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Sustainability evaluation of contrasting *milpa* systems in the Yucatán Peninsula, Mexico

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Abstract

The *milpa* agroecosystem is an intercropping of maize, beans, squash and other crops, developed in Mesoamerica, and its adoption is widely variable across climates and regions. An example of particular interest is the Yucatan Peninsula in Mexico, which holds highly diverse *milpas*, drawing on ancestral Mayan knowledge. Traditional *milpas* have been described as sustainable resource management models, based on long rotations within a slash-and-burn cycle in forest areas. Nevertheless, due to modernization and intensification processes, new variants of the approach have appeared. The objective of this study was to evaluate the sustainability of three *milpa* systems (traditional, continuous, and mechanized) in four case studies across the Peninsula, with emphasis on food self-sufficiency, social inclusion and adoption of innovations promoted by a development project. The Framework for the Evaluation of Agroecosystems using Indicators (MESMIS, for its Spanish acronym) was used for its flexible, participatory approach. A common group of indicators was developed despite regional differences between study cases, with a high level of farmer participation throughout the iterative process. The results show lower crop yields in traditional systems, but with lower inputs costs and pesticide use. In contrast, continuous *milpas* had higher value in terms of crop diversity, food security, social inclusion, and innovation adoption. Mechanized *milpas* had lower weed control costs. Profitability of cash crops and the proportion of forest were high in all systems. Highly adopted innovations across *milpa* types and study cases included spatial crop arrangement and the use of residues as mulches. However, most innovations are not adapted to local conditions, and do not address climate change. Further, women and youth participation is low, especially in traditional systems.

Keywords Sustainability · *Milpa* · Food security · Innovation · Social inclusion · Yucatan Peninsula · MESMIS

Extended author information available on the last page of the article

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1 Introduction

1.1 Milpa agroecosystems in the Yucatan Peninsula

The Yucatan Peninsula in Eastern Mexico is characterized by highly diversified agroecosystems, integrating crops, livestock, and forest management. The region is of special importance for the conservation of biodiversity and cultural heritage (Terán, 2010). The *milpa*, a traditional association of maize with other crops, is a central component of farming systems, which include cash crops and forest management in long-term slash-and-burn cycles (Granados et al, 1999; Toledo et al, 2008).

Milpa agroecosystems in the Peninsula represent a pre-Hispanic cosmological and ecological paradigm and a backbone of Mayan people's livelihoods (Camacho-Villa et al., 2021; Konrad, 2003). Their multiple functions have been widely studied from ecological, economic, and social perspectives (Teran and Rasmussen, 1995; Toledo et al., 2008; Martin-Castillo, 2016). Ecological studies have focused on the sustainability of the shifting cultivation practices and the balance between *milpa* productivity and forest conservation (Dalle et al., 2011; Daniels et al., 2008). Studies on the economic dimension have paid special attention to its contribution to food security, nutrition and livelihoods (Falkowski et al., 2019; Lopez-Ridaura et al., 2019; Salazar-Barrientos & Magaña-Magaña, 2016), while social studies have mostly focused on local meanings attached to cultural identity and social interaction (De Frece & Poole, 2008; Jouault et al., 2018). However, there is a need for holistic assessments of *milpa* in terms of sustainability, integrating all three dimensions (economic, environmental and social). Of special attention should be the social dimension of *milpa* sustainability concerning equity in participation and decision-making processes at family, community, and market levels (De Frece & Poole, 2008).

1.2 Agroecosystem sustainability, innovation, and social inclusion

Over the last decades, agricultural modernization and rural development projects conducted by public institutions and non-government organizations have caused changes in *milpa* management in the Peninsula, including the shift from rotational to continuous and/or mechanized management, with variable external input and modern technology use (Castillo, 2016; Zapata, 2010). As with most development projects, the impact of these innovations is not always clear. Considering the importance of *milpa* systems in the livelihoods of rural families and the conservation of natural resources, there is a need to assess their sustainability across varying degrees of intensification and modernization. Since the concept of sustainability encompasses the satisfaction of multiple environmental, economic, and social goals, the assessment of innovations needs to be carried out in a systemic, integrated, multi-criterial and participatory manner. Innovations in the Mayan *milpa* system have been of different types, from those related to the modernization paradigm (Rodríguez-Canto et al., 2016) to those associated with the agroecological movement (Astier et al., 2017).

The Framework for the Evaluation of Management Systems using Sustainability Indicators (MESMIS, for its Spanish acronym) (López-Ridaura et al., 2002) is a system-based framework that has flexibility and adaptability across a diverse range of farming contexts (Acosta-Alba & Van der Werf, 2011; Eichler Inwood et al., 2018). It seeks to facilitate the path to sustainable rural development, incorporating the concepts of functional landscapes and agroecological models (Arnés et al, 2019). Since its publication, more than a hundred case studies have been reported, especially in Mexico and other Latin American countries (Astier et al., 2012; Speelman et al., 2007). Although it is a fundamental tool for assessing the sustainability of peasant farming systems, empirical experience shows certain limitations. The first one is related to the scale of application; its participatory nature makes it complex to consider geographic scales beyond communities or municipalities. This would imply greater budgetary requirements and probably another level of analysis and additional tools. The second limitation refers to the under-representation of social indicators.

Addressing the above, most sustainability evaluations have focused on productive or environmental aspects. Although some recent studies have integrated the element of social capital (Galicia-Gallardo et al., 2019), a less commonly studied sustainability component is social inclusion. Social inclusion is a process of increasing opportunities for social participation, enhancing capabilities of broadening social ties and enhancing cohesion, integration, or solidarity (Silver, 2015). This is crucial for agroecosystems sustainability, as they rely on the social fabric at both family and community levels. Although the general perception is that peasant agriculture is mainly practiced by the adult male head of the family, there is wide evidence that other members actively participate (Rodríguez-Canto et al., 2016; Terán, 2010). The inclusion of all community members in innovation processes is another key element in adapting agroecosystems to emerging challenges (Cortés & Castillo, 2019). Community inclusion can be evaluated, for example, by assessing the level of family influence within the community in terms of participation in collective activities, or the level in which farmers implementing innovations share them with others to be replicated (Xu, 2019). These elements can ensure not only greater inclusivity, but also the sustainability of innovation processes (Rogers, 2003).

The aim of this paper is to present the results of adapting and applying a sustainability assessment framework (MESMIS) to contrasting *milpa* systems in the Yucatan Peninsula, together with the adoption of innovations promoted by a development project. First, a brief description of *milpa* types in the Peninsula is presented. Then, the innovations promoted with local farmers through the project are described. The results are then compared by *milpa* type across four case studies, emphasizing the social inclusion component of innovation processes and their relation to agroecosystems sustainability.

2 Predominant *milpa* systems and innovations

The Yucatan Peninsula is dominated by a low and almost flat limestone bedrock with shallow soils (Vázquez-Domínguez & Arita, 2010). The climate is tropical with two distinctive seasons, rainy from May to November and dry from December to April (Islebe et al., 2018). Rainfall is distributed unevenly, ranging from 500 mm/year in the north-west to 1,200 in the south-east (Terán-Contreras & Rasmussen, 1994). Because of its geographic location, the Peninsula is frequently hit by hurricanes, tropical storms and winter rains (Vázquez-Domínguez & Arita, 2010). Knowledge about these events has been present since ancient times, as the variation in rainfall is associated with partial or total crop losses (Campos-Goenaga, 2012). Thus, climate has shaped traditional agroecosystems, with diversification as a key resilience strategy (Terán, 2010; Terán & Rasmussen, 1995).

The destructive effects of hurricanes on forests in the Peninsula have been mimicked by slash-and-burn practices, which form the basis of local forest management (Konrad, 2003). Thus, traditional agriculture takes place within long-rotation (> 20 yrs) slash-and-burn cycles, in which forest areas are used for beekeeping, wood fuel and medicinal plant collection, and to a lesser extent hunting. The main cropping activity is rainfed production under the *milpa* system, an ancient combination of several varieties of maize, beans, *ibes* (*Phaseolus lunatus*), squash and other crops. Other important sources of food and income outside the *milpa* include fruit trees, cash crops, small livestock, and off-farm employment (Terán & Rasmussen, 1995; Zizumbo et al, 2010). *Milpas* have evolved over centuries as a result of the transmission of practices, seeds, and knowledge (Ebel et al, 2018). Their diversity is closely linked to specific culinary uses (Cahuich-Campos et al., 2014; Ku-Pech et al., 2020). The rotational *milpa* is still largely dominant, although in some places it has been substituted by continuous and/or mechanized management (Rodríguez-Canto et al., 2016). The main features of these *milpa* types are shown in Table 1.

Geological differences across the Peninsula partly explain the type of practiced *milpa*, as shallow and stony soils limit the use of machinery (SEMARNAT 2008). It is important to note that there can be more than one *milpa* type in a single farm, depending mainly on soil characteristics. Work is mostly covered by the family, although in large areas external labor is hired for harvesting, regardless of *milpa* type. According to Rodríguez-Canto et al. (2016), fallow length is becoming shorter, which suggests a trend toward continuous cropping.

In this context, the project "Sustainable Modernization of *Milpa* in the Yucatan Peninsula (*Milpa Sustentable*)" was implemented from 2016 to 2020 by the International Maize and Wheat Improvement Center (CIMMYT), with the objective of developing, validating and implementing a methodology to facilitate innovation, co-development, adaptation, adoption and dissemination of innovative and sustainable technologies, adapted to the needs and context of smallholder farmers. The project aimed to improve rural livelihoods by increasing *milpa* productivity, improving food security, conserving and harnessing native agrodiversity, and reducing environmental impact through sustainable soil, water and crop management, while implementing a social inclusion strategy, understood as the possibility of most families having access to promoted innovations (https://idp.cimmyt.org/hubs/). Most innovations were not new to farmers, as they had been promoted by other projects and institutions (Table 2).

3 Materials and methods

3.1 Sustainability evaluation

We used the MESMIS framework (López-Ridaura et al., 2002) to evaluate the sustainability of contrasting *milpa* systems. The sustainability of an agroecosystem is defined in MESMIS with seven attributes: high productivity, high stability in the face of frequent disturbances, resilience in the face of extreme events, reliability against infrequent events, adaptability in the face of permanent changes, self-reliance/autonomy to regulate the system internal and external interactions and equity among the members of the system (Speelman et al, 2007). From these attributes, diagnostic criteria are derived to highlight the specific challenges to be addressed. Subsequently, identification of critical points, as well as the definition and measurement of indicators, are carried out through participatory tools that include all agents involved in resource management processes (Fig. 1). In contrast to other frameworks in which indicators are previously defined for any context or

Table 1 Predominant *milpa* agroecosystems in the Yucatán Peninsula

Milpa type	Traditional (TM)	Continuous (CM)	Mechanized (MM)
Soils	Hilly, rocky	Fertility patches (*Chan caab*)	Deep, non-rocky
Plot rotation	Yes	No	No
Labor	Manual	Manual	Mechanized plowing and sowing
Slash-and-burn	Yes	Often	No
Agrochemical use	Low pesticides and fertilizers	Low pesticides and fertilizers	Low-medium pesticides, low fertilizers
Crop arrangement	Mostly multicrop	Monocrop/multicrop	Monocrop/multicrop
Seed varieties	Mostly native	Native/hybrid	Native/hybrid
Water regime	Rainfed	Mostly rainfed	Rainfed/irrigated
Production objective	Mostly self-consumption	Self-consumption and sale	Self-consumption and sale

Based on Rodríguez-Canto et al. (2016)

Table 2 Innovations promoted by the *Milpa Sustentable* project (2016–2020)

Breeding	Soil management	Crop nutrition	Pest management	Postharvest
Recovery of native maize varieties	Soil analyses*	Organic fertilizers (liquid, compost, and forest mulch)	FAW (Fall Army worm) pheromone traps	Crop residue management (no-burn)
Appropriate native maize varieties*	Machinery adapted to *milpa* (manual seeders, power tillers and seeders, sprayer calibration)	Integrated fertilization management (4Rs: right source, amount, moment and application)	Agroecological pest management*	Postharvest management (airtight storage bins)
Participatory breeding	Spatial arrangement (1 m wide rows, 0.5 m between holes, 1–2 seeds per hole). Cover crops		Integrated weed management*	Marketing of surplus production

*Not promoted by previous projects

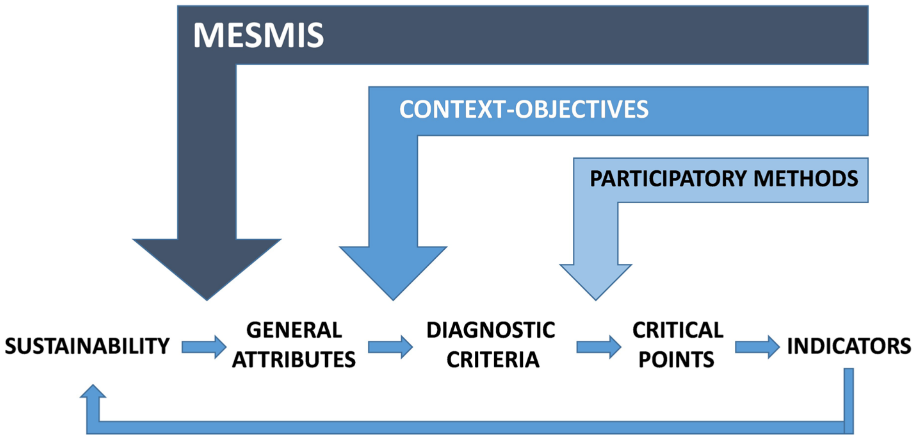

Fig. 1 From the concept of sustainability to the definition and measurement of criteria and indicators in the MESMIS framework

agroecosystem type (Grenz et al., 2009; Zahm et al., 2008), MESMIS emphasizes the use of participatory methods to define locally adapted indicators.

MESMIS integrates information on the interactions of system components in such a way that the effects of the social, economic and environmental processes are identified (Binder et al., 2010). An important premise is that sustainability cannot be measured per se, but rather is evaluated through the comparison of two or more systems. In this respect, sustainability evaluations are system, space and time specific (López-Ridaura et al., 2002). A robust, but non-exhaustive group of sustainability criteria and indicators must be selected. Thus, indicators should relate to all the attributes; be able to reflect changes in management practices; be adapted to the capacities and resources of the evaluation team; be clear and easy to communicate; and become decision-making tools at different scales (Astier & González-Esquivel, 2008).

3.2 Case studies

Four regions of interest were selected by the project to improve the sustainability of *milpa* systems (Fig. 2). Yaxcabá, in the Center-East of Yucatan State has traditionally been a major maize producing region. The high presence of rocks implies that only traditional (TM) and continuous (CM) *milpas* can be practiced, very much in the way that has been carried out over thousands of years by the Mayas. In Peto, South of Yucatan, more agricultural modernization efforts have taken place. However, as these have focused on commercial crops, self-consumption oriented *milpas* are still TM or CM. The third region is José María Morelos (JMM) in the central area of Quintana Roo State, where settlements were first established for rubber and tropical timber exploitation after the exile of the XIXth Century Caste War rebels (Barrera-Rojas & Reyes-Maya, 2013). This region is geologically older and has therefore deeper soils that allow mechanization. The last region is the late XXth century-colonized region of Calakmul in Campeche, with migrations from southern Yucatán and several states of Mexico. This region also has deep soils which can be mechanized and diverse productive systems including self-consumption *milpa*, cash

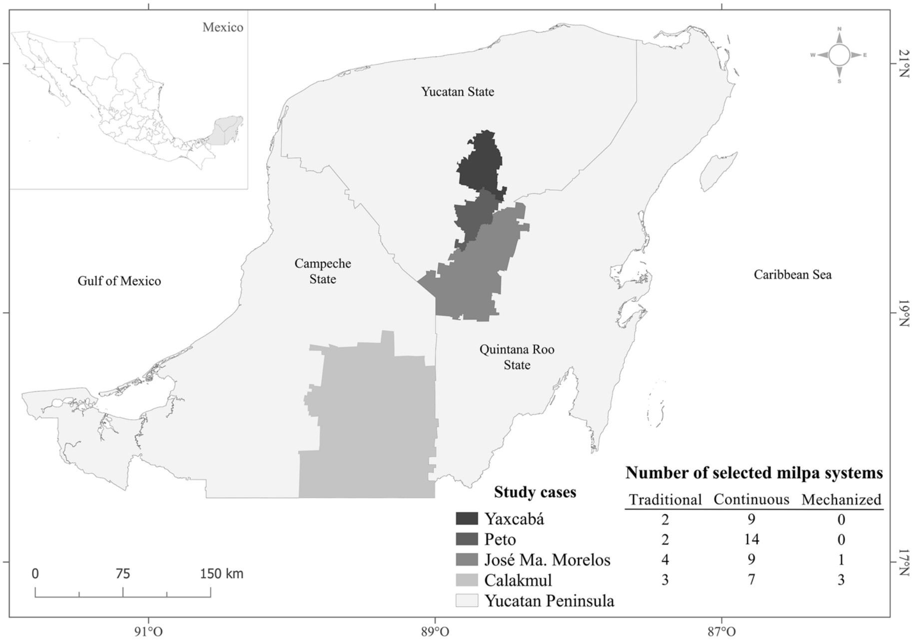

Fig. 2 Location of case studies and selected systems in the Yucatan Peninsula, Mexico

crops, beehives and cattle, within a context of increasing conservation efforts due to the proximity to the Calakmul Biosphere Reserve.

3.3 Characterization and identification of critical points

An evaluation team was established with three technicians from the *Milpa Sustentable* project. Those communities with a higher number of farmers participating in the project were selected. A total of 50 semistructured interviews were applied to farmers between September and November 2018, in order to characterize the *milpa* systems in terms of components, inputs, outputs and internal flows. Selected farmers were those considered by project technicians as innovators, leaders, or were actively exchanging knowledge within their communities. The results were presented to interviewees and other farmers in workshops carried out in each study case in November 2018. Critical points for the different farm unit components (*milpa*/orchard, forest, off-farm activities) were identified by workshop participants, using the strengths, weaknesses, opportunities, and threats (SWOT) technique (Geilfus, 2002). Strengths and weakness were considered internal, and opportunities and threats external to their farms. As social inclusion was an interest of the project, the subject was included in the workshops.

3.4 Definition and measurement of indicators

A training workshop on the MESMIS framework was carried out with 19 participants, including project technicians, invited academics and *milpa* experts in March 2019, in order to reach a final list of diagnostic criteria and indicators linked to the project objectives

Table 3 Selected sustainability criteria, critical points, and indicators for *milpa* systems in the Yucatan Peninsula

General attributes	Criteria	Critical points	Indicators	Level of analysis	Optimum value
Productivity Stability Resilience Reliability Adaptability Self-reliance Equity	Productivity and efficiency	Low crop productivity	Crop yield index (kg/ha)	Milpa	Regional average*
		Inefficient weed control	Time invested in weed control (%)	Milpa	Max 25%
		High pest damage	Crop losses index (%)	Milpa	Max 10%
		Low prices /unfair trade	Benefit–cost of cash crops	Farm unit	2
	Food security	High diversity of non-farm income sources	Complementarity of income sources (ratio)	Farm unit	1:1 on-farm/off-farm
		Low/high year-round food and feed sufficiency	Crop self-sufficiency (no. months)	Milpa	12
	Biodiversity Conservation	Productive diversity	Food products from *milpa* (no.)	Milpa	Regional average
		High crop diversity	Conserved cultivars (no.)	Milpa	Regional average
	Natural resource conservation	Exposure to agrochemicals	Risk from pesticide use (index)	Milpa	Min
		Forest degradation	Forest cover (%)	Farm unit	40
		Soil degradation	Soil conservation practices (no.)	Milpa	4
			Fallow length (no. years)	Farm unit	> 20
	Equity and social inclusion	Increases in input costs	Cost of inputs ($/ha)	Milpa	Regional minimum
		High home production of fertilizers, pesticides, seeds			
		Low prices /unfair trade	Relation with markets (index)	Farm unit	0
		Low adoption of innovations	Adoption of innovations (%)	Milpa	100
		Low participation of women and youth	Social inclusion (index)	Milpa	10

*See Appendix 1

(Table 3). From this list, a semistructured interview was developed and applied to 54 selected farmers from the original sample (see Fig. 2) between June and August 2019, corresponding to the 2018 cropping cycle.

3.5 Calculation of indicators and reference values

A composite crop yield index was calculated considering the importance of each crop in the family diet. According to Arnés et al. (2013), maize, beans and pumpkin contribute with 89%, 9% and 2%, respectively, of a *milpa* family self-consumption diet. Thus, yields reported by interviewed farmers for the 2018 crop cycle were transformed using these values and added into an index. Where both native and hybrid maize varieties were present, each one was allocated a value of 44.5%. In case both beans and *ibes* were present, each one was allocated a value of 4.5%. Finally, when squash was not present, maize was allocated a value of 90% and beans/*ibes* a value of 10%. Regional yield averages, used as reference values, were obtained in the final workshops with farmers (Appendix 1).

The percentage of labor invested in weed control was calculated in relation to total labor in the *milpa*, as this was perceived by farmers as one of the main weaknesses of the system. This was based on the number of labor hours/year reported by interviewed farmers for each activity in the *milpa*.

The crop losses index was calculated based on the same parameters used in the crop yield index. Regional averages were obtained in the workshops with farmers.

The profitability of cash crops in terms of benefit: cost was calculated from the data supplied by interviewees on total costs and income. Data were then transformed into percentages using 2 as an optimum value and 1 as a minimum.

Complementarity of income sources. The number of on-farm and off-farm income sources was registered. A ratio was calculated by dividing the lower obtained value by the higher one. A balance between on-farm and off-farm income sources was considered ideal to maintain high levels of stability and resilience. Therefore, an optimum proportion of 1:1 indicates balance between both income sources.

Crop self-sufficiency was estimated by asking interviewees the number of months/year that family food consumption is met with the produce from *milpas*.

Farmers were directly asked about the **number of food products** and the **number of conserved cultivars** at the *milpa* scale. Regional averages were used as optimum values.

The **index of risk from pesticide** use was calculated by multiplying the number of liters of products ha^{-1} yr^{-1} (insecticides, herbicides, fungicides) reported by farmers by the level of toxicity reported by WHO (2020) for each product applied, where extremely toxic = 5, highly toxic = 4, moderately toxic = 3, slightly toxic = 2 and unlikely toxic = 1. All values were then added and standardized using zero as optimum value and the highest value obtained as maximum.

Forest conservation was assessed according to the proportion of forest cover, estimated by subtracting the area used for agriculture to the total farm area and transforming the result into percentage. An optimum value of 40% forest cover was determined according to the minimum suggested by Arroyo-Rodríguez et al. (2020) to allow for biodiversity conservation and environmental service provision.

Soil conservation was estimated differently according to the *milpa* type. For TM, the length of the fallow period was considered, using 20 years as an optimum value. In the case of CM and MM, the number of soil conservation practices reported by interviewees was registered, using four practices as an optimum value (Appendix 2). Obtained values were then transformed into percentages for normalization.

The **cost of inputs** was calculated on a hectare basis by adding the cost of all purchased inputs (seeds, fertilizers, pesticides) at the *milpa* scale.

In terms of the **relation with markets and value chains**, an index was calculated using four variables: (a) the degree to which the farmer can negotiate prices with middlemen, (b) the immediacy of payment, (c) the impact from seasonal cost increases and (d) the impact from price reductions. The first two were assessed in a 0–3 scale, where 3 = never, 2 = sometimes, 1 = frequently and 0 = always. For the latter variables 0 = none, 1 = low, 2 = medium and 3 = high. All values were added to obtain a 0–12 scale, where an optimum value of zero indicates no negative market impacts. Values were then transformed into percentages for normalization.

The **adoption of innovations** indicator estimated the proportion (%) of innovations promoted by the *Milpa Sustentable* project that the farmer has applied and could carry on doing without technical assistance, as well as the proportion (%) of such innovations solving relevant problems. Both values were then averaged.

A **social inclusion** index was constructed using four variables: (a) inclusion of women, (b) inclusion of youth, (c) level of family participation in the community and (d) level of farmer influence in the community in terms of innovations to the *milpa* system. Women inclusion was estimated by calculating the proportion (in a 0 to 1 scale) of female family members older than 15 participating and taking decisions related to the *milpa*, the proportion that participates but does not take decisions and the proportion that does not participate at all. Each proportion was multiplied by 2, 1 and 0, respectively, for an optimum value of 2. A similar method was used to estimate youth participation, considering family members between 15 and 35 years old.

The level of family participation in community decisions was estimated according to the following scale: No participation (= 0), attending meetings (= 1), attending meetings and making proposals (= 2), attending meetings, making proposals, collective work and taking office (= 3).

Finally, the level of farmers' influence on innovations was estimated according to the following scale: A high level (= 3) was assigned when the farmer shared an innovation, and this was replicated by other farmers. A medium level (= 2) was assigned when the innovation was shared by inviting other farmers to visit the plots. A low level (= 1) was assigned when the farmer shared the experience by means of informal conversations and null (= 0) when the innovation was not shared at all. All four variables were added to obtain a total value in a 0 -10 scale. Obtained values were then transformed into percentages for normalization.

3.6 Integration and presentation of results

Results were presented to participating farmers in a second series of workshops in September 2019, in order to agree on reference values and discuss management alternatives for each case study. A final review of reference values was carried out in a workshop with five project technicians and the project manager. Definitive results are discussed first by *milpa* type and then by study case, emphasizing those indicators in which important differences were found.

4 Results and discussion

4.1 Milpa types

Results for each indicator, study case and *milpa* type are summarized in Table 4. Figure 3 summarizes normalized indicator values by *milpa* type. In the indicators associated with productivity and efficiency, CM and MM showed generally higher crop yields and cost:benefit compared to TM, along with lower crop losses. Labor use for weed control was high for most traditional and continuous farmers, who have expressed that mechanical trimmers would be an efficient and sustainable alternative to manual or chemical control. However, interviewees mentioned the high cost of these equipment as an obstacle, even though they can be complemented with other conservation practices, such as growing cover crops or using crop residue mulches.

Despite the low productivity of TM, we consider that this weakness is counterbalanced by the high income from cash crops and off-farm activities. This complementarity between agricultural and non-agricultural activities was also observed in a recent evaluation of *milpa* systems in the Western Highlands of Guatemala (González-Esquivel et al., 2020). Still, attention needs to be put in improving market equity for both agricultural and non-agricultural products and services, as it was considered a sensitive point by most interviewees. To improve productivity, it is essential to implement practices to reduce the impact of droughts and pests, particularly wildlife causing damage to crops (coatis, racoons and birds). In all *milpa* types, project technicians reported higher yields when using the alternative spatial plant arrangement.

In general, *milpas* supply family food needs for an average of 6 months a year (from 5 in TM to 6.7 in CM). Therefore, food security of families cannot depend on self-consumption. Behind the efforts to cultivate *milpa*, many authors point to identarian, cultural and cosmological roots that exceed the economic or material benefits it provides (Camacho-Villa et al., 2021; Isakson, 2009). For many families, ensuring their basic food for a few months through their own harvest is a form of savings and a personal satisfaction. Higher yields in continuous systems can be attributed to the use of improved hybrid seed varieties.

For many interviewees, it would be of value to increase the diversity of food products obtained and the use of organic fertilizers to improve crop nutrition and health. It is important to recognize that food self-sufficiency does not only depend only on family consumption, but also on biophysical factors. For example, in Yaxuná and many areas of the Peninsula, rocky, shallow soils do not allow higher crop yields. Similar findings were obtained in the WHG, where small farm size and slopes are a constraint to self-sufficiency (González-Esquivel et al., 2020; Arnés et al., 2019).

In terms of conserved cultivars, there is a high risk of substantial crop losses in bad years, which could lead to seed loss. Therefore, it would be useful to promote community seed banks, which have proved successful in regions with high climatic variability (Hellin et al., 2018). It is also urgent to generate strategies to allow facing climatic uncertainty in terms of rain cycles. These could include the use of short-cycle, drought resistant varieties, together with agronomic practices to maintain soil moisture and improve soil fertility (Ku-Pech et al., 2020).

In most cases families keep a high level of income complementarity, along with a high profitability of cash crops and products, especially honey, and to a lesser extent pigs, sheep, and fruits. However, most interviewees mentioned that prices are not fairly

Table 4 Sustainability indicators for contrasting *milpa* systems in the Yucatan Peninsula

Indicator	Yaxcabá		Peto		Jose Ma. Morelos			Calakmul		
	TM	CM	TM	CM	TM	CM	MM	TM	CM	MM
Crop yield index (kg/ha)	45	600	712	1974	1180	1571	1009	735	2265	856
Time invested in weed control (%)	37.5	52.9	44.5	34.4	63.5	41.0	26.0	50.7	24.3	16.5
Crop losses index (%)	98.6	57.1	40.8	40.2	68.6	32.6	45.5	21.3	26.6	42.8
Benefit:cost of cash crops	1.4	3.2	NA	3.9	2.4	2.9	3.8	2.4	3.9	0.9
Complementarity of income sources (index)	0.6	0.5	0.4	0.5	0.6	0.4	0.4	0.6	0.6	0.7
Crop self-sufficiency (no. months)	5.0	5.1	5.8	7.8	6.2	7.1	5.7	3.3	6.8	6.5
Food products from *milpa* (no.)	5.5	6.2	7.0	4.9	3.0	4.7	4.0	4.0	4.6	1.3
Conserved cultivars (no.)	8.0	7.8	12.0	6.9	4.3	4.8	4.0	4.0	7.0	1.3
Risk from pesticide use (index)	6.4	19.2	7.1	15.6	11.3	18.1	33.3	0.2	16.3	8.2
Forest conservation (%)	89.5	83.8	90.5	87.0	95.0	75.6	47.0	98.0	93.4	91.0
Soil conservation (n° of fallow length years and practices)	22.5	1.0	2.0	1.8	5.8	0.9	2.0	6.3	2.6	2.0
Cost of inputs ($/ha)	3546	2842	2349	3241	4683	5162	18,675	1818	3958	2887
Relation with markets (index)	6.0	6.0	5.0	7.5	5.7	7.2	7.0	5.3	4.3	5.7
Adoption of innovations (%)	25.0	42.6	52.1	57.9	NA	15.3	100.0	33.3	80.0	88.9
Social inclusion (index)	4.3	6.0	6.8	5.2	4.2	5.2	7.2	6.3	6.8	7.5

TM—traditional, CM—continuous, MM—mechanized

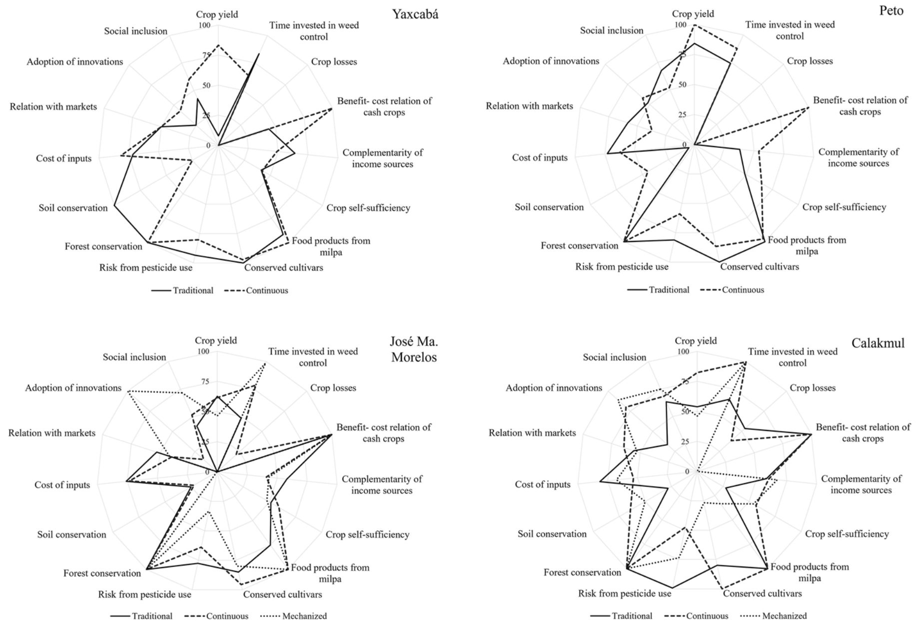

Fig. 3 Sustainability indicators for evaluated *milpa* systems in the Yucatán Peninsula

agreed, and that the cost of inputs is constantly increasing. It is therefore important to generate practices of collective input production/purchase and crop sale, and to promote fair trade networks.

The level of pesticide use is generally low, especially in TM, and needs to be kept as such, since an increase could greatly affect honeybee production, which is the main cash source of most families. Forest conservation had optimum values in all systems as the proportion of cropping land is still low. In the case of farmers switching to continuous cropping, agroecological practices need to be increased to maintain good soil quality and sustained productivity. Soil conservation values were higher in TM, reflecting longer fallow periods and a higher number of conservation practices.

Table 5 shows the results of the social inclusion index variables. Family and community inclusion were highly ranked in CM and MM. Women participation in *milpa* is relevant in all cases, especially in CM in Calakmul, where they also take decisions. This is in line with the findings of Teran (2010), challenging the common narrative that minimizes the contribution of women to the *milpa* system. However, our results indicate that womens' participation is mostly limited to supporting activities, rather than decision making. In addition, youth participation was generally low, except for MM. This can be partially explained by the level of education and employment opportunities outside the communities (de Freece and Poole, 2008). As elsewhere in rural Mexico (Vizcarra-Bordi et al., 2015), this finding raises questions on the impact on intergenerational transmission of *milpa*-related knowledge, especially in traditional systems, which showed the lowest values.

The lowest values of women and youth inclusion were found in TM. This could point to a low intergenerational sustainability of these systems as it seems that they are maintained by individual farmers who are normally adult or elder men. Important differences in family influence were only found in traditional systems in Peto. However, in most cases the

Table 5 Variables composing the social inclusion index for contrasting *milpa* systems in the Yucatan Peninsula

Variables	Yaxcabá		Peto		JMM			Calakmul			Optimum
	TM	CM	TM	CM	TM	CM	MM	TM	CM	MM	
Inclusion of women (index)	1.3	1.4	1.3	1.3	1.3	1.3	1.5	1.2	1.7	1.3	2
Inclusion of youth (index)	0.0	1.0	1.0	0.9	0.8	1.1	1.7	1.2	1.1	1.5	2
Level of family influence in the community (index)	2.0	2.1	3.0	1.9	1.5	1.8	2.0	2.0	2.6	2.7	3
Level of farmer influence in *milpa* innovations in the community (index)	1.0	1.6	1.5	1.1	0.5	1.0	2.0	2.0	1.4	2.0	3
Total	4.3	6.0	6.8	5.2	4.2	5.2	7.2	6.3	6.8	7.5	10

TM- Traditional, CM- Continuous, MM- Mechanized influence of families was limited, as they only attended community meetings and sometimes made proposals, but rarely engaged in collective work. Similarly, farmer experiences were not always shared, or only by informal conversations.

Farmers influence on community innovations was low in most study cases, with little differences between *milpa* types. This point is important since innovative farmers were selected for the project, expecting that they would share their knowledge with other community members. There is already a rich literature that questions the fact that innovators are always good disseminators (Rogers, 2003), while exclusion–inclusion processes take place at community level due to various factors (Xu, 2019). This implies that the reach of *Milpa Sustentable* and other projects in disseminating innovations is limited by both external and contextual conditions (Roldán-Suarez, 2019).

Most innovations promoted by the project are not highly appropriate for traditional *milpas*. Those which will continue to be used include spatial plant arrangement and crop residue mulches. According to interviewed farmers, crop reside mulches keep soil moisture for longer, therefore reducing the effects of droughts or changes in rainfall patterns. However, other innovations such as pheromone traps and grain storage bins were not used in most cases, as molasses and airtight containers are difficult to access in the region. The farmers reported that problems including crop damage by wildlife or weeds were weakly addressed and to a lesser extent the effects of drought. In some parts of the Peninsula, *milpas* are sown in the middle of the forest only to attract game and hunt it for food (mainly deer) (Santos-Fita et al., 2013). This practice could be an option to control mammal pests in the studied communities.

4.2 Study cases

According to interviewed farmers in the four study cases, the 2018 crop cycle was poor, resulting in low crop yields compared to the average over previous years. Losses due to extreme climatic events and wildlife were substantial, and self-sufficiency in staple crops was low in most cases, although the amount of rainfall was not too dissimilar from regional averages. Each case presented variances in the sustainability indicators captured in Table 4 and these are described below.

In the case of **Yaxcabá,** only TM and CM were compared. Crop yields were meager, and TM losses were almost total, mainly due to the invasion of forest mammals into the crop areas (coatis, *Nasua narica*). These invasions may result from either habitat degradation in other areas or a lack of natural predators. Crop losses were substantially lower in CM. Self-sufficiency was also low for both types of *milpa*, although the number of conserved cultivars was the highest compared to other cases. The cost of inputs was lower in CM, but the time invested in weed control was higher. Concerning social indicators, inclusion of women was similar in both *milpa* types. Nevertheless, a wide gap in youth inclusion was observed, with zero participation in TM. The level of family influence in the community was also similar between *milpa* types. However, the influence level of farmers on innovations was higher in CM.

Spatial plant arrangement, crop residue mulches and liquid organic fertilizers were the most tested and adopted innovations during the project in this case. These innovations directly addressed input costs and crop losses to drought. However, a highly reported and unattended problem is crop damage by wildlife.

There was a high complementarity between farm and off-farm income sources in both systems. These included textile and wooden handcrafts (sold at nearby archeological zones), beehives, squash seed and government support. Honey is the main income source and is highly profitable. However, the relationship of farmers with markets was described as inconvenient, as they are frequently affected by input cost rises and the low stability (with a downward trend) of product prices. Moreover, interviewees observed no possibility of negotiating fair prices with middlemen. In contrast, project technicians observed that farmers organized as groups or cooperatives have a higher negotiating power in farm product sales and input purchases.

In the **Peto** study case, TM and CM were present. Crop yields were more acceptable than in Yaxcabá, especially in CM, and losses due to pests were higher in TM. As a result, self-sufficiency improved in CM, albeit with higher costs and increased risk from pesticide use. In contrast, TM showed higher numbers of obtained products and conserved cultivars.

Of the eleven proposed innovations, the most utilized ones were plant spatial arrangement, crop residue mulches, liquid organic fertilizers, and pheromone traps. A high proportion of farmers have successfully adopted the first two innovations. Common problems unrelated to innovations included crop damage by hurricanes, weeds, and wildlife. TM were not highly affected by input cost rises, with honey being a highly profitable product. In contrast, farmers implementing CM rarely reported being able to negotiate fair prices, although they did receive payments at the point of sale. Income sources are mainly off-farm for TM and on-farm for CM. The primary income sources include honey, handcrafts, surplus maize, squash seed, small livestock (poultry and pork), and provision of labor on other farms or in construction.

In the **José María Morelos** case, the three *milpa* systems were reported; however, only one MM was found; thus, the findings are not analyzed in detail. CM had much higher crop yields and lower losses. Self-sufficiency also improved, but the cost increase was insignificant compared to TM. The risk from pesticide use was higher for CM, but the time dedicated to weed control decreased. No innovations were promoted for TM. In the case of CM, innovations such as different maize varieties, synthetic fertilizers and straw mulches were not appropriate to address their problems, including drought, weeds and insect, bird, or mammal pests. Income complementarity was more balanced between on-farm and off-farm sources in TM, while the main income sources for CM are cash crops such as citrus fruits, maize, beans, squash seed, wood, and honey. In this case, most farmers reported that they received government support. Cost:benefit was higher for CM. However, both types had optimum values, with wood, fruits and honey being the most profitable activities. The relation with markets showed lower values on negotiation ability for CM, as the farmers are constantly affected by input cost rises and a decrease in product prices.

In **Calakmul**, it was possible to compare the three *milpa* systems. CM had substantially higher crop yields, although with similar loss proportions compared to traditional systems. MM had the highest level of crop losses. Both self-sufficiency and the number of conserved cultivars increased substantially in continuous systems, while the lowest values were for mechanized ones. However, input costs and pesticide risk were also much higher. Time invested in weed control was higher in TM. In general, promoted innovations were more appropriate for CM and MM than for TM, mainly spatial plant arrangement, crop residue mulches and liquid fertilizers. However, innovations did not address climate change effects (droughts, delays in the start of the rainy season) nor common insect pest control (mainly aphids and stemborers).

All *milpa* systems showed moderate levels of income complementarity, with honey and government support being the primary income sources. Cash crops, mainly honey, were highly profitable in TM and CM. The relation with markets had medium levels in all systems, the main conflicts being constant input cost rises and few chances of negotiating product prices.

4.3 Methodological considerations

An important contribution of this study was the active participation of farmers through all steps of the evaluation, especially in defining critical points, indicators, reference values and generating recommendations after reviewing the results. This contrasts with numerous study cases using MESMIS or other frameworks, where indicators were previously defined by external agents, mainly academic experts (Wiget et al., 2020).

When defining indicators, the evaluation team tried to achieve complementarity between simple indicators and composed indices. The need to have a relatively small number of indicators while managing large amounts and types of information implies designing indices which can relate directly to critical points of the systems under evaluation, yet simple enough to be understood by decision-makers. In the case of food security, there is plenty of recent literature on the subject, yet little efforts to express it in measurable values (López-Ridaura et al., 2019). Novel indices were also designed for complex variables, such as income complementarity, adoption of innovations and social inclusion. The latter variable is an attempt to assess the quality of the social fabric in rural communities. The weight assigned to each sub-variable can be debatable and therefore subject to changes when applying these indices to these and other study cases and contexts.

5 Conclusions and recommendations

All studied *milpa* systems showed acceptable values in most indicators. TM showed generally lower input costs and low pesticide use, along with lower crop yields and higher losses. Interestingly, CM had slightly higher diversity, food self-sufficiency, social inclusion, and innovation. MM showed similar values to those of CM but with much lower weed control costs. Considered together, the three *milpa* types could complement each other in a given situation. The fact that a farm unit can have more than one *milpa* type within their farming system calls for further research to explore their complementary contribution to farm sustainability. Important challenges in terms of sustainability include food security, especially in TM, as it can be limited by environmental factors such as climate and soils. Strategies should be developed to cope with increasing risks from climate change in all studied systems. Although this study documents the high risks of crop losses due to climate variability and wildlife damage, it did not explore the social strategies required to face climate change challenges.

Across study cases and *milpa* types, spatial plant arrangement and crop residue mulches were among the most adopted innovations. Promoted innovations were more appropriate for CM and MM. Therefore, it is necessary to address in future projects the innovations adapted to TM, based on farmer needs. This is particularly relevant because TM systems proved to be more sustainable in terms of wildlife and soil conservation. Future studies are needed to explore the contribution of *milpa* types on successional cycles of tropical forests.

Low values for youth participation raise concerns for intergenerational knowledge sharing and intergenerational sustainability of these systems. Another concern is the reported low influence of innovative farmers, along with their limited efforts to share the promoted innovations, especially in traditional systems. This suggests there is a need to embed actions to enhance the social fabric across rural communities in terms of women recognition and youth and community integration. The findings also highlight the limitations of the *Milpa Sustentable* project, by focusing mostly on technological innovations, with little attention to social innovation processes that can improve sustainability. The participatory approach used in the study allowed for integrating farmers throughout the evaluation process, not only as informants, but also as decision-makers and validators. The interaction between farmers, project technicians and academics created spaces for open discussion on the different meanings of sustainability, how it is measured, and the underlying causes of the differences in indicator values across *milpa* types. It is only through such transdisciplinary approach that locally adapted and relevant innovations toward sustainability can be co-created.

Appendix 1: Average crop yields and optimum values (kg/ha) per *milpa* type for the 2018 harvest. Ranges in brackets.

Study case	Yaxcabá				Peto			
Milpa type	Traditional		Continuous		Traditional		Continuous	
Crop	Obtained	Optimum	Obtained	Optimum	Obtained	Optimum	Obtained	Optimum
Native maize	50 (0–100)	600	656 (0–1600)	800	799 (365–1223)	900	1024 (275–1800)	1200
Hybrid maize	NA	NA	NA	NA	NA	NA	3375 (2000–4500)	3000
Pumpkin seed	2	100	71 (0–341)	100	8 (2–15)	110	83 (0–250)	300
Bean	0	100	45 (0–125)	100	15	125	157 (0–712)	150
Ibes	0	75	11 (0–30)	75	24 (10–38)	83	215 (8–700)	83

Study case	José Ma. Morelos						Calakmul					
Milpa type	Traditional		Continuous		Mechanized		Traditional		Continuous		Mechanized	
Crop	Obtained	Optimum	Obtained	Optimum	Obtained	Optimum	Obtained	Optimum	Obtained	Optimum	Obtained	Optimum
Native maize	685 (0–1938)	1200	1125 (600–1778)	1600	750	2250	567 (400–800)	1500	1174 (427–2000)	2000	950 (650–1500)	2000
Hybrid maize	1968	3000	2308 (400–3500)	4000	NA	NA	NA	NA	3801 (3602–4000)	4000	NA	NA
Pumpkin seed	20 (3–37)	125	98 (15–150)	300	NA	NA	45 (10–80)	125	130 (0–438)	300	12	600

Study case	José Ma. Morelos						Calakmul					
Milpa type	Traditional		Continuous		Mechanized		Traditional		Continuous		Mechanized	
Crop	Obtained	Optimum	Obtained	Optimum	Obtained	Optimum	Obtained	Optimum	Obtained	Optimum	Obtained	Optimum
Bean	0	200	497 (208–831)	600	3338	1500	3200	200	324 (0–844)	600	NA	NA
Ibes	1	150	465 (150–745)	700	NA	NA	NA	NA	NA	NA	NA	NA

NA-Not applicable.

Appendix 2: Soil conservation practices reported by farmers

Minimum tillage
Not burning crop residues
Use of crop residues as mulch
Use of synthetic fertilizers
Use of organic fertilizers
Growing legumes
Crop rotation
Mechanical weed control
Fallow periods

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Data availability Data are available from the authors upon request.

Declarations

Conflict of interest The authors declare that there are no conflicts of interest.

References

Acosta-Alba, I., & Van der Werf, H. (2011). The use of reference values in indicator-based methods for the environmental assessment of agricultural systems. *Sustainability, 3*(2), 424–442.

Arnés, E., Antonio, G. J., del Val, E., & Astier, M. (2013). Sustainability and climate variability in low-input peasant maize systems in the central Mexican highlands. *Agriculture, Ecosystems and Environment, 181*, 195–205.

Arnés, E., Astier, M., Marín-González, O., & Díaz-Ambrona, G. C. H. (2019). Participatory evaluation of food and nutritional security through sustainability indicators in a highland peasant system in Guatemala. *Agroecology and Sustainable Food Systems, 43*(5), 482–513.

Arroyo-Rodríguez, V., Fahrig, L., Tabarelli, M., Watling, J. I., Tischendorf, L., Benchimol, M., ... & Tscharntke, T. (2020). Designing optimal human-modified landscapes for forest biodiversity conservation. *Ecology letters, 23*(9), 1404–1420.

Astier, M., García-Barrios, L., Galván-Miyoshi, Y., González-Esquivel, C. E., Masera, O. R. (2012). Assessing the sustainability of small farmer natural resource management systems. A critical analysis of the MESMIS program (1995–2010). *Ecology and Society*, *17*(3).

Astier, M., Argueta, J. Q., Orozco-Ramírez, Q., González, M. V., Morales, J., Gerritsen, P. R., Escalona, M. A., Rosado May, F. J., Sánchez Escudero, J., Martínez Saldaña, T., Sánchez Sánchez, C., Arzuffi Barrera, R., Castrejón, F., Morales, H., Soto, L., Mariaca, R., Ferguson, B., Rosset, P., Ramírez, H., … Ambrosio, M. (2017). Back to the roots: Understanding current agroecological movement, science, and practice in Mexico. *Agroecology and Sustainable Food Systems, 41*(3–4), 329–348.

Astier, M., & González-Esquivel, C. (2008). Formulación de indicadores socioambientales para evaluaciones de sustentabilidad de sistemas de manejo complejos. In M. Astier, O. Masera, & Y. Galván (Eds.), *Evaluación de sustentabilidad. Un enfoque dinámico y multidimensional* (pp. 59–79). SEAE.

Barrera-Rojas, M. A., & Reyes-Maya, O. (2013). Pobreza y transferencias monetarias en comunidades mayas de México : José María Morelos y Sabán, Quintana Roo, 2011. *Equilibrio Económico, Revista de Economía, Política y Sociedad, 9*, 201–228.

Binder, C. R., Feola, G., & Steinberger, J. K. (2010). Considering the normative, systemic and procedural dimensions in indicator-based sustainability assessments in agriculture. *Environmental impact assessment review, 30*(2), 71–81.

Cahuich-Campos, D., Huicochea Gómez, L., & Mariaca Méndez, R. (2014). El huerto familiar, la milpa y el monte Maya en las prácticas rituales y ceremoniales de las familias de X-Mejía, Hopelchén, Campeche. *Relaciones. Estudios De Historia y Sociedad, 35*(140), 157–184.

Camacho-Villa, T. C., Martinez-Cruz, T. E., Ramírez-López, A., Hoil-Tzuc, M., & Terán-Contreras, S. (2021). Mayan traditional knowledge on weather forecasting: who contributes to whom in coping with climate change? *Frontiers in Sustainable Food Systems, 5*, 1–17.

Campos-Goenaga, M. I. (2012). Sobre tempestades con remolino y plagas de langosta. Siglos XVI al XVIII en la península de Yucatán. *Relaciones. Estudios de Historia y Sociedad, XXXIII*, 125–160.

Castillo, M. (2016). Milpa y capitalismo: opciones para los campesinos mayas yucatecos contemporáneos. *LiminaR. Estudios Sociales y Humanísticos, 14*, 101–114.

Cortés, C. I., & Castillo, B. M. T. (2019). Los mayas y la agricultura de riego en el Oriente de Yucatán. *Desacatos: Revista de Ciencias Sociales, 61*, 130–149.

Daniels, A. E., Painter, K., & Southworth, J. (2008). Milpa imprint on the tropical dry forest landscape in Yucatan, Mexico: Remote sensing & field measurement of edge vegetation. *Agriculture, Ecosystems & Environment, 123*(4), 293–304.

Dalle, S. P., Pulido, M. T., & Blois, S. D. (2011). Balancing shifting cultivation and forest conservation: lessons from a "sustainable landscape" in southeastern Mexico. *Ecological Applications, 21*(5), 1557–1572.

de Frece, A., & Poole, N. (2008). Constructing Livelihoods in Rural Mexico: *Milpa* in Mayan Culture. *The Journal of Peasant Studies, 35*(2), 335–352.

Ebel, R., Aguilar, M. D. J. M., & Putnam, H. R. (2018). Milpa: One sister got climate-sick. The impact of climate change on traditional maya farming systems. *The International Journal of Sociology of Agriculture and Food, 24*(2), 175–199.

Eichler Inwood, S. E., López-Ridaura, S., Kline, K. L., Gérard, B., Monsalue, A. G., Govaerts, B., & Dale, V. H. (2018). Assessing sustainability in agricultural landscapes: A review of approaches. *Environmental Reviews, 26*(3), 299–315.

Falkowski, T. B., Chankin, A., Diemont, S. A. W., & Pedian, R. W. (2019). More than just corn and calories: A comprehensive assessment of the yield and nutritional content of a traditional Lacandon Maya milpa. *Food Security, 11*, 389–404.

Galicia-Gallardo, A. P., González-Esquivel, C. E., Castillo, A., Monroy-Sánchez, A. B., & Ceccon, E. (2019). Organic hibiscus (Hibiscus sabdariffa), social capital and sustainability in an indigenous non-governmental organization from La Montaña, Guerrero, Mexico. *Agroecology and Sustainable Food Systems, 43*(10), 1106–1123.

Geilfus, F. (2002). *80 herramientas para el desarrollo participativo*. IICA.

González-Esquivel, C. E., Camacho-Moreno, E., Larrondo-Posadas, L., Sum-Rojas, C., de León-Cifuentes, W. E., Vital-Peralta, E., ... & López-Ridaura, S. (2020). Sustainability of agroecological interventions in small scale farming systems in the Western Highlands of Guatemala. *International Journal of Agricultural Sustainability, 18*(4), 285–299.

Granados, D., López, G. F., & Trujillo, E. (1999). La milpa en la zona maya de Quintana Roo. *Revista de Geografía Agrícola, 28*, 52–72.

Grenz, J., Thalmann, C., Stämpfli, A., Studer, C., & Häni, F. (2009). RISE–a method for assessing the sustainability of agricultural production at farm level. *Rural Development News, 1*, 5–9.

Hellin, J., Ratner, B. D., Meinzen-Dick, R., & Lopez-Ridaura, S. (2018). Increasing social-ecological resilience within small-scale agriculture in conflict-affected Guatemala. *Ecology and Society, 23*(3), 5.

Isakson, S. R. (2009). No hay ganancia en la milpa: The agrarian question, food sovereignty, and the on-farm conservation of agrobiodiversity in the Guatemalan highlands. *The Journal of Peasant Studies, 36*(4), 725–759.

Islebe, G. A., Torrescano-Valle, N., Aragón-Moreno, A. A., Vela-Peláez, A. A., & Valdez-Hernández, M. (2018). El Paleoantropoceno de la peninsula de Yucatán: evidencias palinológicas de cambio ambiental. Boletín de la Sociedad Geológica Mexicana, 70(1), 49–60.

Jouault, S., Enseñat-Soberanis, F., & Balladares-Soberano, C. (2018). La milpa maya en Yucatán: ¿una transición entre la patrimonialización y la turistificación? *Gremium, 5*(10), 9–24.

Konrad, H. W. (2003). Caribbean tropical storms: Ecological implications for pre- hispanic and contemporary Maya subsistence on the Yucatan Peninsula. *Revista de la Universidad autónoma de Yucatán, 224*, 99–126.

Ku-Pech, E. M., Mijangos-Cortés, J. O., Andueza-Noh, R. H., Chávez-Pesqueira, M., Simá-Polanco, P., Simá-Gómez, J. L., & Arias-Reyes, L. M. (2020). Estrategias de manejo de la milpa maya en Xoy, Peto, Yucatán. *Ecosistemas y Recursos Agropecuarios*, *7*(1).

Lopez-Ridaura, S., Barba-Escoto, L., Reyna, C., Hellin, J., Gerard, B., & van Wijk, M. (2019). Food security and agriculture in the western highlands of Guatemala. *Food Security, 11*(4), 817–833.

López-Ridaura, S., Masera, O., & Astier, M. (2002). Evaluating the sustainability of complex socio-environmental systems. The MESMIS Framework. *Ecological Indicators, 2*(1–2), 135–148.

Martín-Castillo, M. (2016). Milpa y capitalismo: Opciones para los campesinos Mayas Yucatecos contemporáneos. *LiminaR. Estudios Sociales y Humanísticos, 14*, 101–114.

Rodríguez-Canto, A.; González Moctezuma, P.; Flores Torres, J.; Nava Montero, R.; Dzib Aguilar, L A.; Pérez Pérez, J. R.; Thüerbeck, N.; González Iturbe, J. A. (2016). Milpas de las comunidades mayas y dinámica de uso del suelo en la Península de Yucatán. México: Centro Regional Universitario Península de Yucatán, Universidad Autónoma Chapingo. Mérida Yucatán. 436 pp. https://pdf.usaid.gov/pdf_docs/PA00MW9J.pdf

Rogers, E. M. (2003). *Diffusion of innovations*. Simon and Schuster.

Roldán-Suárez, E., Islas-Moreno, A., Sánchez-Gómez, J., & Rendón-Medel, R. (2019). Redes de innovación en sistemas de producción de milpa. *Revista De Geografía Agrícola, 63*, 45–62.

Salazar-Barrientos, L. D. L., & Magaña-Magaña, M. A. (2016). Aportación de la milpa y traspatio a la autosuficiencia alimentaria en comunidades mayas de Yucatán. *Estudios sociales (Hermosillo, Son.), 24*(47), 182–203.

Santos-Fita, D., Naranjo Pinera, E. J., Bello Baltazar, E., Estrada Lugo, E. I., Mariaca Méndez, R., & Macario Mendoza, P. A. (2013). La milpa comedero-trampa como una estrategia de cacería tradicional maya. *Estudios De Cultura Maya, 42*, 87–118.

Secretaría de Medio Ambiente y Recursos Naturales. (2008). Informe de la situación del medio ambiente en México. *Compendio de estadísticas ambientales*. Available at: https://apps1.semarnat.gob.mx:8443/dgeia/informe_2008_ing/pdf/cap_3_suelos.pdf

Silver, H. (2015). The contexts of social inclusion. United Nations Department of Economic and Social Affairs. DESA Working Paper No. 144. Available at SSRN: https://ssrn.com/abstract=2879940

Speelman, E., López-Ridaura, C. N., Astier, M., & Masera, O. (2007). Ten years of Sustainability Evaluation using the MESMIS framework: Lessons learned from its application in 28 Latin American case studies. *International Journal of Sustainable Development and World Ecology, 14*, 345–361.

Terán, S., & Rasmussen, C. (1994). La milpa de los mayas. *DANIDA, Talleres Gráficos del Sudeste, Mérida, Yucatán*

Terán, S. (2010). Milpa, biodiversidad y diversidad cultural. In R. Durán & M. Méndez (Eds.), *Biodiversidad y Desarrollo Humano en Yucatán* (p. 496). CYCY, PPD-FMAM, CONABIO, SEDUMA.

Terán, S., & Rasmussen, C. H. (1995). Genetic diversity and agricultural strategy in 16th century and present-day Yucatecan milpa agriculture. *Biodiversity and Conservation, 4*(4), 363–381.

Toledo, V. M., Barrera-Bassols, N., García-Frapolli, E., & Alarcón-Chaires, P. (2008). Uso múltiple y biodiversidad entre los mayas yucatecos (México). *Interciencia, 33*(5), 345–352.

Vázquez-Domínguez, E., and Arita, H. T. (2010). The Yucatan Peninsula: biogeographical history 65 million years in the making. *Ecography, 33*, 212–219. https://doi.org/10.1111/j.1600-0587.2009.06293.x

Vizcarra-Bordi, I., Thomé-Ortiz, H., & Hernández-Linares, C. (2015). Miradas al futuro: El relevo generacional en el desarrollo de la conciencia social como estrategia de conservación de los maíces nativos. *Carta Económica Regional, 115*, 55–73.

WHO (World Health Organization) (2020). The WHO recommended classification of pesticides by hazard and guidelines to classification 2019. World Health Organization.

Wiget, M., Müller, A., & Hilbeck, A. (2020). Main challenges and key features of indicator-based agroecological assessment frameworks in the context of international cooperation. *Ecology and Society, 25*(3), 1–20.

Xu, Y. (2019). Politics of inclusion and exclusion in the Chinese industrial tree plantation sector: The global resource rush seen from inside China. *The Journal of Peasant Studies, 46*(4), 767–791.

Zahm, F., Viaux, P., Vilain, L., Girardin, P., & Mouchet, C. (2008). Assessing farm sustainability with the IDEA method–from the concept of agriculture sustainability to case studies on farms. *Sustainable Development, 16*(4), 271–281.

Zapata, R. (2010). Persistencia y cambio de los patrones indígenas de aprovechamiento de la biodiversidad. In R. Durán & M. Méndez (Eds.), *Biodiversidad y Desarrollo Humano en Yucatán* (p. 496). CYCY, PPD-FMAM, CONABIO, SEDUMA.

Zizumbo, D., Colunga, P., May, F., Martínez, J., & Mijangos, J. (2010). Recursos fito-genéticos para la alimentación y la agricultura. In R. Durán & M. Méndez (Eds.), *Biodiversidad y Desarrollo Humano en Yucatán* (p. 496). CYCY, PPD-FMAM, CONABIO, SEDUMA.

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