Sustainability of the community model of avocado production in the Monarch Butterfly Biosphere Reserve, Michoacán, México

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Abstract The avocado is a commodity crop that has generated severe environmental and social impacts in Michoacán, the world's leading producer. Current studies overlook the diversity of avocado production by focusing on Michocán's central region, while the regions of a more recent expansion remain poorly studied. We analyzed the model of avocado production in five indigenous communities in the municipality of Zitácuaro that have part of their territory within the Monarch Butterfly Biosphere Reserve. We use the Framework for the Evaluation of Management Systems using Sustainability Indicators to characterize and evaluate the sustainability of the Community Model of Avocado Production (CMAP). Based on 42 interviews with producers, we identified eleven critical points related to environmental (small-scale production; forest conservation; high prophylactic use of agrochemicals; high dependence on irrigation), economic (high crop diversity; low profitability; high yield loss to pests; low economic diversification), and social (high dependence on technical advisors; low dependence on labor force external to the community; few changes in land ownership) aspects of sustainability. The CMAP has productive and socio-political characteristics that represent strengths and weaknesses for its sustainability. The main environmental results suggest that the avocado expansion (2007–2022) in the communities did not involve a change in forest land use. Socially, the CMAP favors the local workforce and facilitates the maintenance of land ownership. The sustainability of CMAP is mostly limited by its economic aspects. With adequate economic support for socially and environmentally sustainable productive practices, the CMAP can improve the local livelihoods while promoting forest conservation.

Keywords Commodity crops · MESMIS · Sustainable agriculture · Protected area · Forest conservation · Agricultural land use

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Introduction

Nearly half (46%, 48 million km^2) of the world's habitable land is used for agriculture (FAO, 2023; Ritchie and Roser, 2019). Cropland continues to expand globally in response to growing populations and consumption rates (Eigenbrod et al., 2020). This increase is occurring through the conversion of natural ecosystems, primarily forests, to agricultural land, making this process a major source of greenhouse gas emissions, biodiversity loss, soil degradation, and overuse of water resources (FAO, 2023; Olsson et al., 2019).

The regions with abundant land and natural resources where the production of raw agricultural products is rapidly expanding over other land uses are known as *agricultural commodity frontiers* (le Polain de Waroux et al., 2018).[1] The global changes in the agri-food regime favor transitions to agro-industrial production models. Agro-industrialization brings changes in the dynamics of land control, increases the agency of large agribusiness, and introduces rent-capture behaviors (Barrett et al., 2001; Eigenbrod et al., 2020). This is followed by an increase in the use of agricultural inputs for production intensification which puts pressure on local and communal models of production and threatens the sustainability of local livelihoods, resulting in a range of ecological, social, and ethical impacts (González, 2014; Orozco-Meléndez & Paneque-Gálvez, 2023; Qi et al., 2018).

Efficient land use and land management plans and strategies are needed to maximize crop productivity while minimizing the potential environmental and social impacts. Protected areas have been confirmed as efficient strategies for conserving biodiversity and environmental services, but we still do not know enough about whether and how they can be a viable alternative for the local people (Brockington & Wilkie, 2015; Macura et al., 2015; McKinnon et al., 2016; Naidoo et al., 2019).

México is the leading producer of avocado (*Persea americana*) contributing to up to 45% of the world market (Cruz-López et al., 2022; Olivares, 2023). With a production of more than 2.5 million tons, Michoacán state is the leading avocado producer in México, covering 72.8% of the total national production (SIAP, 2024). The avocado in Michoacán is produced in 24 municipalities,[2] 19 in the central-western part of the state and five in the east (SIAP, 2024). These municipalities form the largest avocado producing region in the world, known as the Avocado Belt. Michoacán's Avocado Belt is a contiguous geographic region within the Trans-Mexican Volcanic Belt that provides optimal biophysical and climatic conditions for avocado growth. Avocado production in Michoacán has reached an industrial scale, and since the 1970s the expansion of avocado orchards has occurred rapidly at the expense of the temperate coniferous and oak forests (Borrego & Allende, 2021).

The Monarch Butterfly Biosphere Reserve (MBBR) is the largest federal protected area within the Avocado Belt. The MBBR area covers seven municipalities in Michoacán, but only two are producing avocado: Ocampo (since the 1990s, < 100 ha under avocado orchards) and Zitácuaro (since the 1970s, > 100 ha) (Borrego & Allende, 2021). Although avocado production was reported in the municipality of Zitácuaro since the 1970s, it increased with the opening of the United States market in the 1990s (Borrego & Allende, 2021; Morales & Cuevas, 2011).

Since then, the land area under avocado production has been increasing principally in the communal agrarian nucleus (indigenous communities and *ejidos*) in the buffer and influence zones of the MBBR (Ramírez et al., 2019). The highest growth in the area under avocado production in the MBBR was observed from 2006 to 2011, reaching 3500 ha in 2011 (Morales & Cuevas, 2011). The study by España Boquera et al. (2022) includes three zones in the Avocado Belt: Tancítaro (west), Pátzcuaro (center) and Zitácuaro (east). The last one includes the municipality of Zitácuaro and only 1% (5106 ha) of its total area in 2020 was covered by avocado orchards, much less than in the central (9%) or western (16%) zones (España Boquera et al., 2022). Although Zitácuaro is not among the top 18 municipalities that concentrate 90% of the total area under avocado production, it is

[1] Principal seven agriculture commodities in a global deforestation include: oil palm, soy, cattle, wood fiber, cocoa, coffee, and rubber (Goldman et al., 2020).

[2] Municipality is the second-level administrative division in México. There are 113 municipalities in the state of Michoacán.

the largest producer in the eastern region of the state (Borrego & Allende, 2021; SIAP, 2024). Furthermore, Zitácuaro plays an important role in the state as a producer of other commodity crops such as guava and blackberries, with avocado plantations being the largest crop in the municipality (7397 ha) (Hernández-Aguilar & Ramírez, in press).

Avocado is a commodity crop that generates serious negative socio-environmental impacts in México (Borrego & Allende, 2021; Merlo-Reyes et al., 2024). The expansion of avocado into the territories of protected areas in México is recognized by the federal environmental authorities as a sustainability problem, and certain actions are prescribed: forest conservation for water supply, best practices and models of sustainable production, organic certification, integrative conservation-sustainable production local business, and increase of the area under payment for ecosystem services initiatives (CONANP-SEMARNAT, 2023).

However, the policy discourse is based on existing scientific evidence of environmental and social impacts that has largely overlooked the diversity of production models. Studies that analyze the impacts and sustainability of avocado production distinguish only between conventional and organic production (Astier et al., 2014; Villamil et al., 2018) or focusing on central Michoacán (De la Vega-Rivera & Merino-Pérez, 2021; Toribio-Morales et al., 2019). This categorization simplifies the diversity of practices (e.g., local land governance, coexistence of subsistence and market-oriented production, imperfect market integration) by focusing mainly on a central part of the Avocado Belt where the dynamics of large-scale agriculture commodity frontier production occur (Eigenbrod et al., 2020).

The objective of this study was twofold. The first was to characterize economically, socially, and environmentally the model of avocado production developed by the indigenous communities in the municipality of Zitácuaro, given the difference this might have in comparison to the more conventional and commercialized orchards in central and western municipalities in Michoacán. The second objective was to evaluate the sustainability of the community model of avocado production (CMAP).

We used the Framework for Assessing the Sustainability of Natural Resource Management Systems (MESMIS) because it includes the steps that provide a methodology to respond to both of our objectives. MESMIS assesses sustainability in relative terms by comparing at least two natural resource management systems based on their performance on a set of locally constructed indicators (López-Ridaura et al., 2002; Masera et al., 1999). The indicators correspond to environmental, economic, and social criteria of sustainability represented in the seven fundamental attributes of the management system: productivity, stability, resilience, reliability, adaptability, equity, and self-reliance (López-Ridaura et al., 2002). The application of MESMIS to avocado production is scarce.

To the best of our knowledge, this is the first study that examines avocado management systems other than the dominant agro-industrial production or its organic alternative. It shows that not all avocados produced in the state are the result of violence and deforestation, as is widely mentioned in the media. Also, it provides valuable information for the national strategy of protected areas to support sustainable production by local communities.

Study area

The municipality of Zitácuaro is located in the easternmost part of the state of Michoacán and its Avocado Belt. Zitácuaro covers an area of 51,412 ha and it is inhabited by 157,056 people, two-thirds of whom live below the poverty line (CONEVAL, 2020; INEGI, 2020). The population living in poverty mainly includes the Mazahua and Otomi indigenous peoples, who represent 6% of the total population and live in 11 indigenous communities (INEGI, 2010a; RAN, 2019). Together with 28 ejidos, another type of communal agrarian nucleus in México, indigenous communities own more than 70% of the municipal territory (Ramírez et al., 2019; RAN, 2019).

The members of the indigenous communities are *comuneros,* who have the access to the common lands, as well as the right to cultivate individual plots, but not to sell them. The general assembly, composed of all comuneros, is its maximum authority. Comuneros also elect the commissary (*comisariado*) of communal goods as their governing body composed of a president, secretary, and treasurer, who are supervised by a vigilance council of tree members (Morett-Sánchez & Cosío-Ruiz, 2017).

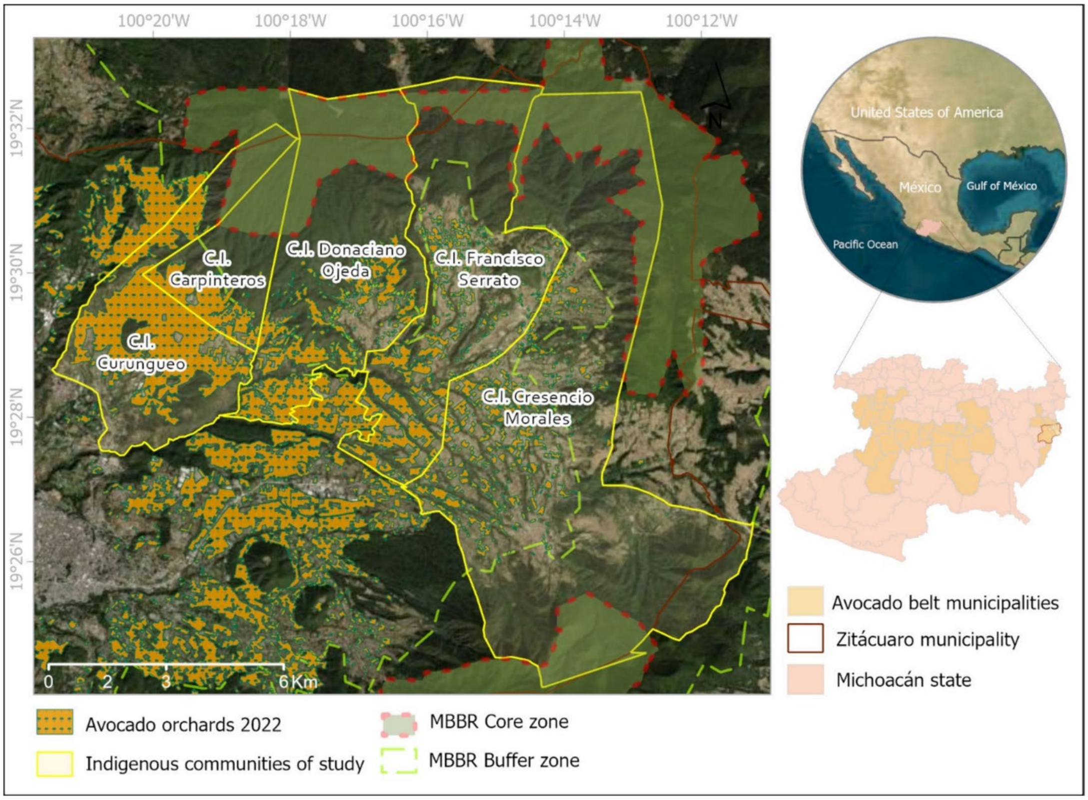

Fig. 1 Distribution of avocado plantations in five indigenous communities in the municipality of Zitácuaro, Michoacán, that are part of the Monarch Butterfly Biosphere Reserve. Sources: Own data, RAN 2019

The municipality has an elevation ranging from 1200 to 3400 m above sea level. The semi-warm and temperate subhumid climate, with annual rainfall between 800 and 1100 mm predominates (García, 1998), while andosol is the dominant soil type (42%) in Zitácuaro (INEGI, 2010b). These climatic and biophysical conditions are optimal for avocado cultivation that with 7397 ha shares the first position with maize (7380 ha) as the most widespread crop in the municipality, followed by guava (2204 ha) (Hernández-Aguilar & Ramírez, in press). Cropland is the main land cover in the municipality (43%), followed by forest (34%) and secondary vegetation (17%), while the rest (6%) is covered by grassland, human settlements and water reservoirs (INEGI, 2013). Forest types present in the municipality include oyamel fir (*Abies religiosa*) forests, mixed pine (*Pinus* sp.) and oak (*Quercus* sp.) forests, and oak and tropical dry forests (Correa-Pérez, 2005; Ramírez et al., 2019).

More than 12,000 ha of the municipality area, mostly forests, are part of the Monarch Butterfly Biosphere Reserve. In the buffer zone only sustainable management of forests and agroecosystems and ecotourism activities can be carried out with official authorization, while the core zone is under strict protection (LGEEPA, 2016).

Methods

Community model characterization and sub-model identification

To characterize the Community Model of Avocado Production (CMAP) and identify the critical points for its sustainability, in 2021 we performed 42 structured interviews with avocado producers in five (out of 11) indigenous communities in the municipality of Zitácuaro that have part of its territory within the MBBR: Francisco Serrato (15 interviewees), Crescencio Morales (12), Rincón de Curungueo (8), Carpinteros (5), and Donaciano Ojeda (2) (Fig. 1). We asked the avocado producers about their production methods regarding water and energy use, agrochemical inputs, safety measures, and waste management.

According to the MESMIS framework, to evaluate the sustainability of what we call the CMAP, we needed to identify two sub-models and contrast their sustainability performance. To distinguish between two possible sub-models, we first categorized the interviewed avocado producers based on the three key characteristics that were identified as important in the interviews. These characteristics include the predominant (1) fertilization and pest control methods (synthetic/organic), (2) type of energy used for irrigation (fossil energy used for pumping water from wells or water bodies/gravity water wheels, rain harvesting, and rainfed), and (3) source of workforces (machinery/human or animal).

We identified two sub-models: "Conventional" which follows traditional agricultural practices for avocado plantations, and "Transition" which represents a gradual move toward organic production. Each sub-model was equally represented by half (21) of the total interviewed producers. The "Conventional" sub-model involves the regular use of synthetic fertilizers and pesticides, along with the use of machinery for their application, irrigation, and other field-related activities, predominantly using fossil fuels. As such, it denotes a significant environmental impact, contributing to soil degradation, water pollution, and harm to beneficial microorganisms and pollinators. Meanwhile, the "Transition" sub-model encompassed cleaner production practices, such as reducing the frequency of synthetic agrochemicals application and integrating natural alternatives for pest and disease management. It also emphasizes the non-machinery labor and the reduced dependence on fossil fuels, through practices such as rainfed production, or gravity-fed irrigation.

Both sub-models are representative of one CMAP. The predominance of one or the other practices was a sum of quantitative criteria for grouping them, which are detailed in the next section. The two groups do not occur naturally, and the mix of both conventional and transition practices can be found in the same orchard. Based on our sample, two groups of producers are present equally in all five communities.

Calculation of sustainability indicators and reference values

In 2023, we administered a questionnaire to 4 producers from the "Conventional" group and 5 from the "Transition" group, representing all communities in our sample. The questionnaire aimed to calculate eleven context-specific sustainability indicators about the critical points obtained in the interview phase (Table 1). To evaluate each producer's sustainability performance, we compared their responses with reference values for each indicator. Published data for the selected indicators is scarce in the study area, and previous studies evaluating avocado sustainability in central and west Michoacán have used different indicators and scales of analysis (e.g., Astier et al., 2014; Villamil et al., 2018). Therefore, we defined most of the reference values based on local data obtained in interviews across the five communities in the study area. According to the MESMIS, some indicators should be *maximized* (the higher their value, the better) or *minimized* (the lower their value, the better), and a corresponding equation should be used (Galván-Miyoshi, 2008).

We asked each producer about their "production scale": their area (ha) cultivated with avocado. To evaluate "forest conservation", we compared the annual land use change (LUC) rate from forest to avocado orchards in the municipality of Zitácuaro and the communities of study. In the municipality of Zitácuaro, this LUC rate was 0.29% from 1974 to 2011 (Morales-Manilla & Cuevas 2011). We obtained the LUC rate at the community scale from Ramírez et al. (2019) and Hernández-Aguilar & Ramírez (in press) for 2007–2022. We evaluated the "use of agrochemicals" by asking about the number of annual applications of agrochemicals, while the "dependence on irrigation" is the number of crop watering during the dry season. "Productive diversification" refers to the number of crop species grown by each producer, either for subsistence or commercialization.

To estimate the producers' economic "profitability", we calculated the benefit:cost ratio using each producer's yearly expenses and income associated with avocado production. The ratio should be higher than 1 to be considered profitable. "Pest

Table 1 Selected sustainability criteria, critical points, and indicators for evaluation of the sustainability of the community model for avocado production in the municipality of Zitácuaro

Sustainability attribute	Critical point (positive ones are in bold)	Criteria	Evaluation sphere	Indicator minimize (−) or maximize (+)	Range (min–max)	Reference	Scale
Productivity	Small-scale production	Area used for avocado cultivation	Environmental	Ha cultivated with avocado/producer (−)	0.5–15	Local data	Producer
Stability	Forest conservation	Conversion of forest to avocado orchards	Environmental	Annual land use change rate (2007–2022) (ha) (−)	0–0.29	Morales-Manilla & Cuevas (2011)	Community
Resilience	High prophylactic use of agrochemicals	Use of agrochemicals	Environmental	Number of agrochemicals applications annually (−)	0–12	Local data	Productive unit
Stability and Resilience	High dependence on irrigation	Water use	Environmental	Number of crop watering during the dry season (−)	0–32	Local data	Productive unit
Resilience and Adaptability	High crop diversity	Crop diversification	Environmental and Economic	Number of species produced (+)	1–5	Local data	Productive unit
Productivity	Low profitability	Economic gains	Economic	Benefit:cost ratio (+)	1–7	Local data	Productive unit
Stability and Reliability	High yield loss to pests	Pest occurrence	Economic	Percentage of trees lost due to pests per year (−)	0–20	Local data	Productive unit
Reliability	Low economic diversification	Diversification of economic activities	Economic	Number of income sources per family unit (in addition to agriculture) (+)	0–3	Local data	Family
Self-reliance	High dependence on technical advisors	Productive autonomy	Social	Number of practices (irrigation, nutrition, pest management) adopted from technical advice	0–3	Local data	Productive unit
Self-reliance	Low dependence on external labor force	Origin of the workforce	Social	Community workers:Foreign workers ratio (+)	0–1	Local data	Productive unit
Equity and Self-reliance	Few changes in land ownership	Territorial autonomy	Social	Level of avocado orchards rented or sold to people outside the community (−)	1 (Very Low) 2 (Low) 3 (High) 4 (Very High)	Local data	Community

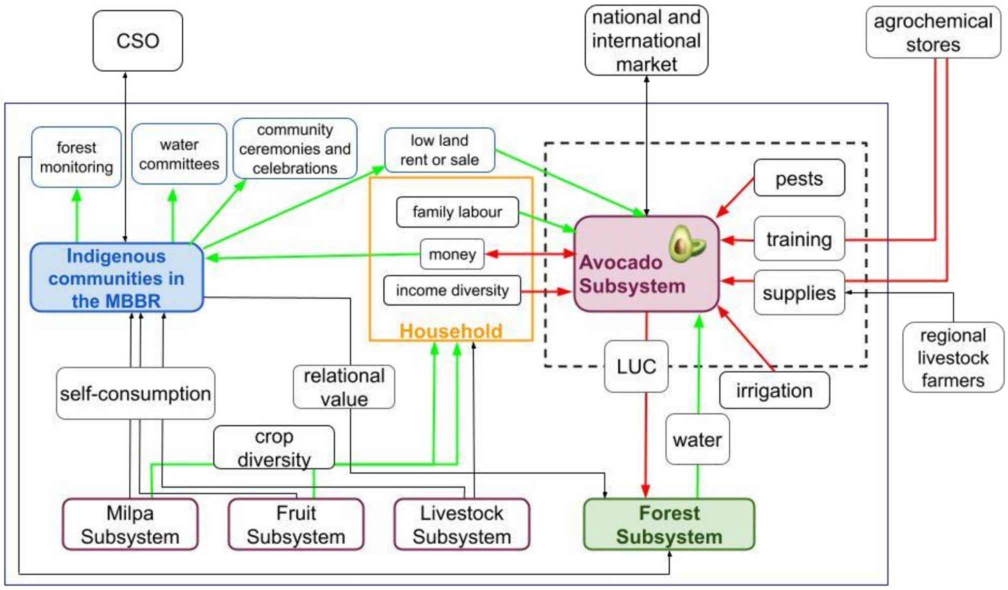

Fig. 2 Characterization of the Community Model of Avocado Production (blue box represents CMAP boundaries, while black box with dotted lines delineates the avocado subsystem; red arrows indicate key relationships and their directions)

occurrence" refers to the percentage of avocado trees lost due to pests. To estimate the "economic diversification", we counted the number of four possible additional income sources besides agriculture per family (full-time or temporary employment, subsidies, and remittances).

We estimated producers' "productive autonomy" by counting the number of new practices in irrigation, crop nutrition, and pest management that were adopted with the advice of technicians or agrochemical stores. We considered fewer practices adopted with technical advice better because local producers highly rely on external advice. To evaluate the level of "local job generation", we calculated the local: foreign workers ratio per productive unit, which indicates the economic revenues that avocado production brings to the members of the same community through paid jobs. The desired score (1:0) indicates that all workers of a productive unit belong to the same community. Finally, we evaluated the level of "territorial autonomy" in the governance of avocado production by asking the producers to identify the level to which they considered that avocado orchards in their community were rented or sold to external actors (1 = very low, 2 = low, 3 = high, and 4 = very high).

Most indicators are evaluated at the scale of productive unit, producer, or family, and only two are assessed at the community scale: "forest conservation" and "territorial autonomy". The reason for this is that these indicators are linked to the local community governance rules in relation to the expansion of the agricultural frontier, which may allow or restrict its members to perform more or less sustainable practices, such as limiting the land use change or prohibiting the rent of the local orchards to external actors. More forest means more water and more stable and constant production, while more orchards managed by local people means more community control over its land, as explained in more detail in the following section.

Results and discussion

Description of the community model of avocado production

Our characterization of the CMAP is embedded in the local structures of community environmental governance. As shown in Fig. 2, local livelihoods engage in five primary sector productive activities, which represent the productive subsystems. The CMAP comprises the material flows between avocado production and other four productive subsystems and institutional interactions within and beyond each community's institutions over use and management of natural resources important for avocado production, principally forests, water, and soil.

In addition to the avocado subsystem, which is the focus of this analysis, the other four subsystems include forestry, traditional agriculture (milpa), big and small livestock breeding, and other fruit orchards. Except for forestry, which is developed in collectively managed forests, all other productive activities, including avocado, are performed in individual plots. This differs from one of the best-known cases of community management, the Indigenous Community of San Juan Nuevo Parangaricutiro, in the western zone of the Michoacán Avocado Belt, where production in collectively owned orchards was one of the elements that led this forestry community to an economically profitable avocado production for export (De la Vega-Rivera & Merino-Pérez, 2021).

Within the communities of Zitácuaro, a share of revenues generated by the individual avocado orchards are directed to support community institutions, including forest monitoring, water committees, and community ceremonies and celebrations. It is important to note that the contribution of avocado income to these activities is additional to the mandatory monetary contribution to community funds and the amount is decided by each avocado producer.

This economic flow for forest monitoring and water committees is crucial for the conservation and management of local forest and water resources, and it is identified as the main key relationship that the avocado subsystem has with the rest of the subsystems. Namely, the avocado crop is highly dependent on water, which directly depends on the conservation of the forest cover. This is acknowledged by the local producers, who depicts the importance of communal rules in preserving small-scale production and conserving the forest for water:

"Our parents were the first to say no to cutting down the forest. […] we don't have much of avocado orchards. The biggest area is 2 or 3 hectares, there are many (producers) who have only half a hectare. There are many [producers] who say -Hey, and if we cut down the forest and plant more avocado? Maybe we would live better. I tell them -Do you think that is the solution? I don't think so, because with the little bit of avocado we have, we've managed to get ahead. Soon we wouldn't have any water. So, it is important to raise consciousness" (interview No.3, "Transition" producer, 2023).

This local approach of keeping individual orchards of relatively small size of on average 1.5 ha, has proven beneficial in preserving original forest patches and their connectivity, which in turn ensures the maintenance of ecological conditions beneficial to avocado production (Pérez-Solache et al., 2023). However, these ecological conditions are under great pressure, especially regarding water. There is unequal and non-constant access to water among the community members (understanding access as the "ability to benefit" from the resource, sensu Ribot & Peluso, 2003), as explained by this interviewee:

"No, there is no water flow in my orchards every day, in fact, we organize, we are a certain number of users and we have to be in contact with the commissioner, who is in charge of distributing the water […] and he makes his list to which we have to sign up so they can tell us when they can give us water to irrigate. So, sometimes it is every month, sometimes every two months, we don't know exactly, because sometimes there is a lot of demand" (interview No.35, "Transition" producer, 2023).

According to our interviewees, due to local governance practices that prohibit communal forests parcelization and rent and sale of communal lands to people outside the community, only a few changes in land ownership of individual plots have been made in their communities:

"Yes, some land is rented, but to people from here. If I want to rent my land, I can do it, but the person must be from here" (interview No.24, "Transition" producer, 2023), and

"We are trying to protect the forest from the avocado. We are making documents that are called 'resguardo' (protection), so that someone is watching over it, taking care of it. […] All forests that you see there, all of it has an owner, and it is a common use area. That is everybody's land and nobody's land. The outgoing commissioners, because of ambition for money or friendship, gave permission to other community members to deforest and plant orchards. To me this is wrong" (interview No.38, "Transition" producer, 2023).

The social capital is further strengthened by the generation of local jobs: "The day laborers are people from here, they are community members, because that is what they say in the community assemblies, that they do not want people from outside cutting (harvesting) avocado" (interview No.24, "Transition" producer, 2023), unlike in other Michoacán municipalities, where either workers from other areas are principal laborers or *communeros* are being employed in their own land by a big producer who rents it (Toribio-Morales et al., 2019).

The CMPA of the eastern Michoacán helps keep economic profit within a family or community, which strengthens the self-reliance and equity of the management system and ensures the maintenance of the producers link with their lands. In addition, investment in ceremonies and celebrations, reported in our case, strengthen the sense of community and social capital against the external actors with different purely economic interests (see Durston, 2002).

These local governance practices that prohibit communal forests parcelization and rent and sale of communal lands to people outside the community were also found as crucial to minimize the environmental impacts of avocado production in the community of San Juan Parangaricutiro (De la Vega-Rivera & Merino-Pérez, 2021). However, that community is rather an exception among forestry-oriented communities in the state of Michoacán (Barismantov & Antezana, 2012; Garibay & Bocco, 2007). In central Michoacán, a significant percentage of avocado expansion is driven by processes of land grabbing (Pérez-Llorente et al., 2019; Velázquez, 2019). Although rent is the main mechanism of avocado agribusiness' expansion on communal lands in the central Avocado Belt, it is often forced through coercion and extortion (Toribio-Morales et al., 2019). Indeed, recent anthropological evidence suggests that the consolidation of avocado agribusiness in central Michoacán has been possible thanks to the articulation of organized crime cartels with government institutions (Román-Burgos & Macip-Ríos, 2022), including its role in money laundering (Ornelas, 2018). This tendency in the central Avocado Belt contrasts with the community governance of avocado production in east Michoacán, where communities use avocado expansion to strengthen their institutions.

The combination of avocado production with other productive activities and sources of income helps the conservation of the remaining communal forest areas. Besides the forest subsystem, other subsystems play a safety net role in the functioning of local avocado production. These include maize and beans from the milpa, and small and big livestock produced for self-consumption and eventual sale of surplus. The same applies to cultivation of other fruits and vegetables that complement the local diet and that cannot be produced beyond self-consumption due to the scarcity of water resources:

"Well, what grows well here is corn and beans. Before, I used to grow vegetables, pumpkins, chickpeas, and green beans, but it has been about 10 years since the water supply became scarce. We can no longer grow vegetables; the water spring now provides little quantity. Besides, the forest land along the canal was occupied (and converted to agriculture) and everyone has irrigation…" (interview No.36, "Transition" group, 2023).

There is a high preventive use of agrochemicals in avocado orchards in our communities. This might be explained by the intention of producers to increase their productivity and the international market demand for certain avocado fruit quality (see Amare et al., 2019). It is principally promoted through a key relationship of high dependency that local producers have with technicians and agrochemical stores. The promotion of synthetic fertilizers and pesticides is not always followed by adequate training to ensure their safe use. In addition, the crops and animals used for self-consumption are produced near avocado orchards. This is of great health concern to the local livelihoods (Merlo-Reyes et al., 2024).

Only a small part of organic fertilizer (manure) is supplied from local livestock farmers. Astier et al. (2014) stated that despite being organic, cow digestion produces CH_4 emissions and should not be considered a necessarily positive element as it contributes to climate change. However, this will depend on the scale of livestock production. We consider it as positive from an economic and environmental sustainability aspect because it supports the regional/local economy and provokes less negative impact on the soil and water than its inorganic alternatives (Campos Mariscal et al., 2020).

In the five indigenous communities studied, a local civil society organization, Alternare A.C., promotes the use of organic "do it yourself" pest and plant disease control alternatives, which are

Table 2 Sustainability indicators for two sub-models of the Community Model of Avocado Production in the municipality of Zitácuaro

Sub-model indicator	Conventional	Transition
Ha cultivated with avocado/producer (−)	5.4	1.2
Annual land use change rate (2007–2022) (ha) (−)	0.0017	0.0019
Number of agrochemicals applications annually (−)	6.5	5.2
Number of crop watering during the dry season (−)	10.5	2.4
Number of species produced (+)	1,8	2.4
Benefit:cost ratio (+)	4.5	2.9
Percentage of trees lost due to pests per year (−)	7.3	7.2
Number of income sources per family unit (in addition to agriculture) (+)	2.3	2
Number of practices (irrigation, nutrition, pest management) adopted from technical advice	2.3	0.8
Community workers:foreign workers ratio (+)	1	1
Level of avocado orchards rented or sold to people outside the community (−)	1.5	1.4

more nutritious and less harmful to the environment. However, this relationship has less impact on the CMPA than the one that producers have with agrochemical store technicians. This is due to the ability of these actors to have a continuous presence in the territory and to the fact that the organic nutrition is associated with lower yield and smaller fruit size, and that the application of chemical fertilizers is the quickest solution to correct low soil fertility (Tapia Vargas et al., 2014).

Nevertheless, despite the high prophylactic use of pesticides, high production losses due to pests are reported, resulting in low profitability. The instability of production due to pests and other climate-related events is a threat to the economy of the families, who are trying to compensate by producing a variety of crops for self-consumption, and further diversifying sources of economic income beyond agriculture. A community or government strategy to diversify the economic incomes would make local producers more resilient to environmental factors and national and international market conditions.

Our case is an example of "a smallholder-driven commodity frontier". Here, commercial and subsistence production coexist, and there is imperfect market integration, because producers' decisions differ from simply capturing the economic optimum, as is the case in "commodity frontiers operated by large-scale agents" (Eigenbrod et al., 2020).

Sustainability of the Community Model of Avocado Production

The final step in MESMIS is a disaggregated evaluation using an amoeba graph. This allows "Conventional" and "Transition" sub-models of the CMAP to be compared by discussing their performance on each sustainability indicator (environmental, economic, and social), and to identify trade-offs between sustainability attributes for each sub-model. Results for each indicator per sub-model are summarized in Table 2, and the amoeba chart (Fig. 3) shows the performance of both sub-systems by indicator, using normalized values.

Both sub-models obtained excellent scores (75–100%) in the case of three indicators, two of which are evaluated at the community level. The top score environmental indicator is the annual LUC rate (2007–2022), which was much lower than the municipal LUC rate (Morales-Manilla & Cuevas, 2011). The top score social indicators were the low level of sale or lease of avocado orchards to outside agents at the community level, and the exclusive employment of local workforce at the avocado orchard level. Both of these social indicators rated excellent, showing that communities use avocado production to strengthen community identity. This contrasts with other regions of avocado expansion in central Michoacán, where the workforce for avocado production is based on foreign day laborers whose labor rights are barely granted (Borrego & Allende, 2021; Velázquez, 2019).

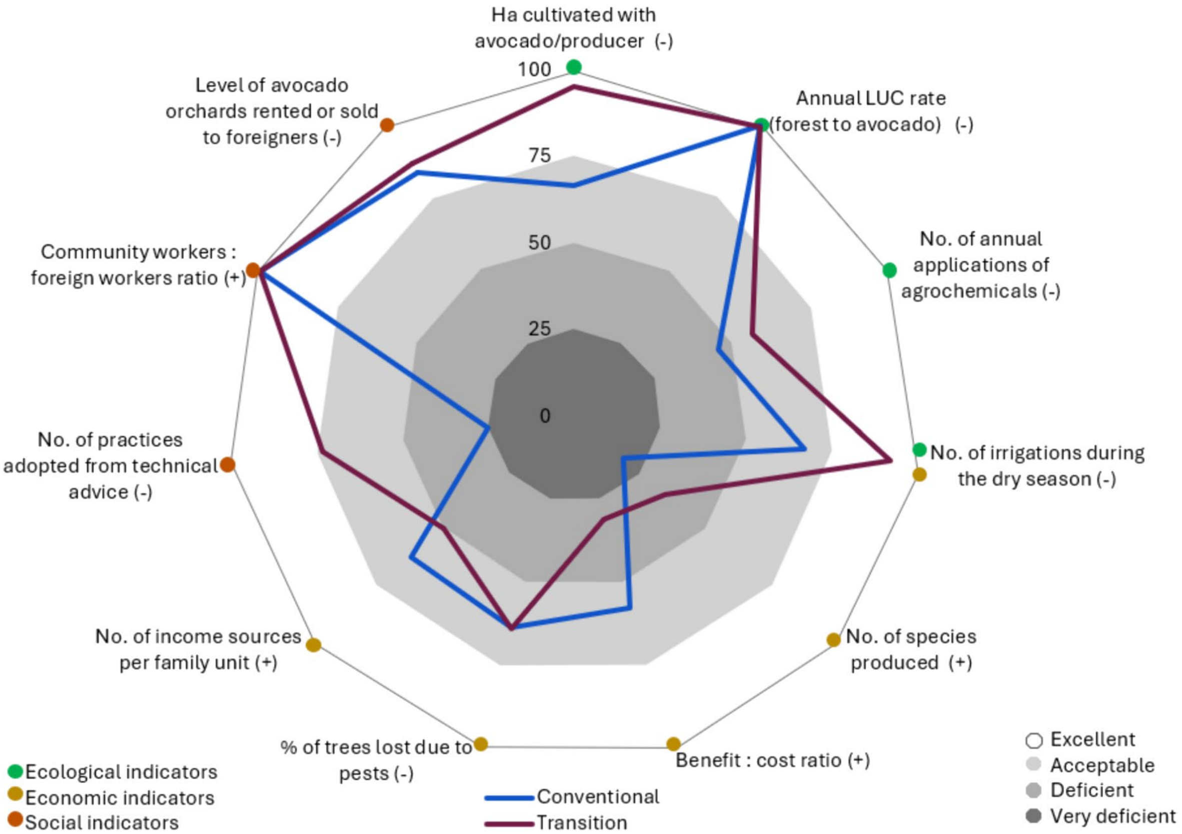

Fig. 3 Sustainability indicators for two sub-models of the Community Model of Avocado Production. Excellent = 75–100%; Acceptable = 50–74%; Deficient = 25–49%; Very deficient = 0–24%

Both sub-models suffer equally from tree losses due to pest damage, and their sustainability in this economic indicator was rated as acceptable (50–74%). However, the losses of up to 20% of the trees are reflected in another economic indicator of benefit:cost, which shows that, although avocado cultivation has improved the economic income of the families, they have, at best, an acceptable level of profitability in the case of "Conventional" and deficient (25–49%) in the case of the "Transition" sub-model.

The fact that the "Conventional" sub-model performs better in this economic aspect, despite the price of inorganic fertilizers, which significantly increases production costs, might be because the producers in the "Transition" group have smaller and younger orchards and that organic fertilizers do not lead to an immediate increase in yield. Organic fertilizers need to be applied in several production cycles to generate the conditions to improve productivity (Campos Mariscal et al., 2020). Although both groups have acceptable levels of income diversification, the score of the "Transition" sub-model is closer to deficient, which, combined with the low profitability, might be more critical for the economic sustainability of producers in this group. On the other side, smaller orchards and a low LUC rate of forest to avocado indicate a balance between productivity and control of the forest frontier.

During the study period, avocado orchards in these communities did not result from deforestation, a dominant process in other parts of Michoacán (Denvir, 2023; Mas et al., 2017; Peréz-Llorente, 2019), but from agricultural land use intensification. The replacement of traditional crops (maize, and other milpa products) by avocado monoculture is reflected in the low diversity of species cultivated by the producers, evaluated as deficient in the "Transition" sub-model and very deficient (0–24%) in the “Conventional” sub-model.

Likewise, during the studied period, in the “Transition” sub-model orchards had less irrigation infrastructure. Thus, despite that they had lower yields, the producers in this group were less dependent on irrigation. Although our indicator (number of irrigations during the dry season) does not tell the exact amount of water use (e.g., in liters per ton), the low dependence on irrigation systems suggests a sustainable performance in water consumption. This contrasts with the findings of Gómez-Tagle et al. (2022) in central Michoacán, where avocado production is highly dependent on irrigation systems and up to 120% of the water legally allocated to agriculture is used for avocado production. Also, in terms of dependence on technical advisors, this indicator rated as acceptable in the case of “Transition” sub-model, since the lower number of practices adopted by the producers in this group from the technical advice makes them slightly more autonomous than those in the “Conventional” sub-model.

In summary, the producers representing the “Transition” sub-model have a higher overall score in the environmental (86 “Transition”/70 “Conventional”) and social aspects of sustainability (87/70), while the “Conventional” sub-model performs better only in the economic aspects (45/50). The application of the MESMIS framework provides a baseline for the performance of the CMAP and for the future evaluation of the strategies to be implemented for its sustainability. This, in turn, contributes to reducing the threats to the conservation of the forests of the Monarch Butterfly Biosphere Reserve (CONANP-SEMARNAT, 2023) and to promoting improved practices for the production of this commodity crop (Vázques-Rowe, 2022).

Conclusion

The Community Model of Avocado Production (CMAP), as a production model developed by the indigenous communities of the municipality of Zitácuaro, has productive and socio-political characteristics that represent strengths and weaknesses for its sustainability. We found that the social sphere is particularly relevant to the sustainability of the CMAP, as it favors the local workforce and makes it easier for communities to maintain ownership over the land and directly control decisions about its use and management. The CMAP is a productive governance scheme that includes a limited openness to external actors, preserves the internal institutions and values, and ensures greater security for its members and their way of life.

In general, the “Transition” sub-model is more sustainable than the “Conventional” sub-model of the CMAP in the municipality of Zitácuaro, mainly due to better scores in environmental and social indicators, based on the smaller size of the area used for avocado cultivation, and less dependence on agrochemicals and irrigation. The worst scores of the “Transition” sub-model were in productive diversification and profitability, both economic indicators rated as deficient (25–49%). However, the continued use of organic fertilizers could generate soil conditions to improve productivity in later cycles.

Our main results in the environmental sphere suggest that the avocado expansion in the studied communities did not involve a change in forest cover during the period 2007–2022. However, we identified that the critical issues related to the economic sphere are the ones that most limit the sustainability of the system. In particular, we argue that with adequate economic support for socially and environmentally sustainable productive practices, the CMAP can improve the local livelihoods of indigenous communities while promoting biological and forest conservation.

Finally, we would like to emphasize the difficulty of identifying two distinct management systems to comply with the MESMIS requirements. The boundary between the groups is rarely strict, and many producers have characteristics of both sub-models, indicating a gradual shift rather than a strict dichotomy. For example, some producers classified as “Conventional” may adopt certain sustainable practices or reduce their environmental footprint in ways consistent with aspects of the “Transition” sub-model. Conversely, some “Transition” producers may still use certain conventional practices or inputs. This overlap makes it challenging to strictly categorize practices and underscores the complex nature of agricultural systems in avocado production.

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Data availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Content of interests The authors have no competing interests to declare that are relevant to the content of this article.

Ethical Approval The authors declare no ethical conflict.

Informed Consent The interviews were conducted with the prior oral consent of the interviewee following the Ethical Code of the National Autonomous University of Mexico (https://www.unaminternacional.unam.mx/archivos/doc/codigo-de-etica/codigo-etica-unam.pdf).

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