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Sustainability and the social fabric in commercial apple orchards in Puebla, Mexico

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ABSTRACT

Apple (*Malus domestica* Borkh.) is a key perennial crop of global economic importance that faces several challenges associated with global change, particularly environmental degradation and climate change. This is due in part to its ecological requirements, including its significant reliance upon managed and wild pollinators that are susceptible to land use/land cover change, as well as climate change. Commercial apple production is performed either following “Conventional agriculture” (CA), “Integrated Pest Management'' (IPM) or “organic agriculture” (OA) production schemes. OA is sometimes described as the preferred strategy to mitigate the vulnerability of apple production in a context of environmental pressures. In this study, we aimed to test the validity of these claims and to identify key sustainability attributes by assessing the sustainability of apple orchards located in Puebla (Mexico). Specifically, we compared the three agricultural management systems described above (“CA” vs. “IPM” vs. “OA'') using a range of sustainability indicators and classification approaches. Our results provide evidence for strong contrasts in sustainability among agricultural management systems, and highlight social organization as the critical attribute towards sustainability in commercial apple production. Our results reiterate the influence of peasant organizations on the effective adoption of sustainable management systems, and the importance of the social fabric to cope with the obstacles towards sustainability faced by agricultural management systems in Mexico. Therefore, the results suggest a need to strengthen agreements and collective actions to increase the probability of success in the implementation of sustainable management systems.

1. Introduction

Sustainable development is often defined as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs (ONU, 1987). Nevertheless, this concept contains too much ambiguity and generalization when seeking to overcome the declarative dimension to reach the operative one because it presents little functionality and applicability (Sarandón, 2002). Sustainability in agriculture is *de facto* a multivariate and complex concept because it implies simultaneously fulfilling numerous objectives in space and time: Obtaining a yield, preserving ecological resources, identifying and managing (positive/negative) impacts on people, embracing cultural heritage and diversity, and encouraging practices that support long-term economic development (Sarandón and Flores, 2009; Latruffe et al.,2016; DeLonge et al., 2015; Czyżewski et al., 2021).

One of the greatest challenges facing the discussion on sustainable development, particularly regarding sustainable agriculture, is to design operational frameworks that tangibly evaluate the sustainability of different projects, technologies or agroecosystems (Masera et al., 2000; Wezel et al., 2015). The lack of clarity in sustainability frameworks can make it difficult for researchers to define a set of variables to observe the attributes of certain agricultural systems, which can eventually hinder the transition from discourse to action, decision making and accurate interventions (Salas-Zapata and Ortiz-Muñoz, 2019).

Sustainability studies are on the rise with the publication of a range

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of new conceptualization approaches (Romero and Linares, 2016) and assessment tools due to the increasing concerns about the effects of the global ecological crisis on our food systems (Dellepiane and Sarandón, 2008; Sarandón et al., 2019). An example of this is the increasing interest in designing sustainability indicators aimed at evaluating and clarifying milestones on the route towards sustainability in agricultural systems (Gan et al., 2017; Gebreegziabher and Kumar, 2018). Indicators are quantified key variables used to detect trends in diverse systems, but also to recognize critical points in sustainability and to provide evidence-based diagnostic tools that represent a pivotal prerequisite for decision-making (Sarandón et al., 2019). Mainstreaming the use of these sustainability assessment indicators is a particularly pressing issue in the current context of agricultural production facing global changes (Gornall et al., 2010) that threaten the global economy, with potentially significant economic, socio-cultural and environmental losses expected for large corporate companies and small-scale producers alike (Gómez-Cruz et al., 2010; Schwentesius-Rindermann et al., 2014; Boza-Martínez, 2010).

In this context, apple (*Malus domestica* Borkh.) is notably relevant, as it is one of the most popular temperate fruits, with an estimated worldwide production of 143 million tons in 2022 (FAOStat, 2024). Currently, apple foreign sales are valued at over USD 10 billion, and its world consumption is increasing every year (Vasylieva and James, 2021). As a crop that is cultivated worldwide, apple is also increasingly exposed to environmental degradation and global change, and its vulnerability stems from a range of ecological traits such as its early blooming period (making it susceptible to periods of frost in early Spring) or its significant reliance upon managed and wild pollinators that are susceptible to land use/land cover change, as well as climate change (Volk et al., 2015; Wolfe et al., 2018; Chand et al., 2018; El-Yaacoubi et al., 2019).

In Mexico, apples stand out as a dietary staple, with a domestic consumption and production experiencing an average annual growth rate of 8.4% from 2012 to 2020. Although this growth has been significant enough to meet over three-quarters of the country's demand, reliance on imports remains substantial, predominantly from the United States (Morales-Brizard et al., 2024). Overall, Mexican Golden Delicious (roughly 70 percent of total production) and Red Delicious (roughly 30 percent of total production) varieties continue to dominate the market with retail prices per kilo ranging from 18 to 25 percent below apples imported from the United States (USDA & GAIN, 2023). By 2022, Mexico reached a national production of 1,212,906 tons of apples, being Chihuahua de main apple-producing state in the country (1,092,788 tons) and Puebla the third state with the highest production (35,476 tons) (SIAP, 2024). Despite the expansion of apple cultivation to most municipalities in Puebla, production is generally carried out on small, rainfed plots, with soils poor in organic matter, high water and wind erosion, without access to structured markets, credit or insurance, with scarce and low-quality technical assistance, little peasant organization and no solidarity work for production, all of which hinders reaching its true potential in the market (López-Cuevas, 2019).

Different agricultural management practices co-exist in Mexico, namely conventional agriculture (hereafter referred as CA), integrated pest management (IPM), and organic agriculture (OA). The public concerns about the impacts that agrochemicals used in CA have on human health and the environment have promoted the development of "lower risk practices". Since the United Nations Conference on the Environment (1992), IPM and OA have become a global trend, even if various obstacles have led to their suboptimal application, or even to a failure (Damos et al., 2015; Coll and Wajnberg, 2017; Parsa et al., 2014; Gómez-Cruz et al., 2010), including Mexico.

Nowadays, commercial apple production under OA is intimately linked with the geography of poverty in Mexico, as most of the territories under these systems are run by small producers who present the highest incidence of rural poverty, inhabiting mainly the south of the country (Gómez-Cruz et al., 2010; Boza-Martínez, 2010; Schwentesius-Rindermann and Gómez-Cruz, 2015; Colmenárez et al., 2016). The relative performance of CA vs. IPM vs. OA assessed by sustainability indicators has not received attention so far, despite the fact that it represents an essential opportunity to identify and to promote agricultural practices capable of offering quality production (Wang et al., 2016; Kellerhals, 2009; Brown, 2012; Granatstein and Peck, 2017), as well as aligning with the sustainability criteria (Romero and Linares, 2016; Sarandón and Flores, 2009).

1.1. Sustainability conceptual framework

Economic approaches often frame the issue of conceptualizing sustainability in terms of human well-being (utility) by contemplating a seemingly simple intergenerational rule that development is considered sustainable "if it does not diminish the capacity to provide non-infinitely diminishing *per capita* utility." This capacity to provide utility is conceptually embodied in different forms of capital (Dietz and Neumayer, 2007). The economic literature has historically led to the emergence of two schools of sustainable development economics: Neoclassical environmental economics and Heterodox ecological economics, with opposite interpretations of sustainability, termed as "weak" and "strong" environmental sustainability, respectively (Godin et al., 2022).

Substitution between the different forms of capital plays a crucial role in this literature. It is because elements of capital are substitutable that compensation mechanisms between generations are possible (Godin et al., 2022). Neoclassical environmental economics focuses on the so-called weak sustainability rule which assumes that the total capital stock is an aggregate stock of man-made and natural capital and so there are no natural resources that cannot be replaced by other forms of capital (Barua and Khataniar, 2016).

The strong conception of sustainability proposes that natural capital (K_N) can rarely be replaced by manufactured capital (K_M) due to the close feedback that exists between them (Sarandón et al., 2019; Sarandón and Flores, 2009; Romero and Linares, 2016). Therefore, profitability cannot be assumed based on natural resource degradation (Sarandón et al., 2019). Furthermore, economies are subsystems inserted in a global system integrated by a larger context of material and energy flows (Beder, 2011). Thus, low-entropy inputs obtained from the ecosphere (K_N) are metabolized by economies and are transformed into K_M (Lawn, 2000; Pelorosso et al., 2017). It is through production and consumption that high-entropy wastes are dissipated into the ecosphere (Lawn, 2000; Liu et al., 2013). This framework also considers social actors as consumers and as citizens who, not only visualize the utilitarian functions of natural resources, but also the social and community values (Beder, 2011).

Therefore, this study resorts to the paradigm of strong sustainability as a conceptual framework for the design of indicators because it seeks to improve the functions of the ecological system, while ensuring sustainable development by maintaining an equilibrium between economic, environmental, and social factors (De Oliveira Neto et al., 2018). Based on this, Sustainable Agriculture will be defined as that which allows a flow of goods and services to be maintained over time, and that satisfies the economic and socio-cultural needs, within the biophysical limits that determine the correct functioning of the agroecosystem. Therefore, it must be: a) Sufficiently productive; b) Economically viable; c) Ecologically adequate (conserving the base of natural resources and preserving the integrity of the environment); d) Culturally and socially acceptable (Sarandón, 2002; Meza and Julca-Otiniano, 2015; Scoponi, 2016; Valdivia-Espinoza et al., 2020).

In this study, we aimed to assess the relative performance of orchards in Puebla by comparing CA, IPM, and OA using a strong sustainability conceptual framework to identify the critical aspects of agroecosystems in a context of commercial apple production. We focused on Puebla to assess through the use of indicators based on the methodological framework proposed by Sarandón and Flores (2009). We performed a literature review, conducted semi-structured interviews and local surveys of wild pollinators to compute the indicators, and we used the resulting multivariate matrix of standardized values to determine (i) which management strategy (considering CA, IPM, and OA) yielded higher sustainability scores, and (ii) if a hierarchical classification could statistically group together management strategies and study sites according to the similarity of their sustainability scores across indicators. The relative contribution of different indicators is discussed to identify levers and pathways towards increased sustainability in the commercial apple production sector of Puebla.

2. Materials and methods

2.1. Indicators construction

Traditionally, agricultural systems have been evaluated using cost-benefit analysis to determine their economic profitability; however, this approach is not functional in the long term because it ignores the equally important social and environmental dimensions (Carrión-Delgado et al., 2021). Thus, indicators designed to assess sustainability in apple orchards were built based on the methodological framework for evaluating agroecosystems, known as EAMIS (Spanish acronym of *Evaluación de Agroecosistemas Mediante Indicadores de Sustentabilidad*) (Fig. 1). It evaluates the critical points of the sustainability of management systems by transforming complex attributes into indicators (Sarandón and Flores, 2009; Tonolli and Ferrer, 2018).

The advantage of this framework is that the indicators can be adjusted to the reality of the locality studied, they are capable of integrating different aspects of the system to be evaluated and they are also measurable (Jácome et al., 2020). Besides, this methodology involves a participatory approach that is applicable to a wide range of agro-ecosystems in a series of geographical and socioeconomic contexts, provided that some indicators are replaced by others that are relevant to the system to be assessed (Caicedo-Camposano et al., 2021).

This framework has been used mainly in Latin American countries, particularly, in horticultural farms (Tonolli and Ferrer, 2018). Although EAMIS has been used for the integrative study of orchards with annual crops, recently it has also been used for perennial and fruit crops (Márquez and Julca-Otiniano, 2015; Valarezo-Beltrón et al., 2020). Apples are perennial trees associated with a greater use of agrochemicals for their commercial production, they are highly dependent on natural pollinators to set fruit, they have strict edaphoclimatic requirements due to being an introduced species in most of the world, and they have high demand and high-quality standards. Particularly in Puebla, it is a crop mainly run by small farmers (Brown, 2012; Granatstein and Peck, 2017).

EAMIS proposes to initially define the conceptual framework of sustainability under which the evaluation will be carried out in order to define the objectives congruently with it. Subsequently, the unit of study to be evaluated is determined, as well as the space-time scales of interest and the dimensions of analysis (usually environmental, social and economic). The dimensions are then categorized into levels of analysis. For this study, the levels were designed from the most general to the most particular as: categories of analysis, indicators and sub-indicators, respectively. Later, the units of each indicator are standardized so that all values are comparable to each other. Once the data collection instruments are prepared, the study systems' data is obtained and the analysis is carried out to determine which values are critical for the agroecosystems. In order to create indicators that are consistent with the objectives, the methodology is cyclical and iterative by readjusting the indicators at the same time that the evaluation is implemented. Thus, there are two points of retrospective analysis to assess whether the indicators are adequate, one before preparing the data collection instruments and another after having determined the critical points. This allows going back to previous steps, if necessary (Sarandón and Flores, 2009, Fig. 1).

2.2. Study area and study systems determination

The agroecosystems studied are distributed in 3 municipalities of Puebla (Table 1). Puebla presents a wide topographic heterogeneity,

Table 1
Characteristics of the study municipalities (Government of the Puebla State, 2014a,b; INEGI, 2009a,b,c).

	Lafragua	Guadalupe Victoria	San Salvador El Seco
Altitude (msnm)	2320 - 3900	2400 - 3400	2300 - 3000
Weather	Sub-humid semi-cold with summer rains and temperate sub-humid with summer rains	Temperate semi-arid, sub-humid semi-cold and temperate climate with summer rains	Temperate sub-humid with summer rains and semi-arid temperate
Temperature range (°C)	4–14	8–14	13–15
Precipitation range (mm)	300 - 1100	300–900	300–900
Surface water bodies	No defined surface currents, only intermittent streams from Sierra Quimixtlán	No defined surface currents, only intermittent streams from Sierra de Quimixtlán	No major surface currents, only intermittent streams from its mountains
Land use	53% agriculture; 33% pine forest, Abies forest and pine-oak association	63% agriculture; 14% pine forest and pine-oak association; 12% rosetophilic desert scrub	65% agriculture; 5.5% forest; 21% halophilic and induced grassland
Study orchards	Conventional 1, conventional 2 and IPM 2	IPM 1	Organic 1 and organic 2

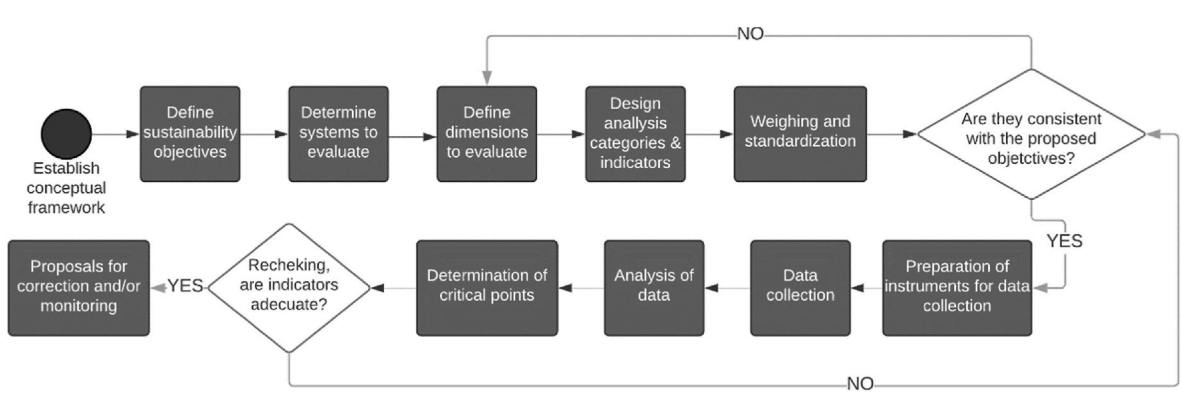

Fig. 1. Methodological proposal to evaluate sustainability. Adapted from Sarandón and Flores (2009).

which gives rise to a wide diversity of climates, mainly temperate (García-Vázquez et al., 2009).

To determine the study systems, a bibliographic review on the apple production in Puebla was carried out. Six different apple producers were selected (Fig. 2) based on information facilitated by M. Sc. Arcadio Hernández Bautista, coordinator of the National Campaign against Fruit Flies of the Plant Health Committee of Puebla (CESAVEP). The orchard selection criteria were: the management systems (CA, IPM and OA), there must be a minimum distance of 2 km between orchards to avoid overlap of pollinator communities and a minimum surface of ½ hectare (Leclercq et al., 2022; Seeley, 1995; Zurbuchen et al., 2010a, 2010b; Cane and Tepedino, 2017). Regarding the criteria of the people interviewed, it was only required that they were in charge of the apple cultivation, without considering gender or age. Although the sample size is far from being representative of apple crops in Puebla which does not allow conclusions to be reached, the case studies open a general overview of important patterns that must be addressed in these agroecosystems (Casas et al., 2023).

A graphic model was also designed to represent the elements considered to perform the sustainability assessment in such a way that the orchards' attributes were visually shown (Fig. 3).

2.3. Definition and standardization of dimensions, categories of analysis and indicators

A first set of indicators was classified into 6 environmental, 3 economic and 6 sociocultural categories. The indicators' values were standardized according to the proposal of Sarandón and Flores (2009) by defining a scale between 0 and 4 to represent, respectively, the less and more sustainable attributes. The values to each indicator were assigned based on a bibliographic review on case studies of the EAMIS framework, sustainable agriculture manuals (CA, IPM, and OA), apple production manuals, regional and national statistical yearbooks, among other sources. (Sarandón, 2002; Sarandón and Flores, 2009; Sarandón et al., 2019; Masera et al., 2000; Dellepiane and Sarandón, 2008; Granatstein and Peck, 2017; Wang et al., 2016; Kellerhals, 2009; Brown, 2012; Zhang et al., 2011; Biddinger et al., 2018; Park et al., 2012; Sheffield et al., 2016; INEGI, 2009a,b,c; Government of the Puebla State, 2014a;b; Abbona et al., 2007; Meza & Julca-Otiano, 2015; Valdivia-Espinoza et al., 2020; Valarezo-Beltrón et al., 2020; Scoponi, 2016; Scoponi et al., 2019). According to these sources, optimal practices for apple cultivation were consulted, as well as other evaluations performed under the EAMIS framework, so that a gradient of options could be generated for each indicator (Supplementary Tables 1–2; Supplementary material).

This standardization was not definitive due to the cyclical and iterative characteristics of the methodology. The ultimate standardization was accepted until the indicators and its values corresponded to the initially defined sustainability objectives. The definitive analysis levels and their measure parameters are shown below (Tables 2 and 3). The entire analysis went through a reliability process to recognize whether the indicators were compatible with the objectives and, if not, they were restructured.

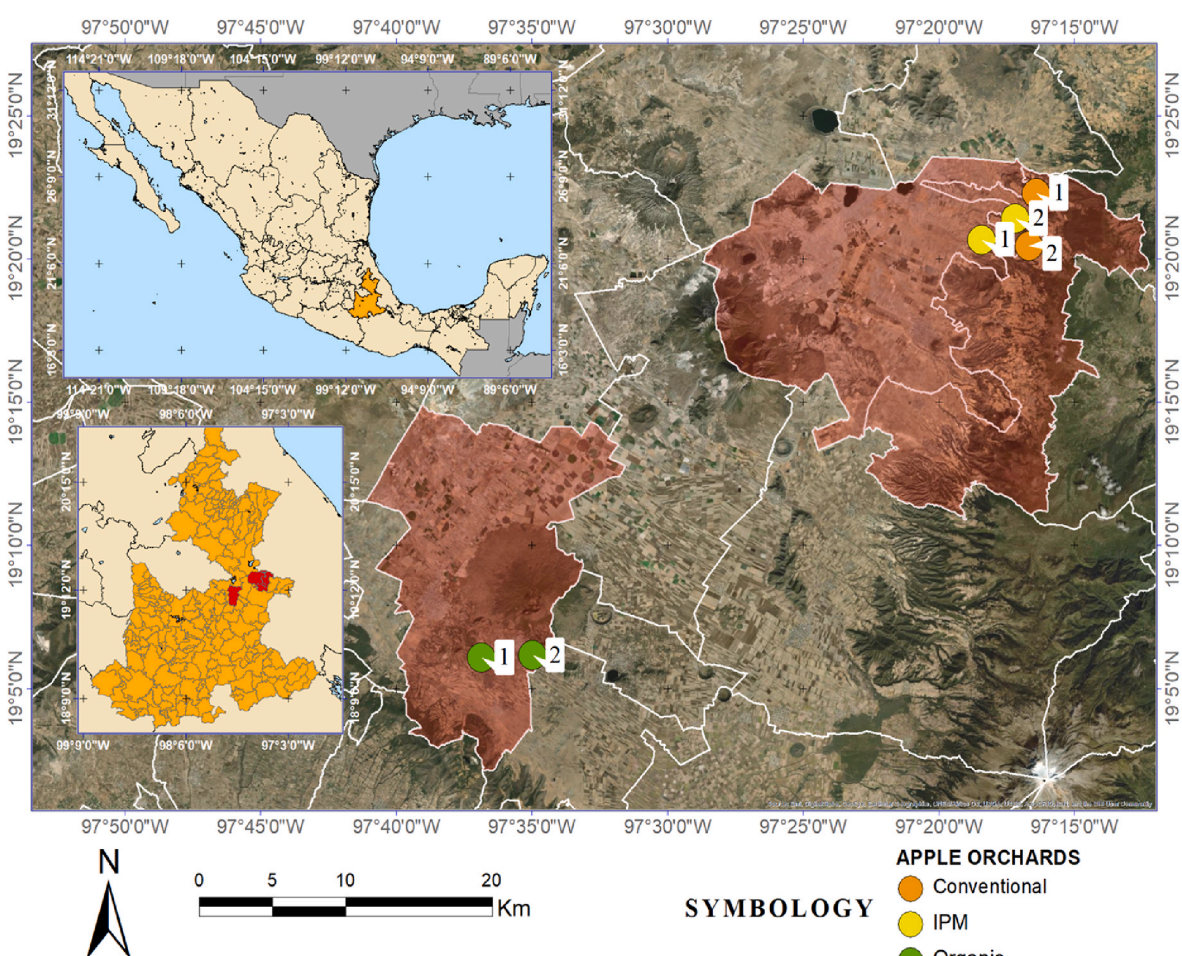

Fig. 2. Location of sampling sites

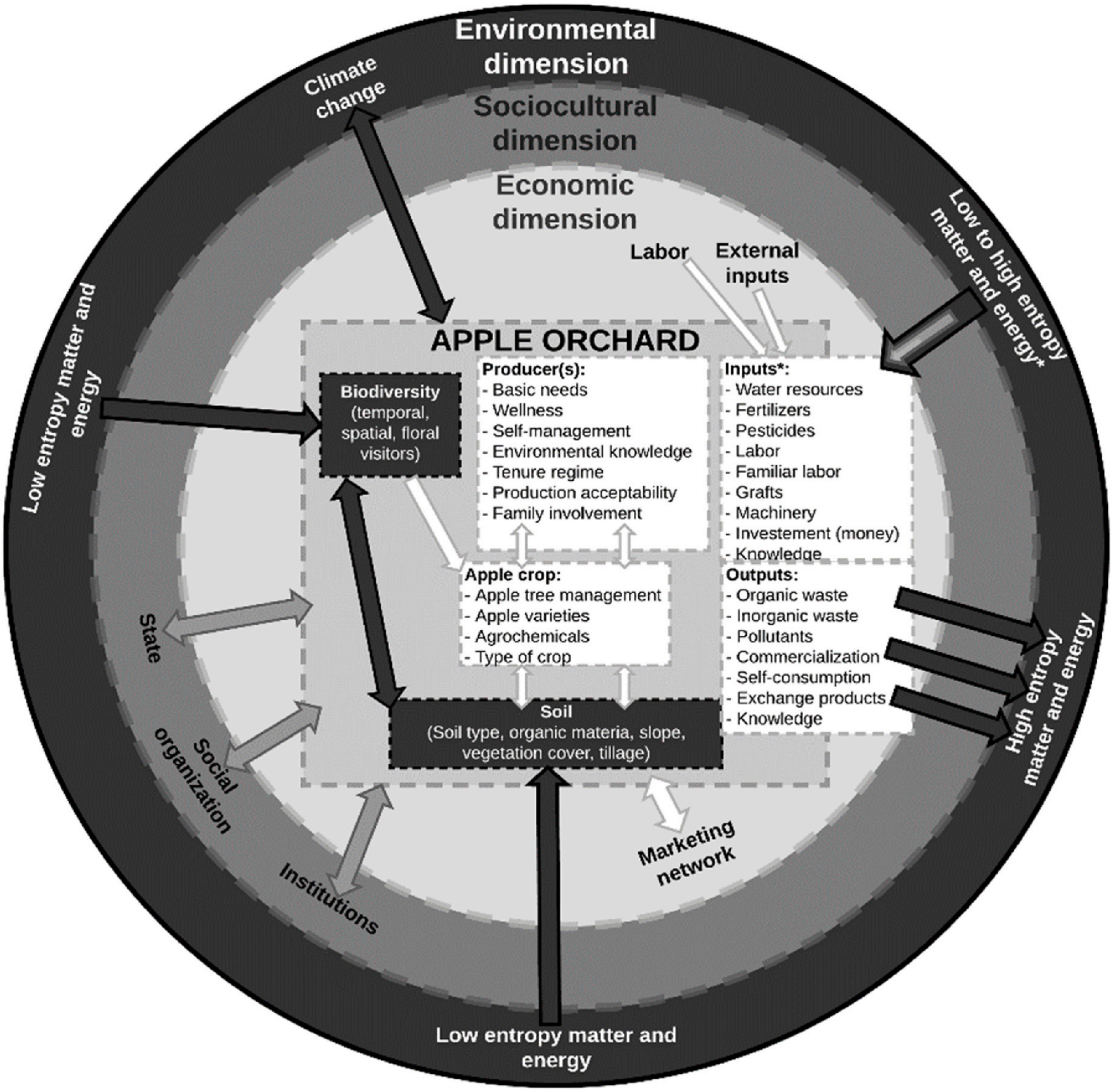

Fig. 3. Apple orchard as study unit. The inputs can go from low to high entropy depending on the agroecosystem's practices and strategies*. (Elaborated by LE. Calderón-Uraga, 2020)

2.4. Instruments and data collection

Two semi-structured interviews were conducted with the producers of each orchard: the first one in March 2019 and the second one in September 2019. The interviews were applied in a focus group, as well as individually, and they were designed so that each question could correspond to at least one of (sub)indicator. Focus groups were used for this study because it is a non-standard technique of information gathering that has the quality of promoting interaction among participants with spontaneity which fosters an environment of trust and flexibility during the sharing of information that, in this case, was linked to the co-construction of indicators (Acocella, 2012; Gundumogula and Gundumogula, 2020).

The purpose of the interviews was to obtain information about the management practices, problems faced on a daily basis and strategies used by farmers to maintain their subsistence, both individually and as a community. MSc. A. Hernández was also interviewed with the aim of triangulating the results. His responses were used in the discussion but not considered for the indicators. All interviews were recorded in writing, audio and photographically after receiving signed informed consent from the participants.

Finally, a capture of floral visitors was made within the orchards during the apple trees blooming season in March 2019. Two capture methods were used: entomological net and pan traps. For the net sampling, two samplings of 90 min were carried out per day: one session in the morning (between 09:30 and 12:00) and one in the afternoon (between 13:30 and 16:00). To reduce sampling bias, participants were given *prior* training and collectors were rotated daily. For the pan trap sampling, 3 triplets of pan traps (1 white, 1 blue, 1 yellow) were placed throughout each orchard and were filled with a soapy water solution. They remained in position from 9:00 to 16:00 (Leclercq et al., 2022).

2.5. Computation of biodiversity indices based on the field surveys

For the floral visitor analysis, a taxonomic identification was carried out at the Colección Nacional de Insectos (CNIN), Instituto de Biología (UNAM) in Mexico City with the collaboration of Mariana de la Cruz. Although the accumulation curve does not show that the sample size was representative (Supplementary Fig. 1; Supplementary material), diversity indices were calculated to be quantitatively integrated into one

Table 2
Classification of quantitative data into the different analysis levels.

Dimensions	Analysis categories	Indicators	Sub indicators	Parameter
Environmental	Soil quality conservation	Crop rotations	–	Rotation frequency in years or months
		Diversity of organic matter	–	Number of organic matter types
	Erosion risk	Slope	–	Grade of slope and orientation
		Furrows orientation	–	Orientation with respect slope
	Biodiversity management	Spatial biodiversity	Apple varieties	Varieties of apples grown in the orchard
			Variety of interspersed plant species	Wild vegetation families found within the orchard
		Temporal biodiversity	–	Rotation frequency in years or months
		Floral visitor biodiversity	Floral visitors by entomological net	Hymenoptera flower visitor diversity indices captured by entomological net
			Floral visitors by pan traps	Hymenoptera flower visitor diversity indices captured by pan traps
			Total floral visitors	Hymenoptera flower visitor diversity indices captured in total
	Climate change	Vulnerability	Harvest season	Conservation of harvest periods
			Rainy season	Conservation of periods of precipitation
				Conservation of precipitation intensity
			Blooming season	Conservation of blooming periods of apple trees
	Access to water resources	Water resources management	–	Irrigation frequency
Economic	Food self-sufficiency	Apple production for self-consumption	–	Amount of apple production for self-consumption per cycle
			–	Amount of apple production for self-consumption in the last cycle (2019)
		Diversification for self-consumption	–	Number of products for self-consumption
	Production	Profit per hectare according to municipality		Profit per ton of production depending on the municipality
		Net income per hectare	–	Net income/hectare (per production cycle)
				Net income/hectare in the last cycle (2019)
	Economic risk and economic-productive fragility	Sale diversification	Additional Sold Products	Number of products for sale per cycle
				Number of products for sale in the last cycle (2019)
				Income in pesos of products additional to the apple, in the last cycle (2019)
		Marketing channels	Number of marketing channels	Number of routes for the sale of products
		Dependence on external inputs	Grafts	Money invested in the purchase of grafts
			Agrochemicals	Money invested in the purchase of agrochemicals
			Technology and tools	Money invested in the purchase and maintenance of tools and machinery
			Labor	Money invested in hiring external labor
			Other inputs	Money invested in other inputs involved in production
		Dependence on production	–	Monetary income from sources other than apple production
Sociocultural	Satisfaction of basic needs	Health and medical coverage	Disease periodicity	Periodicity in months (or years)
			Access	Characteristics of the health system (producer level)
			Efficiency	Characteristics of the health system (municipal level)
	Social organization for self-management	Peasant organization	–	Number of peasant groups involved
		Local marketing network	–	Number of purely local trade routes
	Self-management	Family participation	–	Number of family members participating

of the indicators. Abundance, Species richness (species counts), Shannon's and Pielou's diversity indices were measured using the *vegan* (version 2.5–6) (Oksanen et al., 2019) and *BiodiversityR* (Kindt and Coe, 2005) packages in RStudio (version February 1, 5019).

The Shannon-Wiener's diversity index (H′) measures the degree of equality between the abundances of species belonging to the same community (Pla et al., 2012). Its values range from 0 to 5, where values above 3 indicate a stable and balanced habitat, while below 1 evidence degraded habitats (Pramanik et al., 2017). Otherwise, the Pielou's equity index measures the proportion of the observed diversity in relation to the maximum expected diversity (Pla et al., 2012). Its value is between 0 and 1, so that approaching 1 means that individuals are equitably distributed, or that they are equally abundant and, consequently, dominance is low (Pramanik et al., 2017).

2.6. Quantitative and qualitative data analysis

All the sustainability values were assigned to each indicator and were computed to the formulas constructed considering the analysis levels (Equations (1)–(3); Supplementary material). From these sustainability values, a numerical matrix was generated and was used to perform the hierarchical and K-means clustering analyses using the *pvclust* (Suzuki et al., 2019), and the *vegan* packages (version 2.5–6) (Oksanen et al., 2019).

Additionally, the standard deviations (SD) and the means of each indicator and category of analysis in the matrix were calculated to obtain their corresponding coefficient of variation (CV). The coefficient of variation is calculated by dividing the standard deviation by the mean (Pélabon et al., 2020). The CV is a measure commonly applied to present variation in agricultural traits and it can be used to compare the variation of a trait in two (or more) populations or, more commonly, the variation of different traits in a population of study (Kozak et al., 2013).

Table 3
Classification of qualitative data into the different analysis levels.

Dimension	Analysis categories	Indicator	Sub indicator	Parameter
Environmental	Soil quality conservation	Vegetation cover management	Families of interspersed plant species	Families of plant species found within the orchard interspersed with apple trees
			Species number	Type of crop with respect to number of species
		Tillage System	–	Tillage (from manual to highly technical)
		Soil Type		Orchard soil granulometry
	Biodiversity management	Pest control	Type of pests	Number and type of pests that damage the apple
			Pest frequency	Frequency of damage from diseases or pests
			Pesticides	Types of pesticides applied
			Safety against agrochemicals	Protective equipment to protect against agrochemicals
		Vegetation cover management	Crop diversity management	Type of crop with respect to number of species
			Families of interspersed plant species	Families of plant species found within the orchard interspersed with apple trees
		Spatial biodiversity	Wild vegetation	Type of crop with respect to association with wild species
				Relationship between crops and surrounding natural diversity
			Apple varieties	Fertilization potential among selected apple varieties
		Floral visitor biodiversity	–	Perception of producers about insects that visit apple flowers
	Climate change	Adaptability	Water resources management	Strategies or practices used for the use of water resources
			Crop diversity management	Type of crop with respect to number of species
			Soil management	Strategies or practices used to optimize soil management
			Other type of management	Complementary strategies or practices used to mitigate unforeseen/unwanted environmental phenomena
	Access to water resources	Agriculture type	Water resources management	Strategies or practices used for the use of water resources
	Production quality	Apple characteristics	–	Apples size and shape harvested in the last cycle (2019)
		Apple trees management	Pruning	Procedures for pruning apple trees
Economic	Economic risk and economic-productive fragility	Marketing channels	Qualities of marketing channels	Origin, relationship and recurrence of buyers
		Dependence on external inputs	Grafts	Graft origin used in the orchard
Sociocultural	Satisfaction of basic needs	Health and medical coverage	Access	Characteristics of the health system
			Vulnerability	Groups vulnerable to disease
		Dwelling	Services	Quality of accessible services
		Communication routes	–	State and availability of communication routes
	Wellness	Access to education	–	Accessible academic degrees
		Government support	–	Access to government support programs
	Acceptability of the production system	Identity	Pride	Knowledge transmission
			Owner's identity	Integration of the production system in the producer's life
			Community identity	Integration of the production system in community relations
		Perception	Quality of life	Self-assessment of the quality of life that apple production provides them
			Benefits	Self-assessment of the productivity of the apple orchard
	Self-management	Autonomy	–	Decision making and financial independence
		Family participation	–	Family groups involved in production (family interaction)
			–	Salary
		Land tenure regime	–	Type of land tenure regime in agroecosystem
	Social organization for self-management	Peasant organization	–	Types of peasant groups
	Knowledge and awareness	Environmental	Environmental responsibility	Degree of recognition of the effects of their decision making
		Management	–	Degree of knowledge about the management of the production system

3. Results

3.1. Definition and standardization of dimensions, categories of analysis and indicators

As a result of the iterative construction of the indicators, the definitive levels of analysis were obtained (Tables 2 and 3) and from these their values were standardized according to the scale of 0–4.

3.2. Sustainability assessment of the analysis categories

Numerical values were assigned to each of the indicator parameters according to the previously standardized scale (0 = less sustainable attributes; 4 = more sustainable attributes). Table 4 shows the sustainability values of each category and of the three analysis dimensions by orchard. The sustainability matrix highlights in red the sustainability values ≤ 1.0, as they are considered critical values, and so as the Coefficient of Variation (CV) ≥ 50.00 (Sarandón and Flores, 2009).

No orchard presented critical values at the level of any dimension, however Organic 1 was the least sustainable in the three dimensions. At category level, organic 2 has the highest number of critical categories (four critical categories), followed by organic 1 (three critical categories). The conventional ones presented the highest values, followed by IPM 2. It must be noted that Social organization for self-management (N) showed the greatest variation and the higher proportion of critical values by being critical in four of the six orchards (Fig. 4).

Both organic orchards and IPM 1 were the least sustainable for the environmental dimension, while the conventional ones were the most. In the economic dimension, the organic orchards again presented the lowest values. And in the sociocultural one, all the orchards displayed as critical value the category of Social organization for self-management, excepting IPM 2.

Table 4
Numerical matrix at dimensions and analysis categories level.

		Conv. 1	Conv. 2	IPM 1	IPM 2	Org. 1	Org. 2	SD	Mean	CV (%)
Environmental Dimension	Soil quality conservation	2.4	1.7	2.7	3	1.4	1.8	**0.63**	**2.17**	**29**
	Erosion risk	4	2.5	1.5	3	2.5	2	**0.86**	**2.58**	**33.34**
	Biodiversity management	2.23	1.67	2.04	2.31	1.23	0.95	**0.56**	**1.74**	**32.1**
	Climate change	3.04	3.29	1.92	2.38	1.04	1.63	**0.86**	**2.22**	**38.74**
	Access to water resources	4	4	3	4	4	4	**0.41**	**3.83**	**10.65**
	Production quality	3.5	3.5	3.5	2.5	0.5	2	**1.2**	**2.58**	**46.48**
	Environmental Dimension	**3.2**	**2.78**	**2.44**	**2.86**	**1.78**	**2.06**	**0.53**	**2.52**	**21.05**
Economic Dimension	Food self-sufficiency	2.75	2.5	2	2.75	2.5	0.75	**0.77**	**2.21**	**34.65**
	Production	3.75	3.58	1.83	2.58	0.83	0.83	**1.29**	**2.24**	**57.71**
	Economic risk and economic-productive fragility	1.78	2	2.06	1.4	2	1.51	**0.28**	**1.79**	**15.63**
	Economic dimension	**2.76**	**2.69**	**1.97**	**2.24**	**1.78**	**1.03**	**0.64**	**2.08**	**30.95**
Sociocultural Dimension	Satisfaction of basic needs	3.27	3.27	1.93	1.87	3.13	2	**0.71**	**2.58**	**27.5**
	Wellness	3.5	3.5	2.5	3.5	2	4	**0.75**	**3.17**	**23.77**
	Acceptability of the production system	2.17	3.08	2.5	2.17	1.58	1.88	**0.52**	**2.23**	**23.34**
	Self-management	2.78	2.56	2.89	2.67	3	3.33	**0.28**	**2.87**	**9.61**
	Social organization for self-management	1	1.25	0	2.75	0	0.5	**1.03**	**0.92**	**112.67**
	Knowledge and awareness	1.5	3.5	1.5	3.5	1.5	1.5	**1.03**	**2.17**	**47.67**
	Sociocultural dimension	**2.37**	**2.86**	**1.89**	**2.74**	**1.87**	**2.2**	**0.42**	**2.32**	**18.03**

Note: SD=Standard deviation, CV=Coefficient of variation. Critical values are represented in red.

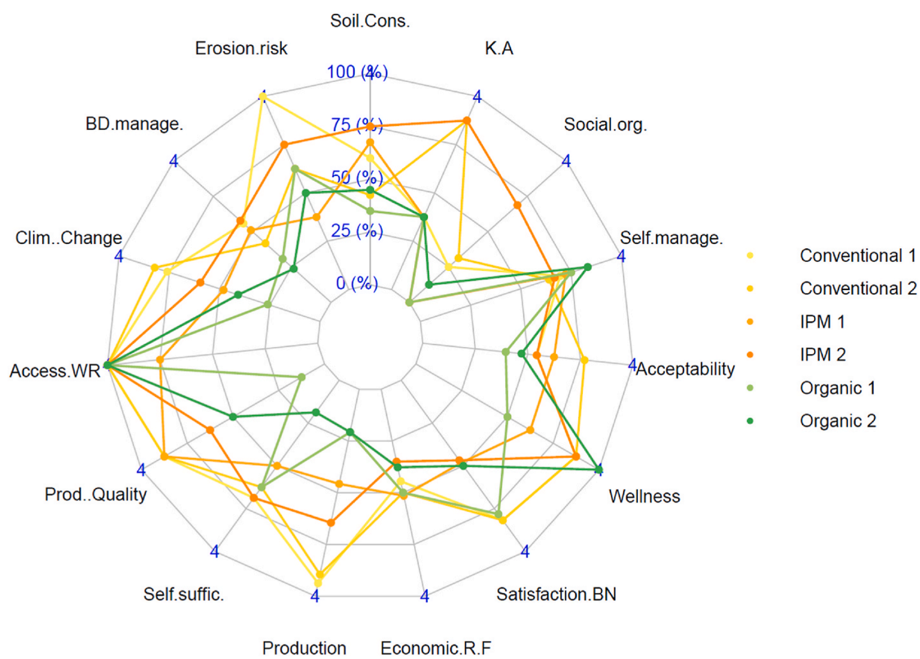

Fig. 4. Analysis categories of the sustainability assessment in the apple orchards. Note: each segment indicates the sustainability level by category. Soil cons. = Soil quality conservation; BD manage = Biodiversity management; Clim. change = Climate change; Access WR= Access to water resources; Prod. Quality = Production quality; Self-suffic. = Food self-sufficiency; Econom. R&F = Economic risk and fragility; Satisfaction BN = Satisfaction of basic needs; Self-manage = Self-management; K&A = Knowledge and awareness.

3.3. Sustainability assessment of the indicators

According to Sarandón and Flores (2009), to robustly evaluate the critical points of the categories, it is necessary to also review the values of the indicators that integrated them (Supplementary Tables 3–5). These matrices highlight in red the same critical thresholds as shown in the matrix of the analysis categories (Sustainability values ≤ 1.0; CV ≥ 50.00). In general, a trend was identified in the sustainability values of the three dimensions. Conventional orchards together with IPM 2 showed the highest sustainability values in their indicators and exhibited the lowest proportion of critical indicators. On the contrary, organic orchards and IPM 1 presented critical values in most of the indicators of the three dimensions.

Some of the lowest CV in the environmental indicators (Supplementary Table 3) corresponds to "Pest Control" and "Diversity of organic matter". These ones are essential since the main criterion to classify the orchards is the agrochemical management. These orchards, whose agrochemical applications theoretically rely on the management system under which they are, did not display a substantial difference. The same occurs for the floral visitor biodiversity which, despite not being critical, shows a tendency to be so in the future if its current situation is not conceived cautiously.

Regarding the economic matrix (Supplementary Table 4), "Profit per hectare according to municipality" showed a marked asymmetry in the fresh apple sale prices (Lafragua's price is USD $0.48/kg; Guadalupe Victoria's price is USD $0.39/kg; and San Salvador El Seco's price is USD $0.12/kg) (SIAP, 2024). Plus, "Dependence on external inputs" was the indicator with the lowest CV even if the expense related to agrochemicals inputs should have presented differences according to the management system.

Concerning the sociocultural indicators (Supplementary Table 5), the critical values are mainly focused on "Social organization for self-management", which can be seen as a rupture in the social fabric of the apple producers. Despite the fact that all the producers come from different backgrounds, there is the particular trait among them of being disjointed from the social fabric of the apple-growing social organizations of their municipalities. This is either due to the absence of social organizations (as seen in organic orchards), the lack of producer's interest (observed in IPM 1) or the difficulty to get fully involved in them (particularly distinguished in IPM 2 and conventional orchards).

3.4. Clustering analysis: hierarchical and K-means

Based on the sustainability values of the analysis categories, the clusters obtained from the K-mean analysis (Calinski value > 3.8) were marked with rectangles within the dendrogram constructed from the hierarchical analysis (Fig. 5). These results reassure the similarity pattern between orchards: the IPM 2 being more similar to the conventional ones (Cluster 1), while the IPM 1 to the organic ones (Cluster 2). The latter cluster has the lowest values and the highest proportions of critical values.

3.5. Interview of MSc. A. Hernández Bautista, coordinator of the National Campaign against Fruit Flies of the Plant Health Committee

According to this interview, the social organization in each municipality has determined different scenarios (Table 5). A change has been observed in the producers thinking about the impact that their management has on the environment. This transition may be associated with the implementation of campaigns to adopt good management practices and the promotion of sustainable management systems; not to mention with the increasing demand for low-insecticide residue apples.

Table 5
Social fabric and its repercussions on the contextual conditions of the study municipalities according to M. Sc. Arcadio Hernández.

	Lafragua	Guadalupe Victoria	San Salvador El Seco
Number of apple producers	Highest	Lowest	Medium
Social Organization	Strong	Strong	Poor
Main crop	Apple	Apple	Corn
Access to government support	Fruit reconversion and damage remedy	Fruit reconversion and damage remedy	None
Apple market type	Table apple	Table apple	Wholesale apple
Community activities	Apple fair organized by municipal governor	Apple fair shared with Lafragua	Low technical knowledge sharing
Acceptability of the production system	High (Part of the identity)		Low acceptability

4. Discussion

The sustainability evaluation framework proposed by Sarandón (2009) allowed us to identify conventional orchards presented the highest sustainability values, followed by IPM 2. While, the organic ones

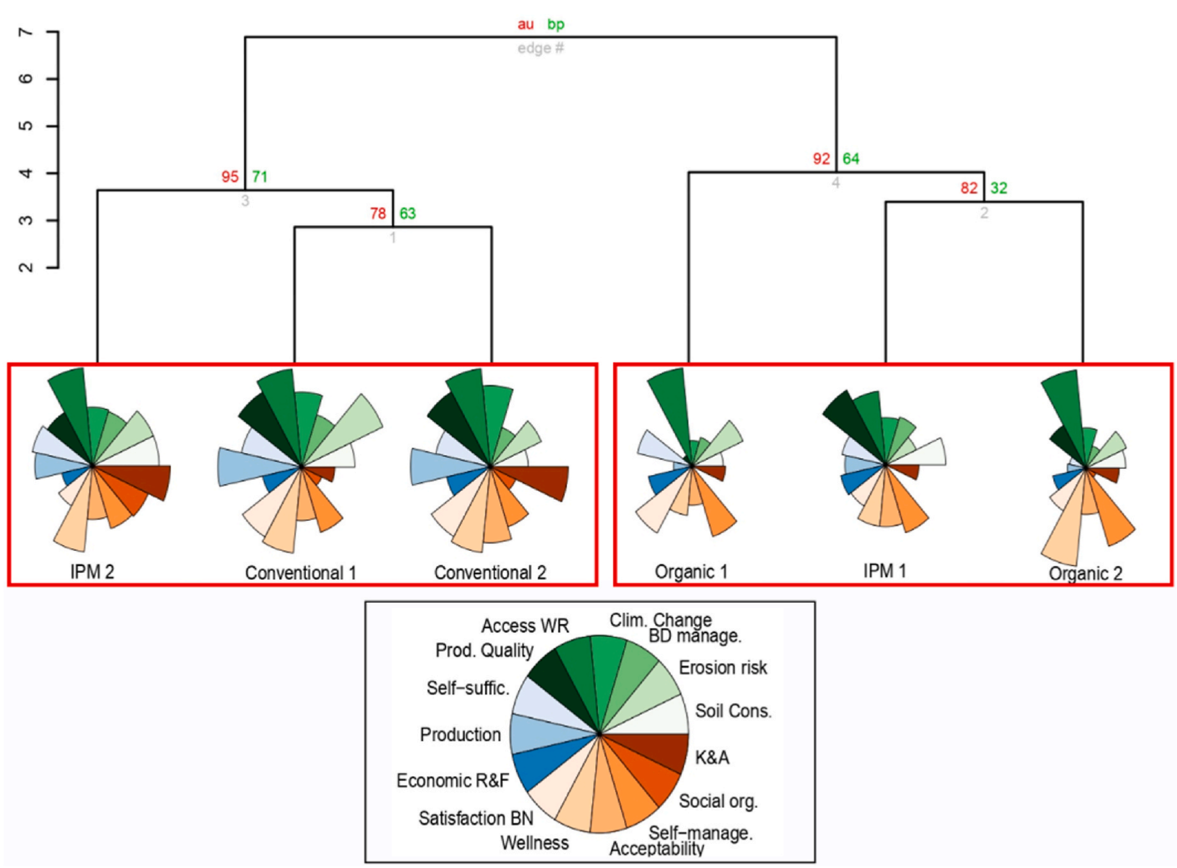

Fig. 5. Hierarchical clustering from the categories of analysis level. (AU = "approximately unbiased" P-values; BP = Bootstrap probability). Note: each segment indicates the sustainability level by category. Soil cons. = Soil quality conservation; BD manage = Biodiversity management; Clim. change = Climate change; Access WR= Access to water resources; Prod. Quality = Production quality; Self-suffic. = Food self-sufficiency; Econom. R&F = Economic risk and fragility; Satisfaction BN = Satisfaction of basic needs; Self-manage = Self-management; K&A = Knowledge and awareness.

and IPM 1 had the lowest. In theory, the clusters we could have expected should have correspond to their management systems, forming three clusters: OA, IPM and CA, or even the two clusters: IPM-OA and CA, considering that OA and IPM systems emerged as more sustainable models (Granatstein and Kupferman, 2008; USDA-ARS, 2018).

Despite the successful implementation of the IPM system in some countries, mainly in core countries (European), this is not the case for peripheral ones (Latin American) (Colmenárez et al., 2016). Indeed, the implementation of IPM systems in Mexico is problematic as more than 50 million people live in poverty, including peasants, who hardly have the chance to afford this model (Parsa et al., 2014). Also, the requirement of collective actions for the adoption of the IPM model is distinguished as a major obstacle. This is due to the fact that the benefits of adopting this system depend on whether other farmers adopt it equally, as well as the fact that pests are more susceptible to move from one crop to another (Parsa et al., 2014). Other obstacles that have been reported in countries of the global South are: lack of local leader(s), lack of support policies, insufficient technical support, low educational and literacy levels among producers, and the strong influence of the pesticide industry (Parsa et al., 2014; Jørs et al., 2017).

Particularly in Mexico, 98% of the organic producers were smallholders in 2007 (Gómez-Cruz et al., 2010). They face numerous obstacles such as: little technical assistance and training, the lack of own economic resources to capitalize the transition to OA and to afford the high certification price, and the absence of public policies, among others (Nelson et al., 2010; Gómez-Cruz et al., 2006, 2010). Besides, the organic certification model has been reduced to a model of substitution (or prohibition) of chemical inputs, having little or no interest in whether the actions are socially fair or ecologically responsible. Hence, this sector is vulnerable to "conventionalization" processes by neglecting issues such as: the entry of agrochemical companies, the protection of small-scale crops and by not favoring local production and consumption networks (Nelson et al., 2010). Thus, “conventionalized” organic orchards adopt tendencies that include larger-scale production units, industrialized monocropping, increased mechanization, hired labor, vertical integration, production contracts, regional specialization and mass marketing (Goldberger, 2011). These processes distance organic orchards from their values of ecological integrity and their transformative potential, dilute the boundaries between different management approaches and, as a result, invite us to transcend dogmas and prescriptive approaches to offer farmers more integrative soil and crop management options (Goldberger, 2011; Brzezina et al., 2016; Giller et al., 2015).

In Mexico ¼ of the small-scale OA land is not certified (Nelson et al., 2010). Thus, several producers have formed cooperatives to share the certification costs and make them more accessible to them (Nelson et al., 2010). Thereby, with the enactment of the Organic Products Law in Mexico, the Participatory Guarantee System (PGS) emerged to distinguish organic producers who do not have access to certification, but who seek to label their products (Ley DOF 07-02-2006, 2006).

In this sense, social organization was the critical category in the studied apple orchards. Its significance was demonstrated by: providing legitimacy and strength to the request of increasing apple sale prices; improving the knowledge transmission; opening the access to financing the transition from one management system to another more sustainable; promoting the incorporation of more farmers to share the costs of certification; and by being a motor for identity intensification.

Commensurate with the technical advisor of the Plant Health Committee, social organization in Lafragua (Cluster 1) has served as a vehicle for producers to obtain benefits as those mentioned above, and even allows them to enter the table apple market. Even though IPM 1 was located in Guadalupe Victoria, by not being part of any social organization, several of its indicators are lower than those found in Lafragua’s orchards and its similarity is greater with the organic ones in San Salvador El Seco.

The presence of social fabric makes it possible to face emerging pressures such as the increasingly strict demand for low insecticide residue apples (Granatstein, 2017; Schwentesius-Rindermann et al., 2014; Boza-Martínez, 2010). Despite its interest, the state of social fabric of many smallholders has prevented them to certificate as the costs are very high and it is unlikely to certify small-scale orchards inserted in a region dominated by conventional ones (Parsa et al., 2014; Nelson et al., 2010, 2015).

The conventionalization of organic and IPM 1 orchards is associated with the neglect of their contexts, exposing producers to maintain environmentally and socially aggressive practices, while not generating economically sustainable incomes. By not considering these factors, even the agrochemical restrictions are conventionalized. Besides, Mexican farmers have been forced to compete toe-to-toe with highly subsidized and better endowed producers since the NAFTA (North American Free Trade Agreement) was signed (Folch and Planas, 2019). Even if it was considered that only the more competitive farmers were supposed to adapt, growth in this sector has been focused on large- and medium-scale producers. This translates into adverse economic conditions for smallholders (Tetreault, 2010; Lazos, 2018).

The spread of organic food to large retailers is considered the main driver of conventionalization. The increase of consumers’ interest in organic food has attracted the interest of large retailing companies and has promoted changes along the supply chain. In response, conventional producers have adopted organic standards while neglecting the principles of alternative agriculture (Rover et al., 2020; Nikol and Jansen, 2021). Particularly, in Mexico there are two organic sub-sectors that sell to different markets: one with large producers that directly contract with international buyers and one with small producers who sell to other market networks involving large retailers and long supply chains (Nikol and Jansen, 2021; Gómez-Tovar et al., 2005).

However, these conventionalization processes have not only been reported in Latin American countries, but also in other apple producing countries. In Southeast France, organic production regions are described as a mosaic of different strategies that coexist with each other, with differences both in the usage of agrochemicals and in management practices (Marliac et al., 2015). Likewise, in central Washington, USA, organic apple orchards have transitioned from zero pesticide use to more intensive usage, while conventional orchards have adopted practices that lean more toward the IPM and organic side (Orpet et al., 2020).

In this context, the adoption of various forms of direct sale for the development of short food supply chains is key in stimulating the diversification of OA worldwide (Rover et al., 2020). Thus, the emergence of PGS in Mexico represents a mechanism for food system governance to cope with the vertically-constructed model of organic certification, as it focuses on returning the regulatory authority to the local level, empowering grassroots actors and fostering collective learning. However, PGS relies upon and helps to strengthen, relationships of trust within a food system (Nelson et al., 2015; Lazos, 2018).

Regarding the floral visitor diversity, even though the diversity indices did not generate critical results in the sustainability evaluation, it is important to emphasize the dominant frequency with which *Apis mellifera* was caught in comparison with the rest of the species. Pollination services in apple orchards increase with greater abundance and richness of wild bees, as they enhance seed formation in apple trees due to a greater functional complementarity, while an increase in the *A. mellifera* abundances does not (Blitzer et al., 2016; Garibaldi et al., 2013).

It must be reiterated the importance of native bees as potential pollinators of apple trees considering the trend that producers have identified regarding the growth of asymmetric apples in years in which the presence of bees decreases. According to Park et al. (2012), the most observed wild bee species for the pollination of apple crops are the mining bees, such as *Andrena* sp., *Lasioglossum* sp. and *Agapostemon* sp.; because they tend to nest in well-drained soils that are the most appropriate for growing apples. Other common species in these orchards are cavity nesting bees (*Bombus* spp.) and mason bees (*Ceratina* spp., *Osmia* spp.) (Supplementary Table 6; Supplementary materials) (Martins et al., 2015; Sheffield et al., 2016; Park et al., 2012). All of them found in at least one of the studied orchards in this study.

As previously discussed, the weak sustainability paradigm reduces the management systems to defining agrochemical restriction standards (Nelson et al., 2010; Romero and Linares, 2016). As a result, it exposes the systems to obstacles that threaten their maintenance and functionality in the long term (Boos, 2015; Boos and Holm-Müller, 2016; Nelson et al., 2010). Whilst, a more integrative approach opens up possibilities to identify the obstacles that producers face, to recognize critical points of sustainability and to design new methodologies to measure sustainability, which may be sensitive to identify conventionalization processes. In this study, the strengthening of collective agreements and actions is an advisable way to increase the probability of success in the implementation of more sustainable management systems.

5. Conclusions

When assessing apple orchards in Puebla (Mexico), the "Social organization for self-management" was identified as the critical attribute. This reiterates the influence that peasant organizations have on the effectiveness in the adoption of sustainable management systems. Thereby, depending on the organization's structure and on the contextual pressures, different scenarios are established. Lafragua's organizations shaped scenarios to the Conventional and IPM 2 orchards such as the transition to the table apple market, a fairer sale price, access to government financing, the creation of trade networks and strengthened the producers' identity. Despite being under a "sustainable" management system, San Salvador El Seco (Organic) and Guadalupe Victoria (IPM 1) orchards are exposed to processes of conventionalization, by being disarticulated from their social fabric, or due to the absence of it. The significance of reinforcing the social fabric among smallholders lies in coping with the obstacles faced by sustainable management systems in Mexico, reversing conventionalization and consolidating a local and fair market. To do so, scientific research must transcend the epistemological barriers that have forged top-down agricultural models with prescribed management practices, in order to move towards bottom-up schemes that respond to the particular needs of each region, such as PGS.

Additionally, by finding a dominance of *Apis mellifera* in the floral visitor community and by the recognition of some producers about the bees as apple pollinators, it is essential to generate knowledge about the state of wild bee communities in Puebla. Hence, having the theoretical background and the capacity for extension and integration of scientific and local knowledge, it is possible to develop strategies for the protection and diversification of these species. Finally, despite the limited sample size, the results made evident trends that give us a glimpse into the need to abandon prescribed management approaches and to design systems that rely on practices more consistent with the characteristics of each crop, from an environmental to a social and economic level. Further research is needed to open the scope of the EAMIS framework for the evaluation of a larger sample of orchards that enrich the results obtained, as well as to perform assessments in large-scale systems and with other crops.

CRediT authorship contribution statement

Eduardo Calderón-Uraga: Writing – original draft, Investigation, Formal analysis, Data curation. **Nathalie Cabirol:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Marcelo Rojas-Oropeza:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Ismael Alejandro Hinojosa-Díaz:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Nicolas Leclercq:** Writing – review & editing, Validation, Investigation. **Nicolas Vereecken:** Writing – review & editing, Validation, Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2024.100507.

Data availability

Data will be made available on request.

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