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Sustainability of peasant agroforestry systems of San Andrés Calpan, Calpan, Puebla

La sustentabilidad de los sistemas agroforestales campesinos de San Andrés Calpan, Calpan, Puebla

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ABSTRACT

Agroforestry systems (AFS) provide economic, sociocultural and environmental benefits. The combination of elements of agriculture and forestry makes them multifunctional and more sustainable systems. The objective of this study is to evaluate the sustainability of AFS with different management, in San Andrés Calpan, municipality of Calpan, Puebla, Mexico. The study was carried out in two stages: a characterization was developed in the first, for which a survey was applied to a sample of 81 producers out of a population of 527 registered in PROAGRO. Three types were identified: the Tejocote Agroforestry System (TAFS) and the Capulín Agroforestry System (CAFS), both with traditional management, and the Apple Agroforestry System (AAFS) with specialized management. In the second stage, six orchards were selected, two from each system; the activities carried out by the producers were recorded for one year. The MESMIS (Framework for the Evaluation of Natural Resource Management Systems incorporating Sustainability Indicators) was used. It is a comparative cross-sectional study where 19 indicators were analyzed. The results show that traditional AFS tend more towards sustainability (66% for CAFS and 61% for TAFS); the alternative AAFS system obtained 45%. The conclusion is that traditional AFS are more sustainable.

KEY WORDS: Sustainable agroecosystems, family farming, agroforestry, indicators, agricultural multifunctionality.

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RESUMEN

Los sistemas agroforestales (AFS) proporcionan beneficios económicos, socioculturales y ambientales. La combinación de elementos de la agricultura y forestaría los convierte en sistemas multifuncionales y más sustentables. El objetivo del estudio es evaluar la sustentabilidad de AFS con diferente manejo, en San Andrés Calpan, municipio de Calpan, Puebla, México. El estudio se realizó en dos etapas: en la primera se elaboró una caracterización, para lo cual se aplicó una encuesta a una muestra de 81 productores de una población de 527 registrados en PROAGRO. Se identificaron tres tipos: Sistema Agroforestal Tejocote (TAFS) y Sistema Agroforestal Capulín (CAFS) ambos con manejo tradicional, y el Sistema Agroforestal Manzana (AAFS) con un manejo especializado. En la segunda etapa se seleccionaron seis huertos, dos de cada sistema. Durante un año se registraron las actividades realizadas por los productores. Se utilizó el MESMIS (Marco para la Evaluación de Sistemas de Manejo de los Recursos Naturales incorporando Indicadores de Sustentabilidad). Es un estudio transversal comparativo, se analizaron 19 indicadores. Los resultados muestran que los AFS tradicionales tienden más a la sustentabilidad (66 % para el CAFS y 61 % para el TAFS); el sistema alternativo AAFS obtuvo un 45 %. Se concluye que los AFS tradicionales son más sustentables.

PALABRAS CLAVE: Agroecosistemas sustentables, agricultura familiar, agroforestería, indicadores, multifuncionalidad agrícola.

Introduction

Presently, agriculture is quite diverse in its forms of management; there are systems with high productivity based on an intensive use of external inputs and technology, and traditional systems such as peasant agriculture that are characterized by using local resources and developing different strategies to adapt to various economic and environmental restrictions (Hernández & Alcaraz, 2020).

These strategies are related to an adequate management of their resources, diversification within and outside the agroecosystem, conservation of native knowledge and cultural values, as well as some social relations that favor producers, which together contribute to the generation and conservation of agroecological practices (Fonseca-Carreño et al., 2019) that provide traditional

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systems with stability and productivity, as it happens in Agroforestry Systems (AFS) (Altieri & Koohafkan, 2008).

AFS are land use systems that combine perennial woody plants (trees, shrubs, palms, or bamboos) with crops or livestock in the same plot with some type of spatial and chronological disposition, and can provide a large variety of economic, socio-cultural and environmental benefits (Navia, 2017).

In the world, there are around 400 million hectares managed as AFS, where the broad spectrum of plant associations potentiates the production of timber, firewood, fruit, food, medicine, fodder, oil, and ornamental plants (Torres et al., 2019). The combination of these elements makes them systems oriented toward sustainability (Farrell & Altieri, 1997).

Sustainability offers an opportunity to improve human welfare by conserving natural resources. Although agricultural systems produce most foods, they cause significant environmental degradation. This tension between the objectives of development and environmental conservation does not have to be an unalterable result, since agricultural systems depend on and provide ecosystem services, at the same time.

Recognizing this duality allows the integration of environmental and production objectives, taking advantage of the services provided by the agricultural ecosystem to attain the objectives of sustainability (DeClerck et al., 2016). In this sense, Conway (1985) considers the sustainability of agriculture as "the capacity of an agroecosystem to maintain its production through time, overcoming, on the one hand, the ecological tensions and abuse and, on the other, the pressures of socio-economic nature".

The following objectives for sustainable agriculture are considered: stable and efficient production, food security and self-sufficiency, use of agroecological or traditional practices, conservation of local culture and small-scale property, assistance for the poorest through a self-management process, high level of community participation, and conservation and regeneration of natural resources (Altieri & Nicholls, 2000).

This implies the combination of various technological and social practices as in peasant agriculture, framed by a diversity of strategies that peasants use to manage their agroecosystems (Altieri et al., 2012). In this sense, some AFS present characteristics with a more traditional management, constituted by a main basic crop (corn) that can be interspersed with other crops such as squash, bean, chili pepper and fava bean, and with fruit trees, called Milpa Interspersed with Fruit Trees (MIAF).

The MIAF is constituted by three species: the fruit tree (epicrop), corn (mesocrop), and bean or another edible species (sotocrop). They are in intense agronomic interaction to produce corn and bean for food security, increasing the family income, increasing the content of organic matter, controlling soil water erosion, and achieving a more efficient use of family labor (Cortés et al., 2005).

These AFS systems are present in the study zone, which have been transformed according to the objectives of each family production unit, and this is reflected in the management and diversity of species that make up their systems. This study was carried out in San Andrés Calpan, municipality of Calpan, Puebla, Mexico. It is a geographic area that presents the agroclimate conditions for the development of diverse traditional AFS, so the objective is to evaluate the sustainability of agroforestry systems with different management. The hypothesis was set out that the systems with the most traditional characteristics are more sustainable than the specialized AFS.

Materials and Methods

Characteristics of the study area

The study was conducted in the locality of San Andrés Calpan, located in the central west part of the state of Puebla, Mexico. Its geographic coordinates are parallels 19º 06´36" and 19º 41'12" of LN and meridians 98º 23´54" and 98º 32´24" of LW; with an altitude between 2,200 and 3,200 meters. In San Andrés Calpan there are agroecosystems with diversity of fruit trees interspersed with annual crops. The fruit trees that constitute the various AFS in the zone are: capulín (*Prunus salicifolia*), tejocote (*Crataegus mexicana*), pear (*Pyrus communis*), plum (*Prunus domestica*), walnut (*Juglans regia*), fig (*Ficus carica*), and peach (*Prunus pérsica*). And the annual crops are: corn (*Zea mays*), bean (*Phaseolus vulgaris*), squash (*Cucurbita pepo*), and fava bean (*Vicia faba*).

Approach of the study

Quantitative and qualitative techniques were used to analyze the environmental, economic and social aspects considered in the evaluation of sustainability of the systems selected (Tonolli et al., 2019).

Population and sampling

The AFS with traditional management and the AFS with specialized management were selected with technology generated by the study. For the selection of the AFS with traditional management, first, a characterization of the systems was carried out with information from the producers. Starting from a population of 527 corn producers (PROAGRO registry from the Ministry of Agriculture and Rural Development, SADER, 2018), a sample size resulting in 81 producers was obtained. The following mathematical expression was used (Equation 1) to determine the size of the sample considering the maximum variance:

$$n = \frac{N\, Z^2_{\alpha/2}\,(0.25)}{N\, d^2 + Z^2_{\alpha/2}\,(0.25)}$$

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Where: N= Number of producers

Z(∝⁄2)= 1.96 (value of the table of normal distribution)

α=0.05 (that is, there is a reliability of 95 %)

d= accuracy (0.1)

n= 81

Then, the 81 producers with AFS that plant corn between fruit trees were identified, and they responded to a questionnaire. A MIAF that is in the stage of technological transference in producers' plots was considered as a specialized MIAF, which is characterized by having as fruit tree the apple tree with technology generated by the research program.

Choice of groups and plot selection

The two groups belonging to traditional AFS were chosen according to the results of characterization proposed by Toledo et al. (1999), selecting those with broad representability in the zone and of traditional category: capulín (Capulín Agroforestry System, CAFS) and tejocote (Tejocote Agroforestry System, TAFS), and these were compared with the one with apple (Apple Agroforestry System, AAFS). Two plots were selected from each to have a repetition, in total six plots (2 CAFS, 2 TAFS, and 2 AAFS), were monitored for one year to record the activities that the producer performs (Figure 1).

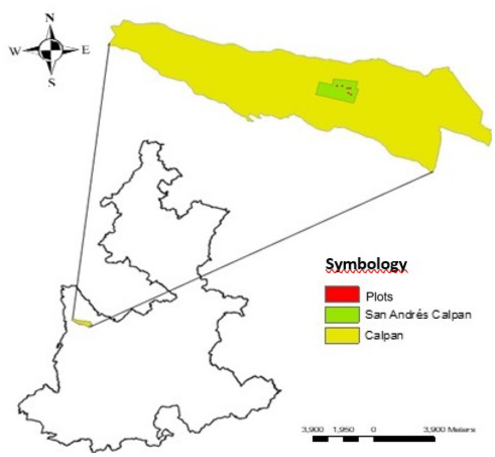

Figure 1. Geographical location of the town of San Andrés Calpan and the evaluated plots.

Source: Prepared by the authors based on INEGI, 2015.

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Methodologies for the evaluation of sustainability

In recent decades, curiosity to find mechanisms that allow evaluating the sustainability of productive systems has emerged. The evaluation of the sustainability of agricultural production systems through the use of a methodology that incorporates various indicators allows observing the trend in the development of productive systems. In this sense, different methodologies have been designed, such as the one proposed by Sarandón and Flores (2009), which consists in a series of steps that lead to obtaining a set of adequate indicators to evaluate the critical points of sustainability of agroecosystems, looking for it to be simple, of low cost and which could allow evaluating those aspects that compromise the attainment of sustainability of agricultural systems.

SAFE (Sustainability Assessment of Farming and the Environment Framework) is a methodology developed by Sauvenier et al. (2006), which proposes evaluating sustainability in three scales: agrarian system, agricultural exploitation, and plot; then, Van Cauwenbergh et al. (2007), proposed evaluating through the use of a hierarchical structure. SAFE derives its principles and criteria from the combination of the functions of agriculture with the three bases of sustainability, which allows obtaining indicators for each of the dimensions (economic, social and environmental). It is difficult to obtain the integrated indicators since the method proposed by Sauvenier et al. (2006) for the statistical analysis of the indicators is based on the multivariate study, which uses the methodology of diffuse logic to estimate the weighting between variables; these rules of reasoning prevent the variables from being extrapolated to other fields (Saavedra, 2015).

FESLM (Framework of Evaluating Sustainability of Land Management) is a methodology developed by Smyth and Dumanski (1993) for FAO (Food and Agriculture Organization of the United Nations), which consists of an integral analysis strategy of the management of agricultural lands, directed toward the environmental dimension to prevent soil degradation, but also including economic and social aspects.

MESMIS (Marco para la Evaluación de Sistemas de Manejo de Recursos Naturales incorporando Indicadores de Sustentabilidad, Framework for the Evaluation of Natural Resource Management Systems incorporating Sustainability Indicators) was developed by Masera et al. (1999) to evaluate the sustainability of farms through multi-criteria analysis. MESMIS is one of the most useful tools for agricultural, forestry and livestock activities in rural communities, which allows understanding the limitations and possibilities for sustainability of the management systems in an integral way (Masera et al., 1999), which is why it was selected as the methodology for this study.

MESMIS as a methodological tool for evaluation

The methodological tool used to evaluate sustainability was MESMIS (Framework for the Evaluation of Natural Resource Management Systems incorporating Sustainability Indicators) proposed by Masera et al. (1999); 19 indicators were analyzed, which were selected through bibliographic review and monitoring each plot during the agricultural year, to record all the practices.

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A weighted value was assigned to each of the indicators to be able to integrate the results and represent them graphically, considering 100 % as the optimal value established.

A transversal study was conducted, with a temporal scale of two years: 2018 and 2019, and spatial at the level of plot. Three AFS were compared: capulín, tejocote (traditional), and apple (alternative).

Description of sustainability indicators

Productivity

1) Yield of the Basic Crop (Ecological): Amount harvested in tons per corn hectare (t ha-1).

2) Yield of the Fruit Tree (Ecological): Relationship between the best yield of the fruit tree of interest in the zone (capulín, tejocote, and apple) with regards to the yield obtained in the systems selected (t ha-1).

3) Relative Efficiency of the Land (REL) (Ecological): Total area required in single crop to reach the yields obtained in polycrop. A REL higher than one means that the interspersed crop is higher than the single crop; the higher the REL value, the interspersed crop will be more advantageous (t ha-1) (Turrent et al., 2015).

4) Benefit-Cost Ratio (Economic): It represents the economic efficiency of the resources used and shows the amount of money returned by each money unit invested during a specific period (Herrera et al., 1994). This indicator measures the relationship between the income from a project and the expenses incurred throughout its useful life including the total investment. If B/C>1, the project is profitable since the benefit is higher than the cost; B/C= 1 it is irrelevant to carry out the project because there are no benefits or losses; B/C< 1, the project is not profitable and should be rejected (Vásquez et al., 2017).

Resilience, Stability, and Reliability

5) Index of Agroecological Practices (IA) (Ecological): Number of agroecological practices for management of the agroecosystem with the total of practices (11 practices) that are conducted. According to Herrera et al. (2017), when: IA = 1, the system is agroecological; 1> IA ≥ 0.75, the system is highly agroecological; 0.75> IA ≥ 0.5, the system is moderately agroecological; 0.5> IA ≥ 0.25, the system is poorly agrocological; 0.25 > IA, the system is not agroecological.

6) Plant Biological Diversity (Ecological): It is the abundance of species found in a specific study unit. For this purpose, the Shannon index was used, which suggests that “more diversity corresponds to more uncertainty in randomly selecting an individual of a species in particular” (Gliessman, 2002, p. 242).

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7) Carbon Capture (Ecological): Amount of biomass per hectare captured, which is in function of the heterogeneity of the system's components. The carbon stored is expressed in tC/ha^{-1} (Arévalo et al., 2003). For each species, the pertinent equation was developed from the previous sampling of branches of each species.

Apple: $B = -0.5562(D^2L)^2 + 74.23(D^2L) - 77.905$

Tejocote: $B = 29.422(D^2L) + 118.35$

Capulín: $B = 325.97D - 941.34$

Where: B= biomass; D = diameter; L = length

The R^2 for each species was: Apple: 0.9784; Tejocote: 0.8839; and Capulín: 0.9248.

8) Access to Credit and Insurance (Economic): Number of credits and/or insurances that producers have in relation to their agroforestry system.

Adaptability

9) Adoption of Technological Innovations (Social): Number of new practices that farmers incorporated into their system. According to Herrera et al. (2017), the following criterion is established to classify the system according to the number of new practices that they perform, where they are considered highly innovative when they have more than 70 % of new practices (8 practices) compared to the total number of practices (11 practices): Number of new practices > 8 = highly innovative; between 4 and 7 = moderately innovative; between 1 and 3 = scarcely innovative; 0 = without innovation.

Equity

10) Index of Equipment by Producer (Economic): Relationship between the equipment that the farmers own compared to the equipment they use (tractor, yoke, machete, pump, mattock, scissors, shovel). A weighted value is assigned according to the contribution of the equipment to the system's sustainability, and if they are needed.

$IEP= T (0.1) + B (0.1) + Y (0.5) + I (0.3)$

Where: T= tractor; B= pump to apply agrichemicals; Y= yoke; I= Implements (mattock, machete, scissors, shovel, ladder).

11) Degree of Adoptability (Social): Percentage of producers in the locality that have adopted the different systems evaluated.

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Self-Management

12) Index of Food Security (IFS) (corn) (Social):

$$IFS=\frac{(R)(SS)/NMF}{500^{*}}$$

Where: R= corn yield in kg ha-^{1}; SS= surface sown (ha); NMF= number of members in the producer's family; *Factor that is equivalent to 500 kg of corn per year.

According to Damián and Toledo (2016), when: IFS<1: there is no food security and IFS≥1: there is food security.

13) Genetic Self-Sufficiency (Social): Percentage of the seed of the basic crop used in this cycle, which was obtained from the system evaluated from previous cycles.

14) Independence from External Inputs (Socioeconomic): Amount of fertilizers, insecticides, fungicides, and herbicides that are applied to the system (kg ha-^{1} year) that come from outside the agroecosystem.

Total volume: kg ha-^{1} de fertilizer + kg ha-^{1} insecticides + kg ha-^{1} fungicides + kg ha-^{1} herbicides.

For the agrichemicals in liquid presentation, their density was considered to carry out the conversion to their weight in kg.

15) Labor (Social): Percentage of labor from the family.

16) Intergenerational Replacement (Social): Participation of the youngest members of the family in activities of the agroecosystem.

17) Income from the Forestry Agroecosystem for the Family Unit (Economic):

Percentage of income from the AFS = AI/ TI *100

Where: AI = Income from the agroecosystem; TI= Total income of the family unit.

Sources of income: a) corn production, b) production of other annual crops, c) fruit trees, d) sale of labor, e) social programs, and f) other trades.

18) Diversification of the Sale (Economic): Amount of different products from the system that are available for sale.

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19) Marketing Channels (Economic): Number of possible ways that producers have to be able to place their products in the different markets.

Results and Discussion

Productivity

Results from the systems evaluated regarding an optimal established according to the zone are presented in Table 1. In the indicator yield of the basic crop, the AAFS is closer to the optimal (6 t ha^{-1}) with a production of 4.5 t ha^{-1} while the TAFS and the CAFS presented lower yields, 2.5 and 2.75 t ha^{-1}, respectively. The AAFS only has one fruit species (apple), so the roads with corn (basic crop) have larger space and the ones for the fruit tree have better pruning management, so there is a yield above average for the municipality of Calpan (2.4 t ha^{-1}) (SIAP, 2018). The AAFS is the only one that receives external advice. In this sense, the TAFS and the CAFS present a greater diversity of fruit trees, while corn is basically for auto-consumption.

Regarding the index of fruit tree yield, the TAFS are superior with yields of 5.9 t ha^{-1} that are closer to the optimal found in the zone (7 t ha^{-1}), while the AAFS present an average yield of 1.0 t ha^{-1} compared to the 15.0 t ha^{-1} of the optimal reported in the experimental MIAF system (García, 2020). A defining element of this result is that traditional AFS have species that were introduced many years ago, while improved apple is a species that is being reintroduced into the zone with other varieties, in addition to requiring more specialized technological management to be able to reach the yields reported by the study's results.

In the REL, traditional AFS have very similar values: 1.26 for the TAFS and 1.24 for the CAFS, which indicates that 1.26 and 1.24 hectares of monocrop are required to reach the yields of one hectare of polycrop, values closer to the optimal of 1.3. The previous results are lower than those reported by Turrent et al. (2017), REL 1.53 for an experiment with peach, corn, and rainfed shrub bean; however, they are higher than one due to the topological arrangement different from the historical milpa. Hernández (2022) reports that in various modalities of MIAF, the REL was higher, indicating an advantage over single crops; however, this contrasts with what was obtained in the AAFS which requires 0.79 ha of monocrop to obtain the yield of a hectare of polycrop. A REL higher than one means that the interspersed crop is better than the single crop and vice versa. Meanwhile, the higher the value of REL, the crop will be more advantageous (Albino et al., 2015). In the traditional systems, which have higher agrobiodiversity, a better relationship between their components is promoted, which is why there are better yields than if they were managed through mono-crop. In the AAFS the opposite happened, which is why we suggest reviewing the arrangement proposed.

In the benefit-cost ratio (income by costs), the AAFS obtained a value of 1.56, which is very similar to the ones obtained in MIAF systems that have been recently established with peach in the zone, where Regalado-López et al. (2020) report that the benefit-cost ratio is 1.72 and, from the economic point of view, reflects an attractive profitability for the producers. The same happened in the MIAF with peach in slope conditions on the northern sierra of Oaxaca: in the Mazatec region, it was between 1.49 and 1.61, and in the Mixe region, between 1.48 and 1.62, proving to be a profitable system for 15 years (Jiménez et al., 2016). The traditional AFS presents a greater advantage, especially for the TAFS with a value of 2.32; that is, for each peso invested a profit of 1.32 pesos is obtained, which makes the CAFS and the TAFS more profitable. In the case of capulín the investment is minimal, obtaining profits from the fruit sale, and if it is affected by pests (fruit worm), the seed is sold (fruit pit). In the TAFS, the fruit tree is well-located in the market. Calpan is identified by a high production of tejocote with a surface sown with 128 hectares and a production of 843 t annually (SIAP, 2023); Lozano et al. (2016) describe this fruit tree as a source of good-quality pectin, with possible applications in the food industry, pharmaceutical industry, and others. Robles et al. (2020) point out that this fruit is not only used as food for human consumption but also as an ornament in celebrations and traditional medicine.

Resilience, Stability, and Reliability

In the index of agroecological practices, the CAFS is the closest to the optimal. It was found that 8 out of 11 practices are classified as agroecological, and they are manual weeding, furrowing with yoke, clearing with yoke, manual sowing, manual harvesting, amogote to conserve the soil moisture, cutting fruit trees, and incorporating residues from pruning to the soil. The TAFS presents an index of 0.6, which means that 7 out of 11 practices carried out are classified as agroecological; in the AAFS there is an index of 0.5, which means that 5 out of the 11 practices are considered as agroecological. The AAFS producers carry out most of their activities with a tractor, in contrast with the CAFS where a yoke is used. In capulín the use of agrichemicals is nearly nonexistent, in tejocote and apple, higher amounts of these inputs are required. The three systems are below the optimal (11 practices) in a similar proportion, and the use of agrichemicals is necessary for pest control, as well as fertilization to nourish the plants. Applying the criteria of Herrera et al. (2017), the AAFS and the TAFS are within a category of moderately agroecological, while the CAFS is highly agroecological.

Regarding the diversity, the CAFS with a Shannon index of 1.21 are closer to the optimal with index of 1.23, since they conserve a large variety of species for their consumption and sale. The TAFS, although considered traditional, reflect a reduction in their diversity (index = 0.16) and that is because despite the presence of other species, the producer prioritizes tejocote. After all, it is the main product for sale. In the case of the AAFS, they are systems with quite low biodiversity (the basic crop and a fruit species), obtaining an index of 0.06. The traditional MIAF systems like CAFS and TAFS have the diversity of species as main characteristic, as shown by the following studies: the MIAF system of the Cuicateca, Mazateca and Mixe regions (Jiménez et al., 2016); agroforestry systems of the high valleys of Puebla (Reyes-Reyes et al., 2020); Mazahua communities (Pillado-Albarrán et al., 2022).

The indicator of carbon storage shows that traditional AFS are better, storing 0.68 t ha^{-1} for the case of the TAFS and 1.63 t ha^{-1} for the CAFS; however, they are still values below the

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optimal found in the field (1.77 t ha-[1]). In the CAFS, trees are of greater diameter and height, showing a higher amount of biomass compared to the TAFS, and the AAFS stores an amount of 0.45 t ha-[1]. It should be highlighted that the number of trees in the case of the CAFS (60 capulín trees on average per hectare) is much lower than in the AAFS (200 apple trees on average per hectare). The importance of the AFS lies in that they provide ecosystem goods and services, such as climate change mitigation by capturing carbon as part of biomass (Forero et al., 2018). In this sense, Pocomucha and Alegre (2014), describe that the inclusion of trees in the plots is not being adequately valued, only in function of the potential of stored carbon, and not over other additional benefits such as the improvement of economic income, situation that is reflected in the study zone.

According to Villa et al. (2020), among the main benefits that these types of systems provide, some are the recovery, conservation and improvement of biodiversity, the increase in carbon reserves, the biological fixation of nitrogen and nutrient cycling, the decrease in erosion, and the maintenance of soil fertility.

In access to credit and insurance, the trend toward greater sustainability is that systems do not depend or depend minimally on external economic resources. None of the AFS evaluated have had these services, since they are focused on monocrops. To overcome this problem, producers have implemented different strategies so that they do not have access to loans and credits.

Adaptability

The index of appropriation of innovations for traditional AFS is found in zero practices with regards to the optimal (11 practices). In these systems, producers are between 61 and 79 years old, so they base their practices on traditional understanding, experience, and knowledge and are not very flexible with change. Toledo (2013) points out that knowledge, worldview, rules, regulations, and technological understandings are appropriated through a specific process by social relationships established, which is why the appropriation of a new element becomes complex, particularly for older people. Another factor is education since these producers have not finished primary school; González and Coelho (2014) mention that the age of the producer and their education are variables that affect the decision on the adoption of innovations. However, Jiménez et al. (2023) point out that variables such as age and education are limited to explain the adoption of innovations, because they only function in concrete contexts, so no producer innovates more than their relationships allow.

There are other challenges for technology transference, such as the intensity of technological knowledge, the investment in fruit tree seedlings at the beginning, adequate sources of financing and technical assistance, and access to the fresh fruit market (Turrent et al., 2017), as well as the unavailability of inputs (mainly chemical fertilizers) (Ruiz et al., 2012). The AAFS has innovations such as the decrease of distance between plants, tree management with different types of pruning, the dose of fertilization, and the introduction of a new variety of fruit tree in the zone (Agua Nueva apple variety). The introduction of this species was eased by the support

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received by producers to get the seedling; in addition, the practices are conducted by the staff sent by the advisor, so some of the costs are not covered by the producers. Although they are commercial plots (they are no longer experimental), the producer makes few decisions about fruit tree management. According to the scale proposed by Herrera et al. (2017), the traditional AFS are systems of external innovation, while the AAFS is considered scarcely innovative. Regarding the latter, there is a difference with what is reported by Jiménez et al. (2016) for the northern Sierra of Oaxaca, where producers have adopted the technology of the MIAF system on the hillside. Likewise, another study in the Mixe region reports that peasants decided to innovate in components such as pruning, graft, tracing level curves, sowing the milpa within the MIAF system, and not burning the stubble, and the rejection of other practices due to the socio-cultural and economic structure of the peasant (Ruiz et al., 2012). Likewise, Ordóñez-Ovalle et al. (2022) point out that the main strength for this innovation to be adopted is that the milpa system is based on productive diversification and in the association of corn-bean-squash crops.

Equity

The index of equipment by producer places the three AFS in a very similar range, presenting an index of 0.9. The weighting was made with regards to the type of machinery that they use; those who base their practices on the use of yoke and manual tools presented the best results, and the CAFS is closer to the optimal when performing all their activities with yoke. A similar element for the three AFS is that plowing is always done with a tractor, so they have to rent this equipment; the preparation of the furrows for sowing is carried out with yoke, since they obtain better results than with a tractor.

An indicator that presents greater difference is the degree of adoptability of each system. The AAFS (alternative) has been adopted by 2.5 % of the producers, while 97.5 % of the producers have a traditional AFS, with TAFS (tejocote) being the one with greatest presence because of the importance of this fruit species in the market.

Self-management

The Index of Food Security in Corn (CIFS) resulted in a value of 2.05 in the AAFS, closer to the optimal (2.5) and exceeding the TAFS which obtained a value of 1.45 and 1.55 for the CAFS. The corn yields per hectare were: 4.5 t ha^{-1} for the AAFS, 2.5 t ha^{-1} for the TAFS, and 1.45 t ha^{-1} for the CAFS. And the amount of people who depend on the system is 4 to 5 in every case. The AAFS has the most surface for corn farming, because it only has the apple fruit tree (in contrast with the traditional AFS that have a higher number of fruit trees interspersed with corn); this is reflected in the yields. However, according to the classification by Damián and Toledo (2016), both the alternative AFS (AAFS) and the reference ones (TAFS and CAFS) have food security because they have values higher than 1.0. González et al. (2019) report that the municipality of

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Calpan has on average a CIFS (Index of Food Security) of 1.44, and for the particular case of the locality of San Andrés Calpan a CIFS of 1.58, values that are quite close to those obtained in the AFS evaluated.

Regarding the genetic self-sufficiency in corn, the three AFS are in optimal, that is, 100 % of their seeds are obtained in their plots. López et al. (2019) report that in the municipality of Calpan, this practice is conducted more generally, which consists of making a selection of criollo seed immediately after the harvest; the peasants select the corn seed from the barn after the harvest, considering the size of the corncob, size of cob and shape of seed.

Regarding the independence from external inputs (use of agrichemicals) for corn and fruit tree management, the AAFS resulted further from the optimal level of sustainability, since it is the system that occupies a higher amount of agrichemicals for fertilization, and pest and disease control (1,259 kg ha-1 year). According to producers in the zone, this responds to the need for having apples with good presentation so they can be placed at a better price in the market. On the contrary, traditional AFS showed less use of agrichemicals: TAFS 1,062 kg ha-^{1} year and CAFS 964 kg ha-^{1} year; this happens because they do not need excellence in their aesthetic appearance to sell the fruit, although the size is important. In the three cases, there is a dependency on the use of chemical inputs. In addition to this, another phenomenon takes place that is also reported by Guzmán et al. (2016) who describe that there is an absence of technical knowledge and training in the management and use of agrichemicals. González (2023) highlights that agricultural activity at the national level threatens itself due to overexploitation of the land and the excessive use of agrichemicals, in many cases because of the lack of technical backing for the producer. This absence has caused for the empirical reproduction of knowledge by the producer, which has passed from generation to generation and with it, the inappropriate management of these chemical products.

Traditional AFS use more family labor. From the 66 day laborers that are occupied for the different tasks during the agricultural cycle, 38 (58 %) come from the family, compared to the AAFS, where from 88 day laborers required only 13 (15 %) come from the family. In both cases, the optimal is not reached, where 100 % of the occupied labor would come from the family. In the case of the traditional AFS, most of their practices are carried out by members of the family (children, wife, brothers, nephews and uncles); however, in the season of fruit cutting, they are in need of hiring external labor to collect the fruit, situation that repeats during corn sowing and harvest. For the AAFS, the family does not intervene in fruit production and is concentrated in the practices related to corn. González et al. (2019) mention that this type of agriculture depends on abundant family labor, which in many cases comes from children; and this is coordinated by the head of the family who is in charge of distributing the tasks according to sex and age.

For the participation of the children in the plot's activities, an index of intergenerational replacement was applied. For the three AFS the value is low (less than 25 %); that is, they are families with 5 children on average, of which only one continues with the management of the agricultural system, and in some cases none of the children. In the three systems the older children are the ones that take over the work in the plot, or those who did not study. The new generations opt for migrating to jobs away from the farmland; they consider that staying to work in the farmland represents stagnation. This phenomenon agrees with what was found by Briones -Aranda et al. (2024), who describe that in a polycrop system 45 % of family employment is generated, which causes a low level of intergenerational replacement and the abandonment of the agricultural activity, mainly by the youngest members of the family. De Grammont (2016) highlighted that agricultural employment has been substituted and/or complemented by activities carried out in the secondary and tertiary sectors. In the same sense, Venegas et al. (2021) agree that peasant pluriactivity is a phenomenon associated to the de-agrarianization of the farmland, which consists in the decrease of the contribution of agricultural activities to the family income, in addition to the increase of migration and ageing in the farmland, which is reflected in peasant permanence.

An indicator that reflects the importance of the fruit species in the AFS is the economic contribution to the family economy. The AAFS represents only 15 % of the income, while the traditional systems base their economy on the sale of the products obtained from their fruit species, representing 65 % in the case of the TAFS and 80 % in the CAFS. This phenomenon is because the producers with AAFS do not base their economy on the agricultural sector, and they have some type of marketing or commerce which sustains their economy. The producers of the traditional AFS have agriculture as their main activity.

The diversification of products allows producers to have lower risks. The CAFS have a higher number of components for sale (10), TAFS (5) in second place, and the farthest from the optimal is AAFS (2). The optimal was obtained from a system where 11 different crops were reported for consumption and sale, among which there are corn, bean, squash, fava bean, chili pepper, among others, and fruits such as capulín, tejocote, pear, plum, peach and walnut. A greater diversity of products in the system represents a low risk of a complete loss of the harvest in the case of a disturbance, in addition to a better use of time for the producer, since not all the crops develop simultaneously, which at the same time allows receiving an income at different times of the year (Ebel et al. 2017). This agrees with what Alcázar and Gómez (2022) report in their study, describing that the diversity of crops makes the agricultural activity more diverse and multifunctional, and provides peasants with several business alternatives in different amounts and different seasons of the year.

The possible marketing channels are on average two for the three systems: the local market and the direct sale to intermediaries on the plot; there is a third one that some producers report: regional markets located outside the municipality.

Table 1. Integration of the sustainability indicators of the Apple, Tejocote and Capulín agroforestry systems in San Andrés Calpan, Puebla.

Indicator	Criterion for the optimal	Optimal	AAFS	TAFS	CAFS
1. Basic crop yield	Information provided by MIAF researchers, 2019. Data in t ha-1	6 100 %	4.50 75 %	2.50 42 %	2.75 46 %
2. Fruit yield index	The optimal is considered 1 Best yield: Apple 15 T (Inf. MIAF, 2019); Tejocote 7 T; and Capulín 3.9 T (SIAP, 2018)	1 100 %	0.07 7 % 1.05 t ha-1	0.84 84 % 5.9 t ha-1	0.78 78 % 3.05 t ha-1
3. Relative land efficiency	According to Cortés and Turrent, 2018	1.3 100 %	0.79 53 %	1.26 84 %	1.24 82 %
4. Benefit/Cost Ratio (B/C R)	The highest value was considered with field data R B/C = 1:3	3 100 %	1.56 52 %	2.32 77 %	2.13 71 %
5. Agroecological Practices Index	Maximum possible value. The relationship is based on the 11 registered practices	1 100 %	0.60 60 %	0.60 60 %	0.75 75 %
6. Plant biological diversity	Maximum value found in the field	1.23 100 %	0.06 5 %	0.16 13 %	1.21 98 %
7. Carbon capture	Maximum value found in the field	1.77 100 %	0.45 25 %	0.68 38 %	1.63 92 %
8. Access to credit and insurance	Maximum possible value	0 100 %	0 100 %	0 100 %	0 100 %
9. Appropriation index of technological innovations	Maximum possible value. The relationship is based on the 11 registered practices	1 100 %	0.09 9 %	0 0%	0 0 %
10. Equipment index by producer	Maximum possible value	1 100 %	0.9 90 %	0.9 90 %	0.95 95 %
11. Degree of adoptability	Maximum possible value	100 %	2.5 %	65 %	32.5 %
12. Food security index	Maximum value found in the field	2.5 100 %	2.05 82 %	1.45 58 %	1.55 62 %
13. Genetic self-sufficiency	Maximum possible value	100 100 %	100 100 %	100 100 %	100 100 %
14. Independence from external inputs	Maximum possible value	0 100 %	1259 0 %	1062 16 %	964 23 %
15. Labor	Maximum possible value	100 100 %	16 16 %	58 58 %	58 58 %
16. Intergenerational replacement index	Maximum possible value	1 100 %	0.10 10 %	0.20 20 %	0.13 13 %
17. AFS income to the family unit	Maximum possible value	100 100 %	15 15 %	65 65 %	80 80 %
18. Sales diversity	Maximum value found in the field	11 100 %	2 18 %	5 45 %	10 91 %
19. Marketing channels	Maximum value found in the field	3 100 %	2 67 %	2 67 %	2 67 %

Note: The values presented in the table, in the case of some indicators, do not represent direct data; that is, ranges or inverse percentages were established to be able to assign a value that represents what is desired with regards to sustainability levels.

Source: Prepared by the authors with field information.

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Finally, to integrally compare the systems evaluated, an Amiba type representation was chosen (Figure 2), which shows the results from the indicators graphically. The evaluation of the state of sustainability of the AFS allows understanding that traditional systems are the ones that have a better state of sustainability with a percentage of 66 % for the CAFS and 6 % for the TAFS, compared to the alternative system (AAFS) with a value of 45 %. The results are similar to those found by Ordónez-Ovalle et al. (2022) for a MIAF system in a community in Chamula, Chiapas, which showed a sustainability index of 6.47.

Economically and ecologically, the CAFS obtained the best values; in second place, the TAFS, superior only in the social part by 4 % compared to the CAFS.

The AAFS obtained the highest value in only 2 indicators: yield of the basic crop and index of food security. Indicators such as access to credit and insurance, genetic self-sufficiency, and marketing channels have the same behavior in the three systems.

Traditional AFS have a higher degree of adoptability than the alternative one. The producers that have AAFS have pointed out that they do not feel completely identified or safe in this system, which is why their scaling has been limited; however, they have agreed to implement it as a result of the advice they receive and backing for the costs of fruit tree management. The AAFS represents a second option for the producers who have adopted it, since their main source of income derives from a shop or another AFS with traditional characteristics.

A study on the multifunctionality of peasant family agriculture carried out by Blanca et al. (2024) in the municipality of Calpan, Puebla, found that this type of agriculture (with the structure of traditional AFS), “continues generating various functions, among which the ones with greatest presence are: conservation of knowledge, conservation of agricultural biodiversity, agroecological practices, food security, employment generation, configuration of the landscape, and territorial rootedness. They highlight the environmental sphere such as agroecological practices and conservation of agrobiodiversity, and those of the territorial sphere such as landscape configuration”. With an Index of Multifunctionality of Peasant Agriculture (IMPA) of 72.61 of multifunctionality (medium high), this type of agriculture remains at a medium high level of sustainability, as the results show.

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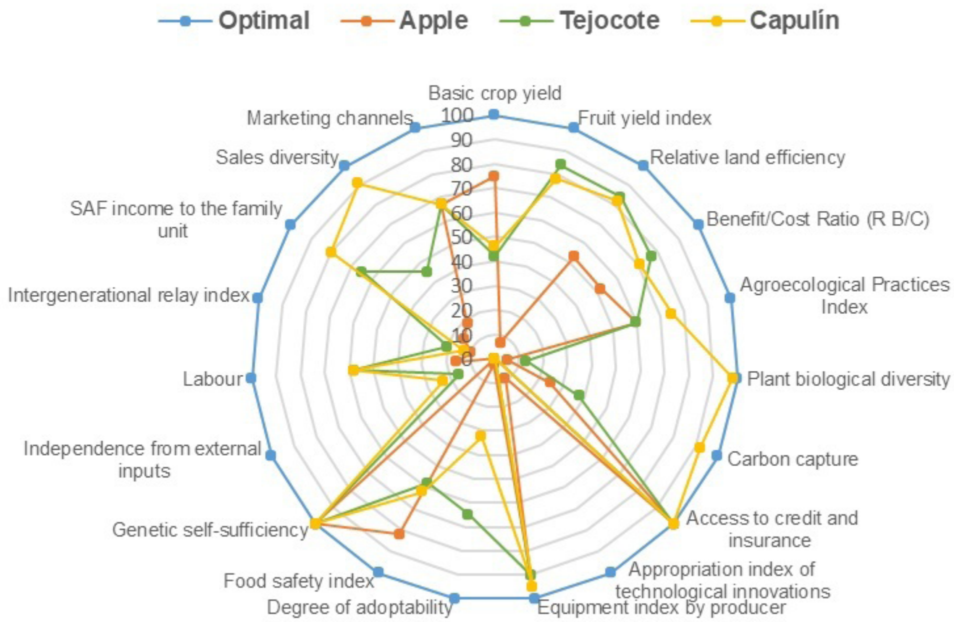

Figure 2. Sustainability status of Agroforestry Systems: Apple, Tejocote and Capulín, in San Andrés Calpan, Puebla. Source: Prepared by the authors based on field information.

Conclusions

Traditional AFS resulted in a higher percentage of sustainability; the capulín AFS 66 % and the tejocote AFS 61 %, while the apple AFS showed 45 %, so the traditional AFS are more sustainable and fulfill various objectives of the family production unit, among the most important being higher diversity of foods for subsistence and diversification of income during different seasons of the year.

The three peasant agroecosystems evaluated (AAFS, TAFS, and CAFS) have some similar characteristics in the social dimension: marketing channels, access to credit and insurance and equipment by producer, but they present more differences in technological aspects and in management of practices, showing contrast in plant biological diversity, productivity and profitability.

Therefore, the producers opt for systems with predominant species from the zone such as capulín and tejocote, and systems with greater diversity of fruit trees, in contrast with the apple AFS with a single fruit species.

Contribution by the authors

Study conceptualization, Reyes-Reyes A. K., Ocampo-Fletes I.; development of the methodology, Reyes-Reyes A. K., Ocampo-Fletes I.; software handling, Reyes-Reyes A. K., Ocampo-Fletes I.; experimental validation, Reyes-Reyes A. K., Ocampo-Fletes I., Ramírez-Valverde B; analysis of results, Reyes-Reyes A. K., Ocampo-Fletes I.; data management, Reyes-Reyes A. K., Ocampo-Fletes I.; manuscript writing and preparation, Reyes-Reyes A. K., Ocampo-Fletes I.; writing, revising and edition, Reyes-Reyes A. K., Ocampo-Fletes I., Ramírez-Valverde B.; Ortiz-Torres E.; Sánchez-Morales P.; Acosta-Mireles M.; project administrator, Reyes-Reyes A. K., Ocampo-Fletes I.; procurement of funds, Reyes-Reyes A. K., Ocampo-Fletes I.

Every author of this manuscript has read and accepts the published version.

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Declaration of informed consent

The informed consent of all the subjects involved in the study was obtained.

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Conflict of interest

The authors declare not having any conflict of interest.

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