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Agroecological Zoning for Hemp (*Cannabis sativa sativa* L.) in Mexico: A Geospatial Approach

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Abstract

Hemp was introduced to Mexico by the Spanish and reached its peak in the 18th century, when it was cultivated alongside other fibers such as flax and cotton. In recent years, interest in hemp (*Cannabis sativa sativa* L.) has resurged in Mexico, likely due to its potential uses in various industries. Therefore, the objective of this study was to delimit the most suitable areas for rainfed hemp in the Mexican territory using the agroecological zoning method. To achieve this, a literature review was conducted to identify the soil and climatic requirements for hemp. Using geographic information system tools, an agroecological zoning analysis was performed to identify suitable, unsuitable, and moderately suitable areas for growing hemp. Subsequently, a site where the species is cultivated was visited to gather insights from local producers. The results indicate that 5 % of the national territory shows edaphoclimatic suitability for hemp; 17 % of the country is classified as having moderate suitability with certain limitations, while the remaining 78 % is unsuitable. The states of Chiapas, Tabasco, Oaxaca, Veracruz, and Hidalgo have the largest areas suitable for rainfed conditions. Climatic factors were identified as the primary limitation for hemp under rainfed conditions in Mexico. Producers highlighted the potential for growing hemp in their regions and across the country. The research concludes by pointing out the regions that are suitable for the growth of the crop. There is natural potential for growing hemp in the country, however, it is necessary to develop a regulatory framework that differentiates this crop from psychoactive Cannabis.

Keywords: Suitability, feasibility, conversion, edaphoclimatic requirements.

Introduction

Hemp (*Cannabis sativa sativa* L.) is a versatile plant with industrial and medicinal uses. Its origins date back to around 8000 B.C. in Asia, where evidence of hemp use for textiles has been found (Lozano, 2017). Additionally, traces of its use have been discovered in Egypt around 4000 B.C., where it was employed as an alternative to papyrus for making paper and textiles (Muriel-Páez & Pullas, 2022). Hemp has been a subject of controversy, as marijuana is derived from the same plant genus but a different subspecies. Legally, marijuana is defined as a *Cannabis* subspecies with a tetrahydrocannabinol (THC) content greater than 1 %, whereas hemp refers to a *Cannabis* subspecies with less than 1 % THC.

Some distinctions between hemp and marijuana can be identified, but the most significant is that the former refers to the plant's stem, while the latter refers to the fruit containing psychoactive compounds used as a drug. It is important to note that the term *cannabis* is used in botanical, therapeutic, medical, and classical contexts. The term *hemp* is reserved for industrial and environmental uses, while *marijuana* is used in recreational contexts (Díaz-Rojo,

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2004). Since hemp refers to the stem of *C. sativa sativa*, it lacks psychoactive properties and is not classified as a drug (Huarcaya-Minauro & Escobar-Cruz, 2022). The THC content determines the psychoactive effects of marijuana. Hemp contains significantly low levels of THC, and it is legal if the THC content does not exceed 0.3 % in the United States and Canada or 1 % under Latin American regulations by weight.

A total of three subspecies have been identified: *Cannabis sativa sativa*, *Cannabis sativa indica*, and *Cannabis sativa ruderalis* (Laursen, 2015). All of these have been subject to crosses and polyhybrids, each with botanical characteristics, growing conditions, and specific uses (Sandiego-Villaverde, 2020). The subspecies *C. sativa indica* is cultivated for its psychoactive content due to its high THC concentration. It is used for recreational and medicinal purposes. On the other hand, the subspecies *C. sativa sativa* is known as industrial or agricultural hemp, as it can be used in the paper, textile, construction material industries (such as bioplastics and particle boards), and food production (Díaz-Rojo, 2004). The seeds, known as hemp seeds, are rich in proteins and fats, with therapeutic properties.

Hemp is categorized as one of the most interesting crops. In the textile industry, hemp is an alternative to cotton, offering superior quality, being up to ten times more resistant than cotton fibers (Muriel-Páez & Pullas, 2022). It is used to make awnings, tarps, and hemp bricks (Arroyave-Zapata & Soto-Lorza, 2016). In the paper industry, hemp shows resistance and durability similar to traditional wood-derived paper, and it maintains its color for many years. Hemp crop also produces cellulose annually, and it has been suggested that one hectare of hemp can generate four to five times more paper than one hectare of forest (Hernández & Munguía, 2022).

Hemp also has potential applications in sustainable construction. It can be used to produce hempcrete, an eco-friendly material that offers benefits such as being pesticide-free, providing protection against various forms of radiation, and reducing electromagnetic fields (Brümmer, 2015). Hemp is also an efficient source of biofuels, including both bioethanol and biodiesel (Toro-Santos & Huertas-Cárdenas, 2021). In agriculture, hemp stands out for its role in phytoremediation, a technique for cleaning contaminated land. Its short growth cycle of approximately 100 days makes it a more sustainable option compared to other plants used in phytoremediation (Trejo, 2017).

In Mexico, hemp was introduced by the Spanish in the 16th century and reached its peak in the 18th century when it was sown together with other fibers such as flax and cotton. By the 19th century, production declined, and by the early 20th century, hemp was subjected to the same prohibition as marijuana (Florescano, 1995). In 1920, the use of industrial hemp was banned in the country (Astorga, 2005).

In recent years, there has been a renewed interest in hemp, likely due to global trends and its previously mentioned potential uses. In 2017, a reform to the General Health Law was approved in Mexico, allowing the medicinal and scientific use of *Cannabis*, including hemp with low THC content (DOF, 2017). More recently, in 2021, a law was passed to regulate the industrial use of hemp, aiming to provide a regulatory framework for this crop, sowing, production, and commercialization (Cámara de Diputados, 2021). Consequently, identifying regions with potential for hemp has become increasingly relevant, and the agroecological zoning method has proven to be appropriate for this purpose.

Agroecological zones are described as areas with similar classifications based on climatic properties, soil characteristics, and agroecological performance, reflecting the specific scale of limitations and potential for land management (Benacchio, 1984; FAO, 1997). According to this principle, agroecological zoning is defined as the cartographic delineation of the natural suitability of land for a specific crop, based on the agroclimatic and soil-physical characteristics of each area and the requirements of the crop under specific environmental conditions (Antoine, 1994; FAO, 1997).

Thus, recognizing the potential of hemp, this study aimed to perform an agroecological zoning analysis for hemp in Mexico, identifying the biophysical parameters required by the plant under open field and rainfed conditions to identify suitable geographic areas, thus contributing to the potential development of a robust and sustainable hemp industry in the country. The hypothesis is that Mexico has potential agroclimatic suitability for growing hemp under rainfed conditions.

Methodology

The study comprised four stages: identifying crop requirements, cartographic data processing, agroecological zoning, and field verification. It is important to emphasize that the work focused on *C. sativa sativa* L., aiming to assess its potential edaphoclimatic suitability, commonly referred to in the country as rainfed conditions.

The stages are outlined as follows:

Crop Requirements. The edaphoclimatic requirements that determine the establishment and growth of hemp were obtained through a literature review. Sources consulted included, preferably, scientific articles and online references such as popular science journals. The keywords defined for the search were: hemp, hemp zoning, hemp requirements, *C. sativa sativa*, and hemp crop requirements. The bibliographic references provided edaphoclimatic parameters, which were organized and classified into suitability levels for the crop.

A table was developed to outline the soil and climate requirements for each phenological stage of *C. sativa sativa*. Instead of focusing on specific varieties, the general needs of the species were considered. The requirements were classified into three levels of suitability: unsuitable, moderately suitable, and suitable. Furthermore, maps were created for each variable to pinpoint the main production constraints, which included soil factors (texture, pH, depth, and salinity) and climatic factors (minimum and average temperature, precipitation, or climatic formula). This follows FAO's recommendation (1997) for agroecological zoning studies.

Cartographic inputs. The study adopted a national continuous scale of 1:1,000,000. The primary cartographic inputs at this scale included maps of average annual temperature and total average annual precipitation (Monterroso & Gómez, 2021). At a 1:250,000 scale, soil classes (INEGI, 2006) were incorporated, along with data on soil depth, texture, pH, and salinity from INEGI (2004), which had been previously spatialized. The Köppen-modified climate types were derived from García (2004) at a 1:1,000,000 scale. All cartographic data were processed in vector format and managed using ArcGIS 10.8 (Esri, 2020).

Agroecological Zoning. Based on the crop requirements, suitability maps were initially generated for each variable. This process evaluates individual edaphoclimatic characteristics and identifies production constraints (FAO, 1997). The procedure involved assigning suitability levels to each layer of soil variables (texture, pH, depth, and salinity) and climate variables (minimum and average temperature, precipitation, and climatic formula), as detailed in Table 1. Subsequently, in the GIS software, the maps were merged to obtain a single suitability map for *C. sativa sativa* in Mexico. In this way, the most suitable areas for this crop were delimited, but also those with limitations for its production. It should be noted that the criterion followed was that of growing under rainfed or non-irrigated conditions.

Field verification. Given the inability to conduct verification across the entire country, a visit was made to explore an existing hemp crop and utilization experience in Mexico. The community of Santa Martha Chichihualtepec, Oaxaca, was chosen as it is home to one of the pioneering organizations in the growing and promotion of *C. sativa sativa* in Mexico. This community was selected because preliminary results indicated favorable suitability for hemp crops in the region, along with prior knowledge of the organization's work. In this area, *C. sativa sativa* is experiencing growth due to the favorable combination of climate and soil conditions, as well as community support for the crop.

The field verification focused on assessing the edaphoclimatic requirements and understanding the local producers' perceptions regarding hemp crops. The conditions of the land and climate were verified by comparing them with the previously identified requirements. Direct observations of soil and climate characteristics were made. To gather the producers' perspectives, open-ended interviews were conducted with local farmers. A total of 16 interviews were carried out using snowball sampling, which involves starting with one producer and subsequently reaching out to others based on the recommendations of the first. The interview questions included: What are the main growing requirements you can identify? What is the motivation behind the decision to grow this plant? What are the main experiences and challenges faced during the growing cycle? And what are the economic impacts and benefits derived from hemp production?

Results and Discussion

Crop requirements

Table 1 shows the edaphoclimatic requirements for *C. sativa sativa*. It is observed that the crop thrives best when temperatures range between 20 and 25 °C, with annual total rainfall between 800 and 1,200 mm. These data indicate that the climates preferred by *C. sativa sativa* included those that are humid temperate, with climate classifications Cf, Cw, and Cb according to the Köppen classification (García, 2004). Cf climates are humid temperate, with rainfall throughout the year and well-defined seasons. Cw climates are temperate subhumid, with a rainy summer and dry winter. Cb climates are also temperate, characterized by moderate or drier summers. Crops under rainfed conditions prosper in humid temperate, moderate temperate, and dry temperate climates, although with certain limitations.

The previous criteria allowed the identification of areas with varying degrees of suitability for growing *C. sativa sativa* based on each variable.

Suitability for Hemp in Mexico

Figure 1 shows the suitability maps for each edaphoclimatic variable. The regions classified as suitable in each map represent areas with the best conditions for this crop. There are few or minimal limitations according to that variable, making it easier to identify the ecological potential for assessment (Espinosa & Roquera, 2007). On the other hand, regions with moderately suitable conditions are areas facing significant challenges or limitations to produce *C. sativa sativa*.

The analysis indicates that the soil in the study area shows moderate to suitable conditions for growing hemp. Regarding soil texture, 69 % of the area was classified as

Table 1. Edaphoclimatic requirements for *C. sativa sativa* and suitability level.

Type	Variable	Unit	Suitability level			Reference
			Not Suitable	Moderately Suitable	Suitable	
Soil	Soil depth	cm	Less than 30	from 30 to 50	Greater than 50	Acosta, 2001; LABISER, 2021
	Texture	Dimensionless	Clayey		Sandy and silty	Acosta, 2001, 2003; LABISER, 2021
	pH	Dimensionless	below 5.5 and greater than 8	from 5.6 to 6 and from 7.5 to 8	From 6 to 7.5	Acosta, 2003; LABISER, 2021; Duke, 1982.
	Salinity	Phase	Saline phase			Acosta, 2001, 2003; Werf et al., 1999.
Climate	Sunlight exposure	Hours	Less than 8 and More than 13	From 8 to 9 and From 12 to 13	from 9 to 12	Werf et al., 1999; Struik, 2000; Lisson, 2000.
	Average annual temperature	°C	Less than 15 and More than 25	From 15 to 18 and From 20 to 25	from 18 to 20	Haberlandt, 1879; Duke, 1982; LABISER, 2021
	Minimum annual temperature	°C	Less than 13	From 13 to 15	More than 15	Duke, 1982; Frank 1988.
	Average annual precipitation	mm	Menor de 500 y Mayor de 1500	From 500 to 800 and From 1200 to 1500	From 800 to 1200	Duke, 1982; Ranalli, 2004.
	Köppen climate type	Type	Arid and cold	Warm and dry	Humid temperate	Werf et al., 1999; Acosta, 2003
	Köppen climate formula	Dimensionless	E	Am, Aw, Ax Bs, B	Cf, Cw, Cb, Ca,	Werf et al., 1999

suitable, while 35 % of the land was deemed suitable based on soil pH. For soil depth and salinity, approximately 59 % and 92 % of the national surface, respectively, showed some level of suitability. These findings are similar to that found by Bart (2017), who reported that loose soil is essential for adequate water drainage, benefiting hemp growth. High soil salinity levels can adversely affect the plant's development. In soils with high clay content, the root system can become waterlogged, leading to flooding conditions. The soil's pH is a critical factor; if it is too high or too low, plants may struggle to absorb essential nutrients, leading to deficiencies that inhibit growth. An optimal pH range for growing hemp is between 6.0 and 7.5, as it allows the plants to effectively extract nutrients from the soil (Bart 2017). Historically, the importance of deep, well-fertilized soils with consistent moisture levels was emphasized as essential for successful hemp growing (Alexander, 2016).

Climatic variables were identified as the primary constraints for growing *C. sativa sativa* in Mexico. Figure 1 shows the suitability of each variable for this crop. Notably, red zones, representing unsuitable areas predominate for three out of the four variables analyzed: temperature, precipitation, and climate type. This indicates that these regions face significant climatic limitations for this crop. Specifically, 68 % and 12 % of the country were found to be unsuitable based on minimum and average temperatures, respectively. Precipitation, the most significant limiting factor, rendered 89 % of the country unsuitable due to insufficient rainfall and humidity. These findings are consistent with those of Bart (2017), who emphasized that climate is one of the key factors affecting crop development. The same study found that for open field crops it is essential to control temperatures and sun exposure.

The most favorable climate for growing hemp is a temperate humid environment, with average temperatures between 20 °C and 25 °C and high relative humidity. During the day, the plant thrives at temperatures ranging from 20 °C to 25 °C, while at night, it tolerates between 13 °C and 15 °C. Deviations from these ranges can lead to biotic stress, reducing crop yield. Hemp is particularly sensitive to low temperatures and late frosts, especially during its early development stages. Sowing should not begin until average temperatures exceed 12 °C. Although the plant can survive in an extreme range of temperatures, from 2 to 45 °C.

Figure 2 presents detailed agroclimatic suitability maps for *C. sativa sativa* in Mexico. In the characterization shown in Figure 2a, the primary constraints for hemp production are highlighted. In other words, it emphasizes the moderately suitable zones, identifying the climatic or soil inputs required by the crop.

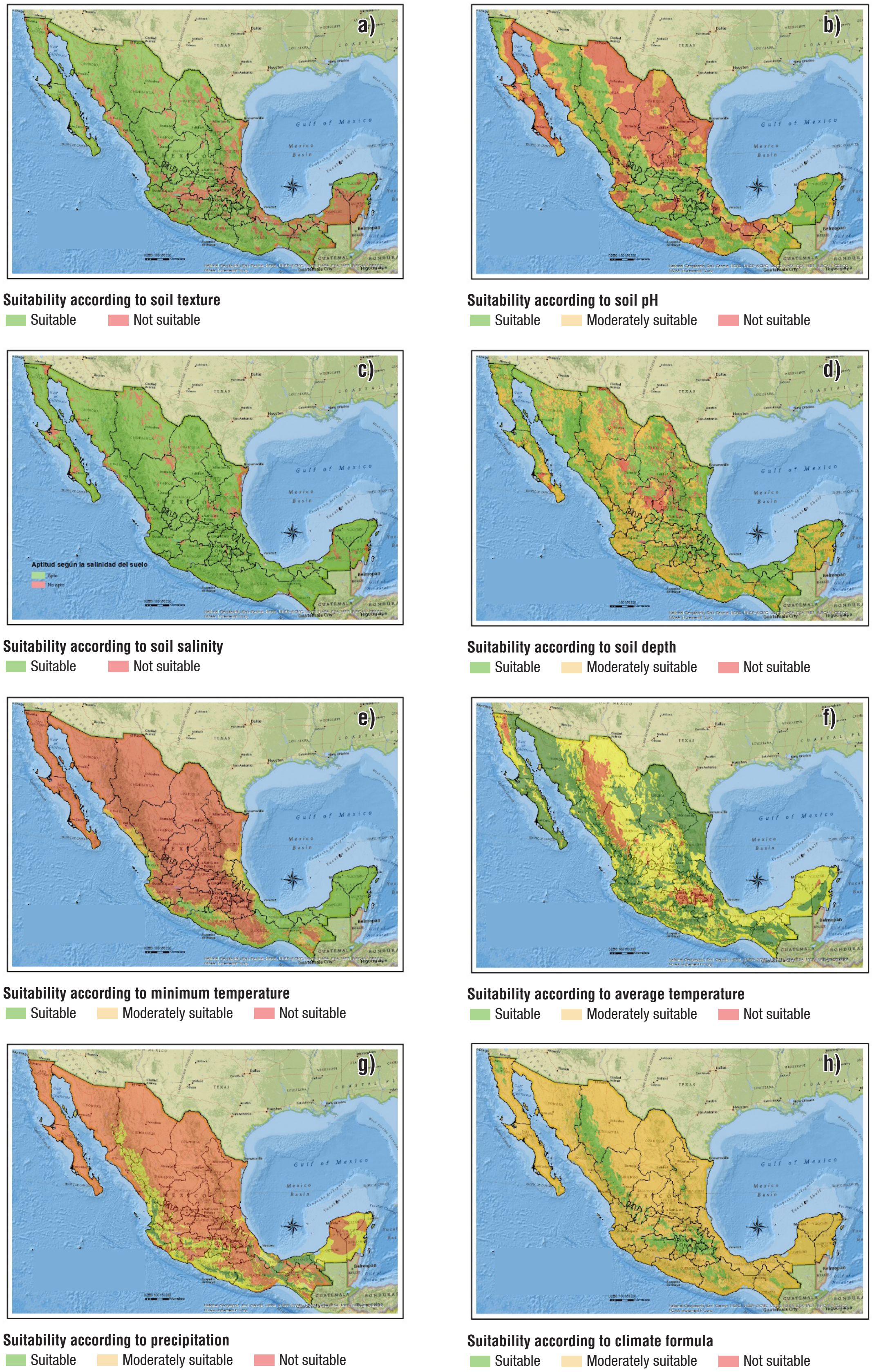

Figure 1. Suitability for the establishment of *Cannabis sativa sativa* based on: (a) soil texture, (b) soil pH, (c) soil depth, (d) salinity, (e) minimum temperature, (f) average temperature, (g) precipitation, and (h) climatic formula.

The characterization represents a semi-detailed agroclimatic classification for Mexico. Most of the Mexican territory is categorized as unsuitable for hemp. However, more favorable conditions were identified in the southwestern and southern regions of the country. The areas with the best conditions for *C. sativa sativa* are located in the states of Guerrero, Oaxaca, Chiapas, Veracruz, Tabasco, and the south of the Yucatan Peninsula. Additionally, suitable zones extend along the Sierra Madre Occidental, spanning from Jalisco to a small portion of Sonora, passing through Durango, Chihuahua, Sinaloa, Nayarit, and Zacatecas.

The climatic factor is the one that significantly limits the potential for growing hemp, so that only small portions of the national territory, located in the southeast, are considered suitable for this crop. While these areas are identified as viable for hemp, they may still require agricultural management practices, including the selection of hemp varieties adapted to the specific climatic conditions of the region and the implementation of soil management practices to improve fertility and structure. These findings are consistent with Castaño et al. (2014), who emphasized that defining areas with suitable climates for this crop requires understanding the behavior of climatic variables.

For this crop it is important to differentiate between meteorological frosts and agrometeorological frosts (García Leva & Valtorta, 2008). Meteorological frosts occur when the minimum temperature recorded in the thermometer is below 0 °C (Hirschhorn, 1958) and agrometeorological frosts are those recorded in the thermometer located 5 cm above the ground (Shindoi et al., 2003).

The regions by state that show some degree of suitability are presented in Table 2. The states of Chiapas, Tabasco, Oaxaca, Veracruz and Hidalgo are those with the largest

Table 2. Area (hectares) according to suitability for hemp (*Cannabis sativa sativa* L.) by state in Mexico.

State	Suitable	Moderately Suitable	Not suitable
Aguascalientes			562 799
Baja California			7 209 132
Baja California Sur			6,910,840
Campeche	241 824	2 865 988	2 401 295
Chiapas	1 840 957	1 943 145	3 437 342
Chihuahua		1 998 162	22 975 723
Coahuila	21 267	43 523	84 524
Colima			15 076 267
Durango	29 758	270 516	254 499
Guanajuato	74 702	2 907 542	9 456 362
Guerrero		15 480	3 046 294
Hidalgo	1 055 694	4 154 930	1 092 899
Jalisco	2 927	128 676	1 948 982
México	735 116	2 650 590	4 474 491
Ciudad de México	106 728	1 137 680	989 378
Michoacán	354 356	2 513 964	2 975 369
Morelos	27 102	224 252	236 152
Nayarit	748 431	1 483 239	519 368
Nuevo León		9 502	6 402 220
Oaxaca	1 477 158	2 580 838	5 149 359
Puebla	38 995	347 578	3 042 990
Querétaro		20 554	1 147 835
Quintana Roo		2 626 539	1 578 386
San Luis Potosí		200 376	5 913 071
Sinaloa	4 126	1 554 002	3 972 714
Sonora		123 655	18 175 555
Tabasco	1 516 932	286 476	605 396
Tamaulipas		72 342	7 554 284
Tlaxcala		38 228	361 197
Veracruz	1 309 507	1 841 010	3 823 565
Yucatán		1 658 061	2 328 434
Zacatecas		112 750	7 436 148
National	9 585 582	33 809 597	151 142 870

areas suitable for growing C. sativa sativa. Also, the results indicate that under rainfed conditions in most of the northern and central part of the country, growing hemp is not suitable. The above, with the exception of some reduced and well-located places that can be identified with red color, cover approximately 65 % of the national surface in Figure 2.

Social perception for hemp production

We visited the community of Santa Martha Chichihualtepec, in the municipality of Ejutla de Crespo in the state of Oaxaca. It is a region where hemp is grown, but it is also possible to find maize, beans, coffee and vegetable crops. There is livestock and local handicraft production. Tourism is a developing activity as it is a largely agricultural area (INEGI, 2014).

In the community of Santa Martha Chichihualtepec, a group of women are part of the Indigenous Association of Cannabis Producers (AIDPC). Some of them have family greenhouses in which they have planted *C. sativa sativa*. Oaxaca is one of the first states in the country to promote hemp for bioconstruction purposes and its transformation into sustainable products. Its main objective is to provide women in these communities with access to new work opportunities to have another source of income (Ramírez, 2024).

Field observations coincide with the zones identified in the zoning proposal for hemp that meet historical criteria in the community. For example, interviewees indicate that it is not necessary to use large amounts of fertilizer or chemical inputs for weed control in the crop. The biggest challenge they point out is pest control, in this case rodents, which has caused significant yield losses.

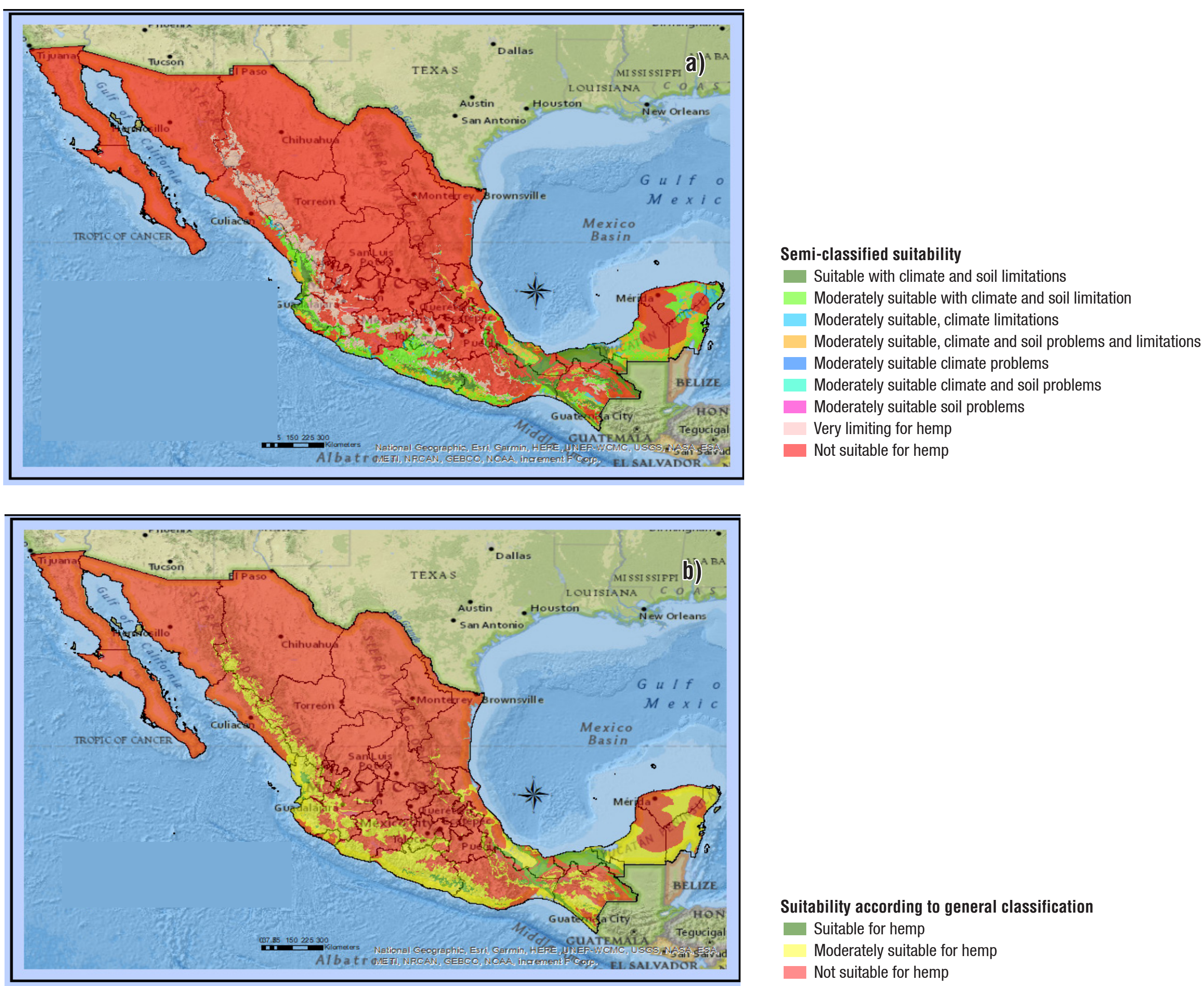

Figure 2. Agroclimatic Suitability for *Cannabis sativa sativa* in Mexico: (a) Characterization highlighting production limitations and (b) general crop suitability map

In the community, the interviewees have authorization to plant hemp. The sanitary authorization No. COFEPRIS-CAS-DEREPSQ-7947-2022, which complies with the Regulations of the General Health Law regarding sanitary control for the production, research and medicinal use of cannabis and its pharmacological derivatives (Presidential Decree, January 12, 2021).

Hemp varieties planted are known as Yuma, Puma 3 and Hanma, of Chinese origin (Isidro, 2024). They are widely known for their suitability for fiber production. There are varieties with a THC content lower than 1 % according to the decree published in 2017 (DOF, 2017). It should be noted that they are non-narcotic varieties and do not produce any effect when consumed. It is commonly grown in June and harvested in January of the following year. Table 3 shows a summary of the production schedule and process.

The municipality is located near a mountainous area with a wealth of biodiversity. It is home to pine-oak forests and wildlife such as deer. For this reason, the interviewees commented that growing hemp is an alternative to reduce pressure on the forest and conserve it (Isidro, 2024). They comment that the plant has the capacity to decompact and remediate contaminated soils, which opens the possibility of promoting new studies

Producers indicate that they are growing hemp on a pilot basis, approaching the process with care and meticulous attention to detail, including maintaining records and statistics. They acknowledge that there remains a legal gap in hemp regulation. Despite its lack of psychoactive properties, they emphasize that it should be regulated differently from marijuana (Ramírez, 2024). The project coordinator states, "*We are working to communicate this situation to the relevant authorities and obtain the necessary authorizations to continue with our crop*."

The perception of producers is that hemp has a high potential for use and socioeconomic benefits for the communities, as reported by Gutiérrez (2020). They particularly mention the recent legislation that allows its industrial use. This regulation opens new opportunities to take advantage of the benefits of this plant, such as in the textile and construction industries (Figure 3). It is possible to have access to high quality raw material while fostering local economies. Recently, new initiatives have emerged in various parts of the country, including the states of Morelos and Yucatán. Some of them face difficulties specific to their region, such as the absence of rain or irrigation. In the case of the community of Santa Martha Chichihualtepec, in the municipality of Ejutla de Crespo, Oaxaca, they have managed to overcome these obstacles effectively. The future is still uncertain, but they will continue to grow and demonstrate that hemp is viable for Mexico.

Conclusions

The objective of agroecological zoning to assess hemp suitability throughout Mexico has been successfully achieved. Relevant information was presented on the most suitable areas for this crop, considering climate and soil variables. Regions with varying degrees of suitability were identified—those meeting the necessary edaphoclimatic requirements for hemp growth. Approximately 22 % of the national territory was found to be suitable for hemp (5 % highly suitable and 17 % moderately suitable). These previously unknown findings are significant for promoting production and encouraging the development of this industry, particularly in regions with natural potential.

The results also align with the historical and traditional knowledge shared by producers already growing hemp in the central region of Oaxaca. However, the regulatory framework should be clarified and differentiated from that

Table 3. Schedule and productive activities related to growing hemp, Santa Martha Chichihualtepec, Oaxaca

Activity	Description
Sowing date	June, in Luvisol soil.
Soil preparation	'Bocashi' (substrate with oats) and another mixture including yeast and molasses are used.
Sowing method	With tractor and big plate planter, originally used for maize.
Sowing density	Density is close to 12 000 plants per hectare.
Seed quantity	600 kg of hemp seed is sown.
Row spacing	55 cm to avoid weeds between them.
Weeding	Two months after sowing; only once.
Fertilization	No fertilizer was applied.
Pests	The plant had no pests but faced difficulties with leafhoppers in the first stage. Presence of rodents.
Flowering	In September, males grew more than females.
Cosecha	Harvest End of January, by hand.

Figure 3. Products derived from *Cannabis sativa sativa*: hemp thread (left) and briefcase (right).

of marijuana. Since hemp does not contain psychoactive substances, it holds potential for use in various industries.

Hemp's properties and potential applications still require further study across multiple fields, opening opportunities for future research. Clothing and vehicle manufacturers need to understand its performance, while agronomists and soil scientists can explore its potential for restoring contaminated and degraded soils.

As technology and legislation in this area continue to advance, it is expected that hemp will play an increasingly significant role in the national industry.

This study has limitations regarding the specific parameters of commercial hemp varieties, which restricts a more comprehensive understanding of its applications. Additionally, the lack of reliable data and ongoing regulatory changes, particularly concerning THC, make comparisons between production zones impossible. Future research could focus on a detailed analysis of commercial varieties and their adaptation to specific conditions, as well as on legislative evolution and production within an environmentally sustainable framework, with deeper exploration of ecological impacts.

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