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Agroclimatic Conditions for Growing *Sorghum bicolor* L. Moench, under Irrigation Conditions in Mexico

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Abstract

Faced with the possible depletion of fossil fuels and the growing demand for energy; the liquid biofuels are being considered as a renewable energy alternative with low impact on carbon emissions. Sweet sorghum (*Sorghum bicolor* (L) Moench) is a good alternative as it has several advantages in relation to other plant species. Given the interest of the Mexican Government to promote biofuels and *S. bicolor* in particular, this work aimed to spatially delimit the optimal and suboptimal areas to produce this crop in Mexico. The database information considered was the crop agro-ecological requirements for optimal production under irrigation conditions. To process and analyze the information, the QGIS version 3.6 software was used. In high potential areas all variables interact favorably for best crop development and in the suboptimal ones both climatic and edaphological factors interact properly with some limitations; in the unsuitable areas all factors are constraining ones. The study quantified more than 19 million hectares with high optimal conditions under irrigation conditions. The states with the largest areas to produce sweet sorghum are: Veracruz, Campeche, Tamaulipas, Tabasco, Guanajuato, Sonora, Sinaloa, Nuevo Leon, Michoacan, Chihuahua and Quintana Roo; however, should water is provided, practically, it can be grown in all the states of the country.

Subject Areas

Agricultural Engineering

Keywords

Biofuels, Alternative, Sweet Sorghum

1. Introduction

The accelerated growing rate of large cities in the world requires a high energy demand which is mainly provided by fossil fuels, generating environmental pollution. Fuel depletion is being predicted in the future soon.

Therefore, exploring renewable energy from different sources is the focus of current research [1]. Biofuels are an energy alternative as they are considered a renewable energy source [2]. One of these sources is bioethanol, which favors the environment, the economy and society [3]. This biofuel is produced from a wide range of crops, such as corn, wheat, barley, sugar cane, cassava, sweet potatoes, sugar beets, sweet sorghum, among others [4]. And more recently with oleaginous, inedible plants, which do not compete directly with food, such as *Jatropha curcas* [5].

Despite having a wide diversity of potential crops to produce biofuels, sorghum [*Sorghum bicolor* (L.) Moench] is the most widely used crop due to its broad qualities such as: adaptation to worldwide agroclimatic conditions, it requires 36% less nitrogen [6] and water compared to sugar cane and corn, and produces more ethanol per hectare per unit of time [7] [8]. It is tolerant to drought, salinity, high temperatures [9] [10] and flooded soils [11]; it has a short growth cycle and is widely adapted.

Sorghum bicolor, is a C4 photosynthesis grass, which forms four carbon compounds [12], which accumulates large amounts of fermentable sugars in the stem and biomass, has wide adaptability and tolerates adverse production conditions, Furthermore, sowing is feasible in areas not suitable for other crops [6] [13]. Therefore, it can be used for the production of refined sugar, alcohol and gasoline, among others [14]. In Mexico, the federal government promotes the production of biofuels without neglecting food security and the efficient use of the raw material derived from agricultural, forestry and livestock activities; as well as that derived from algae and enzymatic and biotechnological processes [15]. The national 2017-2030 agriculture plan in Mexico, considered three strategic bioenergetic crops such as: castor (*Ricinus communis*) and pinion (*Jatropha curcas* L.) for biodiesel and sweet sorghum (*Sorghum bicolor* L.) for bioethanol [16].

However, sweet sorghum, in the country, does not achieve the desired yield potential since green forage production, in both, spring-summer and fall-winter seasons are 20 and 17 $t \cdot ha^{-1}$ respectively. These are very low yields as compared with new materials evaluated by the National Institute for Forestry, Agriculture and Livestock Research (INIFAP) in the state of Tamaulipas. The Fortuna variety yielded 99.12 $t \cdot ha^{-1}$ of bio-mass (73.5 $t \cdot ha^{-1}$ of stems) in the 2009 spring-summer season whilst in the fall-winter season 2008-2009 the same variety, obtained 127 $t \cdot ha^{-1}$ of biomass (94.7 $t \cdot ha^{-1}$ of stems) under irrigation conditions [17]. Taking into account, the importance of sweet sorghum, as strategic crop, and the interest of the Federal Government to expand the surface with high potential yields; it was considered very important to delimit the best agroclimatic areas for sweet sorghum cultivation.

2. Material and Methods

The study was carried out at the INIFAP Southeast Regional Research Center in the city of Mérida, Yucatán.

2.1. Agro-Ecological Requirements Determination

The distribution of crops in the world depends on climatic conditions. Since sowing, the plants are subjected to asynchronous variations of climate elements. These elements are critical factor which determine the probability of success of a crop cultivation [18] [19] [20] [21].

The crop requirements are normally described by agroclimatic ranges and are usually reported by species and even by genotype. The resulted potential areas will depend on the agroclimatic intervals considered in the diagnosis; if real optimal values are taken in to account, then, consequently, the best yields and economic profitability of the crop will be reflected.

Based on the reviewed information to determine the potential areas for *S. bicolor*, under irrigation conditions; it was considered high potential areas where all variables interact favorably for best crop development whilst in the suboptimal conditions the climatic and edaphological factors interact properly but with some limitations; and finally the unsuitable areas where all factors are constraining ones for crop development. Sorghum requirements were determined by consulting the bibliography, databases and expert knowledge.

The soil type (texture, depth, pH, drainage), average annual temperature, altitudes and slopes, among others (Table 1) were the factors considered to regionalize the different potential production areas.

Table 1. Agro-ecological requirements of *Sorghum bicolor* L. Moench.

Variable	Unit	Optimal	Suboptimal	No suitable
Average annual temperature	˚C	25 - 30	20 - 25 30 - 35	<20 >35
Altitude	*m*	0 - 1000	1000 - 1200	>1200
Soil	*Types*	-Fluvisols -Luvisols -Nitisols -Regosol -Andosols -Phaeozem -Kastanozem	-Cambisols -Gleysoles (Slope > 5%) -Vertisoles (Slope > 5%) -Calcisoles	-Solonchaks -Leptosols -Gleysols (Slope < 5%) -Vertisoles (Slope < 5%) -Arenosols
Soil texture	*Types*	Medium	Light	Heavy
Soil Depth	*m*	<1	1 to 0.5	>50
Soil pH	*Indicator*	6.0 to 7.0	7.1 to 8.0	<5.5 >8.0
Drainage	*Types*	Good 15 to 20% of O_2	Medium 5 to 15% of O_2	Deficient <of 5% of O_2
Photoperiod	*Hours*	1000	800	600

Source: Own elaboration based on consultation of experts and different sources of information.

2.2. Identification of Potential *Sorghum bicolor* (L.) Cultivation Areas

To process and analyze the information, the QGIS version 3.6 software was used [22]. This is a program created by Gary Sherman with the name of Quantum GIS in 2002; it was incubated by OSGeo in 2007 and in 2009 version 1.0 was launched. All QGIS activity takes place within the project which is a collection of associated manageable documents during the session. Projects can contain five types of documents: views, tables, charts, layouts (or printed outputs), and scripts. The corresponding file format is *.qgs.

The project is formed by particular configurations saved in a data frame. The system can also accept: the coordinate reference system, the composition of the layers, the symbology of the layers, the configuration of the system and the network. The QGIS also ensures that the map layers are displayed in the correct coordinate reference system (provided the first settings are correct).

In this work, vector maps *.shp were used in which geoprocesses of cuts, dissolutions, unions and intersections were carried out. Once reclassified, based on crop requirements, the intersection of the variables was computerized in order to generate and de-limit optimal, suboptimal and unsuitable potential areas (Figure 1). Maps were generated through cartographic intersections between polygons, and potential classes were also defined. As a result, the final map, based on the inter-sections, provided in-formation about potential growing areas.

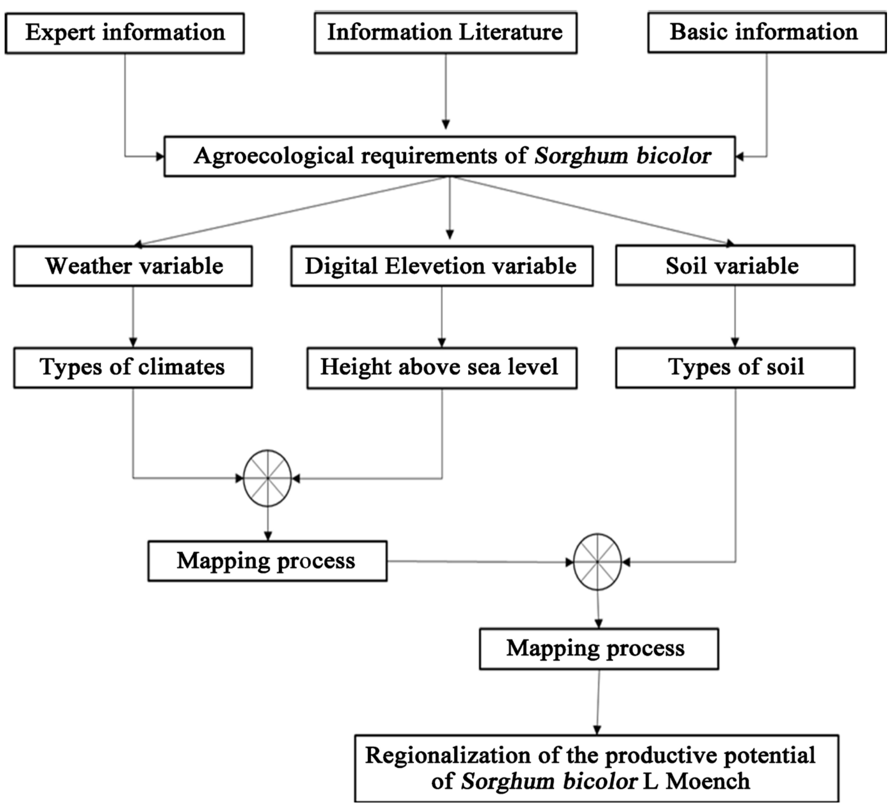

Figure 1. Methodological model used to determine the production potential.

3. Results and Discussion

3.1. Temperature

Sweet sorghum can be cultivated in large parts of the Mexican Republic; however, there is a great affinity for the coasts, especially in the Gulf of Mexico (**Figure 2**). This plant develops well in warm climate conditions, with moderate and well distributed rains according to Pérez, 2010 [23]; the ideal temperature should be above 18˚C in order to germinate and grow properly [24].

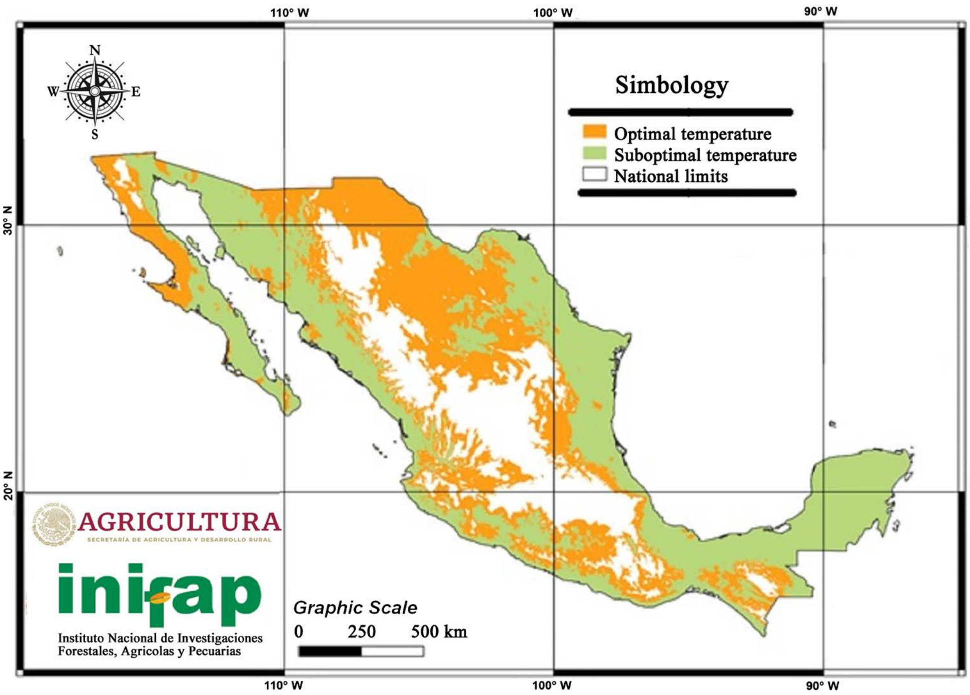

Figure 2. Optimal and suboptimal temperatures for sweet sorghum in Mexico.

The optimal growth temperature is from 26.7˚C to 29.4˚C. Temperatures above 38˚C are harmful, despite the fact that this plant tolerates heat and drought better than corn [25]. Other authors such as Acuña *et al.*, (2002) [26], suggest good temperatures for sweet corn of 24˚C to 30˚C. During the germination phase, it needs temperatures of 12˚C to 13˚C, therefore, temperatures below these are considered unsuitable; growth is activated above 15˚C, with the optimum around 32˚C [27]. When temperature decreases, during flowering, grain yield can be reduced; sterility of the spikelets and pollen grain viability is also affected [28]. On the other hand, very high temperatures (greater than 38˚C), after flowering, reduce the final weight of the grain and cause abortion of flowers [23]. By instance, it has been suggested that 27˚C, is the optimal temperature; being 21˚C the minimum temperature for good growth [29].

3.2. Irrigation Requirements

At the national level, sorghum is produced under both irrigation and rainfed conditions. During the 2012-2016 period, 35.5% of the total sorghum area was harvested under irrigation conditions, producing 47.3% of the total production with an average yield of 4.9 $Mg \cdot ha^{-1}$, while 64.5% of the total surface harvested was cultivated under rainfed conditions producing 52.7% of the total production with an average yield of 3 $Mg \cdot ha^{-1}$ [30].

Sweet sorghum adapts to different humidity conditions, so rainwater is sufficient to complete its vegetative cycle, especially in the sub-humid tropics [31], where rainfall ranged between 700 and 1600 mm per year. However, additional water by irrigation is needed in areas where the rainfall distribution is erratic and less than 700 mm per year. Provided water is important especially in the emergency stages, vegetative development, stem and spikelet formation according to studies carried out by INIFAP, in the Experimental Field Station of Valle de Mexicali [32]. When necessary it is recommended to apply 10 cm of water before sowing. Two supply irrigations should be added, with 20 cm each; the first at 40 days after sowing and the second at 65 - 70 days after planting [17] [33].

3.3. Elevation

Due to its high temperature requirements, sweet sorghum is rarely cultivated beyond 1800 m high; however, in the African continent it is cultivated between 400 m and 2500 m altitude [34]. In the American continent, it adapts to an altitude ranging between 20 and 850 meters above sea level [35] considered as optimal for its development. It has been suggested that this plant can grow from 0 to 1500 meters above sea level [23]. It is common to find good areas close to water bodies, with low elevation, and favorable warm and humid climate. In Mexico, the optimal and suboptimal altitude for sweet sorghum is shown in **Figure 3**.

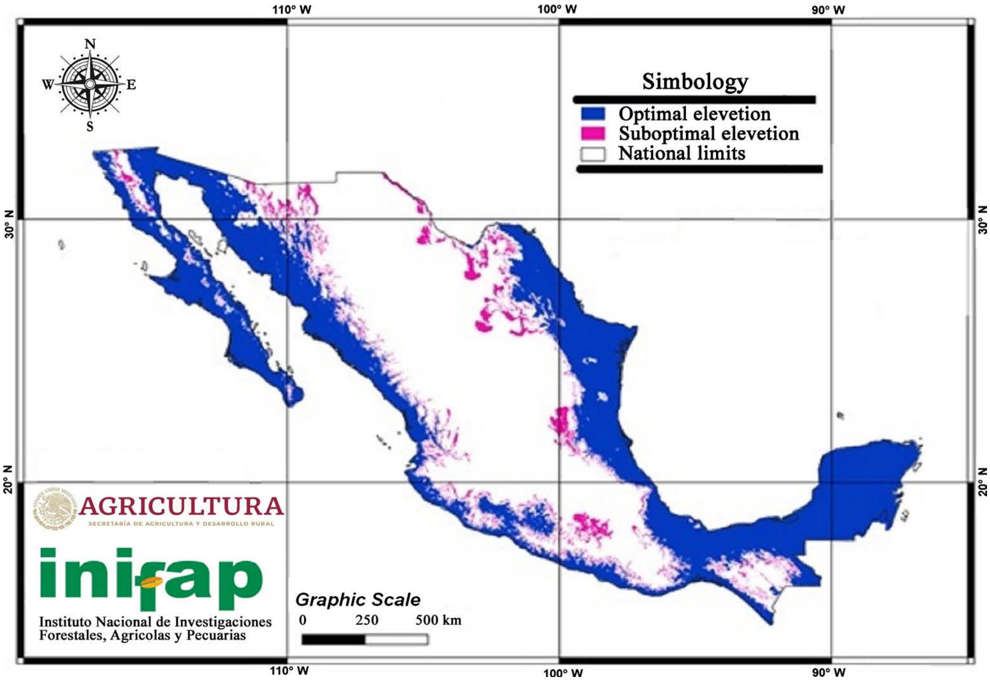

Figure 3. Optimal and suboptimal elevations for sweet sorghum in Mexico.

3.4. Soils

The best soils for *Sorghum bicolor* (L.) are those of high fertility, sandy, loamy or clayey texture [23] [35]. Sweet sorghum prefers deep soils, without excess salts, with good drainage, without hardened layers. It is moderately tolerant to soils with some salinity and/or alkalinity. According to studies the presence of calcium carbonate in the soil increases the content of sucrose in the stem and leaves [36] [37] [38] [39]. It grows better, under salinity conditions, than other crops such as wheat, soybeans and corn.

The soils must have good drainage, since excessive humidity affects the normal development of the plants. The edaphic requirements of the crop [25] [35] [40] are classified as: Fluvisols, Regosols, Luvisols, Nitisols, Andosols, Phaeozam and Kastañozem among others. These soils have a depth greater than 50 cm, with good moisture retention and very porous. In Mexico, the distribution of optimal and suboptimal soils is being shown in **Figure 4**.

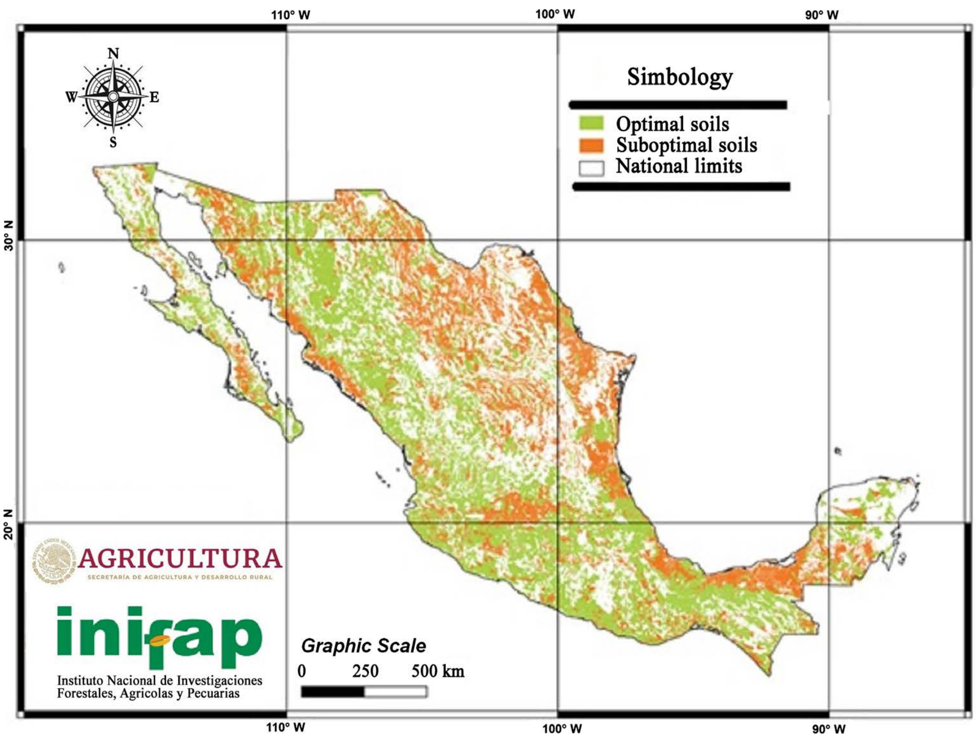

Figure 4. Optimal and suboptimal soils for growing sweet sorghum in Mexico.

3.5. Slope

It is considered that 0 to 16% is the optimal slope range for good crop development [41], and 16% to 20% as a sub-optimum one. Naidu *et al.*, (2006) [42] assures that soil inclination should be less than 16% when the purpose is to produce the greatest amount of biomass for sugar production. Mexico is a country characterized by having a significant surface area with slopes between 0 and 16%; while in contrast, slopes of 16% - 20% are mainly found in the mountain ranges of the country (**Figure 5**).

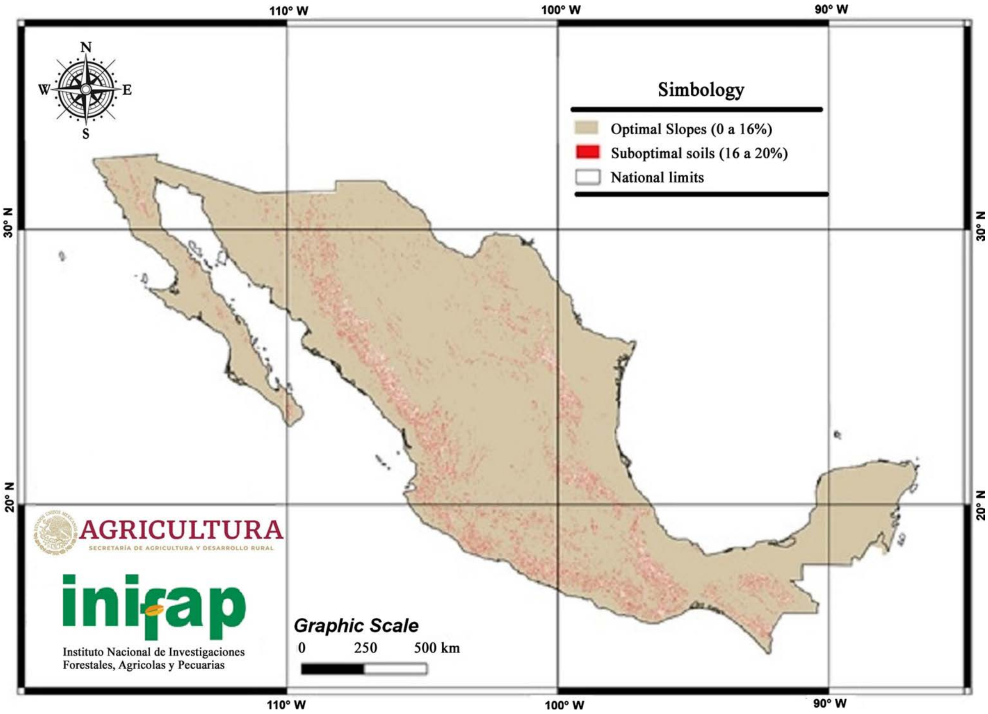

Figure 5. Optimal and suboptimal slopes for growing sweet sorghum in Mexico.

3.6. pH

Sweet sorghum grows well in soils with pH ranging between 5.5 and 8.5; however, the ideal pH is between 5.5 and 6.5 [23] [43]. It supports salt and it is suggested that sugary varieties require the presence of calcium carbonate in the soil, which increases the sucrose content of the stems and leaves [23].

3.7. Photoperiod

The environment plays an important role in sugar production [44]. Reports indicate that sweet sorghum is very efficient to produce sugar in warm environments [45] [46] with high light intensity [45]. However, it is considered a short day crop (<12 hours), although there are neutral day cultivars [47]. Panicle formation and flowering accelerates in short days while delaying in long days [48].

3.8. Potential Cultivation Zones for Sweet Sorghum under Irrigation

Sorghum bicolor L. Moench is one of the oldest crops and currently one of the most important cereals in the world [49]. It grows well in all continents, in tropical, subtropical and temperate regions; in lands of medium and low agricultural aptitude, and especially suitable for regions with little precipitation [50]. Sorghum can be cultivated in large parts of the Mexican Republic; however, the best region is located in the coasts, especially in the Gulf of Mexico, where soils such as Cambisol and Vertisol type are the most common. On the other hand, it is suggested that Tamaulipas and Guanajuato are the best states (**Figure 6**, **Table 2**) where sorghum can be produced with better yields under irrigation; a practice that is currently carried out intensively.

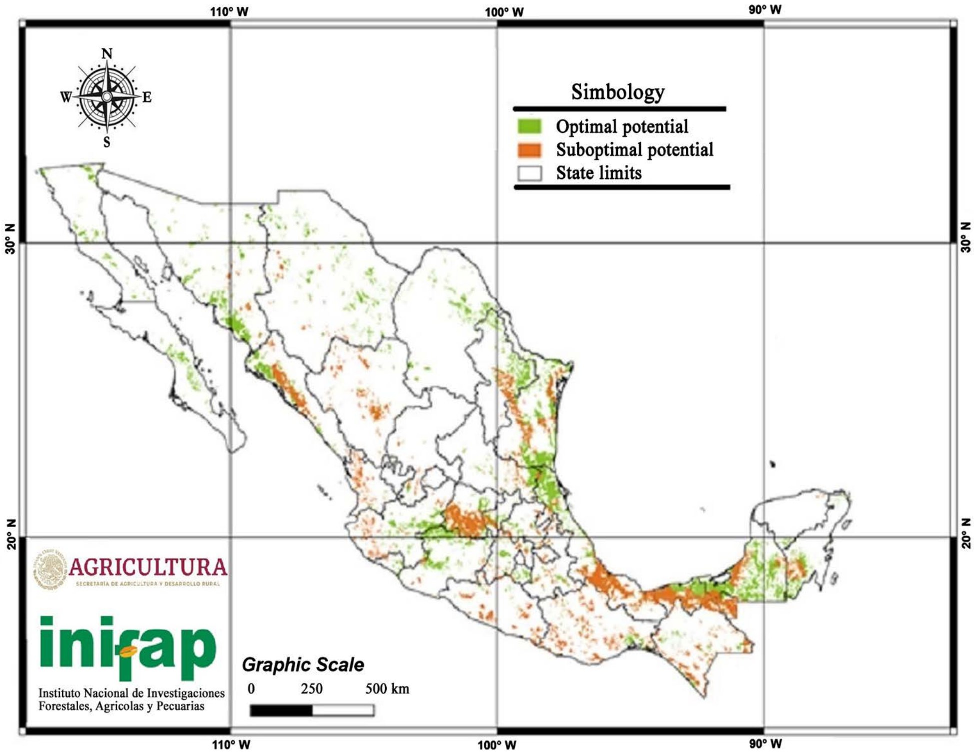

Figure 6. Optimal and suboptimal areas where sweet sorghum can be grown under irrigation conditions in Mexico.

Table 2. Potential areas for growing *Sorghum bicolor* L. Moench. under irrigation in Mexico.

State	Optimal areas (ha)	Suboptimal areas (ha)	Total (ha)
Baja California	358,510	0	358,510
Baja California Sur	259,440	0	259,440
Campeche	2,189,687	673,483	2,863,170
Chiapas	515,826	934,821	1,450,647
Chihuahua	783,518	164,450	947,968
Coahuila	468,205	0	468,205
Colima	47,767	14,510	62,277
Ciudad de Mexico	985	2130	3115
Durango	254,036	508,892	762,928
Guanajuato	1,211,451	1,030,421	2,241,872
Guerrero	79,529	512,416	591,945
Hidalgo	192,174	192,641	384,815
Jalisco	596,650	392,350	989,000
Estado de Mexico	228,639	197,753	426,392

Continued

Michoacan	935,902	241,645	1,177,547
Morelos	103,467	16,442	119,909
Nayarit	36,852	304,429	341,281
Nuevo Leon	956,575	318,339	1274,914
Oaxaca	346,328	1,174,983	521,312
Puebla	191,160	202,616	393,776
Queretaro	252,719	173,523	426,242
Quintana Roo	622,307	268,560	890,867
San Luis Potosi	478,354	188,817	667,171
Sinaloa	1,000,633	677,399	1,678,032
Sonora	1,108,679	123,608	1,232,287
Tabasco	1,587,146	1,531,283	3,118,429
Tamaulipas	1,994,243	848,451	2,842,694
Tlaxcala	3572	49,483	53,055
Veracruz	2,250,587	1,555,576	3,806,163
Yucatan	55,446	10,200	65,646
Zacatecas	70,968	86,844	157,812
TOTAL	**19,211,355**	**12,396,065**	**31,607,420**

4. Conclusion

There are optimal agro-ecological conditions to produce sweet sorghum under irrigation conditions in order to improve its productivity in the Mexican Republic. The states with the largest areas to produce sweet sorghum are: Veracruz, Campeche, Tamaulipas, Tabasco, Guanajuato, Sonora, Sinaloa, Nuevo Leon, Michoacan, Chihuahua and Quintana Roo; however, practically it can be grown in all the states of the country if water is provided. The high optimal potential areas, found in this work, far exceed the current surface planted. The study quantified more than 19 million hectares with high optimal conditions when irrigation is supplied.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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