Evaluation of sustainability of agricultural systems of indigenous people in Hidalgo, Mexico

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Abstract: Agricultural sustainability depends on complex relationships between environmental, economic and social aspects, in particular with the small farmholders from indigenous communities. This work was centred in two municipalities of Hidalgo State in Mexico, Ixmiquilpan (mainly irrigated systems) and El Cardonal (rainfed systems). Our objective was to understand the relationships between the small farm-holders and their agricultural systems, evaluating their sustainability and design strategies and pathways for the sustainable development for indigenous communities. For this, we applied the Framework for the Evaluation of Management Systems using Indicators (MESMIS, Spanish acronym). Thirty one indicators were identified and quantitative indexes were established to be used to assess sustainability. The results showed that adaptability was a critical factor for both systems, and the main problem identified was youth migration. Additionally, the access to water and economic resources, as well as management of environmental resources, are imperious needs to increase the yield of agriculture crops. Therefore, integral strategies need to take into account the organization of small producers and the combination of indigenous and modern technologies, to design technologies for the territorial development of the communities.

Keywords: sustainability; agricultural practices; sustainability indicators, productive system.

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1. Introduction

Agricultural sustainability is the interrelation between three cornerstones: social, economic, and environmental, related to production, resilience, adaptability, organization, social equity and self-sufficiency for the development of the community[1]

The expansion of conventional agricultural techniques, mainly monoculture, and the massively increased use of agrochemicals cause an environmental crisis at global scale and the necessity of new approaches to solve it, such as sustainab1le agriculture. The main objectives of sustainable agriculture are: i) improving the health of producers and consumers (food security, organic agriculture); ii) maintain the stability of the environment (biological methods of fertilization and pest management); iii) ensure long-term benefits for farmers; and iv) considering for the needs of current and future generations[2, 3]. Traditional farming systems could be an option, for example, rural indigenous communities in Central Mexico combine polyculture (corn, beans, squash, chili and other crops) with organic fertilizers, no-tillage farming, no-agrochemicals and rainfall. Comparison of sustainability indicators of these traditional and other agricultural systems will allow to identify advantages and bottlenecks. Furthermore, socio-economic, and environmental indicators could serve as a tool in planning and decision-making processes at community and regional levels. These indicators belong to five main categories: production, resilience, adaptability, organization, social equity and self-sufficiency.

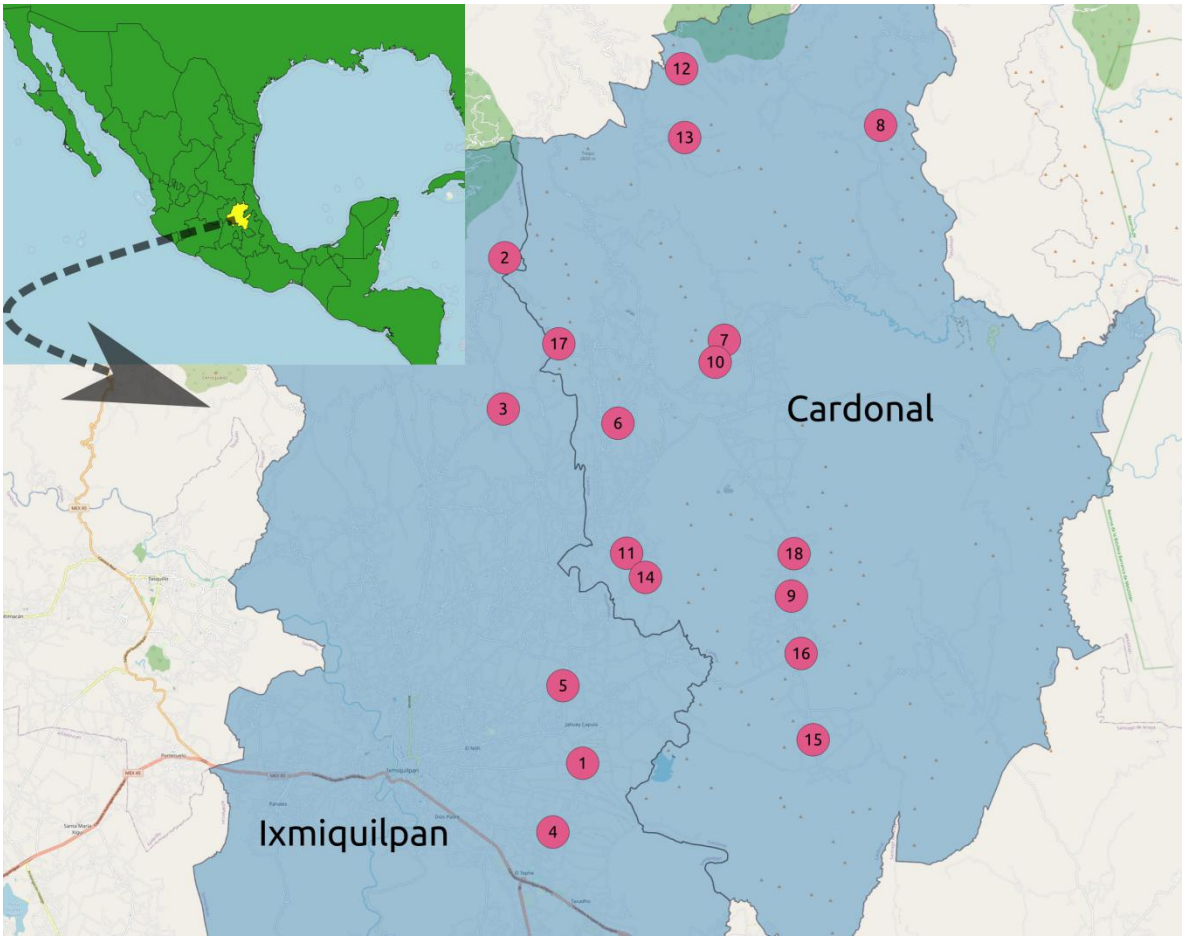
Concerns about agriculture sustainability go farther than environmental conditions and changes in internal trade; they also include the nature of the agricultural crisis that most of the

countries are going through[4]. However, there are considerable discrepancies on translating the most appropriate philosophical and ideological aspects of sustainability, as well as what are the most appropriate methodologies to evaluate it. In this way, the evaluation of sustainability is affected by problems inherent to the multidimensionality of the concept itself, which includes ecological, economic, social, cultural and temporal dimensions. Therefore, the evaluation requires a holistic [5] and systemic approach, where multi-criteria analysis predominates. Thus, there is a need to develop methods for evaluating the sustainability and performance of agricultural systems, as well as guide actions and policies for the sustainable management and preservation of natural resources. Even more Sustainable Management of Natural Resources (SMNR) has mainly focused on "sustainable agriculture", but several authors have argued that SMNR should be understood in a broader sense, including activities such as forestry, livestock production, fisheries, mining, and ecotourism [6].

We consider the most adequate technology for evaluation of sustainability of complex agricultural systems is the framework for the evaluation of management systems using indicators (MESMIS, by its acronym in Spanish, Marco para la Evaluación de Sistemas de Manejo de Recursos Naturales Incorporando Indicadores de Sustentabilidad). This framework proposes six cyclic steps: 1) characterization of the systems; 2) identification of the critical points that are linked to the sustainability attributes, for example productivity, stability, reliability, resilience, adaptability, equity, and self-reliance; 3) identification and selection of indicators; 4) measurement and monitoring; 5) analysis and integration of data; and 6) conclusions and recommendations. [7–10] . Therefore, we used MESMIS, to evaluate and compare the sustainability of rainfed and irrigated agricultural systems of Otomies' communities in two municipalities of the Hidalgo State in Mexico. These communities stand out as a low agricultural productivity region with semiarid climate and volcanic soil, hillocks, ravines, thorny scrub and few streams. In the last five years the average annual precipitation was 140 milliliters in El Cardonal and 142 milliliters in Ixmiquilpan [11, 12]. In both municipalities, an ancestral polyculture system, termed milpa, is the basis of rainfed agriculture, and includes corn, beans, squash, chilli and many other crops. In irrigated lands, in contrast, industrialized monoculture is typically farmed. This area was selected as a case study due to its long tradition of polyculture farming despite these challenging environmental conditions, and the presence of both irrigation and rainfed farming.

2. Materials and Methods

Our study area included 18 villages located in the municipalities of Ixmiquilpan and El Cardonal, in the Hidalgo State, Mexico (Figure 1). This State is located in the central region of the country (Figure 1), with a number of relatively intact native cultures such as the Otomi (or Hñahñu, as they refer to themselves). Ixmiquilpan is located at 20° 29' 03" N, 99° 13' 08" W, with an altitude of 1680 meters above sea level. This is an area dedicated to irrigated agriculture, the main crops being forage, vegetables, and grains [13]; the water source for irrigation is wastewater from Mexico City. El Cardonal is located between latitudes 20° 24' 58"N and 20° 46' 31"N and longitudes 98° 55' 54" W and 99° 10' 46" W, with an altitude between 900 and 2900 meters above sea level. This is an area dedicated to rainfed agriculture and grazing livestock (mainly sheep); the main crops are agave, corn and fruit trees [14]–[16]. Inhabitants of both municipalities belong to the Otomi culture; their villages are communities of high and very high marginalization, and medium social backwardness.



(**a**)

Figure 1. Location of municipalities and communities, **Ixmiquilpan**: (1)Bangandhó, (2) El Nogal, (3) El Olivo, (4) Pueblo Nuevo, (5) San Pedro Capula. **El Cardonal**: (6) Cerro Colorado, (7) Chalmita, (8) Cieneguilla, (9) Durango Daboxtha, (10) El Bondho, (11) El Botho, (12) El Potrero, (13) El Tixqui, (14) Los Reyes, (15) Pozuelos, (16) San Andrés Daboxtha, (17) San Miguel Jigui, (18) Santa Teresa Daboxtha.

We interviewed small-scale producers who participated in the governmental-social program "Territorial Development Projects" (PRODETER, by its acronym in Spanish) and live in the municipalities of Ixmiquilpan and El Cardonal. We used an application on a mobile device, which we adapted to study the social, environmental, and economic relationships of agricultural systems. The mobile application koBoCollect v1.25.1, [17] allows collecting quantitative and qualitative data through a series of questions, including multimedia files, such as photos and GPS location. Data collection was carried out during January and February 2020, under a non-probability test sample [18, 19], considering between 15 and 20 percent of the producers registered in the database of PRODETER (121 interviews). Data includes socio-economic characteristics, family structure, economic incomes and outcomes from agricultural and non-agricultural activities, land use, food crops and yields, end use of crops (sale, self-supply), agricultural practices, peasant awareness of climate change, use of chemical and biological pesticides, fertilizers, and herbicides, agricultural infrastructure, and adoption of new technologies.

Following the MESMIS methodology, the first step was the characterization of the system including socio-economic and environmental features. The second step focused on identification of the critical points related to the attributes of productivity, stability, reliability, resilience, adaptability, equity, and self-reliance. The third stage was the selection of sustainable indicators and their corresponding normalization, these indicators should be flexible, easy to measure and to understand and should comprise social, economic, and environmental development (Table 1). The

last steps focused on diagnostic criteria based on the general attributes of sustainability and finally we analyzed and integrated all data and made recommendations.

Selection of indicators followed the structure proposed by the MESMIS methodology; each indicator was calculated according to the specific class and normalized to 100 as the optimal sustainable value.

Table 1. Sustainability attributes, critical points and indicators selected for the agricultural production systems.

Sustainability attribute	Critical point	Indicator[1]	Reference
Productivity	Sales from agriculture producers	(a-b) Total agricultural sales.	[20]
	Profitability	(c) Cost-Benefit Ratio [1]	[9], [20]
Stability Resilience and Reliability	External supplies	(d) Agricultural supplies	[20]
	Water supply	(e) Water access	[20]
	Fertilizers	(f) Organic Fertilizer	[1], [7], [20]
	Agrobiodiversity	(g) diverse crops in the same agricultural field	[20]
	Corn Seed variety	(h)Use of native, hybrid and GMOs seeds	[21]
	Associated crops seed variety.	(i)Use of native, hybrid and GMOs seeds.	[20], [21]
	Use of agroecological practices	(j)Agroecological practices	[20]
	Biocontrol	(k)Pests and diseases	[20]
	Sources of income	(l)Income diversification	[7], [20]
	Extension services	(m)Access to extension services	[7], [20]
	Farm desertion	(n)Permanence of workers	[20]
Adaptability	Education	(o)Educational level	[20]
	Global climate change	(p)Aware of the global climate change	[9], [20], [22]
	Availability and reuse of soil and water	(q)Management of natural resources	[20]
	Generation renewal	(r)Transmission of traditional agricultural techniques	[9]
	Technological adoption	(s) Scientific and technological innovation	[20]
	Infrastructure	(t) Machinery disponibility	[9]

Equity	Capacitation	(u)Agricultural advisory services	[20]
	Agricultural workforce	(v)Permanent workforce	[20]
	Agricultural workforce	(w)Temporal workforce	[20]
	Infrastructure distribution	(x)Equipment and machinery distribution in the community	[9]
	Income distribution	(y) Gini coefficient	[9]
	Gender equity	(z) Women participation	[20]
	Food security level	(aa) Fractional food security level for maize	[9]
Self-management	Agriculture system inputs	(ab)Pesticides	[20]
	Agriculture system inputs	(ac) Chemical fertilizers	[20]
	Agriculture system incomes	(ad) Average agriculture income	[20]
	Dependence of external inputs	(ae)Dependence of agrochemical and agriculture machinery	[9]
	Organization and participation	(af) Organization and participation	[9]

[1] Indicators for a agricultural production in the MESMIS schema.

The indicators are expressed as percentage of peasants for each parameter with the exceptions of fractional food security, permanent workforce, demand for temporary work force and income distribution. Each indicator was defined as follows:

a) Total agricultural sales (irrigation) were calculated considering all the agricultural profits. The parameters used for classification were peasants with lower profits than the second quartile, with a profit between second and third quartile and a yield higher than the third quartile. The average yield was calculated based on the last year, either from irrigated or rainfed fields.
b) Total agricultural sales (rainfed) were calculated considering all the agricultural profits.
c) Cost-Benefit Ratio (CBR) was calculated considering all the agricultural inputs divided by the total sales associated with agricultural activities for each producer.
d) Agricultural supplies were the average of consumables and capital inputs. Three levels were defined: lower than the first quartile, between the second and third quartile and greater than the third quartile.
e) Water access includes the natural water sources and irrigation canals available for agricultural activities. The parameters were defined as minimum when only rainfall was available; average when two different sources of water were accessible; and high when three or more sources of water were handy.
f) Three parameters were defined for fertilizers use: use only of organic fertilizer, employment of both mixed organic and chemical fertilizers and no-fertilizers.
g) Agrodiversity was classified as low when it was monoculture farming, medium when two crops were in the same farmland and high when more than two crops were cultivated together.
h) For corn seeds the parameters were defined as only native seeds, commercial seeds and a mix of native and commercial seeds.

i) For the associated crops (beans, squash, chili, and other crops) the parameters were: only native seeds, commercial seeds and a mix of native and commercial seeds.

j) For agroecological practices the parameters were low when no agroecological practices were used, medium when only one practice was implemented and high when two or more were adopted.

k) For pests and diseases, the parameter was defined as high when agriculture pests and diseases were present in corn and associated crops, medium when only corn was affected, and low when they were not detected in the farmland.

l) Income diversification was calculated as the number of income generating activities; it was defined as low diversification when the income was only from agricultural activities, medium diversification when the farmer, additional to agriculture, realized other remunerated activity and high diversification when he or she had at least two more productive activities in addition to agriculture.

m) For access to extension services, the parameter was defined as high when peasants received technical assistance, low when they did not receive it but had requested it and null when they did not receive assistance and they did not know with certainty if they need it.

n) For generational renewal, we considered workers as youths from 18 to 34 years, adults from 35 to 60 years and seniors older than 60 years.

o) Related to the educational level, inhabitants were classified in three levels according to their scholar level: uneducated, the ones that did not attend school; in the second level we included those who had elementary or junior high school studies and in the third level the ones with high school or college studies.

p) For the impact of global climate change we considered three groups of producers: those who were aware of global climate change and thought it had a big impact on their crops; a second group that thought global climate change did not affect their crops and a third group that did not know whether it had an effect.

q) Management of natural resources. Percentage of producers who cared about water and soil conservation. The parameter was classified as optimal if they had water and soil conservation practices; medium, if they had water or soil conservation practices, and non-conservation if they lacked conservation practices.

r) Generational transmission was the percentage of producers who thought agriculture traditional techniques, knowledge, and skills to the younger generations. The parameters were, high, low, and null.

s) Technological adoption was considered as the percentage of producers who had access to technological components, such as cell phones, internet, etc. The parameters were, high, low and null.

t) Infrastructure was the percentage of tractors and farm equipment available.

u) Agricultural advisory services were defined as the percentage of producers requiring training.

v) Permanent workforce was the number of family members who were permanent agriculture-workers per hectare per year, temporary workers were those hired. The optimal indicator was fitted to 3 workers per hectare.

w) Demand for temporary employment was the number of hired agriculture workers per hectare per year. The optimal indicator was fitted to 3 workers per hectare.

x) Distribution of machinery and equipment was the percentage of producers who own tractors and farm equipment.

y) The Gini coefficient was used to assess inequality. It is defined as [14], [15]:

$$I_G = \frac{\sum_{i=1}^{N-1} P_i - q_i}{\sum_{i=1}^{N-1} P_i}, \quad (1)$$

Where qi is the accumulated relative income of the sample for each system and Pi is the cumulative relative frequency of the population. In our case qi was the peasant's accumulated relative income by agricultural sales and Pi was the accumulated population, i.e. the number of members of the peasant's family. The Gini coefficient was calculated for the peasants owning rainfed farmlands and for those owning irrigated farmlands.

z) The Participation of women was the percentage of women peasants.

aa) Chemical pesticides corresponded to the percentage of peasants who used chemical pesticides.
ab) Chemical fertilizers corresponded to the percentage of peasants who used chemical fertilizers.
ac) The Fractional Food Security Level (FFSL) for corn was calculated as [9]:
This is an example of an equation:

$$FFSL = \frac{Y_C A_C}{200N}, \quad (2)$$

Where Yc is the corn yield in Kg/ha, Ac is the net corn-area cultivated and N is the number of peasant's family members. The value of consumption of corn per year is 200 Kg per person for food security level [23].

ad) Total income was the average income per peasant per year, including non-agricultural activities and income from sons and relatives.
ae) Dependence of external inputs was the percentage of peasants who used fertilizers, herbicides, fungicides, and agricultural machinery.
af) Organization was the percentage of peasants who are members of a peasant association.

3. Results

3.1. Characterization of the system

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

Socio-economic status (Table 2). Most of the inhabitants are "Hñahñus" (Otomi) speak Spanish and Hñahñu, live in nuclear families, and only a few of them live in extended families. The average age of peasants is 51 years, with elementary studies; in contrast their offspring and relatives have an average age of 30 years and have junior and senior high-school studies [24]. Typically, the peasants' farmland extensions are less than one hectare in Ixmiquilpan, and from 2 to 4 hectares in El Cardonal. Peasants usually own from 2 to 3 agricultural lands. In El Cardonal the farmland is rainfed while in Ixmiquilpan 95% have irrigation systems, based on the residual water from Mexico City. It is worth mentioning that in Ixmiquipan most of the agricultural lands are communal; in contrast in El Cardonal 70% are private properties. Even when parcels are very small these are not rented to other producers. Most noteworthy, migration plays an essential role in both municipalities; inhabitants migrate to other Mexican States or mainly to the USA, in order to improve their living standard. In El Cardonal 62% of the families have at least one member who migrated and 44% of the families in Ixmiquilpan.

Table 2. Socioeconomic indicators of El Cardonal and Ixmiquilpan municipalities..

Indicator	Level	Ixmiquilpan	Cardonal
Average age (years)	----	49 ± 11	53 ± 12
Education (%)	College	11.1	7.4
	Senior High School	27.7	7.4
	Junior High School	44.4	44.4
	Elementary School	16.6	25.9
	uneducated	0	14.8
Number of land parcels per peasant (%)	1	22.2	25.9
	2	33.3	40.7
	3	22.2	25.9

	4	5.5	3.7
	5	5.5	3.7
	6	5.5	0
	8	5.5	0
Farmland area (%)	0-1 Ha.	55.5	25.9
	1-2 Ha.	22.2	0
	2-3 Ha.	0	25.9
	3-4 Ha.	5.5	25.9
	4-5 Ha.	11.1	7.4
	5-8 Ha.	5.5	14.8
Land tenure (%)	Communal	73	30
	Private property	27	70
Estate in land (%)	Ownership	94	93.4
	Borrow	2	3.3
	Rent	4	3.3
Family members in household (%)	2	16.6	33.3
	3	22.2	33.3
	4	50	25.9
	5	11.1	7.4
Family members who migrated (%)	Yes	44.4	62.96
	No	55.5	37.03

[1] Tables may have a footer.

3.2. Sustainability attributes and critical points

3.2.1. Productivity

Productivity. The total agricultural sales from rainfed parcels is higher than that of irrigated parcels, although corn-yield is lower. Moreover, rainfed agricultural products include several crops, livestock and edible wild plants from milpa and wilderness, and edible insects; and those of irrigated systems are monocultures. Notably, the inputs including investment and agricultural supplies for both agricultural systems are similar (Table 3).

Table 3. Productivity indicators for El Cardonal and Ixmiquilpan municipalities.

Indicator	Class[1]	Ixmiquilpan	Cardonal	Sustainability Dimension[2]
Agricultural total sells (irrigation)	* High (irrigation) > $4.7 K/year	16	20	E
	*Medium (irrigation) $ 3.3K/year - $ 4.7K/year	33	20	E
	Low (irrigation) < $3.3 K/year	50	60	E
Agricultural total sells (rainfed)	*High (rainfed) > $4.7 K/year	33.3	22.7	E
	*Medium (rainfed) $ 3.3K/year -	33.3	31.8	E

	$ 5.9K/year			
	Low (rainfed) < $3.3IIII K/IIIyear	33.3	45.4	E
Cost benefit ratio(CBR).	Low < 1	27.7	29.6	E
	*High ≥1	72.2	70.4	E
Agricultural supplies	High > $1.7 K	27	33.3	E
	Medium $1.7K - $1.3 K	66.6	29.62	E
	* Low < $1.3K	33.3	37.0	E

[1] The cells indicated by an asterisk (*) are selected to compare Ixmiquilpan and El Cardonal municipalities
[2]Sustainability dimensions are EN: Environmental, E: Economic, and S: Social.

3.2.2. Stability, resilience, and reliability

Stability, resilience, and reliability. Water shortage, dry land, and drought, move the peasants to other strategies to have stability in their crops, such as polycultures and use of natural fertilizers to maintain their production, either for self-consumption or sales. Usually, the crops come from native seeds in rainfed farmlands and commercial seeds in irrigated lands. It is worth mentioning that peasants in rainfed systems use agroecological practices, including minimum tillage, natural fertilizers, corn and associated crops and pest-repelling plants (Table 4). Notwithstanding pests and phytopathogens are an important problem mainly in the irrigated farmlands, identification and biological control of pests and diseases in both agricultural systems could increase resilience.

Table 4. Stability, resilience, and reliability indicators for El Cardonal and Ixmiquilpan municipalities.

Indicator	Class[1]	Ixmiquilpan	Cardonal	Sustainability Dimension[2]
Water resources	(residual water and underground water)	11.1	3.7	EN
	Medium (residual water)	72.2	14.81	EN
	Low (Rainfall)	16.6	84.48	EN
Fertilizers.	* Organic	100	92.6	EN
	Mixed	0	11.1	EN
	Null	0	7.4	EN
Agrobiodiversity	Low (monoculture)	0	11.1	EN
	Medium (Two crops)	27.7	37.03	EN
	* High (Three or more crops)	72.3	51.81	EN
Corn Seed variety	* Native	73.3	87.5	EN
	Hybrid	26.6	12.5	EN
Seed variety of associated crops	* Native	70.9	87.32	EN
	Hybrid	23.6	8.45	EN
	Mixed	5.4	4.22	EN
Agroecological	Null	16.6	29.62	EN

practices				
	Medium	27.7	25.92	EN
	* High	55.5	44.4	EN
Pests and diseases	* Null	16.6	33.3	EN
	Medium	2	0	EN
	High	81.4	66.6	EN

[1] The cells indicated by an asterisk (*) are selected to compare Ixmiquilpan and El Cardonal municipalities
[2]Sustainability dimensions are EN: Environmental, E: Economic, and S: Social.

3.2.3. Adaptability.

Adaptability. This attribute is the main bottleneck for both municipalities. Although smallholder farmers have noticed a climate change, they are not aware and have not yet adopted some new strategies. Conservation of soil is a concern for few, but for all of them water supply is the most important problem. However, they do not have a plan for water management, and neither for diversification of water sources. Even more, in both municipalities, traditional knowledge is scarcely transmitted to the new generations and it is being lost, since the youths abandon the farmland and the communities (Table 5).

Table 5. Adaptability indicators for El Cardonal and Ixmiquilpan municipalities.

Indicator	Class[1]	Ixmiquilpan	Cardonal	Sustainability Dimension[2]
Income diversification	* Low	72.3	44.5	S
	Medium	27.7	55.5	S
	High	0	0	S
Access to extension services	* High	16.6	22.2	S
	Low	77.7	37.14	S
	Null	5.5	29.62	S
Generational renewal	* Youth workers 18 - 34 years	5.5	3.7	S
	Adult workers 35 - 59 years	72.2	62.96	S
	Senior workers ≥ 60 years	22.2	33.34	S
Educational level	Uneducated	0	14.81	S
	Elemental and Junior High School	61.1	66.6	S
		38.8	18.51	
	* Senior high school and College	38.8	18.51	S
Impact of global climate change (GCC)	Aware of GCC with impact.	16.6	14.81	EN
	* No impact	38.8	40.74	EN
	Unknow	44.4	44.4	EN
Management of natural resources.	* Optimal	50	25.92	S
	Medium	44.4	25.92	S
	Non conservation	5.5	48.14	S
Generational transmission	* High	5.5	3.7	S

	Low	72.2	62.96	S
Technological adoption	Null	22.2	33.3	S
	* High	27.7	11.1	S
	Low	61.1	81.48	S
	Null	11.1	7.40	S

[1] The cells indicated by an asterisk (*) are selected to compare Ixmiquilpan and El Cardonal municipalities
[2]Sustainability dimensions are EN: Environmental, E: Economic, and S: Social.

3.2.4. Equity.

Equity. Equity focuses mainly on social justice and profit distribution. Labor cost and operation cost per hectare are similar in both municipalities. However, the distribution of benefits indicates an inequity of profits distribution, with 0.26 for Ixmiquilpan and 0.44 for El Cardonal. This coefficient is the same for irrigation or rainfed parcels in Ixmiquilpan, but it is different in El Cardonal for irrigated parcels (0.24) and the rainfed ones (0.46). Indeed, since the profit equity is higher in El Cardonal for rainfed agriculture, the introduction of irrigation systems could have a negative impact on equity. On the other hand, women are the 18 percent of the small producers in El Cardonal and almost 27 percent in Ixmiquilpan (Table 6); in fact, cultural and legal discrimination prevent them from accessing productive assets, finance, education and technology. Nonetheless, a feminization of agriculture exists, since males migrate, leaving women in charge of the agricultural work (Table 6).

Table 6. Equity indicators for El Cardonal and Ixmiquilpan municipalities.

Indicator	Class[1]	Ixmiquilpan	Cardonal	Sustainability Dimension[2]
Infrastructure	* High	17.1	18.51	E
	Medium	68.5	44.4	E
	Null	14.2	37.03	E
Agricultural advisory services	Request	57.14	62.96	S
	*Does not request	40	33.3	S
	Null	2.8	3.7	S
Permanent workforce	*Family members per ha	1.43	1.95	S
Demand for temporary workforce	* Wages per ha	2.16	2.29	S
Distribution of machinery and vehicule.	*Own (tractor)	15.6	7.4	E
	*Borrowed (tractor)	5.5	3.7	E
	*Rented (tractor)	61.1	77.7	E
	Null (tractor)	16.6	11.1	E
	Own (veh)	77.7	66.6	E
	Borrowed (veh)	0	0	E
	Rented (veh)	0	0	E
	Null (veh)	22.2	33.3	E
Income distribution (Gini coefficient)	* Total agricultural activities	0.2623	0.4455	E
	Irrigation system	0.2296	0.2494	E

	Rainfed system	0.2234	0.4681	E
Women participation	* Woman	27.7	18.51	S

[1] The cells indicated by an asterisk (*) are selected to compare Ixmiquilpan and El Cardonal municipalities
[2]Sustainability dimensions are EN: Environmental, E: Economic, and S: Social.

3.2.5. Self-Management and self-sufficiency.

Self-Management and self-sufficiency. The autonomy of peasants in the control of their crops and household economy refers to self-management and self-sufficiency. The farmer's decision on use of external agricultural supplies depends on price and availability of seeds, agrochemicals, and other products with local suppliers. Every one purchases by himself, usually at a very high price what he or she can find, since they are not organized. In Ixmiquilpan, more than half of the peasants use chemical fertilizers, pesticides, and commercial seeds in their irrigated parcels; in contrast only 18% of peasants use chemicals in El Cardonal. At the same time, the corn-fractional food self-security (i.e., the extent to which the peasants can satisfy the corn needs of their families from their own domestic production) is sufficient for 51% of peasants in El Cardonal and 70% for Ixmiquilpan. The average agricultural income is above $1500 US dollars/year in both municipalities (Table 7).

Table 7. Self-management and self-sufficiency for El Cardonal and Ixmiquilpan municipalities.

Indicator	Class[1]	Ixmiquilpan	Cardonal	Sustainability Dimension[2]
Pesticides	Yes	44.4	44.4	EN
	* No	55.6	55.6	EN
Chemical fertilizers.	Yes	61.1	11.1	EN
	* No	38.8	88.8	EN
Fractional food security level (corn Kg/population)	* Higher ≥200	70	51.8	S
	Average 199 -100	2	3.7	S
	Under < 100	28	48.14	S
Agricultural income	* above average (>$1.5K/year)	94.4	77.7	E
	in the mean ($1.5K-$770 per year)	5.5	18.5	E
	below average (<$770 per year)	0	3.7	E
Dependence of external inputs	High (2 or more supplies)	44.4	7.4	E
	Medium (One supply)	27.7	40.7	E
	* Null	27.7	51.8	E
Organization	* Intention	66.6	62.96	S
	No intention	5.5	22.22	S

[1] The cells indicated by an asterisk (*) are selected to compare Ixmiquilpan and El Cardonal municipalities
[2]Sustainability dimensions are EN: Environmental, E: Economic, and S: Social.

3.2.6. Radar chart

Results from our study were summarized in a radar chart (Fig. 2), where we selected the indicator values pointed with an asterisk in Tables 3 to 7. Each indicator was plotted on a relative scale from 0 to 100%; the optimal value expected for the radar chart is 100%. This chart allows us to identify the critical points per attribute. The attribute adaptability is minimal for both municipalities, as all the indicators are below 40% excepting income diversification. In contrast, stability-resilience-reliability are close to the optimal values in El Cardonal (three indicators: native corn and associated crop seeds, organic fertilizers, null use of chemical fertilizers) and in Ixmiquilpan (four indicators: native corn and associated crop seeds, organic fertilizers, and agrobiodiversity). Also, three indicators of equity attribute are over 50% (permanent workforce, distribution of machinery and vehicles and temporal workforce) in both municipalities.

There is an important difference between both municipalities on dependence of external inputs; El Cardonal has a dependence of less than 50% while Ixmiquilpan has 73%. In the case of self-management, the most relevant indicator for Ixmiquilpan is the average agricultural income, with a value of 92%, while for El Cardonal it was the null use of chemical fertilizers. On the other hand, the organization indicator was similar for both municipalities, as well as the cost-benefit ratio, although the total agricultural sales were slightly higher for Ixmiquilpan for both rainfed and irrigated parcels (Fig 2).

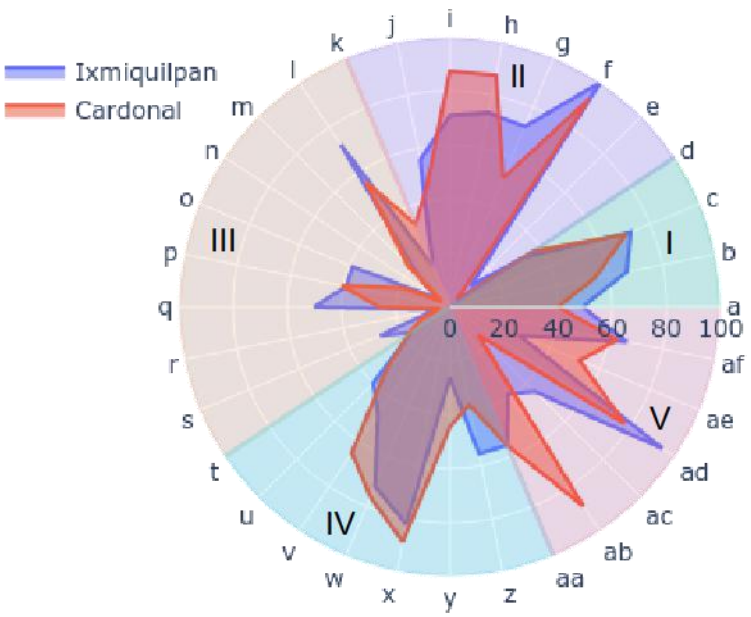


Figure 2. Indicators of sustainability for Ixmiquilpan and El Cardonal municipalities. Each color sector corresponds to an attribute, starting in indicator "a" and continuing in an anticlockwise direction. Attributes are: (I) productivity, (II) Stability, resilience and reliability, (III) Adaptability, (IV) Equity, and (V) Self-management and self-sufficiency. The indicators are: (a) Agricultural total sales (irrigation), (b) Agricultural total sales (rainfed), (c) Cost-benefit ratio(CBR), (d) Agricultural supplies, (e) Water access, (f) Fertilizers, (g) Agrobiodiversity, (h) Corn Seed variety, (i) Seed variety of associated crops, (j) Agroecological practices, (k) Pests and diseases, (l) Income diversification, (m) Access to extension services, (n) Generational renewal, (o) Educational level, (p) Impact of Global Climate Change (GCC), (q) Management of natural resources, (r) Knowledge Generational knowledge transfer, (s) New technology adoption, (t) Infrastructure, (u) Agricultural advisory services, (v) Permanent workforce, (w) Demand for temporary workforce, (x) Distribution of machinery and vehicles, (y) Income distribution (Gini coefficient), (z) Women participation, (aa) Pesticides, (ab) Chemical fertilizers, (ac) Corn-fractional food security level (corn Kg/population), (ad) Income from Agriculture, (ae) Dependence of external inputs, (af) Organization.

Since rainfall is minimal in both municipalities (lower than 150 mm per year), water availability is critical for agriculture and thus for stability, resilience, and reliability (Fig 2). This indicator is higher in Ixmiquilpan than in El Cardonal, because the fields are irrigated there with wastewater from Mexico City; also underground water is used, but it represents only 7% of water availability [25]. Regarding the diversity of crops in the parcels, peasants in Ixmiquilpan usually own two parcels; in one they grow a single crop and in the second they plant milpa. On the other hand, peasants from El Cardonal have mainly milpas, which include agaves. In both municipalities, mainly native seeds are planted in the milpa system and agroecological practices are mostly utilized; animals graze in the field and manure is left as natural fertilizer. These practices have been developed for centuries and are inherited from parents to sons. However, both agricultural systems are vulnerable due to pests and diseases, lack of extension services and shortage of generation renewal. It is worth mentioning that pests and diseases are a bigger problem is monoculture systems.

4. Discussion

The evaluation of sustainability through the MESMIS methodology involves different attributes, which allow us to design strategies and identify critical points for the implementation of programs for agricultural sustainability. In both municipalities, the agricultural sales are low, but the total incomes are high; therefore the cost-benefit is in a medium range. This discrepancy is due to the financial transfers by migrants. The critical points identified in both municipalities belong to three attributes, which are adaptability, equity and self-management and self-sufficiency. All these attributes indicate an economic and food security fragility, associated to the inequity of income distribution and low corn-fractional food security level (Fig 2.). Fragility is understood as the vulnerability of small farm holders to changes or uncertainty in the economic, social, and environmental conditions [26]. The external factor migration has the most important impact on both economic and social fragility (Fig. 3). In 2015, injection of remittances represented from 9.0 to 14.6% of the gross domestic product of Ixmiquilpan municipality and 14.6 to 36.2% in the Cardonal municipality [27]. This economic input reduces the likelihood of the family members to continue agricultural activities, and the absence of generational renewal. Indeed, it decreases the possibility to transfer the traditions and cultural practices to young generations, affecting the adoption of new technologies and appropriation of new solutions to improve agriculture yields and sustainability.

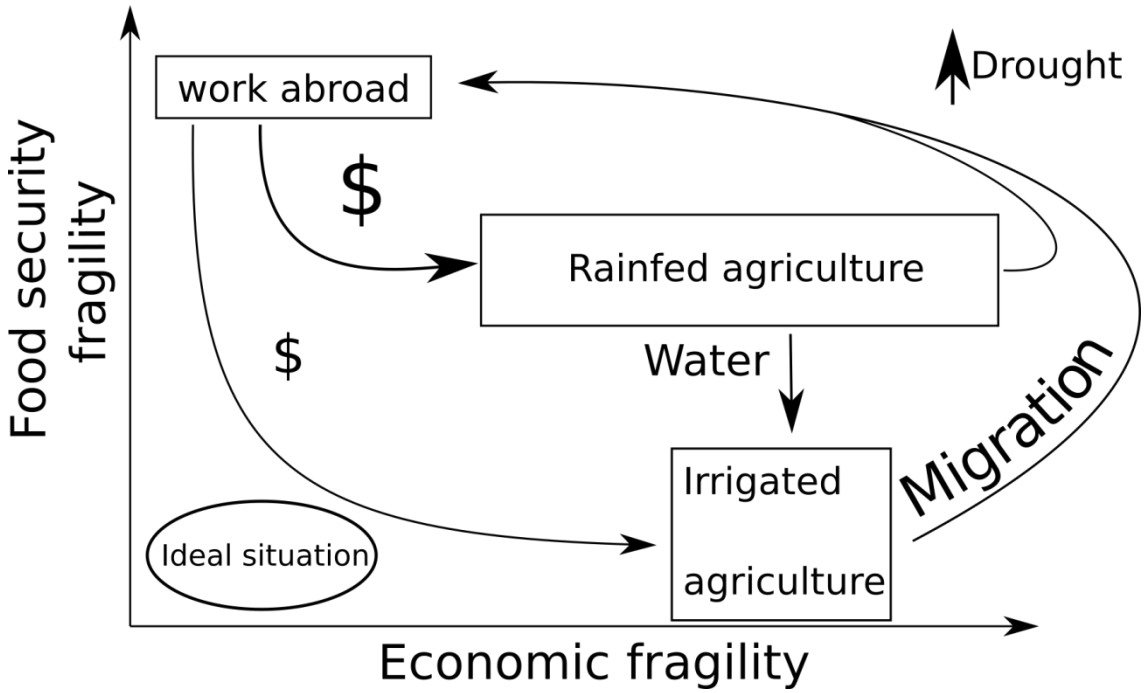


Figure 3. Model of interactions between economic and food security fragilities.

In addition, since the small-scale producers in Ixmiquilpan depend on external agricultural supplies and their agricultural infrastructure is scarce, the remittances lead to an unsustainable economic cycle, increasing the fragility of agricultural system (Figure 3). On the other hand, in El Cardonal, money injection does not compensate the low agriculture yield and the producers must diversify their activities to be able to satisfy their food necessities, and as a result they neglect their farmlands. Thus, remittances increase the vulnerability of agriculture.

Furthermore, the increase of food security fragility is affected by insufficiency of water, decrement of native corn consumption and introduction of foreign food products to the diet, by peasants' relatives. These industrialized food products are also purchased by the peasants with remittances.

Previous studies developed on mezquite tree (Prosopis laevigata) in community of Ixmiquilpan [28], also pointed to the influence of migration on the stability and reliability attributes, on the lack of generational knowledge transmission that affects the adoption of traditional techniques by new generations. Also, the untreated wastewater irrigation system in the Ixmiquilpan (Mezquital Valley) impacts agriculture both in positive and negative ways, as it has a negative effect on the inhabitants health, and increases the vulnerability to climate change [29]. Indeed, the increment of agricultural yields due to waste water irrigation is linked to a high investment on supplies, unsafe food products and diseases and malnutrition, particularly affecting infants, young children, elderly and the sick, and finally affecting the economic income. [30] The social problems related to health are a critical point for the development of dry lands.

In the environmental context, Luján Soto et al. recommend a combination of techniques to regenerate the drylands [31], such as the reforestation of local crops, like agave or cactus and technical services for control of plagues and phytopathogens. In this context the adoption of climate smart agriculture has impacts in carbon sequestration and biodiversity conservation; indeed it could generate additional incomes for the small holders by ecosystem services [32].

The vulnerability of the agricultural system to crop pests and diseases needs also to be addressed, as it reduces productivity and the associated profits, forcing peasants to seek other economic activities such as trade, construction or other jobs, and ultimately migration. In addition, the lack of technical services adequate to the territorial development and management is a bottleneck, which hinders more effective agronomic practices. Furthermore, technical services are also needed to apply other agroecological practices for solving problems such as optimal use of water resources and pest and diseases control. This lack of technical services, together with the economic problems, contribute to breaking the generation renewal, and force the youth to migrate to find a better life.

The recommendations for both municipalities, to reduce the food security fragility, are implementation of integral systems management and water acquisition including rainfall capture, underground water, and treated wastewater, as well as implementation of efficient irrigation systems for decreasing water and energy consumption. These innovations should integrate traditional knowledge and modern science and technology for sustainable development including producers, youths, men and women; the organization of small farm holders is crucial for the development of long term sustainability projects.

Other long term sustainable recommendations are: 1) promotion of polycultures in the region using native plants to increment food security, and lead to a robust economic income; 2) development of rural enterprises, owned by the producers and their families to increase the values of agricultural products, 3) producer's associations to acquire machinery and other infrastructure adequate to their necessities and worldview. 4) appropriation by producers of the supply chain and distribution channels. In this way, the small farm holder would not depend on remittances, and migration would decrease since youths would find what they need in their communities, and the communities could have sustainable development.

These recommendations are aimed at increasing the economic sustainability of milpa agricultural productivity and their resilience to climate change. More robust and profitable milpas would be more attractive to young farmers, stimulating the cross-generational continuity of this ancestral farming system. In that context, migration would turn from a necessity to an option for the youth of the region. Also, a more productive milpa system would encourage those that do migrate, to invest more of their income to the milpas of their families. Thus, by strengthening the milpa

system, the fragility of the socio-economic system of the region would be improved overall, with less migration, and more regional benefits from those that do migrate. Finally, a strengthened milpa could bring robustness for the region in the case of macroeconomic disturbances, as it would ensure food security, in terms of self-nourishment, to the people from the region, if other sources of income were to be disturbed.

In summary: 1) adaptability is a critical factor in both municipalities and it does not depend on economic factors, rather the main problem is youth migration. 2) Access to water, and economic resources as well as management of environmental resources are an imperious need to increase the yield of agriculture crops and equity. 3) Strengthening of resilience requires organization of small producers and the combination of indigenous and modern technologies to design technologies for the territorial development of the communities. 4) The social adaptation of both communities are in a critical level, due to the generational brake between peasants and peasant sons that migrate for a better life quality, interrupting the transmission of traditional knowledge to the youth generations, losing their culture and traditions. 5) The productivity depends in a majority of the agricultural supplies affecting their CBR, leading a same value for rainfed and irrigation agriculture.

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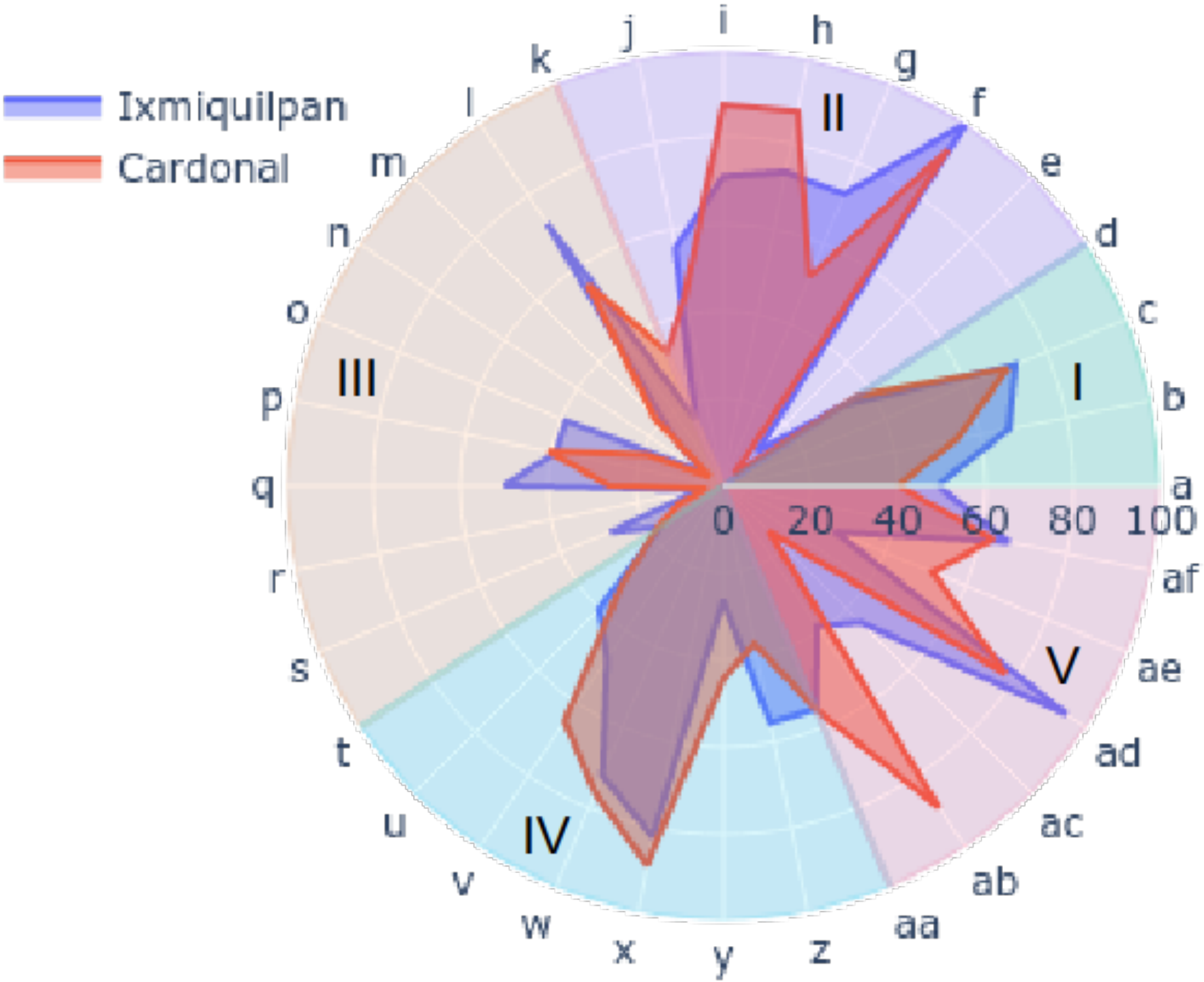
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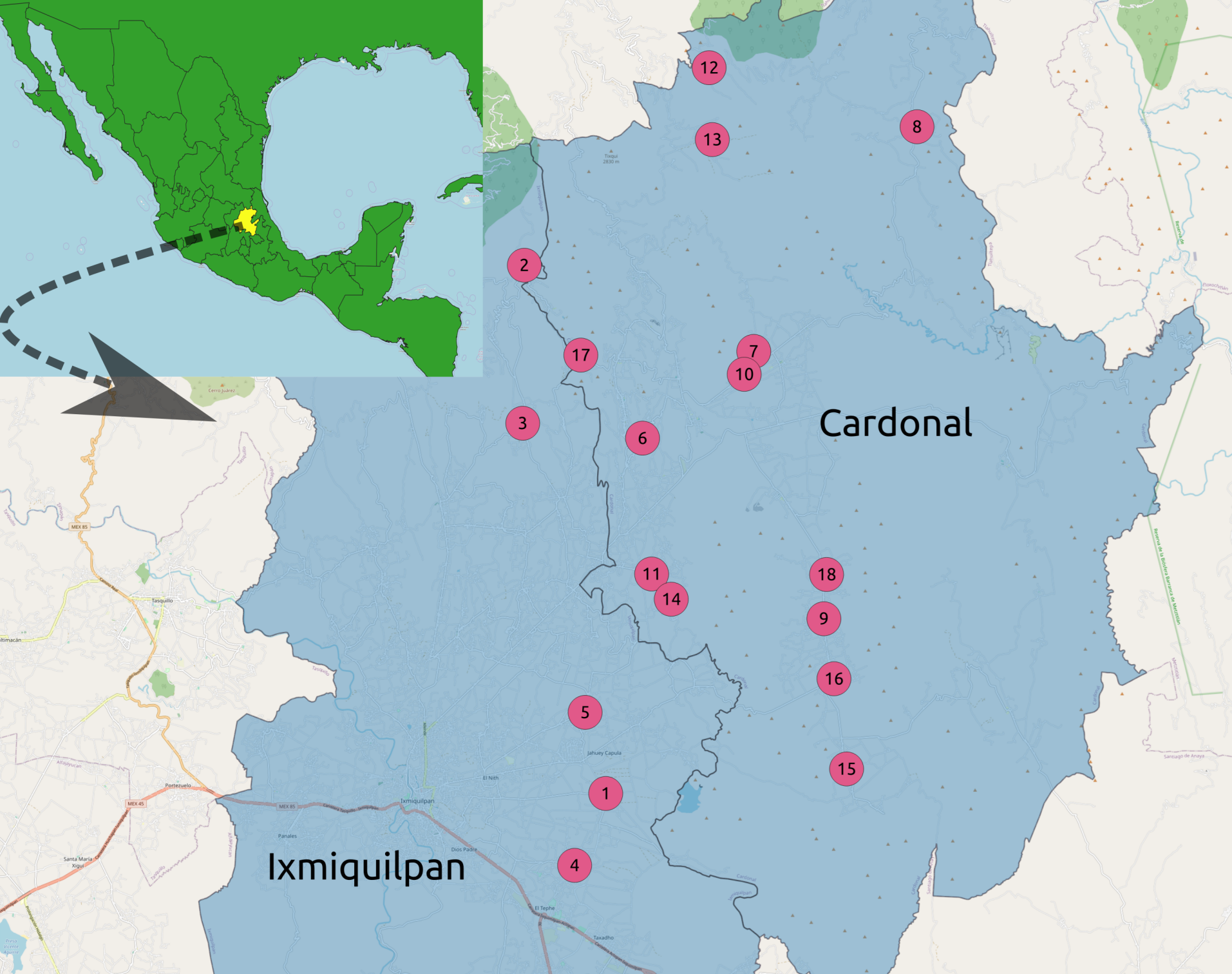

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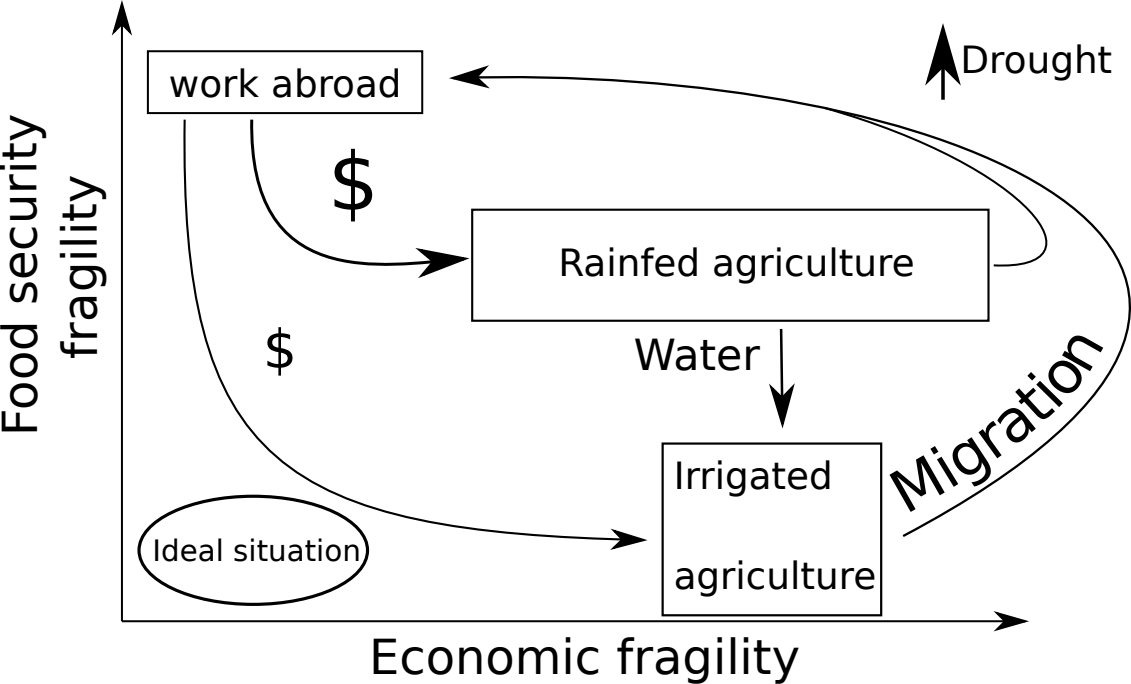
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