

SUSTAINABILITY OF THE CORN AGROECOSYSTEM IN TWO TYPES OF PEASANT MANAGEMENT IN CHIGNAUTLA, PUEBLA

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ABSTRACT

The use of indicators allows measuring the variables of sustainability, and facilitates decision making. The objective of this study was to evaluate two types of management of the corn agroecosystem: polycrop (PcS) and monocrop (McS). Fourteen indicators were assessed through the MESMIS methodology taking into consideration the 2019-2020 cultivation cycle. A survey was applied to a random sample of n=65 peasants. As a result of the assessment, the PcS obtained 68 percentage points, and the McS obtained 60. In addition, the PcS obtained higher yield, with an average of 1.8 tons per hectare (t ha⁻¹) as product of crop association. Likewise, the PcS stood out in grass and corn grain harvested, equivalent use of land, agroecological practices index, agrobiodiversity index, and independence of external inputs. Family livestock production is an important characteristic of the agroecosystem in the zone and the McS generated higher revenues derived from this activity, with an average of \$30,434.30 annually. The proportion of permanent jobs among peasant families was 45% (PcS) and 48% (McS) and the innovation level was low in both cases. It is concluded that the PcS has greater tendency toward sustainable management, which highlights the importance of revaluing this type of agroecosystems, whose productive potential strengthens food sovereignty.

Keywords: ecological crisis, self-sufficiency, subsistence agriculture, sustainable development.

INTRODUCTION

Population growth implies a growing demand of foods, and to face this scenario, an evident increase in agricultural areas is anticipated (FAO, 2017), while the opportunities to test new productive and conservation strategies are increasingly more limited (Hunter *et al.*, 2017), especially in rural areas where close to 40% of the global population lives, which depends primarily on agricultural production for its sustenance (Sotelsek and Laborda, 2019).

The transition towards sustainable agricultural systems is based on holistic approaches, such as Agroecology, whose potential to contribute with the sustainable development goals (SDG) is increasingly recognized (Barrios *et al.*, 2020). A sustainable agroecosystem is a food and raw material production unit where external inputs are substituted by natural processes, such as natural soil fertility and biological control. This favors a greater productivity, emphasizes the conservation of natural resources, and involves social, cultural and economic aspects of the peasantry (Fonseca-Carreño, 2022).

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Gliessman (2020) indicated that the agroecological approach helps to deal with the vulnerabilities of the agrifood system that have manifested since the COVID-19 pandemic, in order to guarantee access to local foods and at the same time promote social movements and changes in public policies. In addition, peasant systems and their traditional lifestyles, knowledge and cultural understandings are associated with the conservation of the diversity of crops. However, traditional practices present a trend toward disappearance, due to the growing implementation of modern agriculture techniques, based on productive specialization and mechanization (Fonseca-Carreño, 2022).

Studies conducted by González *et al.* (2018) in the municipality of Chignautla have evidenced a continuous deterioration of the soils associated with anthropogenic activities. These soils present some degree of erosion, including the rainfed agricultural areas, and the authors attribute the erosion present to poor agricultural practices with corn, fava bean and fodder monocrops, among other factors and other activities such as livestock overgrazing. In addition to this, the simplification of agroecosystems to increase productivity brings with it soil degradation, contamination of underground water, and a continuous loss of biodiversity (Tissier *et al.*, 2016). All of this constitutes a threat to sustainability in the region.

The objective of this study was to evaluate the sustainability of the peasant corn agroecosystem in its two types of management: monocrop and polycrop, in two communities of Chignautla, Puebla.

MATERIALS AND METHODS

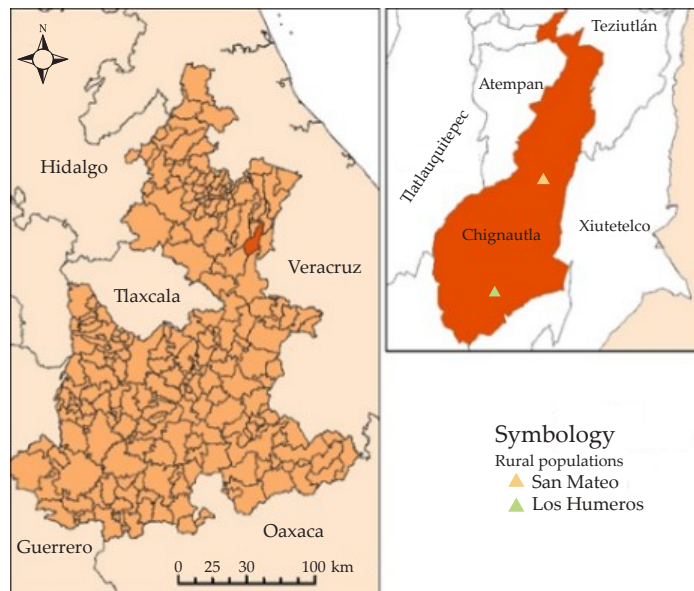
Characteristics of the study zone

The study was conducted in the municipality of Chignautla, located in the northwest of the state of Puebla, on parallels 19° 39' 18" and 19° 51' 12" N, and meridians 97° 22' 18" and 97° 29' 4" W. It borders east with the municipality of Xiutetelco, northeast with the municipality of Teziutlán, north with Hueyapan, west with Têteles de Ávila Castillo and Tlatlauquitepec, and southwest with the municipality of Cuyoaco (INEGI, 2010).

The study area includes the communities of Los Humeros and San Mateo, located south of the municipality (Figure 1). This area presents an altitudinal gradient of 2,460 to 3,150 m above the average sea level. Rainfed agriculture is developed, whose axis in agricultural activity is the production of basic crops such as bean and corn. Creole corns adapted to the conditions of the zone are cultivated, among which white, yellow, blue, purple and red corns stand out. Corn growing is carried out in two types of management: monocrop and polycrop systems or the milpa system, where it can be interspersed with bean (*Phaseolus vulgaris*), squash (*Cucurbita argyrosperma*), or broad bean (*Vicia faba*). The latter is also cultivated in monocrop.

Sampling

An observational study was carried out and the universe considered was the registry of recipients of the federal PROAGRO-2018 program, for the municipality of Chignautla,



Source: Prepared by the authors.

Figure 1. Localization of the study area.

with $N=122$ recipients, of which 90% are corn producers from Los Humeros and San Mateo. To calculate the sample size, the following formula for finite populations was used:

$$n = \frac{NZ_{\alpha/2}^2 * pq}{Nd^2 + Z_{\alpha/2}^2 * pq}$$

where N : total population (122); $Z_{\alpha/2}$: critical value of the standard normal distribution (1.96); p : approximate proportion of the phenomenon under study in the population (0.9); q : proportion of the population that does not present the phenomenon under study ($1-p=0.1$); d : absolute level of accuracy (0.05).

The application of the formula had the result of a sample size of $n=65$ corn producers. Due to their characteristics in management, 43 were classified in the polycrop system (PcS) and 22 in the monocrop system (McS).

Research techniques

With the objective of understanding the physical and social context, as well as the interactions and connections between stakeholders and their environment, a semi-structured interview as applied to 21 key informants (municipal, *ejido* and communal authorities, members of the vigilance council, people who exercised some position in their community, representative producers found through local public workers, technicians and

representatives of institutions). Likewise, direct observation was carried out in agricultural plots. To obtain information related to the physicochemical properties of the soil, field soil sampling was done, and in addition a survey was applied to the peasant sample selected, $n=65$.

Methodological approach

Given the multidimensional nature of sustainability, this research was approached from a theoretical approach to Agroecology, considering the agroecosystem as a fundamental unit of analysis. The study was transversal on the same time scale (agricultural cycle 2019-2020), and two types of management of the corn crop: PcS (reference system) and McS (alternative system).

The Framework for the Evaluation of Systems of Natural Resource Management incorporating Sustainability Indicators (*Marco para la Evaluación de Sistemas de Manejo de Recursos Naturales incorporando Indicadores de Sustentabilidad*, MESMIS) proposed by Masera *et al.* (2000) was used as methodological tool, which consists in a six-step operative structure for each assessment time: 1) determination of the study object, 2) determination of critical points of the system, 3) selection of strategic indicators, 4) measurement and monitoring of indicators, 5) presentation and integration of results and 6) conclusions and recommendations.

Fourteen indicators were selected, of which six belong to the economic sphere, three to the environmental area, and four to the social sphere, and one indicator about the proportion of permanent jobs per family belonging to the economic-social area.

A Welch *t*-test for independent samples was conducted to compare the means of the groups.

RESULTS

The results are presented following the six steps of MESMIS, and the two types of management are described.

Characterization of the management systems

Polycrop system (PcS): Of the corn producers, 23.3% do not have any level of schooling, 39.5% have primary school, 18.6% finished secondary school, 4.7% reached high school, 7% have studies at the technical level, and 7% have university education. The average age of the interview respondents was 51 years and only 11.6% of the interview respondents are younger than 30 years. The land ownership regime of rural producers is social property in 95.4% of the area, followed by private property with 4.7%. The peasants from this group use Creole varieties of corn, bean and squash, and on average the surface planted is 3.5 ha per producer and the average yield is 1.4 t ha⁻¹ of corn, 0.3 t ha⁻¹ of bean, 0.2 t ha⁻¹ of squash, and 0.5 t ha⁻¹ of broad bean.

Monocrop system (McS): Of the interview respondents, 13.6% do not have primary school, 45.5% had access to primary education, 27.3% described having secondary

education, 9.1% went to high school, and 4.6% have a technical level. The proportion of interview respondents without basic education agrees with the information reported by the National Institute for the Evaluation of Education (*Instituto Nacional para la Evaluación de la Educación*, INEE, 2016) for rural zones whose proportion of illiteracy is 13.2%. The producers from this group cultivate Creole corn, and the average surface planted is 3.2 ha per producer with average yield of 1.2 t ha⁻¹.

Table 1 presents details of the biophysical context, as well as the general characteristics of compared agroecosystems.

Table 1. Determinants of the agroecosystems.

Determinants of the agroecosystem		Polycrop system (reference)	Monocrop system (alternative)	
Biophysical	Climate	C(w): mountainous temperate humid and sub-humid, with mean annual temperature of 17.5 °C, with frosts (-3.3 °C) from October to March, humid season from May to October, and annual precipitation of 380–680 mm		
	Geology	Geological substrate of volcanic origin from the Mesozoic such as limestone and shales from the Late Jurassic.		
	Altitude	2400–2700 m (San Mateo) and 2700–2880 m (Los Humeros), above the average sea level.		
	Soils	Regosols associated with Andosols predominate, known for their volcanic origin, and Leptosols.		
	Vegetation	Pine forests, pine-oak forests with secondary vegetation, xerophile shrub, and induced grassland.		
Technological and management	Managed species and varieties	Different Creole corns associated with climbing bean or broad bean, and squash.	Corn: Yellow and White.	
	Dominant species	Corn in the milpa system	Corn in monocrop	
	Traction	Farming	Animal traction	Rent of agricultural machinery or animal traction for soil preparation with manual sowing
		Farming tasks	Manual sowing	
	Soil management	Soil conservation practices	Yes	Yes
		Fertilization	Manure and chemical fertilization (DAP and urea)	Manure and chemical fertilization (DAP and urea)
	Management of pests and diseases	Prevention or control is not done	Use of pesticides to control yellow underwing	
Management of weeds	Manual weeding	Use of glyphosate		
Socioeconomic	Livestock management	Poultry, pigs, sheep and cattle	Mainly pigs and sheep	
	Total surface	4.2 ha	4.9 ha	
	Main objective of the production	Auto-consumption with sale of surplus		
	Type of workforce	Family and external for sowing and harvesting		
	Organization for the production	Does not belong to any productive organization		

Source: prepared by the authors with information from key stakeholders.

Identification of critical points

For the second step of the MESMIS, eight critical points of the management systems of the agroecosystem were identified, as presented in Table 2. The diagnosis criteria and the strategic indicators were identified from each attribute, and the measurement method and area to which they belong were defined.

With the information generated in the field through the different techniques, results were obtained for each indicator per attribute.

Table 2. Critical points, diagnosis criteria, and indicators for the evaluation of the sustainability of the agroecosystems.

Attribute	Critical points as research themes	Diagnosis criterion	Indicator	Area	Method of data collection
Productivity	Low agricultural productivity and low profitability	Energetic and economic efficiency	1. Yield by management system (t ha ⁻¹)	E	Survey, interview
			2. Amount of grain and fodder harvested (t ha ⁻¹)	E	Survey, interview
			3. Percentage (%) of families that have a livestock production activity	E, S	Survey, interview
			4. Annual income from sale of livestock by management system (\$)	E	Survey, interview
			5. B/C (benefit–cost) rate by ha	E	Survey, interview
			6. Equivalent use of land (EUL) (EUL>1)	E, A	Survey
	Contribution of family workforce in the production process	Conservation of jobs	7. Percentage of permanent jobs per family	E, S	Survey
Stability, resilience and reliability	Low level of soil conservation	Conservation of natural resources	8. Agroecological practices index (0-1)	A	Survey, direct observation and interview
			9. Physicochemical properties of the soil (%)	A	Field sampling
			10. IDA: Index of agrobiodiversity (0-1)	A	Survey
Adaptability (flexibility)	Low level of innovation	Capacity for change and innovation	11. Index of adoption of new techniques (appropriation of technological innovations) (0-1)	S	Survey, interview
	Loss of traditional knowledge	Use of ancestral techniques	12. Index of ancestral techniques in use (0-1)	S	Survey, interview
Equity	Low participation of the new generations in activities of the agroecosystems	Inter-generational equity	13. Inter-generational replacement: Proportion of younger members of the family in the agroecosystem (0-1)	S	Survey

Table 2. Continuation.

Attribute	Critical points as research themes	Diagnosis criterion	Indicator	Area	Method of data collection
Self-reliability (Self-management)	High dependency on government backing for the production and low economic resources available	Dependency on external resources	14. Dependency on external inputs (%)	S	Survey

Source: prepared by the authors.

Productivity **Yield by cultivation system**

The grain corn harvested per hectare reported by the survey respondents was considered, as well as the yields of associated crops in each production unit (bean, squash, broad bean). Average yields of 1.8 t ha⁻¹ (PcS) and 1.2 t ha⁻¹ (McS) were calculated. Regarding the optimal value (4.5 t ha⁻¹), taken from Ebel *et al.* (2017), the scores from the polycrop and monocrop systems were 40% and 27%, respectively, and this highlights the productive potential of crop associations compared to monocrops.

Amount of grain and fodder harvested

The mean of the amount of corn stubble and grain harvested was 3.8 t ha⁻¹ in the PcS and 2.7 t ha⁻¹ in the McS, and values of 74% and 43%, respectively, were obtained with the relation to the optimal value of 6.22 t ha⁻¹ (Muñoz-Tlahuiz *et al.*, 2013).

Percentage of families that have livestock production activities

Of the interview respondents, 100% from the McS and 95% from the PcS developed some type of livestock production activity; therefore, both were located in an optimal level of this indicator. This activity is characterized by breeding hens, Creole turkeys, sheep, Creole pigs, cows and horses. The maximum number of species managed by family is six. The production of native species should be highlighted, such as turkey in both management systems, which is of great sociocultural, economic and dietary relevance in the rural sphere.

On the other hand, some livestock species such as horses are used as traction in activities of the agroecosystem and as transport.

Income from animal sale by management system per year

In the PcS, the mean of annual income was \$20,184.20, while in the McS the annual income was \$30,434.30 during the period of January 2019 to January 2020. The criterion to establish the optimal was the maximum income reported in the study zone, that is, \$30,434.30. All the interview respondents from the McS mentioned selling the livestock,

while only 84% in the PcS reported selling the species that they bred. That is, the remainder 16% destines the animals they breed to auto-consumption.

Benefit-cost rate per hectare

First, the system's incomes were listed, according to the following segments: income derived from crop harvest (corn grain and stubble, squash, bean, broad bean), and on the other hand, the expenditures derived from the workforce for the tasks of soil preparation, sowing, farming tasks and harvest; likewise, the costs for the purchase of basic incomes for production were counted: seed, organic (manure) and synthetic (primarily urea and diammonium phosphate or DAP) fertilizer, as well as insecticides, fungicides and herbicides.

The average production costs were \$23,870 (PcS) and \$24,925 (McS), and the incomes \$27,642 (PcS) and \$28,581 (McS). The average of the benefit/cost rate was 1.16 (PcS) and 1.15 (McS). The optimal value suggested for this indicator was 1.0 so that both management systems obtained values of 100%.

Equivalent use of land (EUL)

With the aim of evaluating the EUL, which is the relative area of land required under monocrop to obtain the same production that is obtained with an association under similar levels of management, according to Mead and Willey (1980), the data of yields of the main associations in the management systems were analyzed. That is, the EUL of corn in monocrop was contrasted with the EUL corresponding to the PcS associations: corn-bean, corn-squash, corn-broad bean, and corn-squash-bean. Average yields of 1.2 t ha⁻¹ (monocrop corn), 1.4 t ha⁻¹ (corn-bean), 1.1 t ha⁻¹ (corn-squash), 1.6 t ha⁻¹ (corn-broad bean) and 1.5 t ha⁻¹ (corn-squash-bean), were obtained; therefore, a higher yield was observed in the associations of corn-squash-bean and corn-broad bean. In Tukey's multiple means comparison of the yield variable, no statistically significant differences were found between these groups, as presented in Table 3.

To evaluate this indicator, the following formula was used (Mead and Willey, 1980):

$$UET = La + Lb = \frac{Ma}{Sa} + \frac{Mb}{Sb}$$

where *La* and *Lb*: relative yield for individual crops; *Ma* and *Mb*: yield of crops in polycrop; *Sa* and *Sb*: yield of crops in monocrop.

According to Mead and Willey (1980), if the EUL value > 1 there is an advantage in crop association; for a monocrop system the EUL value was 1, and for the polycrop system the mean of the EUL was 1.9, which evidences a greater advantage in the different crop associations used in the zone, as well as higher efficiency in the use of resources. Table 4 shows the EUL value for each cultivation system. The optimal value for EUL is proposed to be EUL=1.5 in which 50% more is produced than in the same surface destined to

Table 3. Tukey's multiple means comparison with a confidence level of 95%.

Crop associations (I)	Crop associations (J)	Means difference (I-J)	p value	Confidence interval at 95%	
				Inferior limit	Superior limit
Corn-squash-bean	Corn-squash	0.41	0.45	-0.28	1.10
Corn-bean	Corn-squash	0.24	0.86	-0.44	0.91
	Corn-squash-bean	-0.17	0.83	-0.64	0.30
Corn-broad bean	Corn-squash	0.51	0.44	-0.33	1.35
	Corn-squash-bean	0.10	0.99	-0.59	0.79
	Corn-bean	0.27	0.78	-0.40	0.95
Monocrop corn	Corn-squash	0.08	1.00	-0.58	0.74
	Corn-squash-bean	-0.33	0.26	-0.77	0.12
	Corn-bean	-0.15	0.86	-0.58	0.28
	Corn-broad bean	-0.43	0.37	-1.09	0.23

Source: prepared by the authors with survey data.

monocrop. Regarding this value, the management systems obtained scores of 100% (PcS) and 66% (McS).

Percentage of permanent jobs per family

The proportion of family workforce in the total number of employees that carry out the activities derived from the cultivation cycle was established, and the proportion of permanent jobs in the family was 45% (PcS) and 48% (McS). In this sense, the level of employability is good, but the family workforce is only partially rooted, and at the same time this is related with the low level of inter-generational replacement and the

Table 4. Equivalent Use of Land by corn cultivation system.

Cultivation system	Relative yield				
	Corn	Bean	Squash	Broad bean	EUL
Monocrop corn	1.0	-	-	-	1.0
Monocrop bean	-	1.0	-	-	1.0
Monocrop squash	-	-	1.0	-	1.0
Monocrop broad bean	-	-	-	1.0	1.0
Corn-bean	1.1	0.3	-	-	1.5
Corn-squash	1.1	-	0.1	-	1.2
Corn-broad bean	1.4	-	-	0.7	2.0
Corn-squash-bean	1.4	0.3	0.3	-	2.0

Source: prepared by the authors with survey data.

abandonment of the activity, mainly by the youngest members. The optimal level of this indicator was established as 100% of family workforce, taking into consideration that in search for more sustainable agricultural systems, there is an emphasis on responding not only to the nutritional demands of the peasant family but also to the generation of lasting employment within it.

Stability, resilience and reliability Agroecological practices index (API)

An index was built based on practices identified in the study zone: 1) interspersed crop, 2) incorporation of organic matter, 3) tracing furrows in leveled curves, 4) stubble grinding in the plot, 5) manual weeding, 6) construction of side trenches, dams, terraces, 7) crop rotation, 8) land resting, 9) minimal application of herbicides and pesticides, and 10) minimal movement of the soil (minimal farming). The API was determined through the product of the number of agroecological practices incorporated multiplied by the number of total agroecological practices reported (Table 5), according to the methodological proposal by Herrera-Pérez *et al.* (2017).

A mean of 0.52 was obtained for this index in the PcS, value that is classified in an intermediate level of API, and of 0.32 in the McS, which places it in a low level. The most frequently implemented practices among producers were: incorporation of organic matter, minimal application of pesticides, and tracing furrows perpendicularly to the slope.

Physicochemical properties of the soil

Sampling was made in a field prior to determinations in the laboratory, and the following were considered to determine: texture, pH, field capacity (FC), organic matter (OM), inorganic nitrogen (NO₃), phosphorus (P), cationic exchange capacity (CEC), and electric conductivity (EC). The soils from both management systems presented sandy and silty-loam texture, while moderately alkaline soils (pH=7.4-8.5) were observed in both groups, with fast filtration capacity (FC=33-36%), with intermediate levels of inorganic nitrogen (0.01%), but with low levels of phosphorus and potassium. According to the reference

Table 5. Agroecological practices index carried out by management system (API).

Agroecological practices index	Polycrop system		Monocrop system	
	Frequency	%	Frequency	%
Very low [0.0-0.3)	0	0	5	22
Low [0.3-0.5)	6	14	13	59
Intermediate [0.5-0.6)	21	50	3	14
High [0.6-0.8)	15	36	1	5
Very high [0.8-1.0)	0	0	0	0
Total	42	100	22	100

Source: prepared by the authors with survey data.

values of OM from the NOM-021-RECNAT-2000 (SEMARNAT, 2000) in volcanic soils, the soils from both groups were within a medium range (6.1-10.9%). The EC of the saturation extract is one of the most evaluated indices for the soil saline concentration, its interest lies in the fact that the high content of soluble salts in the soil can affect the growth of the crops and their health in general. Likewise, when $EC < 1.0 \text{ dS m}^{-1}$ the effects of salinity in the soil are insignificant, and such is the case of the soils of both management systems.

Table 6 shows the results of the determinations in soils from both groups, as well as the optimal value for each aspect analyzed and the score of each system in relation to those optimal levels; intermediate levels were obtained: 65% (McS) and 72% (PcS).

Agrobiodiversity index (ADI)

The Agrobiodiversity index (ADI) was evaluated, methodological proposal by Leyva *et al.* (2008), integrated by four sub-indices: biodiversity for the human diet (IFER), biodiversity for animal feed (IFE), biodiversity for soil nutrition (IAVA), and complementary biodiversity (ICOM) of use for humans and the agroecosystem. The diversity of different species reported in the PcS was 57, while in the McS it was 28, which may be related to the specialized production in both cases, where beyond generating interactions between

Table 6. Optimal values for the physicochemical properties of the soil.

Parameter	Unit	Optimal value	McS		PcS	
			Value	Percentage	Value	Percentage
EC	dS m^{-1}	$<1.0^*$	0.3	100	0.34	100
pH	0-14 Scale	7.5^{\S}	7.9	97	7.8	94
OM	%	13.5^{\dagger}	8.8	65	9.3	69
N	mg Kg^{-1}	220^{**}	132	60	144	65
P	ppm	24^{\ddagger}	2.5	10	1.0	4
K	ppm	175	21.8	12	27.2	16
Ca	ppm	220	128.3	58	143.2	65
Mg	ppm	180	129.8	72	188.3	100
RAS	Mmol L^{-1}	<3	0.2	100	0.2	100
CEC	Cmol (+) Kg^{-1}	25^{\ddagger}	17.7	71	26.9	100

*When $EC < 1.0 \text{ dS m}^{-1}$ the effects of salinity in the soil are insignificant (NOM-021-RECNAT-2000).

§ The limits of pH between which nitrification takes place are between 5.5 and 8.0 with an optimal between 6.9 and 7.5 (Benimeli *et al.*, 2019).

† According to the reference values suggested in the NOM-021-RECNAT-2000 for the classification of the organic matter contents in soils of volcanic origin.

** N: The optimal value corresponds to soils under a system of minimal farming according to what was reported by Benintende *et al.* (2008).

‡ The optimal values were taken from the soil fertility Guide and the plant nutrition in integrated production (Villar and Villar, 2016).

‡ The nutritional reserve is considered abundant when the CEC is higher than $25 \text{ Cmol (+) Kg}^{-1}$ of soil (NOM-021-RECNAT-2000). Source: Prepared by the authors.

crops it is sought to increase the production of basic crops such as: corn, bean and squash, depending on the plot and management system. The indices reached in both systems are below 0.66, the PcS obtained an ADI of 0.58 and the McS 0.42, which is why according to the criteria of the methodology used it was not considered sustainable. The PcS presented higher values than the McS in the sub-indices: biodiversity for the human diet (IFER), biodiversity for soil nutrition (IAVA), and complementary biodiversity (ICOM), while the McS obtained a higher value in the sub-index biodiversity for animal feed (IFE). The fact that the IFER showed a higher value compared to the other categories evidences the fact that among producers the family's food security is prioritized.

The indices evaluated show the need to work in maintaining the present biodiversity and increasing it in the medium and long term, with the objective of favoring the integrality and functionality of the production systems. However, it is important to highlight the conservation of native corns by the peasants in the study zone, whose importance extends among consumers at the local and regional level. Among peasants of the McS, the cultivation of white and yellow Creole corn, and in the PcS, the cultivation of three to five varieties of Creole corn (white *arrocillo*, yellow, blue, red and purple), which is destined to different purposes, such as animal feed and human food, with various gastronomic uses as main ingredient in traditional cuisine, in the elaboration of tortillas and tamales, and in the preparation of ancestral beverages such as *xole*⁴ in the case of blue corn.

Adaptability

Index of adoption of new techniques (appropriation of technological innovations)

Of the interview respondents, 44.2% in the PcS and 31.2% in the McS pointed out having been trained in matters of agricultural technology. The innovations described were grouped into the categories of agronomic management: 1) leveled curves, 2) minimal farming, 3) milpa system interspersed with fruit trees (MIAF), 4) mass selection in the corn crop, 5) management of forest species and those destined to the nutrition of crops and the soil: 6) composting/vermicompost, 7) corn fertilization, and 8) application of biofertilizers. Based on this, the index of adoption of new techniques was built, through the quotient of the number of new practices incorporated divided by the number of total practices in which training was received. The average of this index in the PcS was 0.3, while in the McS it was 0.4.

Index of ancestral techniques in use (ATI)

The list of practices was obtained through a semi-structured interview with key stakeholders, and they are the following: 1) use of yoke, 2) time prediction through observation of the environment, 3) blessing of animals and seeds, 4) seed exchange, 5) crop rotation, 6) polycrops, 7) use of traditional measurement units, 8) use of ancestral tools, 9) observation of lunar phases to perform agricultural activities. Among the methods of meteorological prediction that the interview respondents describe, there were the following: cloud observation, observation of mountains or hills, *cabañuelas*⁵, observation of the moon and

the sky, observation of the behavior of some insects. The ATI was calculated as the number of ancestral practices listed for the study zone. Thus, it was grouped into the classifications: low (1 to 2 ancestral techniques), medium (3 to 5 ancestral techniques), and high (6 to 9 ancestral techniques). Therefore, it was weighed in three categories: low (0.1-0.3), medium (0.3-0.6) and high (0.6-0.9). Intermediate values of 0.50 (PcS) and 0.56 (McS) were obtained, which placed both systems in an intermediate level in the use of ancestral techniques.

Equity

Inter-generational replacement index (IRI)

For the construction of the IRI, the total of children who actively participate in the tasks of the agroecosystem such as soil preparation, sowing, farming and harvesting tasks, as well as activities in the livestock production subsystem, was divided by the total of children for each family. The mean for the IRI for the PcS was 0.5, while for the McS it was 0.4, with both systems found at a level considered as “medium” regarding this index, and the optimal value proposed of 1, where the inter-generational replacement is adequate, considering that this allows the continuity of the activities in the agroecosystem in the next generations.

Dependency on external inputs (DEI)

The inputs and the amounts necessary for the production in each agricultural cycle per crop and area cultivated were listed: seeds (corn, bean, squash, broad bean, and others), synthetic fertilizers (nitrogenous, phosphate, and potassium), and organic (biofertilizers, composted manure), herbicides, insecticides, and fungicides. Then, each input was classified according to its origin: local or external; finally, the proportion of dependency on external inputs such as the total quotient of external inputs divided by the total of inputs used during the agricultural cycle for each production unit was calculated.

In the PcS, 422 kg of external inputs were used from a total of 1,850 kg of inputs per hectare. In the case of the McS, a mean of 495 kg of external inputs from a total of 2,028 kg of inputs was used. The mean of DEI was 0.22 (PcS) and 0.23 (McS), which, expressed in percentage, means that close to 20% of the inputs used in the agricultural cycle come from outside. A level of dependency of zero kg of inputs from outside was considered as the optimal level, and the value regarding this optimal level was expressed in terms of independence, that is, 78% (PcS) and 77% (McS). The difference in the amount of external inputs used consists mainly in a higher demand of organic and synthetic fertilizers by the McS.

Presentation and integration of results

In the integration of results, the level of performance of the management systems by indicator was determined, with the aim of determining their comparative advantages, and optimal values were proposed with this purpose, which are presented in Table 7.

Table 7. Attributes, indicators, optimal values, and comparison of results from the evaluation of sustainability indicators.

Attribute	Indicator	Criterion for the optimal	Optimal value (100%)	Current calculated value			
				PcS	%	McS	%
Productivity	1. Yield by cultivation system	Average yield of the corn, bean and squash polycrop under agroecological management. *	4.5 t ha ⁻¹ (100)	1.8	40	1.2	27
	2. Amount of grain and fodder harvested	Yield of corn and stubble for Creole varieties of rainfed corn. [§]	6.22 t ha ⁻¹ (100)	3.8	74	2.7	43
	3. % of families that have a livestock production activity	Total number of families by management system.**	100% (100)	95	95	100	100
	4. Income from sale of animals by management system (\$) per year	Annual income mean from sale of animals at the local level.	30,434 (100)	20,184	66	30,434	100
	5. B/C (Benefit/Cost) rate per ha	It is considered that there is profitability when there is a margin of benefits higher than those of investment costs $B/C \geq 1.0$. [‡]	1.0 (100)	1.2	100	1.1	100
	6. Equivalent use of land (EUL)	If the EUL value > 1: there is an advantage in the production in crop association. [†]	1.5 (100)	1.9	100	1.0	66
	7. Percentage of permanent jobs per family	Maximum value of permanent jobs per family unit inside the system.	100% (100)	44.2	44.2	44.6	44.6
Stability, resilience and reliability	8. Agroecological practices index	Maximum possible value.	1 (100)	0.52	52	0.32	32
	9. Physicochemical properties of the soil	Value closest to the optimal level of each property analyzed.	100% 100	72	72	65	65
	10. ADI: Agrobiodiversity index	If ADI > 0.66 the system presents sustainability. †	0.66 (100)	0.6	86	0.4	64
Adaptability (flexibility)	11. Index of adoption of new techniques (appropriation of technological innovations)	Maximum possible value in relation to the total of innovations identified.	1 (100)	0.32	32	0.36	36
	12. Index of ancestral techniques in use	Maximum possible value.	1 (100)	0.5	50	0.5	50

Table 7. Continuation

Attribute	Indicator	Criterion for the optimal	Optimal value (100%)	Current calculated value			
				PcS	%	McS	%
Equity	13. Index of inter-generational replacement: Participation of the youngest members of the family in activities of agroecosystem.	Maximum possible value	1 (100)	0.5	50	0.40	40
	14. Dependency on external inputs	That the dependency of inputs from the outside is minimal. ^φ	0 (100)	0.22	78	0.23	77

*The yield reported by Ebel *et al.* (2017) was taken as reference value for the corn, bean and squash polycrop.

[§]The value reported by Muñoz-Tlahuiz *et al.* (2013) was established as optimal, as a result of the sum of the harvest of grain and fodder in Libres, Puebla.

** Since there is lack of direct information from the study zone, the optimal value of 100% families from each system was proposed.

[¥] According to the formal selection criterion of the investment projects based on this indicator, the project is accepted or not as profitable or it is catalogued as profitable if the B/C is higher than one.

[†] According to the methodology by Mead and Willey (1980), if the value of UEL of an association is lower than 1, a disadvantage comes up in the production in association; when it is equal to 1, there is no difference or advantage, and if it is higher than 1, there is an advantage in the production of the association.

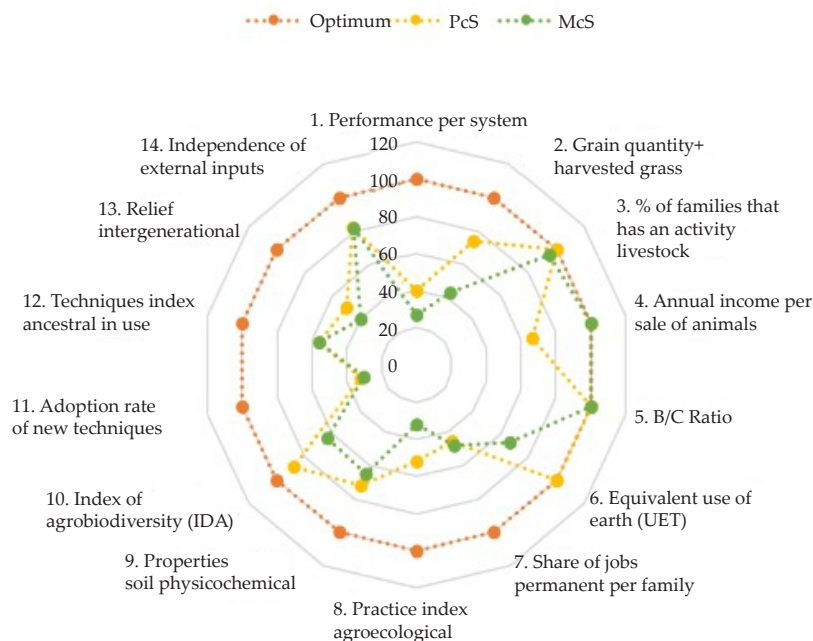
[‡] Agrobiodiversity index: Leyva and Lores (2012) point out that ADI values below 0.66 are not considered sustainable, with 1.0 as the maximum value possible to be obtained.

^φFor the case of the indicator Dependency on inputs, the values of the agroecosystems evaluated compared to the optimal were expressed in terms of independence from inputs from outside.

Source: prepared by the authors.

As product of comparative evaluation, an ameba type graph (Figure 2) was made, which shows that the PcS has a greater tendency toward sustainable management, since it stood out in five of the fourteen indicators evaluated: Yields by system, corn fodder+grain harvested, equivalent use of land, agroecological practices index, agrobiodiversity index, and inter-generational replacement; on the other hand, the McS stood out in the indicator annual income from sale of animals.

A Welch t-test was conducted, for independent samples in the programming language R version 4.2.2 (R Core Team, 2014), which has the characteristic of being robust when the sample size is different and the variance is not equal (Derrick *et al.*, 2016). Statistically significant differences were observed in the indicators: Yield by system, amount of grain and fodder harvested, equivalent use of land, agroecological practices index, and agrobiodiversity index (Table 8).



Source: prepared by the authors.

Figure 2. Ameba graph of the management systems evaluated.

DISCUSSION

This section presents the discussion about results obtained in the indicators corresponding to the five attributes of sustainability according to what Masera *et al.* (2000) suggest.

Productivity attribute

The production of grain and fodder was found in the range of 1.35 to 3.25 t ha⁻¹ reported by Muñoz-Tlahuiz *et al.* (2013), who point out that the local varieties of late cycle are high stubble producers, which is associated to a greater accumulation time of dry matter. Likewise, diversification plays an important role in the agroecosystem in the availability of biomass, together with other agroclimatic factors that may limit the productivity of crops, such as water stress. López-Castañeda (2011) mentioned that for rainfed zones with drought problems, water stress has very severe effects on the grain yield and production of aerial biomass.

The results in the benefit-cost rate of the PcS and the McS show a slight increase, lower to what was reported by Uzcanga-Pérez *et al.* (2022), who obtained a benefit/cost rate of 1.7 (conventional system) and 1.5 (traditional system). Ramírez *et al.* (2018) point out that when the cost of land and workforce are included, there are losses, so they maintain that corn growing has ceased to be profitable, which at the same time has generated land desertion. Creole turkey (*Meleagris gallopavo* L.) is a species in danger of extinction in family livestock production (Aquino-Rodríguez *et al.*, 2003), whose social importance lies in

Table 8. Welch t-test for independent samples.

Variable	Group	Average	Standard deviation	t statistic	P-value
Yield by system	PcS	1.8	0.7	-4.6	0.00***
	McS	1.2	0.3		
Amount of grain and fodder harvested	PcS	3.8	1.8	-3.9	0.00***
	McS	2.7	0.6		
Annual income from sale of animals	PcS	20,184.2	17,321.3	1.76	0.15
	McS	30,434.3	24,288.7		
B/C rate	PcS	1.2	0.5	-0.0928	0.94
	McS	1.1	0.8		
Equivalent use of land (EUL)	PcS	1.9	0.9	-6.25	0.00***
	McS	1.0	0.2		
Proportion of permanent jobs per family	PcS	44.2	23.6	0.0745	0.94
	McS	44.6	23.7		
Agroecological practices index (API)	PcS	0.5	0.1	-8.18	0.00***
	McS	0.3	0.1		
Agrobiodiversity index (ADI)	PcS	0.6	0.0	-11	0.00***
	McS	0.4	0.1		
Index of innovation adoption	PcS	0.3	0.4	0.38	0.85
	McS	0.4	0.5		
Index of ancestral techniques in use	PcS	0.5	0.2	1.14	0.35
	McS	0.5	0.2		
Inter-generational replacement	PcS	0.5	0.4	-1.15	0.35
	McS	0.4	0.3		
Independence from external inputs	PcS	0.2	0.1	2.76	0.02*
	McS	0.2	0.3		

Source: prepared by the authors with survey data. *for P<0.05, **for P<0.01, ***for <0.001.

that its breeding is part of the family tradition in rural and marginalized areas, its presence in management systems was 23.3% (PcS) and 18.2% (McS), which agrees with what was reported by Aquino-Rodríguez *et al.* (2003) who report the presence of this species in communities of Veracruz in between 20.6 and 27.6% of the production units studied. The sale of Creole turkey meat was 128.25 kg, which implicated the production of around 30 turkeys, figure higher than that reported by Aquino-Rodríguez *et al.* (2003) of a total of 72 kg sold during one year; these authors point out that there is a close relationship between family livestock production and the development of agricultural systems in the peasant family.

The most productive associations regarding the UEL were: corn-broad bean and corn-squash-bean, with a UEL value of 2 and corn-bean with UEL of 1.5, and this agrees with what was reported by Ebel *et al.* (2017), where the most productive association was corn-bean. This association is attributed with highly functional synergies between the crops. On the other hand, they pointed out that the combination corn-bean-squash under adequate management generates overharvest, since they are crops adapted to coexistence,

since they were domesticated as polycrops. Novotny *et al.* (2021) point out that the milpa systems provide more people per hectare with a group of nutrients and vitamins than the monocrops of corn or bean, with the exception of zinc and vitamins A, C, B₉ and B₁₂. Therefore, depending on the type of polycrop and its yield, the milpa system could provide nutritional sufficiency to up to three people per hectare.

On the other hand, the dynamic of family work agrees with what was reported by Ortiz-Timoteo *et al.* (2014), where the farming and harvesting tasks are carried out by members of the family; in general, the men carry out the activities that demand more physical strength such as sowing, and women and children are integrated to the tasks of manual weeding, removing tips, fertilization, and harvesting.

When it comes to agroecological practices, Herrera-Pérez *et al.* (2017) reported a higher number of practices developed in traditional management systems with characteristics of polycrop, similar to what was observed in the PcS, so they conclude that this type of agroecosystems tend to be more sustainable than the conventional and the monocrop.

Stability, resilience and reliability attribute

Although the physicochemical properties of the soil give a general vision of the state of the soil, it is important to take into account the biological aspect, since it is directly related to soil fertility, since the soil microorganisms keep the structure while the worms turn it over and favor oxygenation (FAO, 2017). Because of all this, it is necessary to integrate the analysis of the biological properties in the determination of the soil quality.

Adaptability (flexibility) attribute

According to Pérez-Guel *et al.* (2016), the adoption of new techniques is associated with the use of technology that allows developing a productive potential. Pérez-Guel *et al.* (2016) reported the analysis of a package of 29 innovative practices in the state of Guerrero, which include the categories mentioned in this study, and also the categories of organization, administration, post-harvest technology, market and financing. Finally, within a sustainable modernization program, the authors suggest reducing the universe of innovations to only those that have greater weight among producers.

Equity attribute

Vizcarra *et al.* (2015) maintain that inter-generational replacement translates into the preservation and reproduction of sustainable local production systems and of biodiversity itself. Conway *et al.* (2019) describe that the population devoted to agriculture is becoming older, the average age of those responsible for the productive units in the agricultural sector is estimated to be 54.7 years (FAO-SAGARPA, 2014), and this agrees with the mean age of the interview respondents: 51 years in the PcS and 54 years in the McS. This ageing of the rural population is closely related to an issue of low inter-generational replacement as observed in both management systems.

Self-dependency (self-management) attribute

One of the problems associated with the dependency on inputs is the increase in prices without precedent that has been experienced since 2021, of 163.9 % in nitrogenous fertilizers (Banco Mundial, 2022), which equally affects farmers and consumers in rural and urban zones.

On the other hand, Llamas-Guzmán (2020) highlight that planting at the global level takes place primarily with seeds that the farmers themselves select and keep in each agricultural cycle, through a selection process based on criteria such as size, color and flavor, which results in a great diversity of local varieties. All the interview respondents from both management systems continue this selection and conservation process of seeds, which is why they do not depend on the outside for subsequent cycles.

CONCLUSIONS

Both types of management of the corn agroecosystem presented similarities in five out of six indicators evaluated from the social sphere: percentage of families that have a small livestock production activity, percentage of permanent jobs per family, index of adoption of new techniques, index of ancestral techniques in use, and inter-generational replacement. In the economic sphere, the differences were accentuated in the indicator income from sale of animals by management system per year, since in the McS, the livestock activity has higher commercial weight, while in the PcS it is a complementary activity that generates extra income and helps to diversify the diet of the family.

Concerning the environmental area, members of the PcS develop a higher number of agroecological practices: more efficient use of the soil, physicochemical properties of the soil with values closer to the optimal reported in the literature, as well as a higher agrobiodiversity index. The PcS showed greater tendency toward sustainability with 68% compared to the McS which obtained 60%. It is important to revalue peasant agroecosystems, in which there is a more efficient use of natural resources and whose productive potential strengthens the food sovereignty of families in the rural sphere.

NOTES

⁴Xole is a type of corn-based atole, of Pre-Hispanic origin from the peoples located in the Northeast Sierra of Puebla that can be found in patron-saint festivities or fairs, whose recipe has been kept alive from generation to generation, in municipalities such as Teziutlán and Chignautla.

⁵Cabañuelas are a traditional method that farmers use, based on the observation of the atmospheric conditions in the first 24 days of January; its objective is to predict the weather throughout the year.

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