

GIS and modeling to determine key areas for conserving the genetic diversity of cotton (*Gossypium* spp.) in Mexico

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ABSTRACT

Objective: to determine the key genetic pool areas that harbor populations of wild relatives of cotton in Mexico, through GIS and modeling.

Design/ Methodology/ Approach: a database with 2594 records of collections of the genus *Gossypium* was used, the data were obtained since 1933 up to 2024. A map was created to visualize the geographical distribution of the species and another for genetic diversity where the Shannon diversity index (SDI) was applied.

Results: an 80% of the records of wild relatives of cotton are conformed by *Gossypium hirsutum* (58.8%), *G. aridum* (14.1%) and *G. davidsonii* (6.7%), confirming that Mexico is the center of diversity for *G. hirsutum*. Five key areas with very high genetic diversity were identified in the states of Oaxaca and Michoacán.

Limitations/Implications of the study: the target of this study were only wild populations, it did not evaluate GMO's genetic cross-contamination. However, the study emphasizes the importance and role of cotton genetic pools that are still preserved in natural populations. This may lead decision making towards the need for conservation areas in public policies.

Findings/Conclusions: five key areas with very high genetic diversity were identified in the states of Oaxaca and Michoacán. In the states of Guerrero, Baja California Sur and Sonora, areas with a high concentration of some *Gossypium* species were identified, and therefore could be considered key areas for the conservation of *Gossypium* genetic diversity.

Keywords: conservation, genetic pool, spatial distribution, *Gossypium*, Shannon Diversity Index.

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INTRODUCTION

At the beginning of the 16th century, Mexico was inhabited by cultures with diverse political, social, agricultural, and economic systems. The development of these cultures was favored by the varied natural conditions that offered a wide diversity of native plants, which allowed for their use and domestication. Such as maize, beans, chili peppers, squash,

cotton, amaranth, and cacao, among others, which have made significant contributions to global agriculture and food security (SNICS, 2020).

There are about 50 known species of cotton (*Gossypium* spp.). The centers of greatest species richness of the genus *Gossypium* are found in Central and South America, 18 species; Australia 17 species, Northeast Africa and Southwest Arabia, 14 species. In Mexico, according to the Germplasm Resources Information Network (GRIN), the USDA's Agricultural Research Service reported 15 out of the 18 existing cotton species in Central and South America, distributed across 87% of the US national territory (USDA-ARS, 2024). The highest concentrations of wild cotton relatives are located in the southeastern region of the country (Coppens d'Eeckenbrugge & Jean-Marc, 2014).

The two most cultivated species are *G. hirsutum* and *G. barbadense*. For *G. hirsutum*, the center of origin and greatest diversity is recorded as located in Southern Mexico and Central America. Its possible center of domestication is located in Southeastern Mexico, in the Yucatán Peninsula. And the species *G. barbadense* comes from Peru.

In Mexico, the first region where cotton is believed to have been cultivated was Veracruz in the 16th century. From 1860 onward, interest in its cultivation increased considerably in various regions of the country (CIBIOGEM, 2014). The Comarca Lagunera (a region encompassing parts of Coahuila and Durango), Chihuahua, Sinaloa, Sonora, Baja California, and Tamaulipas have been the main producing states. Records also exist of cotton cultivation in Campeche, Colima, Chiapas, Michoacán, Nuevo León, San Luis Potosí, Veracruz, and Yucatán (INEGI, 1994).

Between 1950 and 1969, approximately one million hectares (ha) were planted (INEGI, 1994). From 1970 onward, the planted area began to decline, and by the 1980s only 300 000 ha were cultivated, a figure that dropped to 82 000 ha in 2000 (INEGI, 1994). This decline and gradual abandonment of cotton crop was due to factors such as the uncompetitive international price of this fiber, caused by a rapid substitution with synthetic fibers. Also, by the emergence of pests, which led to the use of high doses of agrochemicals that increased production costs (Reyes *et al.*, 2010).

In 1996, with the planting of 896 hectares, Mexico began cotton production using genetically modified (GM) seeds of the species *G. hirsutum*, resistant to pests and tolerant to diseases, to reduce production costs (SNICS, 2020). By 2024, cotton production had recovered, approximately 240 000 hectares were planted, 96% of which used GM seeds (SIAP, 2024). Genetically modified cotton is not cultivated in Oaxaca, Chiapas, and Yucatán, rather wild *G. hirsutum* populations still exist.

One of the risks of genetically modified crops is that the genes can be introduced into the diversity of wild plants and conventional crops grown in a region, potentially leading to genetic contamination (Pons, 2021). Ulloa *et al.* (2006) observed that the expansion of GMOs cultivation has increased the risk of loss of native varieties, as it can cause genetic erosion. For this reason, it is important to consider countries that are centers of origin and genetic diversity, such as Mexico (Pérez *et al.*, 2016).

Regarding this aspect, the Mexican Biosafety Law for Genetically Modified Organisms (LBOGM) establishes criteria for determining the centers of origin and genetic diversity of crops. According to this Law, a center of origin is defined as a geographic area where

the domestication process of a given species took place. Whereas, a center of genetic diversity is defined as a geographic area where considerable morphological and genetic diversity exist for certain species. This site is characterized by harboring populations of wild relatives that together constitute a genetic pool. Due to the importance of identifying key genetic pool areas to prevent the establishment of transgenic commercial crops in their vicinity, this research was designed to provide information for defining public policies for the sustainable production and use of cotton, as well as for the conservation of cotton genetic diversity in Mexico. The objective was to determine the key genetic pool areas that harbor populations of wild relatives of cotton in Mexico, through the use of GIS and modeling.

MATERIALS AND METHODS

Database integration

A database was compiled with 2594 records of collections of the genus *Gossypium*. The data started in 1933 and were collected up to 2024, of which 801 records came from the Conservation Centers Network, coordinated by the Subcommittee on Agricultural Genetic Resources of Mexico's Secretariat of Agriculture (by email communication); 946 records from the National Biodiversity Information System of Mexico's National Commission for the Knowledge and Use of Biodiversity, under the Secretariat of Environment and Natural Resources (CONABIO, 2024); and 847 records proceed from the WN003 Project of Mexico's Conservation Program of Wild Populations of the genus *Gossypium* in Mexico, under the National Commission for the Knowledge and Use of Biodiversity (CONABIO, 2022).

The database included variables such as biological complex, biological status, state, municipality, and origin (locality), in addition to identification data and location coordinates. Duplicated records and those lacking a collection number or code, collection year, or collector identification were eliminated. Likewise, some errors when records were geographically referred, such as those located in inland water bodies or outside municipal boundaries, were identified and corrected. To ensure data accuracy, a detailed verification was performed at municipal scale using the Mexico's National Geo-Statistical Framework, integrated to Mexico's National Geo-Statistical Information System, created by Mexico's National Institute of Statistics and Geography (INEGI, 2023). Finally, those records classified as 'non-wild', 'feral', 'cultivated', or 'semi-domesticated' were excluded. The final database consisted exclusively of wild individuals and comprised a total of 1385 records corresponding to 13 species (Table 1).

In order to systematize the information, the records were classified according to state of origin and species. Then, a temporal classification of the species (by year of record collection) was performed. For this, Jenks's natural break optimization method (Jenks, 1967) was used. This statistical algorithm objectively identifies the optimal breakpoints in the data, resulting in five time intervals that maximize the variance between groups and minimize the variance within each group. This ensures that the resulting interval groups are statistically distinct, internally consistent, and significant.

Table 1. Number of records of wild relatives of cotton (*Gossypium* spp.) in data obtained since 1933 to 2024.

Number	Species	Number of records	Value in database (%)
1	<i>G. hirsutum</i>	815	58.8
2	<i>G. aridum</i>	195	14.1
3	<i>G. davidsonii</i>	93	6.7
4	<i>G. harknessii</i>	74	5.3
5	<i>G. thurberi</i>	49	3.5
6	<i>G. gossypoides</i>	45	3.2
7	<i>G. lobatum</i>	33	2.4
8	<i>G. laxum</i>	29	2.1
9	<i>G. armourianum</i>	14	1
10	<i>G. trilobum</i>	14	1
11	<i>G. schwendimanii</i>	11	0.8
12	<i>G. barbadense</i>	9	0.6
13	<i>G. turneri</i>	4	0.3
	Total	1385	100

Areas with populations of wild relatives

To visualize the geographic distribution of the 13 species of wild relatives of cotton, the 1385 records from the final database were used, and a map was created using the open-source GIS software QGIS (2024). A diversity map was then generated, calculating the Shannon Diversity Index (SDI) with a spatial resolution of $33 \times 33 \text{ km}^2$, using DIVA-GIS, another open-source module (Hijmans, 2024). This index is widely used to quantify species biodiversity (Pla, 2006). A value trending towards 1 indicates very high diversity, while a value trending towards 0 indicates low diversity, since it considers both the number of species present (richness), and their relative abundance (evenness). This map shows how species diversity and richness are distributed in a given area.

RESULTS AND DISCUSSION

Table 2 and Table 3 show the reclassification of records based on the state of origin, species, and year of the record. Thirteen species of wild relatives of cotton were identified (Table 2), with a significant degree of updating, as 50% of these were recruited between 2009 and 2024 (Table 3). This number and type of species identified coincides with Pérez *et al.* (2016), whose study considered cotton records collected since 1978 to 2006.

However, these results do not include the presence of two species, *Gossypium raimondii* with distribution records in the State of Mexico, and *G. lanceolatum* with distribution records in Michoacán and Nayarit, which are reported, as part of the 15 cotton species distributed in Mexico, by the US Germplasm Resources Information Network–GRIN (Campbell *et al.*, 2010; USDA-ARS, 2024).

Results showed that 80% of the records of cotton wild relatives are concentrated in three species *G. hirsutum* 58.8%; *G. aridum* 14.3% and *G. davidsonii* 6.7%. This reflects the

Table 2. Classification of records according to the Mexican state of origin and the species of the genus *Gossypium*.

Mexican state	Species													Total
	<i>G. aridum</i>	<i>G. armourianum</i>	<i>G. barbadense</i>	<i>G. davidsonii</i>	<i>G. gossypoides</i>	<i>G. harknessii</i>	<i>G. hirsutum</i>	<i>G. laxum</i>	<i>G. lobatum</i>	<i>G. schwendimanii</i>	<i>G. thurberi</i>	<i>G. trilobum</i>	<i>G. turneri</i>	
Aguascalientes							1							1
Baja California Sur		14		79		73	4							170
Campeche							16							16
Chiapas			9				31							40
Chihuahua							1				3			4
Colima	21						8							29
Durango	1													1
Guerrero	17						33	29	1	2		1		83
Jalisco	18						8							26
México							2							2
Michoacán	10						27		32	9		12		90
Morelos							5					1		6
Nayarit	13						5							18
Oaxaca	67				44		178							289
Puebla	9				1		8							18
Querétaro							1							1
Quintana Roo							12							12
San Luis Potosí							3							3
Sinaloa	30						7							37
Sonora				14		1					46		4	65
Tabasco							2							2
Tamaulipas							10							10
Veracruz	9						17							26
Yucatán							436							436
Total	195	14	9	93	45	74	815	29	33	11	49	14	4	1385

relevance of *G. hirsutum* in Mexico as the species which is source of diversity and genetic richness. It coincides with what was reported by Wegier *et al.* (2012) who indicated that Mexico is the center of diversity for *G. hirsutum*. Furthermore, the wide distribution of this species as a wild species within Mexican territory was demonstrated.

Yucatán and Oaxaca are the states with the highest number of records of *G. hirsutum*, 436 and 178 (Table 2), which coincides with Pérez & Ruiz (2010) who reported that the center of origin and greatest genetic diversity of *G. hirsutum* is located in the south of the country.

Table 3. Classification by collecting period of the different species of *Gossypium* spp.

Species	Periods (years)					Total
	1933-1955	1956-1975	1976-1993	1994-2008	2009-2024	
<i>G. aridum</i>	4	20	60	94	17	195
<i>G. armourianum</i>	4	4	1	1	4	14
<i>G. barbadense</i>				9		9
<i>G. davidsonii</i>	8	28	21	27	9	93
<i>G. gossypoides</i>		5	15	7	18	45
<i>G. harknessii</i>	7	23	22	13	9	74
<i>G. hirsutum</i>	84	9	30	81	611	815
<i>G. laxum</i>		7	7	12	3	29
<i>G. lobatum</i>	2	1	4	21	5	33
<i>G. schwendimanii</i>			1	9	1	11
<i>G. thurberi</i>	9	2	14	13	11	49
<i>G. trilobum</i>	3	5	4		2	14
<i>G. turneri</i>		1	3			4
Total	121	105	182	287	690	1385

Regarding the geographical distribution of current records of wild relatives of cotton, their presence is evident in 24 Mexican states, from the Northwest (Sonora, Baja California Sur and Sinaloa) to the Southeast in the Yucatan Peninsula and Quintana Roo (Figure 1). These results contrast with those of Pérez *et al.* (2016), who determined the presence of native cotton species in 27 states. The difference is possibly due to the aforementioned study included individuals classified as non-wild, that is, cultivated.

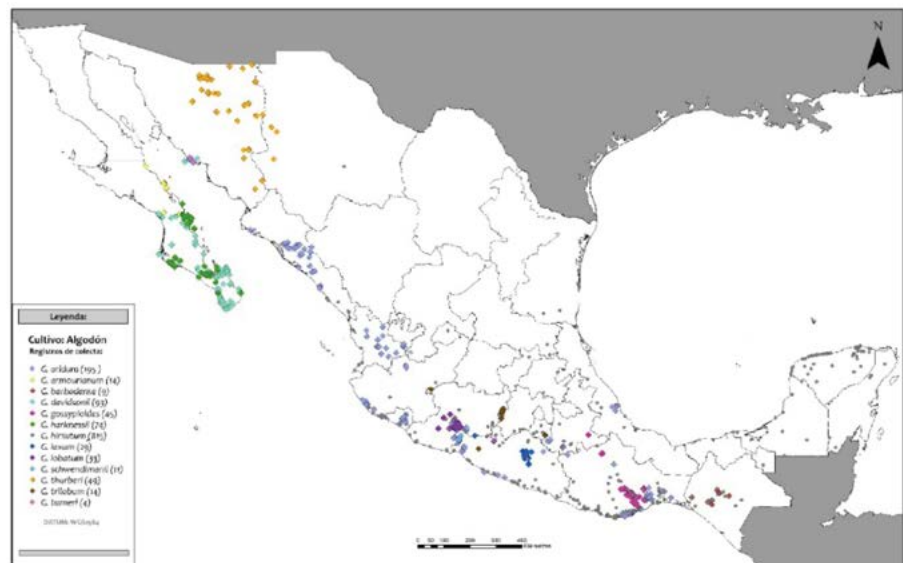


Figure 1. Geographic distribution of wild relatives of cotton (*Gossypium* spp.) in Mexico. Prepared by the authors using QGIS (2024).

These records highlight that 65% of wild relatives, and therefore the genetic richness, are concentrated in Yucatán (31%) and Oaxaca (21%). This coincides with Cronn *et al.* (2003) and Álvarez *et al.* (2005), who located the center of origin of *Gossypium diploides* in Oaxaca, while the origin of *Gossypium tetraploides* was located ‘somewhere in Mesoamerica’, which includes Yucatan.

In the remaining 22 Mexican states, several species have very restricted distributions in terms of both number and geographic range. Some are represented by only a single species record, but are found in various coastal regions of Baja California Sur, the Pacific Ocean, the Gulf of Mexico, and the Yucatán Peninsula. In other words, the genus *Gossypium* is found in areas with conditions ranging from arid to humid and semi-warm to warm, associated with geological and edaphic diversity, as well as different vegetation and habitat types. Five key areas of very high species diversity were identified (within $33 \times 33 \text{ km}^2$ geographic cells) with a Shannon diversity index between 0.76 and 1 (Figure 2).

In these red areas, at least three species are present, *Gossypium aridum*, *G. hirsutum*, and *G. gossypioides*. Two of these areas are located in the central and northeastern regions of the state of Michoacán; five species are distributed within them (*Gossypium lobatum*, *G. hirsutum*, *G. trilobum*, *G. aridum* and *G. schwendimanii*). In a first area, the species *G. aridum*, *G. hirsutum* and *G. lobatum* are located; in a second area we found the species *G. aridum*, *G. lobatum* and *G. schwendimanii*. The remaining three areas are located in the Southeast of Oaxaca and all areas share the distribution of the species *G. aridum*, *G. gossypioides* and *G. hirsutum* (Table 4).

In addition, 24 areas with high diversity (IDS between 0.57 and 0.75) were identified and are depicted in orange in Figure 2. Six areas were recorded in the state of Baja

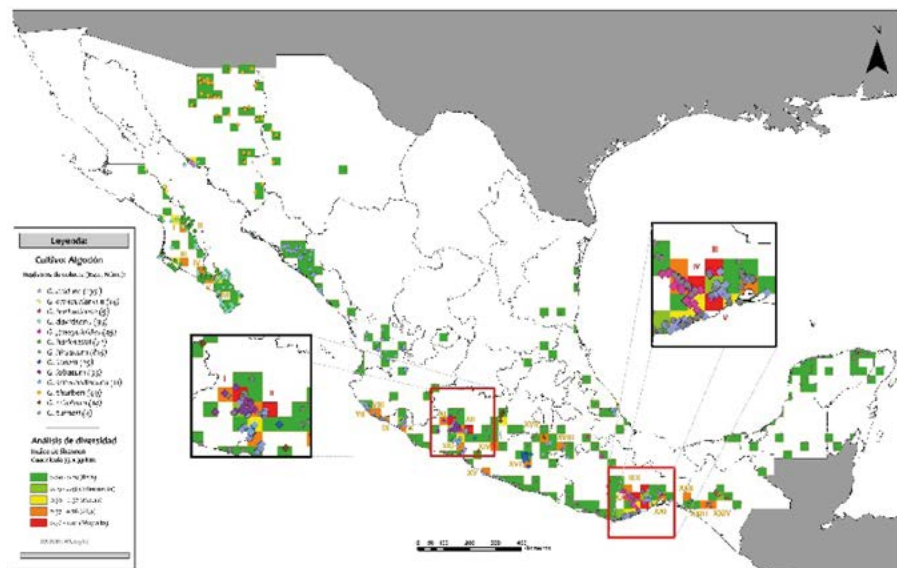


Figure 2. Key areas of very high richness and diversity of cotton (*Gossypium* spp.) wild relatives in Mexico. Prepared by the authors using DIVA-GIS.

Table 4. Key areas of very high diversity based on the Shannon diversity index (SDI 0.764-1.00).

Key Area	State	Municipalities	Species
I	Michoacán	Parácuaro, Múgica y Gabriel Zamora	<i>G. hirsutum</i> , <i>G. lobatum</i> and <i>G. aridum</i>
II	Michoacán	La Huacana, Churumuco y Turicato	<i>G. schwendimanii</i> , <i>G. lobatum</i> and <i>G. aridum</i>
III	Oaxaca	Santiago Ixcuintepec, Santo Domingo Tehuantepec, Santiago Lachiguiri, Nejapa de Madero, Guevea de Humboldt y Santa María Guienagati	<i>G. hirsutum</i> , <i>G. gossypoides</i> and <i>G. aridum</i>
IV	Oaxaca	Santa Ana Tavela, San Juan Lajarcia, San Carlos Yautepec, San Bartolo Yautepec, Santa María Ecatepec, Magdalena Tequisistlán, Santa María Jalapa del Márques y Santa María Totolapilla	<i>G. hirsutum</i> , <i>G. gossypoides</i> and <i>G. aridum</i>
V	Oaxaca	Magdalena Tequisistlán, San Miguel Tenango, Santo Domingo Tehuantepec y San Pedro Huamelula	<i>G. hirsutum</i> , <i>G. gossypoides</i> and <i>G. aridum</i>

California Sur, where cotton species converge, *Gossypium armourianum*, *G. harknessii* and *G. davidsonii*. Also, four areas in Guerrero with *G. aridum*, *G. hirsutum*, *G. laxum*, *G. lobatum* and *G. schwendimanii*; three areas in Oaxaca with *G. aridum*, *G. gossypoides* and *G. hirsutum*; and three areas in Chiapas with *G. barbadense* and *G. hirsutum* (Table 5).

Areas with medium diversity (SDI 0.38-0.57) were also delimited with their species, and were identified with yellow color (Figure 2). These are located in Baja California Sur (*Gossypium armourianum*, *G. hirsutum*, *G. davidsonii* and *G. harknessii*); Sonora (*G. davidsonii*, *G. harknessii* and *G. turneri*); Michoacán (*G. aridum* and *G. schwendimanii*); State of Mexico (*G. hirsutum* and *G. trilobum*); Oaxaca (*G. aridum*, *G. gossypoides* and *G. hirsutum*) and Veracruz (*G. hirsutum* and *G. aridum*). Those areas with intermediate diversity (SDI 0.19-0.38; lime green in Figure 2) are located in Colima (*G. aridum* and *G. hirsutum*); Michoacán (*G. aridum*, *G. hirsutum* and *G. lobatum*); Oaxaca (*G. aridum* and *G. hirsutum*) and Chiapas (*G. barbadense* and *G. hirsutum*).

Areas with low diversity (SDI 0-0.19, dark green in Figure 2) are characterized by the presence of a single species. These low diversity areas are more frequent and dispersed, and are located in northern Sonora (*G. thurberi*), central Sinaloa (*G. aridum*), and a large area in Yucatán (*G. hirsutum*). The latter accounts for 32% of all *Gossypium* records.

In turn, Michoacán, Guerrero, Baja California Sur, Oaxaca, Jalisco, Colima, State of Mexico, Morelos, Puebla and Chiapas are highlighted because these states have areas with greater diversity. This is, considering both the number of species present (richness) and their relative abundance (evenness). In these places, genetically modified cotton could represent a risk of genetic contamination.

Table 5. Key areas of high diversity according to Shannon index (SDI 0.573-0.764).

Key Area	State	Municipalities	Species
I and II	Baja California Sur	Loreto	<i>G. davidsonii</i> and <i>G. harknessii</i>
III	Baja California Sur	Comondú and La Paz	<i>G. davidsonii</i> and <i>G. harknessii</i>
IV	Baja California Sur	La Paz	<i>G. davidsonii</i> and <i>G. harknessii</i>
V	Baja California Sur	La Paz	<i>G. davidsonii</i> , <i>G. harknessii</i> and <i>G. armourianum</i>
VI	Baja California Sur	La Paz	<i>G. davidsonii</i> , <i>G. harknessii</i> and <i>G. hirsutum</i>
VII	Jalisco	La Huerta	<i>G. hirsutum</i> and <i>G. aridum</i>
VIII	Jalisco	La Huerta and Cihuatlán	<i>G. hirsutum</i> and <i>G. aridum</i>
IX	Colima	Cihuatlán and Manzanillo	<i>G. hirsutum</i> and <i>G. aridum</i>
X	Colima	Armería and Tecomán	<i>G. hirsutum</i> and <i>G. aridum</i>
XI	Michoacán	Buenavista, Tancítaro and Apatcingán	<i>G. hirsutum</i> and <i>G. lobatum</i>
XII	Michoacán	La Huacana and Churumuco	<i>G. hirsutum</i> , <i>G. lobatum</i> and <i>G. aridum</i>
XIII	Guerrero	La Unión Isidoro Montes de Oca and Coahuayutla de José María Izazaga	<i>G. schwendimanii</i> and <i>G. aridum</i>
XIV	Guerrero	Coyuca de Catalán, Pungarabato, Tlapehuala and Ajuchitlán del Progreso	<i>G. hirsutum</i> and <i>G. lobatum</i>
XV	Guerrero	Petatlán and Técpan de Galeana	<i>G. hirsutum</i> and <i>G. aridum</i>
XVI	Guerrero	Leonardo Bravo, Eduardo Neri, Tixtla de Guerrero and Chilpancingo de los Bravo	<i>G. hirsutum</i> , <i>G. aridum</i> and <i>G. laxum</i>
XVII	Morelos	Tepalcingo, Tlalquitenango, Teotlalco, Ayala, Tlaltizapan de Zapata and Jolalpan	<i>G. hirsutum</i> and <i>G. trilobum</i>
XVIII	Puebla	Chiautla, Tehuitzingo, Izucar de Matamoros, Chila de la Sal, Axutla, Tecomatlán, Piaxtla, Ahuehuetitla, Chinantla	<i>G. hirsutum</i> and <i>G. aridum</i>
XIX	Oaxaca	San Pedro Quiatoni, San Juan Juquila Mixes, Santa María Tepantlali, Santo Domingo Tepuxtepec, San Juan del Rio, San Lorenzo Albarradas, Tlacolula de Matamoros and San Pedro Totolapám	<i>G. hirsutum</i> and <i>G. gossypioides</i>
XX	Oaxaca	San Pedro Totolapám, San Carlos Yautepec, Santa María Quiegolani, San Bartolo Yautepec, San Carlos Yautepec, San Juan Lajarcia, Santa Ana Tavela and Nejapa de Madero	<i>G. hirsutum</i> and <i>G. gossypioides</i>
XXI	Oaxaca	Asunción Ixtaltepec, El Espinal, Juchitán de Zaragoza, Santa María Xadani, Unión Hidalgo, San Dionisio del Mar, Santiago Niltepec, Santo Domingo Ingenio and San Miguel Chimalapa	<i>G. hirsutum</i> and <i>G. aridum</i>
XII	Chiapas	Cintalapa de Figueroa, San Pedro Tapanatepec, Arriaga and Jiquipilas	<i>G. barbadense</i> and <i>G. hirsutum</i>
XXIII	Chiapas	Villaflores and Villa de Corzo	<i>G. barbadense</i> and <i>G. hirsutum</i>
XXIV	Chiapas	Villaflores, Villa de Corzo and El Parral	<i>G. barbadense</i> and <i>G. hirsutum</i>

CONCLUSIONS

Of the cotton species recorded, three dominate the distribution; *Gossypium hirsutum* (58.8%), *G. aridum* (14.3%) and *G. davidsonii* (6.7%), which emphasizes that Mexico is the center of diversity for *G. hirsutum*, this also coincides with previous research.

Five key areas with very high genetic diversity in species of *Gossypium* were identified, as well as 24 areas with high genetic diversity. It is recommended that these areas be designated as areas where genetically modified cotton cultivation should not be permitted, as this poses a risk of genetic contamination to native species and their conservation.

The greatest genetic diversity of *Gossypium* is concentrated in Michoacán, Guerrero, and Oaxaca, with a significant presence in Baja California Sur and Sonora. This strengthens the theory that Southern Mexico is a center of origin and diversity for these species. It should be emphasized that both, areas with the greatest genetic richness and those with a high concentration of a single species are key to conserving the genetic biodiversity of the genus *Gossypium*.

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