al.* (2012); Espinosa *et al.* (2013); Severino *et al.* (2012); Salihu *et al.* (2014).

Table 5. Mann-Whitneys test to analyse the differences between the willingness of the *ejidatarios* of Coahuila, Mexico to cultivate castor beans and the survey results.

Topic- question	Answer	Mann-Whitneys test α=0.05	Probability
Do you know the castor bean?	No	a	0.72
	Yes	a	
Do you use the castor bean?	No	a	1.0
	Yes	a	
Land tenure	Individual parcels and communal land	a	0.013
	Communal land	b	

Table 6. Kruskal-Wallis test to analyse the differences between the willingness of the *ejidatarios* of Coahuila, Mexico, to cultivate castor beans and the survey results.

Topic- question	Answer	Kruskal-Wallis test α=0.05	Probability
Socioeconomic Regions	Sureste-region	a	0.83
	Norte-region	a	
	Centro-Desierto-region	a	
	Laguna-region	a	
Types of agricultural crops	Vegetable crops and fruit crops	a	0.18
	Basic grains	a	
	Basic grains and industrial crops	a	
	Basic grains y fodder crops	a	
	Fodder crops	a	
	Fodder crops and vegetables	a	
	Fruit crops	a	
	Vegetable crops	a	
	Vegetable crops and Industrial Industrial crops	a	
	Industrial crops	a	
	No crops	a	
Destination of the harvested	No crops	a	0.064
	Self-consumption	a	
	Self-consumption and local market	a	
	Local market	a	
	National market	a	
Hectares of crops	No crop (0 ha)	a	0.015
	Few cultivated areas (≤5 ha)	b	
	A lot (>5 ha)	c	

Table 7. Parameters used to obtain the cultural-productivity index of castor bean cultivation.

Land tenure	Category	Index
Parcelled land with land use for agriculture or bare soil	Very high	10
Common-use land with land use for agriculture or bare soil	Medium	5
Forest, scrublands, or urban land	Not suitable	0

Source: Own elaboration with data from RAN (2019).

Preparation of cartography and map algebra

For the preparation of maps, the shapefiles of the ejido lands of the national agrarian registry were first downloaded from Registro Agrario Nacional (RAN, 2019). Then, for the Edaphic-PI and Climatic-PI, the best interpolation method was selected for each one through cross-evaluations in the Geostatistical module of ArcMap from ESRI (Redlands, CA) (Henríquez *et al.*, 2013). For the Edaphic-PI, the optimal interpolation method was the radial basis function with four sectors. The best interpolator for the Climatic-PI was the Empirical Bayesian Kriging method (Esri, 2019). Finally, map algebra and rasterisation were performed using ArcGIS software to obtain the castor bean EPI (Figure 2).

Results

Edaphic-productivity index

Coahuila State has 760,095 ha of ejido land with an edaphic-PI in the very high category and 5,729,839 ha in the high category (Figure 3A). This represents 99% of the total ejido land area. The Norte region had the most extensive area with very high suitability for castor bean cultivation, with 323,302 ha (42% of the region), followed by the Centro-Desierto region with 255,665 ha (10% of the region). On the other hand, 5,854.8 ha had medium suitability, and only 1000 ha were not suitable for cultivating castor beans (800 ha in the Centro-Desierto region and 200 ha in the Sureste region). The latter corresponds to soils with an effective depth of less than 40 cm, pH greater than nine, and zero drainage.

Topographic-productivity index

The topographic-PI identified 4,428,873 ha of ejido land with very high and high suitability values for cultivating castor beans (Figure 3B). Notably, this represents 68.2% of the study area. Centro-Desierto and Laguna regions have larger surfaces in the very high suitability category, with 1,762,893 ha and 837,598 ha, respectively. In addition, castor bean was found at altitudes ranging from 217 to 1571 metres above sea level. On the other hand, 25.64% of the ejido land has medium Topographic-PI values (1,665,876.74 ha). Land in the low suitability category was 265,537.63 ha, and only 2.10% (140,674.13 ha) was not suitable for growing castor beans.

Climatic-productivity index

Regarding the climatic-PI, there are 1,291,635.67 ha of ejido land in the very high suitability category (Figure 3C), representing 19.88% of the study area. On the other hand, 79.93% of ejido land (5,192,810.74 ha) had low suitability, and 0.19% (12,022.93 ha) was unsuitable for growing castor beans because rainfall is below 200 mm per year (conditions under which castor bean can grow but with low productivity). In general, the largest surface with very high suitability for castor cultivation was found in the Norte region and Sureste region, with 440,676.87 ha and 552,683.90 ha, respectively. On the other hand, 99% of the ejido land in the Laguna region is in the low suitability category.

Cultural-productivity index

Ethnobotanical knowledge

Castor bean was known by 96.2% of the people surveyed in the Laguna and Centro-Desierto regions. In the Norte region, 70% of respondents reported some knowledge of castor beans, and 60% in

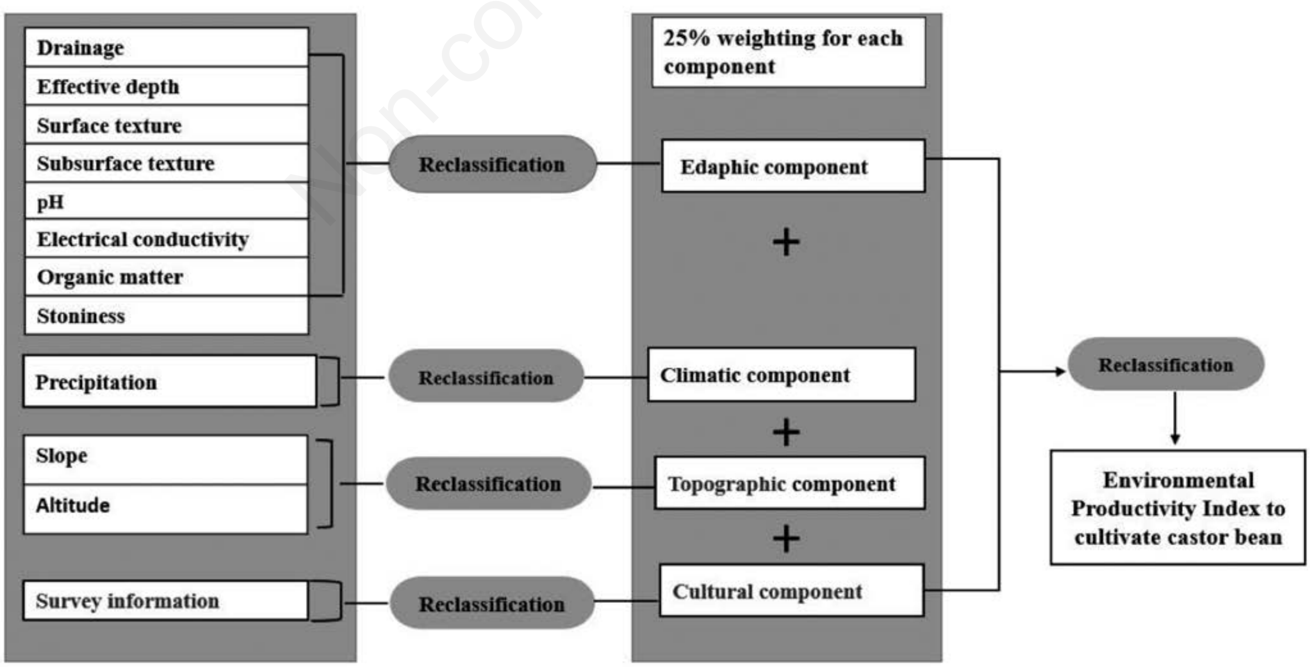

Figure 2. Methodological synthesis to obtain environmental productivity index for cultivating castor beans in Coahuila ejido lands.

the Sureste region. In addition, 61.54% of the connoisseurs of the plant in the Centro-Desierto region reported using the castor bean in some way. In the Norte region, this value was 57.15%, 46.15% in the Laguna region, and only 22.22% in the Sureste region. The most frequent use of castor bean was as a mole repellent; the people from ejidos sow it in the backyard of their houses or the contour of their agricultural lands. As far as veterinary use is concerned, the oil from the seeds is used as a pig dewormer. In addition, castor bean is also used for ornamental purposes (Figure 4).

Main crops in Coahuila ejido lands

The study area has five main groups of crops: fodder, vegetables, industrial crops, fruit trees, and basic grains. The Laguna region has great crop diversity, such as fodder, vegetables, fruit

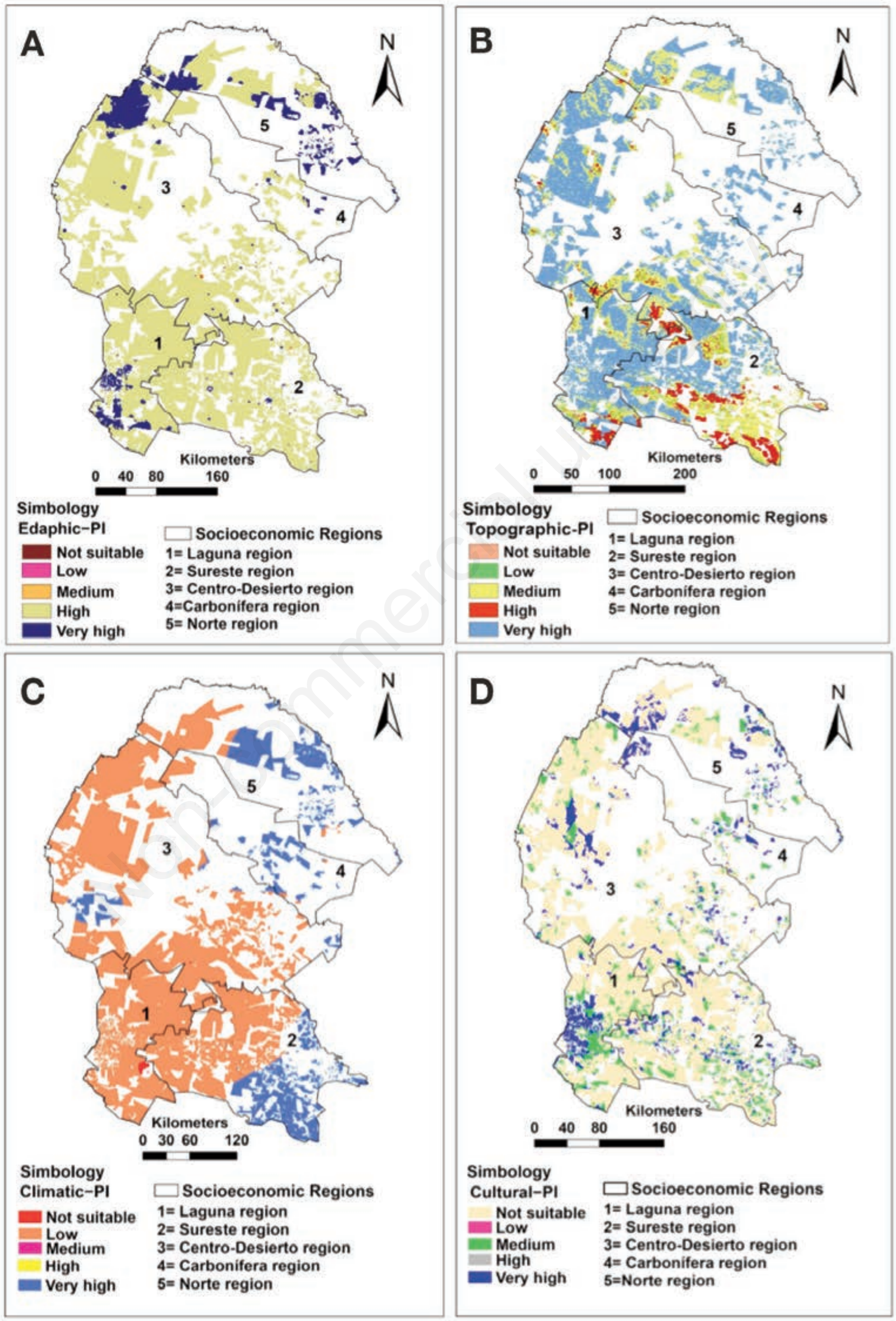

Figure 3. Edaphic productivity index. A) Topographic productivity index; B) Climatic productivity index; C) Cultural productivity index; D) for castor bean cultivation in Coahuila State ejido lands.

trees (date palm and walnut), and industrial crops, such as cotton and broom sorghum (Figure 5). Also, 62% of the ejido members cultivate all of their parcelled lands in the Laguna region. In the Centro-Desierto and Norte regions, 45% of the people surveyed work on their land. In contrast, in the Sureste region, only 16.7% of the people surveyed perform agricultural activities.

The willingness of ejidatarios to cultivate castor bean

Laguna region was the site with the highest percentage of *ejidatarios* with *total willingness* to cultivate castor beans (41%), followed by the Norte region (36.4%). In contrast, the Sureste region exhibited the highest percentage of *ejidatarios* with *low willingness* (63.2%). Evidently, the willingness of the *ejidatarios* to cultivate castor beans was strongly divided throughout the study area (Figure 6). Among the possible causes for a low willingness to adopt the new crop, the *ejidatarios* mentioned the lack of knowledge of the financial profitability and market of castor bean seeds and oil in Mexico, as well as of the agronomic management of the plant.

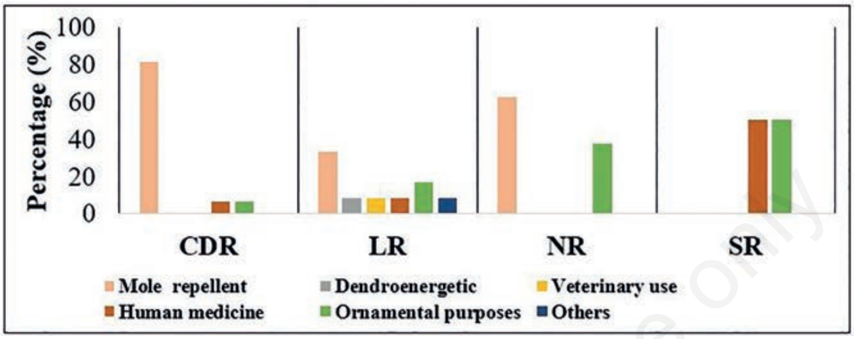

Figure 4. Local uses of castor beans in Coahuila State, Mexico. CDR, Centro-Desierto region; LR, Laguna region; NR, Norte region; SR, Sureste region.

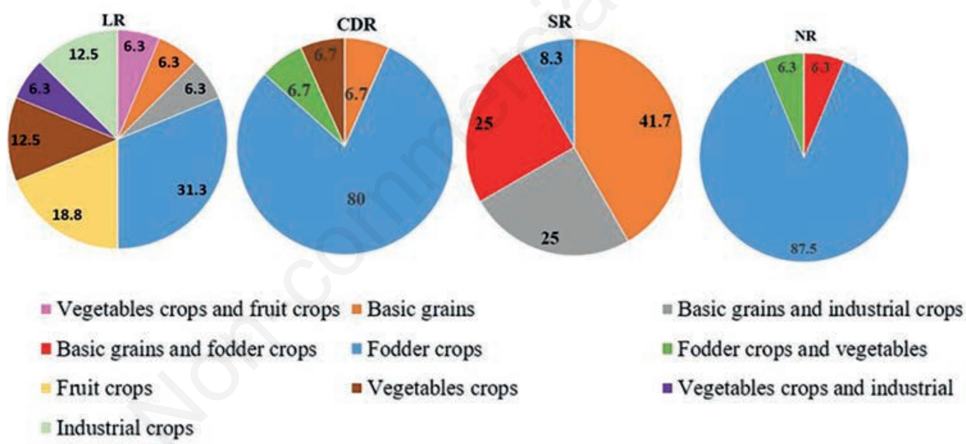

Figure 5. Percentage of the main crops in each region, according to ejidatarios of Coahuila, Mexico. CDR, Centro-Desierto region; LR, Laguna region; NR, Norte region; SR, Sureste region.

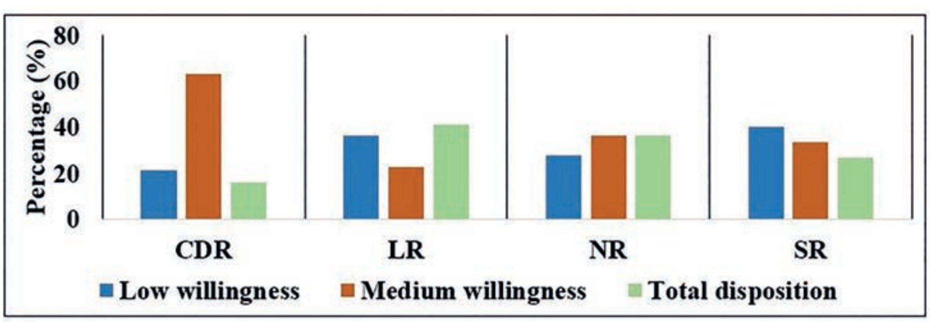

Figure 6. The willingness of *ejidatarios* to cultivate castor beans in different regions. CDR, Centro-Desierto region; LR, Laguna region; NR, Norte region; SR, Sureste region.

Survey analysis for testing the independence between study categories

Communal ejido lands are frequently used for grazing and extraction of forest resources, so agriculture is less represented. Our data show a significant association between land ownership and willingness to cultivate castor beans (P<0.05, Table 5). *Ejidatarios* with parcelled and communal lands are more willing to cultivate castor beans than those who only have communal lands (Table 5). On the other hand, ethnobotanical knowledge (Figure 4) did not significantly influence the willingness to cultivate castor beans (Table 5).

A significant relationship was found between the number of cultivated hectares and the willingness to cultivate castor beans (P<0.05, Table 6). On the other hand, ejido members who do not have crops had a low willingness to cultivate castor beans, relative to those who have 5 ha of crops or less (P<0.05) or those who have 5 ha or more (P<0.05). Although the predominant crop reported by the respondents was forage, no significant differences in the willingness to cultivate castor beans were found between the types of crops already present (P>0.05). Based on these results, the cultural-PI was formulated (Figure 3D). Remarkably, 808,523.74 ha are in the very high category, representing 12.43% of the ejido lands in Coahuila. Interestingly, the Centro-Desierto region has the largest area in this category (202,976.92 ha), although it is not an area of high agricultural productivity. In the medium suitability category, there were 658,774.25 ha (10.13% of the study area); the Sureste region had the largest area in this category (198,986.74 ha). Finally, in the not-suitable category, there were 5,036,352.45 ha of ejido surface, with 42.83% (2,157,361.00 ha) located in the Centro-Desierto region.

Environmental productivity index for castor bean cultivation

The best conditions for sowing castor beans in the ejido lands of Coahuila State (Figure 7) are present in an area of 114,300 ha (1.76%). This land includes parcelled-use lands with soil, topographic, and climatic conditions suitable for maximum castor bean yields. In the category of high environmental suitability, there were 659,100 ha (10.58%) in an area that includes sites with favourable soil and topographic conditions but with rainfall between 200 and 350 mm, which requires additional irrigation to achieve better yields (Table 8).

For castor bean cultivation, there were 688,298 ha with medium values of environmental suitability. This category includes moderately drained soils, with depths less than 100 cm, slightly rocky and alkaline, with an altitude between 1800 and 2500 meters above sea level, and rainfall below 350 mm. In the category of low environmental suitability, 5600 ha of land were found (0.09% of ejido lands). This category includes commonly used lands, coarse-textured soils, are strongly stony, have pH over 8.5, and are located on slopes over 25%. These characteristics would cause low profitability for this crop (Table 8). A total of 5,036,352 ha were classified as not suitable for cultivating castor bean (77.44% of ejido lands, Figure 3B) and included land surfaces classified mainly as *common-use*; these lands were located in areas containing vegetation such as forest and scrub, mainly used for the extraction of forest products, or as grazing land for livestock.

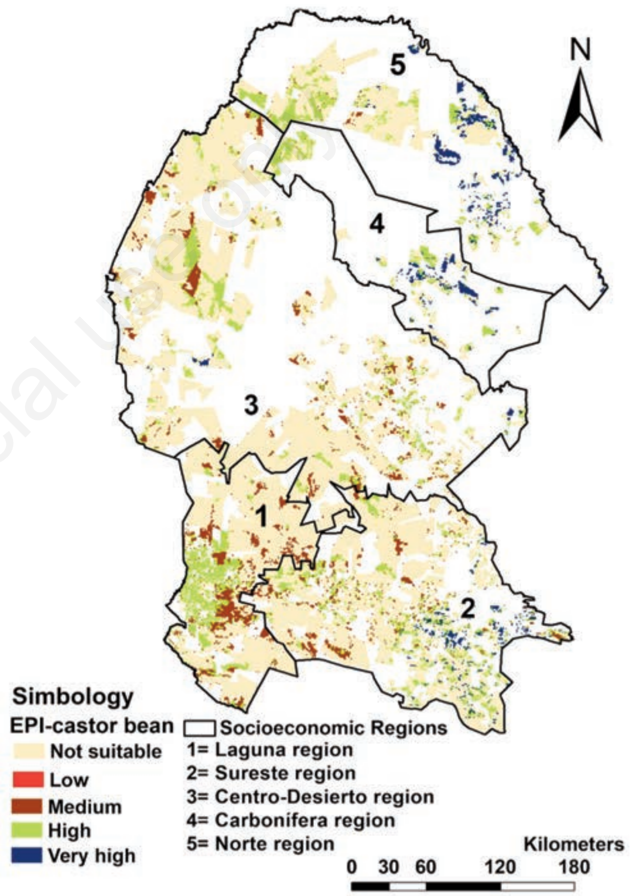

Figure 7. Environmental productivity index for castor bean cultivation in Coahuila State ejido land.

Table 8. Surface area in hectares with environmental productivity index of castor bean cultivation in Coahuila ejido lands.

Category	Norte region	Sureste region	Laguna region	Centro-Desierto region	Carbonífera region
Not suitable	528,896	1,311,021	906,314	2,157,361	132,759
Low	300	500	0	500	4300
Medium	41,497	162,566	200,844	204,529	78,861
High	126,200	168,000	158,100	177,100	29,700
Very high	69,800	38,400	0	6100	0
Total	766,693	1,680,488	1,265,259	2,545,590	245,620

Discussion

This work aimed to examine the potential of castor beans as a crop to be cultivated on unused marginal land within ejido lands. According to the cultural-PI, we found that 808,524 ha (12.4%) of ejido land were very suitable for this crop and that 114,300 ha (1.76%) of ejido lands were very suitable for castor bean cultivation according to the calculated EPI. Initially, we hypothesized that the willingness of the *ejidatarios* to cultivate castor beans was related to their degree of knowledge of the plant and the land available for its cultivation. We found that 75% of people surveyed are familiar with castor beans, and 47% of them report having some use for it. However, their willingness to use castor beans as an alternative crop was not high. The willingness of *ejidatarios* to cultivate castor beans was mostly related to differences in land tenure: *ejidatarios* who own parcelled land were more interested in obtaining benefits from the land through the implementation of novel crops compared to those who only have common-use land. In keeping with our findings, Curry *et al.* (2021) reported that differences in land tenure were an important factor in the adoption of yam (*Dioscorea praehensilis*) cultivation.

We found that the willingness of *ejidatarios* to cultivate castor beans was somewhat limited to parcelled areas, probably because the Agrarian Legislation in Mexico (Ley Agraria) establishes limitations to the introduction of crops in common-use lands of the ejido: new crops must be authorised by the General Assembly of the ejido. The willingness to adopt castor beans is also limited by the current use of land (Morett-Sánchez and Cosío-Ruiz, 2017; Aguirre *et al.*, 2018). In the study area, the main use of scrub is for grazing and extraction of candelilla wax (*Euphorbia antisyphilitica*). According to the edaphic-PI, 99% of the ejido lands of Coahuila are highly or very highly suitable for cultivating castor bean. This is because castor beans can grow favourably in various types of soils, except those that accumulate excess water (Samayoa, 2007; INIFAP, 2012; Salihu *et al*., 2014).

According to the topographic-PI, 68% of the land was highly or very highly suitable for castor bean cultivation. This is because the land in our study area is within the optimal altitude for the growth of castor beans (0 to 1500 m above sea level, Rico-Ponce *et al*., 2011). In addition, Rico-Ponce *et al*. (2011) reported that the oil content of the seed decreases at higher altitudes.

According to the climatic-PI, only 20% of the land was very highly suitable for castor bean cultivation, which means that castor bean crops planted outside highly suitable zones would require irrigation for good productivity.

According to the topographic-PI, only 2.10% of the land was not suitable for castor bean cultivation (land with altitude above 3000 m above sea level and slopes over 45%). Interestingly, regions like the Laguna region were not categorised as suitable for growing castor bean, although in this region, castor bean was found growing wild at many sites. This is probably because the Laguna region is a very productive agricultural area despite the low rainfall (Ramírez-Barraza *et al.*, 2019): in 2016 Laguna region ranked first nationally in the production of melon, forage sorghum, and broom sorghum, was second place in forage corn production, and third place in the production of cotton (González, 2016).

INEGI (2009) reported that in Coahuila, only 34% of parcelled land is used for agriculture, which places it among the states with the lowest agricultural activity (Morett-Sanchez and Cosío-Ruiz, 2017). The challenges to developing successful agricultural activities include the increase in the depth of the phreatic level due to overexploitation, an increase in the costs of extracting water for irrigation, and irregularities in the water market (Ramírez-Barraza *et al.*, 2019). These difficulties are likely reflected in the high percentage of *ejidatarios* in the Laguna region with *total willingness* to cultivate castor beans (41%).

Severino *et al.* (2012) report that the global market demand for castor beans has not been satisfied. Thus, the Mexican government set castor bean seed production goals for 2018, 2024, and 2030 in 10,830, 15,350, and 19,870 tons, respectively. According to the data presented here, using the 114,300 ha of ejido land that was suitable for castor bean cultivation could help meet the objectives of the National Agricultural Planning 2017-2030 for Bioenergetics (SAGARPA, 2017). Instead, officially FAOSTAT (2021) reported that in 2018 and 2019, the area of cultivated castor beans dropped drastically to 102 and 34 hectares, respectively. Although the causes of these decreases are unknown, there is a general lack of knowledge on and market profitability for castor beans in Mexico (Vázquez-Chun, 2020). Thus, knowledge is essential, but few *ejidatarios* know about the more than 500 uses of the castor bean plant. Proper management of social participation will be essential to the successful actions implemented for crop diversification, as has been shown in studies on the management of ecosystem services (Balvanera *et al.*, 2016; Curry *et al.*, 2021).

Assessing the suitability of novel crops should be holistic since local interests are decisive in the success of an agricultural project. However, integrative methodologies that include a social component in crop suitability studies (such as in the present study) are scarce (*e.g.*, Gingold *et al.*, 2012; Gardner *et al.*, 2021). To improve future research, it is recommended to expand sampling coverage. It is also important to improve the link between researchers, the government, and the population, to have a more complete picture and increase the probability of success in crop diversification. In addition, it is also necessary to include workshops for the dissemination of programs for the introduction of new crops where information on the plant and its economic component is provided, such as the profitability of the castor bean in comparison with other crops in the region, cost/benefit, productivity, crop return rate or subsidies for specific crops.

Conclusions

Our integrative method made it possible to identify 114,300 ha of ejido land of high suitability for the cultivation of castor beans in Coahuila, which represents 1.76% of the ejido surface of this region. The climatic and cultural components were the main determining factors for the suitability of castor bean cultivation in the study area. In addition, 79.93% of the ejido land had low suitability for castor beans, implying that additional irrigation would be required to improve crop yields.

The land evaluation tool that we have developed here can be applied to other study areas and other crops (for example, *Glycine max* and *Jatropha curcas*) and modified according to the type of land tenure and social conditions in the area.

According to our data, the use of parcelled land could be increased, contributing to the income of small producers in marginal areas. However, the cultural factor associated with the willingness of the *ejidatarios* to adopt castor bean as an alternative crop is primarily associated with differences in land tenure: *ejidatarios* with parcelled land have greater willingness than those who share land for common use.

References

Adjimoti GO, Kwadzo GTM, 2018. Crop diversification and household food security status: evidence from rural Benin. Agric. Food Secur. 7:82.

Aguirre Villaseñor L, Tobón de Garza G, Mendoza R, 2018. Dinámica de las regiones de Coahuila: entre las fuerzas de la cuarta revolución industrial, el asalto a sus recursos naturales y las luchas por el espacio. In: Hoyos-Castillo G, Serrano-Oswald SE, Cantellano-Mora MP (eds). Ciudad, género, cultura y educación en las regiones. Universidad Nacional Autónoma de México y Asociación Mexicana de Ciencias para el Desarrollo Regional A.C. pp 149-75.

Balvanera P, Arias-González E, Rodríguez-Estrella R, Almeida-Leñero K, Schmitter-Soto JJ, 2016.: Una mirada al conocimiento de los ecosistemas de México. Ciudad de México; México: Universidad Nacional Autónoma de México.

Beraud Macías V, Sosa Ramírez J, Maya Delgado Y, Córdoba M, Ortega Rubio A, 2018. 84 years of Mexico´s land use planning: reflections for biodiversity conservation. Nova Scientia 10:592-629.

Buendía-Tamariz MN, Trejo-Calzada R, Sánchez-Cohen I, Flores-Hernández A, López-Santiago MA, Pedroza-Sandoval A, 2018. Growth analysis of four varieties of Ricinus communis L. in an arid region of México. Interciencia J. 43:457-79.

Carrino L, Visconti D, Fiorentino N, Fagnano M, 2020. Biofuel production with castor bean: a win-win strategy for marginal land. Agron. 10:1-22.

Challenger A, Dirzo R, López-Acosta JC, Mendoza E, Lira-Noriega A, Cruz I, 2009. Factores de cambio y estado de la biodiversidad. Capital natural de México 2:37-73.

Curry GN, Nake S, Koczberski G, Oswald M, Rafflegeau S, Lummani J, Peter E, Nailina R, 2021. Disruptive innovation in agriculture: socio-cultural factors in technology adoption in the developing world. J. Rural Stud. 88:422-31.

de França-Silva FV, da Silva-Mendes B, do Socorro-Rocha M, de Brito-Neto JF, Macêdo-Beltrão N, Sofiatti V, 2015. Photosynthetic pigments and gas exchange in castor bean under conditions of above the optimal temperature and high CO_2. Acta Sci. Agron. 37:331-7.

Esri, 2019. What is EBK regression prediction? Esri. ArcGis Pro. Available from: http://bit.ly/3wa37se.

Falasca S, Uriberich AC, Uriberich E, 2012. Developing an agro-climatic zoning model to determine potential production areas for castor bean (Ricinus communis L.). Ind. Crops Prod. 40:185-91.

FAO, 2003. Evaluación de tierras con metodologías FAO. Proyecto regional “Ordenamiento Territorial Rural sostenible (Proyecto GCP/RLA/139/JPN). Available from: http://bit.ly/3w5fJRt.

FAOSTAT, 2021. Food and agriculture data. Available from: https://www.fao.org/faostat/en/#data/TM. Accessed on: August 2021.

Gardner AS, Gaston KJ, Maclean IMD, 2021 Combining qualitative and quantitative methodology to assess prospects for novel crops in a warming climate. Agric. Sys. 190:1-11.

Gingold B, Rosenbarger A, Muliastra, YIKD, Stolle F, Sudana IM, Manessa MDM, Murdimanto A, Tiangga SB, Madusari CC, Douard P, 2012. How to identify degraded land for sustainable palm oil in Indonesia. Working Paper. Washington D.C: World Resources Institute and Sekala. Available from: http://www.sekala.net/download/Degraded-land-WRI.pdf

González D, 2016. La Laguna destaca en producción agrícola. El Siglo de Torreón. Available from: https://www.elsiglodetorreon.com.mx/noticia/2016/la-laguna-destaca-en-produccion-agricola.html.

Henríquez C, Méndez JC, Masís R, 2013. Interpolación de variables de fertilidad de suelo mediante análisis Kriging y su validación. Agron. Costarricense, 37:71-82.

Hoogesteger J, Rivara F, 2020. The End of the Rural/Urban Divide? Migration, proletarianization, differentiation and peasant production in an ejido, Central Mexico. J. Agrar. Change 21.

Hufnagel J, Reckling M, Ewert F, 2020. Diverse approaches to crop diversification in agricultural research. A review. Agron. Sustain. Dev. 40:1-17.

INEGI, 2013. Conjunto de datos de perfiles de suelos. Escala 1:250 000 Serie II. INEGI. Available from: http://bit.ly/3dohNgQ.

INEGI, 2017. Anuario estadístico y geográfico de Coahuila de Zaragoza 2017. Gobierno del Estado de Coahuila de Zaragoza. Available from: https://www.inegi.org.mx/contenidos/productos/prod_serv/contenidos/espanol/bvinegi/productos/nueva_estruc/anuarios_2017/702825095406.pdf

INIFAP, 2012. Potencial productivo de especies agrícolas de importancia socioeconómica en México. SAGARPA. Available from: https://www.cmdrs.gob.mx/sites/default/files/cmdrs/sesion/2018/09/17/1474/materiales/inifap-estudio.pdf

Kallamadi PR, Nadigatla VPRGR, Mulpuri S, 2015. Molecular diversity in castor (Ricinus communis L.). Ind. Crops Prod. 66:271-81.

Kiran BR, Vara Prasad MN, 2017. Ricinus communis L. (castor bean), a potential multi-purpose environmental crop for improved and integrated phytoremediation. EuroBiotech J. 1:101-16.

Leite JGDB, Justino FB, Silva JV, Florin M, Van Ittersum M, 2015. Socioeconomic and environmental assessment of biodiesel crops on family farming systems in Brazil. Agric. Sys. 133: 22–34.

Ley Agraria, 2018. Cámara de diputados del H. Congreso de la Unión, 2018, 25 de Junio. Ultima Reforma DOF 25-06-2018. Available from: https://www.diputados.gob.mx/LeyesBiblio/ref/lagra/LAgra_ref14_25jun18.pdf

Makate C, Wang R, Makate M, Mango N, 2016. Crop diversification and livelihoods of smallholder farmers in Zimbabwe: adaptive management for environmental change. SpringerPlus 5:1135.

Mazzani E, 2007. El tártago: la planta, su importancia y usos. Rev. Dig. Cent. Nac. Inv. Agropecu. 14:1-9.

McCord PF, Cox M, Schmitt-Harsh M, Evans T, 2015. Crop diversification as a smallholder livelihood strategy within semi-arid agricultural systems near Mount Kenya. Land Use Policy 42:738-50.

Méndez M, Magaña V, 2010. Regional aspects of prolonged meteorological droughts over Mexico and Central America. J. Clim. 23:1175–88.

Morales Poclava C, Sobral, Nakama V, Volante J, Bianchi A, 2015. Evaluación de tierras mediante métodos paramétricos: ajuste del sistema índice de productividad, IP, y su aplicación mediante herramientas SIG para las provincias de Salta y Jujuy. 1 ed. Buenos Aires; Argentina: Ediciones INTA. p. 35.

Morett-Sánchez JC, Cosío-Ruiz C, 2017. Panorama de los ejidos y comunidades agrarias en México. Agric. Soc. Des. 14:125-52.

NASA, 2017. U.S. Releases Enhanced Shuttle Land Elevation Data. SRTM. Available from: https://www2.jpl.nasa.gov/srtm/.

Ogunniyi DS, 2006. Castor oil: a vital industrial raw material. Bioresour. Technol. 97:1086-91.

Patanè C, Cosentino SL, Corinzia S A, Testa G, Sortino O, Scordia D, 2019. Photothermal zoning of castor (Ricinus communis L.) growing season in the semi-arid Mediterranean area. Ind. Crops Prod. 142:2-14.

Peña-Uribe GJ, Valdivia-Martínez O, López-Santos A, Valdez-Cepeda RD, 2021. Morphometry of castor bean seeds from the Durango State's arid zone, Mexico. Seed Sci. Technol. 49:247-60.

Ramírez-Barraza BA, González-Estrada A, Valdivia-Alcalá R, Salas-González JM, García-Salazar JA, 2019. Tarifas eficientes para el agua de uso agrícola en la Comarca Lagunera. Rev. Mexicana Cienc. Agric. 10:539-50.

RAN, 2019. Padrón Histórico de Núcleos Agrarios (PHINA). Available from: http://www.ran.gob.mx/ran/index.php/sistemas-de-consulta/phina.

Raya-Pérez JC, Ramírez-Pimentel JG, Covarrubias-Prieto J, Chablé-Moreno F, Aguirre-Mancilla CL, 2016. Agronomic management of castor bean (Ricinus communis L) [Article in Spanish]. Rev. Int. Inv. Innov. Tec. 4:1-10.

Rico-Ponce HR, Tapia-Vargas LM, Teniente-Oviedo R, González-Ávila A, Hernández-Martínez M, Solís-Bonilla JL, Zamarripa-Colmenero A, 2011. Guía para cultivar higuerilla (Ricinus communis L.) en Michoacán. Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias. Apatzingán, Michoacán, México. Technical Brochure 1. pp. 43.

SAGARPA, 2017. Planeación Agrícola Nacional 2017 – 2030. Secretaría de Agricultura y Desarrollo Rural. Available from: http://bit.ly/ 3qB3cnI.

Salihu BZ, Gana AK, Apuyor BO, 2014. Castor oil plant (Ricinus communis L). Botany, ecology and uses. Int. J. Sci. Res. 5: 1333-40.

Samayoa MO, 2007. Manual técnico del higuerilla. ministerio de agricultura y ganadería. Centro Nacional de Tecnología Agropecuaria y Forestal, CENTA. Programa Agroindustria. El Salvador. p.17.

Sausen TL, Rosa LMG, 2010. Growth and carbon assimilation limitations in Ricinus communis (Euphorbiaceae) under soil water stress conditions. Acta Bot. Bras. 24:648-54.

Secretaria del Medio Ambiente (SEMA), 2016. Available from: https://www.sema.gob.mx/SRN-SIIAECC-DG-UBICACION.php.

Severino LS, Auld DL, Baldanzi M, Cândido MJ, Chen G, Crosby, Tan D, Xiaohua Lakshmamma HP, Lavanya C, Machado OLT, Mielke T, Milani M, Miller TD, Morris JB, Morse SA, Navas AA, Soares DJ, Sofiatti V, Wang ML, Zanotto MD, Zieler H, 2012. A review on the challenges for increased production of castor. Agron. J. 104:853-80.

SIACON, 2021. Sistema de información agroalimentaria de consulta. Servicio de información agroalimentaria y pesquera. Available from: https://www.gob.mx/siap/documentos/siacon-ng-161430. Accessed on: December 15, 2021.

Vázquez-Chun C, 2020. Metodología para determinar aptitud ambiental para la higuerilla considerando el componente cultural del Norte de México. Science Master Thesis. Universidad Autónoma Chapingo. México. 90 p.