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EVALUATION OF THE SUSTAINABILITY OF TWO TYPES OF *Agave tequilana* Weber var. blue AGROECOSYSTEMS IN TEQUILA, JALISCO

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ABSTRACT

Tequila is an alcoholic beverage that must be produced exclusively from the species *Agave tequilana* Weber var. azul (blue) and only in regions with certification of origin within Mexico. The "Tequila Boom" began in 1992, making it a popular beverage in several countries, including Mexico. This boosted exports, production, and the expansion of blue agave plantation areas, which had negative social, economic, and environmental consequences in producing regions and for agave farmers. The aim of the study was to evaluate the degree of sustainability of the *Agave tequilana* crop in two types of agroecosystems: monoculture and polyculture. The research hypothesis was that the *A. tequilana* polyculture agroecosystem is more sustainable than monoculture. A random sample of agave farmers from the municipality of Tequila, Jalisco, was surveyed and distributed equally: 25 agave farmers who practice monoculture and 25 who practice polyculture. The methodology was based on and adapted from the Framework for the Evaluation of the Natural Resource Management Systems incorporating Sustainability Indices (MESMIS), which was used to create a Composite Sustainability Indicator for *A. tequilana* (ICSAT) to compare both agroecosystems. The results show that polyculture is more sustainable than monoculture in 13 of the 15 indicators evaluated. Polyculture displayed a sustainability level of 77.06 % in the Composite Sustainability Indicator, whereas monoculture had 58.43 %. Our conclusion is that the evaluation of sustainability helped to determine that the *Agave tequilana* polyculture agroecosystem is more sustainable than monoculture.

Keywords: Composite Sustainability Indicator, monoculture, polyculture, tequila industry, agroecological practices.

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INTRODUCTION

Tequila is an alcoholic beverage produced from the fermentation of sugars extracted from the *piñas* (hearts) of the *Agave tequilana* Weber var. azul (blue). Tequila was named after the region of Tequila, Jalisco, Mexico, the place where the drink originated in the 16th century (CRT, 2019).

Tequila must be produced exclusively from the species *Agave tequilana* Weber var. blue, and the name "tequila" can only be given to an alcoholic beverage that meets the Official Mexican Standard (NOM-006-SCFI-2012, Alcoholic Beverages, Tequila-Specifications) (Secretaría de Economía, 2012). The resolution of the Secretariat of Industry and Trade (1974), published on December 9th, 1974, in the Official Journal of the Federation, protects the Certificate of Origin of the plantation of *A. tequilana* and the production of the beverage known as tequila for production in municipal areas of five Mexican states: the entire state of Jalisco, eight municipalities of Nayarit, 30 in Michoacán, 11 in Tamaulipas, and seven in Guanajuato. When the beverage is obtained from other agave species or varieties, it is known as mezcal or other local names (IMPI, 2023).

In 1992, the "Tequila Boom" began, making the beverage fashionable in several countries. This resulted in an increase in exports, increased production, and the expansion of the species *A. tequilana*. Between 2009 and 2018, tequila production increased 24.1 %, exports increased 64.3 %, and agave demand grew by 23.1 %. From 2017 to 2018, tequila production increased by 13.9 %, while exports increased by 5.1 % (CRT, 2019).

Because the tequila industry forces farmers to grow agave in monoculture, the "Tequila Boom" has created environmental problems in the production areas. Some of the problems affecting the biophysical environment as a result of agave monoculture include soil deterioration, inefficient nutrient recycling, pest susceptibility, displacement of traditional crops, and biodiversity loss (Gerritsen *et al*., 2011).

Valenzuela-Zapata (2003) and Gómez-Arriola (2012) found that blue agave is produced in polyculture associated with beans, maize, and peanuts. These authors indicate that there are benefits to producing agave in polyculture, such as increased plant coverage, which reduces erosion, retains moisture, and improves soil fertility. When associated with legumes, it helps to reduce pest attacks while also increasing nitrogen fixation in the soil.

Evaluating the sustainability of productive agroecosystems is a complex process since they are dynamic and multidimensional systems. In addition, it must consider farmers' perspectives since agroecosystem management is the result of an evolutionary process that has frequently been passed down from one generation to the next and has adapted to the biophysical, social, and economic circumstances (Astier and Arnés, 2018).

Moreno-Hernández *et al.* (2011) carried out eminently agronomic evaluations of the sustainability of the agave crop and developed a composite indicator known as the Agronomic Management Index (IMA) with five crop practices. Evaluating agroecosystems with productivity and economic yield indicators is crucial for designing sustainable agricultural and food systems (Bolívar, 2011). This vision, however, is not always sufficient to evaluate sustainability since the social and cultural factors of farmers are decisive to the functioning of agroecosystems.

The goal of this study was to evaluate and compare the degree of sustainability of the *Agave tequilana* Weber agroecosystem in two types of agroecosystems: monoculture and polyculture. A Composite Sustainability Indicator for *Agave tequilana* (ICSAT) was developed to help determine which agroecosystem is the most sustainable in the municipality of Tequila, Jalisco, Mexico, based on specific social, economic, productive, agronomic, and cultural indicators. The research hypothesis was that the *Agave tequilana* polyculture agroecosystem is more sustainable and has less negative environmental impact than monoculture.

MATERIALS AND METHODS

Area of study

This investigation was carried out in the municipality of Tequila, in the state of Jalisco, Mexico, which is located between the coordinates 20° 25′ 00″ and 21° 12′ 30″ N, 103° 36′ 00″ and 104° 03′ 30″ W. The altitude of the municipal area ranges between 700 and 2900 m, and the main climates are warm subhumid and semiwarm. Temperatures range between 14 and 26 °C, annual rainfall varies between 700 and 1100 mm, and the predominant soils are Leptosol and Luvisol (Gobierno del Estado de Jalisco, 2023).

Sampling techniques

A survey was conducted among a general sample of 50 *A. tequilana* farmers from the municipality of Tequila, which was subdivided into 2 subsamples: a) 25 farmers that grow agave in monoculture, and b) 25 that grow agave in polyculture.

The general sample was calculated using a maximum variance formula, modified from Martínez-García and Martínez-Caro (2008), with a reliability of 95 % and an accuracy of 10 %, with a universe of 101 agave farmers. The estimated sample size was 49.23 ≈ 50 farmers.

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

where: n = sample size = 50, N = population size = 101, p = *a priori* proportion of the binomial variable = 0.5, q = *a priori* proportion of the other binomial variable = 1-p = 0.5, Z = value of normal distribution tables ($Z_{\alpha/2}$) with a reliability of 95 % = 1.96, and d^2 = error or accuracy at 10 % = 0.1.

Sustainability Evaluation Methodology

The assessment of agroecosystem sustainability for monoculture and polyculture was based on and adapted from the methodology developed by Masera *et al.* (1999)

in the Framework for the Evaluation of the Natural Resource Management Systems Incorporating Sustainability Indices (MESMIS). The methodological approach is based on the comparison of an alternative agroecosystem with another reference agroecosystem. The sustainability assessment compared two types of agroecosystems managed by different farmers: monoculture (reference agroecosystem), linked to the farmers who work in the tequila industry, and polyculture, linked to annual crops (alternative agroecosystem), generally composed of independent farmers, linked to the *tabernas* (distilleries) where the tequila is handcrafted. The information was gathered between 2014 and 2015.

Sustainability indicators

The 15 sustainability indicators and their weighting values were selected based on the diagnosis of the current problem faced by the production of agave in the municipality of Tequila, Jalisco.

The sustainability evaluation used the creation of a Composite Indicator, which is a simplified representation that attempts to summarize a multidimensional concept in a simple index (unidimensional) based on an underlying conceptual model (CEPAL, 2009). The sustainability data for each of the 15 specific indicators (both numerical and categorical) were transformed into percentages. The proposed Composite Sustainability Indicator for *A. tequilana* (ICSAT) is the average of the percentages of the 15 specific indicators, with each indicator receiving the same pondered weight.

Index for Agroecological Practice in *Agave tequilana* (IPAAT)

This was obtained by identifying the number of agroecological practices in the agronomic management of the agave agroecosystem: 1) alternating crops (polyculture); 2) incorporation of organic matter into the soil by cattle grazing; 3) plantation of agave in level curves; 4) soil and water conservation works; 5) crop rotation; 6) lands in fallow; 7) staggering agave plantation; and 8) reduction in the use of herbicides.

The IPAAT values are: null = 0 practices; low= 1-2 practices; medium = 3–4 practices; high= 5 practices; very high = 6–7 practices; and excellent = 8 practices.

Cost-benefit ratio (R B/C)

This was calculated in the monoculture from the estimation of the gross incomes and the costs of the agave in a six-year cycle. The R B/C of the polyculture included the gross incomes and the costs of agave, added to the costs of the perennial crops (lemon and cacti) in a six-year cycle and the annual cycles (maize, bean, and peanut) associated with the first four years.

Agroecosystem Yield (RAG)

Yield in Mg ha^{-1} was obtained: a) in monoculture, the number of plants ha^{-1} was multiplied by the average weight of the agave *piñas;* and b) in polyculture, the production in Mg of agave was added to the production in Mg of the alternate crops, such as maize, bean, and peanut (during the first four years of the total of the agave cycle). The optimum reference yield was 140 Mg of agave *piñas* with a plant density of 4000 ha^{-1} (SAGARPA, 2015).

Percentage of Organic Matter (% MO)

Soil samples were collected in both agroecosystems based on the proposal of Uvalle-Bueno *et al*. (2007). A total of eight samples were analyzed in the Plant Nutrition Laboratory of the Soil Science Program of the Colegio de Postgraduados Campus Montecillo. The optimal percentage of MO was calculated using mean (χ) of the reference value of the Integrated Differential Diagnosis methodology by Uvalle-Bueno *et al*. (2007): $\boldsymbol{X}$ = High 4.39 %. According to these authors, the following strata were determined based on the percentage of MO in agave fields: deficient (less than 0.65 %); low (0.65 to 1.29 %); moderately low (1.29 a 2.13 %); sufficient (2.13 to 3.02 %); moderately high (3.03 to 3.64 %); high (3.64 to 5.16 %); and excessive (more than 5.16 %).

Agricultural Diversification Index (IDA)

This index, modified from the indicator proposed by Moreno-Hernández *et al*. (2011), considers the agricultural and livestock species that coexist in a plot of land for a given amount of time. A higher diversification of crops and livestock leads to more products and income. The parameters obtained were as follows: a) number of crops in the system; b) number of crops in rotation; and c) number of livestock species that graze in the fields.

$$IDA = \frac{\sum \text{number of crops and livestock species}}{\sum \text{maximum number of crops and livestock species}} \times 100$$

Adaptation and Alternatives Index (IAA)

The adaptation and alternative processes of farmers in the face of variations in the prices of agave were identified as follows: 1) added value of the production through the production of tequila (*taberna* owners); 2) alternating crops; and 3) planting other crops. Percentages were assigned depending on the number of alternatives, i.e., if the three were performed = 100 %; 2 = 80 %; and 1 = 50 %.

Intergenerational Relay (RIG)

A lack of intergenerational relay is considered a risk for the continuity of the agroecosystem. This indicator was obtained from the percentage of farmers who believe that their children take over the production of agave in both agroecosystems.

Family Participation in Agricultural Chores (PFLA)

The percentage of the production units in which family members participate in the agave-planting tasks was taken.

Agroecosystem Knowledge Index (ICA)

This integrates the farmer's experience with agave plantation and alternating crops. The variables are: a) average age of the farmer; and b) the number of years they have grown their own agave. This was estimated using the formula proposed by Moreno-Hernández *et al*. (2011).

$$ICA = \left(\frac{ACP}{EA}\right) \Big/ \left(\frac{ACP\ \text{max.}}{EA\ \text{max.}}\right) \times 100$$

where EA = average age of agave farmers, ACP = average of years of farmers planting their own agave, ACP max. = maximum number of years of farmers planting their own agave, and EA max. = maximum age of agave farmers.

Control of the Planting Process through Leasing (CPCA)

The three main forms of agricultural contracts identified in the municipality of Tequila were: 1) leasing; 2) sharecropping; and 3) 50-50 harvest sharing. The index represents a percentage assigned to each restriction imposed on agave farmers by lease contracts. Two forms were considered: a) farmers under contract and b) farmers under restrictive conditions of alternating crops and grazing livestock.

Land Occupancy Index (IOT)

This indicator estimates the efficiency of land use. The number of months in which each crop uses the land was calculated by dividing a) the months of occupancy of the soil by alternate crops, by b) the months of occupation by monocultures. The formula is as follows:

$$IOT = \left(\frac{\sum \text{months of intercrop occupation per year (agave + other crops)}}{\sum \text{months of monoculture occupation}}\right) \Big/ 2$$

Dependency on Technical Assistance (DAT)

This indicator is divided into three categories: 1) farmers who do not receive technical assistance; 2) institutions that provide technical assistance; and 3) the number of service-providing technicians. Farmers in the two agroecosystems who had not received assistance were counted, and institutions and technicians who provided assistance were identified using categories 2 and 3.

Organization of Farmers (OP)

Comprises two aspects: 1) the number of farmers who belong to an organization; and 2) the type of organization. This indicator was calculated using the number of farmers who are members of an organization in each ecosystem, and the percentage was used as the calculated value.

Dependency on External Capital for Production (DCEP)
This indicator considered the percentage of farmers who self-fund their plantations and the percentage of farmers who received external investment funds (such as a credit or crop funding through a buy and sell contract) during the production cycle.

Dependency on Agrochemicals (DAQ)
Three cultural practices were included that reduce or eliminate dependence on agrochemicals such as fertilizers and pesticides: 1) manual weed control; 2) free grazing of animals amongst the agave; and 3) producing and applying organic inputs in the plantations. The indicator was calculated by assigning a percentage to the number of the three agricultural practices used by agave farmers (3 = 100 %; 2 = 80 %; and 1 = 50 %).

RESULTS AND DISCUSSION

The Composite Sustainability Indicator for *Agave Tequilana* (ICSAT) combines the 15 indicators into a single scale and was calculated by taking the simple average of the unweighted values (all variables have the same percentage weight) to compare two types of agroecosystems: monoculture and polyculture.

Index for Agroecological Practice in *Agave tequilana* (IPAAT)

Farmers working in monoculture carried out an average of 3.32 practices out of the eight practices considered, placing the IPAAT at a middle level, while farmers working in polyculture carried out 5.52 practices, ranking it in a very high category. Farmers with polycultures used more agroecological practices, which are crucial components of sustainable agriculture, and agroecological principles based on the use of natural products and local knowledge. Moreno-Hernández *et al*. (2011) evaluated the performance of polyculture and monoculture practices for agave and found that more than 60 % of the polyculture plots had a medium-to-high level of practices carried out, whereas all monoculture plots had a low level.

Cost-benefit ratio (R B/C)

The cost-benefit ratio (R B/C) is 7.91. Both agroecosystems are profitable because the net incomes exceed costs (B/C > 1), with polyculture being 1.05 times more profitable than monoculture (Table 1). When a field is planted following the technical recommendation by SAGARPA (2015) of 4000 plants ha^{-1}, an average yield of 140 Mg ha^{-1} is obtained, leading to a total production cost of MXN 106 197 ha^{-1} and a gross total income of MXN 840 000 ha^{-1} in a six-year cycle (at 2015 prices).

Table 1. Cost-benefit ratio of planting the *Agave tequilana* under monoculture and polyculture in Tequila, Jalisco, Mexico.

Agroecosystem	Costs (MXN)	Income (MXN)	Cost-benefit ratio
Monoculture	88 420.00	665 910.00	7.53
Polyculture	90 208.00	773 780.00	8.58

Agroecosystem Yield (RAG)

Monoculture yield was 110.98 Mg ha^{-1} with an average of 3171 plants ha^{-1}, while polyculture yield was 129.43 Mg ha^{-1} with an average of 3698 plants ha^{-1}. At the end of the six-year agave cycle, the yields of the maize, bean, or peanut crops were added for the first four years. According to the results of the farmers surveyed, the agave density per hectare is low according to the technical recommendations for the Tequila region (4000 plants ha^{-1}) (SAGARPA, 2015).

The average agave yield in the municipality of Tequila ranges from 96.04 to 122.5 Mg ha^{-1} (SIAP, 2016). This confirms the findings of Ebel *et al*. (2017), who state that yield in polyculture increases due to synergies established among the different crops that grow in the same field, resulting in maize, in association with bean and squash, having a yield 1.2 times higher per plant in comparison to maize in monoculture, whereas bean and squash were almost equal.

Percentage of Organic Matter (% MO)

The analysis of the eight soil samples revealed that monoculture had a sufficient percentage of MO with 2.31 %; while polyculture had a moderately high MO level with 3.07 %, according to the reference values on the fertility of soils in *Agave tequilana* proposed by Uvalle-Bueno *et al*. (2007).

The practice of incorporating the annual crop residues that are alternated (maize, bean, and peanut) into the soil is linked to a higher percentage of MO in polyculture plantations. Meanwhile, soils in monoculture have less MO because the residues are not incorporated into the soil due to the absence of other crops. Incorporating residues in the soil is an important component in the maize alternated with fruit trees (MIAF) agroecosystem for recovering soil fertility and generating carbon capture processes in the soil (Cortés-Flores and Turrent-Fernández, 2018)

Agricultural Diversification Index (IDA)

In the reference system, the optimal number of crops and livestock in a plot is ten species (100 %). The distinction between both agroecosystems is substantial. According to the farmers, the average number of crops and livestock species in polyculture is two (20 %) and nine (90 %). Diversification is crucial in sustainability, as pointed out by Spiaggi *et al*. (2016), who claim it is necessary to opt for diversified agroecosystems, such as polycultures, to obtain economically viable and environmentally sustainable products in small-scale fields.

Adaptation and Alternatives Index (IAA)

Agave *piñas* prices fluctuate from year to year, so agave farmers use a variety of strategies to minimize and mitigate the negative consequences of market variations. Three alternatives were identified: 1) the farmers who own *tabernas* allocate the production of agave *piñas* to produce tequila or receive income through contract manufacturing to produce tequila; 2) they alternate crops for selfconsumption and livestock; and 3) in extreme cases, they carry out crop conversion, primarily planting maize instead of agave.

The percentage of IAA found in the monoculture agroecosystem was 80 %, while in polyculture it was 100 %. Agave farmers who practice polyculture face better in terms of agave price volatility than monoculture farmers, because diversifying production and agricultural activities leads to the production of edible crops, which mitigates the risk posed by agave price volatility.

Intergenerational Relay (RIG)

In the survey, some of the agave farmers indicated that many of their married elder sons and daughters do not work in the production of agave. Most farmers believe that even the children who live at home will probably work in other activities unrelated to the agave agroecosystem (60 % of those who produce in polyculture and 15 % in monoculture). This is regardless of whether agave farmers incorporate their children in plantation work or in *tabernas* for the production of tequila, starting at an early age and passing their knowledge down to them throughout the years. This is due to three main reasons: 1) work in agave plantations is "tough"; 2) the economic benefits of agave farming are not very attractive; and 3) there is a growing number of children that have jobs in other production sectors.

Family Participation in Agricultural Chores (PFLA)

The persistence of traditional agroecosystems is a positive factor in sustainability because development is aided by field management and family bonds (Castelán-Vega *et al*., 2014). Family involvement is essential in agricultural activities. There were no differences in the proportion of family members who supported labor in agave monoculture versus polyculture (72 %).

Agroecosystem Knowledge Index (ICA)

The experience gained by farmers through the years favors the knowledge required for the management of the agroecosystem. A farmer with many years of dedication is considered to have a better understanding of agave sustainability than one who has planted it for only a few years (Moreno-Hernández *et al*., 2011). The estimated ICA was 54.7 % for farmers with monoculture and 63.5 % with polyculture.

Control of the Planting Process through Leasing (CPCA)

Out of all the farmers surveyed, 38 % have formal or informal contracts. Out of those with informal contracts, 24 % are under a sharecropping scheme, and 12 % are under 50-50 harvest sharing. In monoculture, nine farmers (seven lessees and three sharecroppers), corresponding to 47.37 %, have production contracts, which impose restrictions on the agave production process management and allow them to only perform the duties authorized by the tequila companies (Orozco-Martínez, 2010).

The tequila industry dictates what they must do, how and when, even if it goes against the agave farmer's criteria (for example, the number of herbicide applications). Polyculture farmers, on the other hand, are not bound by rules or regulations when it comes to managing and controlling their agave plantations, even if they have sharecropping or 50-50 harvest sharing arrangements.

Land Occupancy Index (IOT)

This index calculates the efficiency of arable land surface use. Agave is a semipermanent crop that remains on the ground 12 months a year for six years. In polycultures, the soil between rows of agaves is used for annual crops to be planted. The optimum IOT level (100 %) is 24 months per crop, which is equal to the agave plus another crop, occupying the same surface of land for the 12 months of the year, times the six years that the cycle lasts. In the municipality of Tequila, rainfed maize (*Zea mays*) lasts an average of five months on the soil, bean (*Phaseolus vulgaris*) lasts three months, peanut (*Arachis hypogaea*) lasts five months, and perennial crops such as cacti (*Opuntia albicarpa*) and lemon (*Citrus aurantifolia*) last 12 months.

The IOT for agave monoculture resulted in 50 % because it occupies the ground for 12 months a year for six years. In polyculture, IOT was 78 %, indicating that alternated annual or perennial crops added 3.36 months (28 %) of occupation per year per six-year cycle. Results indicate that polyculture is more efficient in terms of land use than monoculture. This advantage translates into the minimization of production costs because two or more crops benefit from the same cultivation work; more produce is obtained in Mg ha^{-1}, and the soil has greater plant coverage in the year, reducing soil erosion problems (Nicholls *et al*., 2015).

Dependency on Technical Assistance (DAT)

In monoculture, 80 % of farmers pointed out that they do not depend on technical assistance due to the experience they have gained over the years. However, farmers under contract must adhere to the crop practices specified in their contracts, and should they require support, tequila companies have technicians who can assist them. In polyculture, 68 % of farmers have received no technical assistance. They occasionally seek the advice of agrochemical company owners and employees. This information is similar to that found in the study by Sánchez-Soto (2016) in the municipality of Tequila, which states that when farmers require technical assistance, they turn to fellow farmers, agrochemical distributors, or agencies selling machinery to answer questions. This is the only indicator value in which monoculture surpasses polyculture, since 68 % of polyculture farmers receive no technical assistance and 80 % of monoculture farmers do not.

Organization of Farmers (OP)

The Agave Association is the representative state organization in the agave-tequila chain, although few of the interviewees are members. Only 32 % of the farmers of the monoculture agroecosystem belong to the association, along with 36 % of the polyculture agroecosystem.

Farmers affiliated with agricultural organizations such as the Agave Association have greater possibilities of acquiring inputs, machinery, tools, and technical assistance, achieving scale economies. In addition, they have the possibility of accessing better market conditions for marketing: they are eligible for funding and access to government programs. This is an advantage over farmers who are not affiliated.

Dependency on External Capital for Production (DCEP)

This indicator considers the proportion of farmers who fund their own plantations with financial, material, and human resources for agave cropping. Survey results indicate that 18 monoculture farmers (72 %) have covered the expenses for their crops out of pocket, and seven farmers have contracts with distilleries. Polyculture farmers (88 %) have funded the costs of plantations with their own funds, and only three of them have formal contracts for buying and selling produce. Results show that farmers using polyculture depend less on external capital for planting and production maintenance.

Dependency on Agrochemicals (DAQ)

Three practices were evaluated in order to know the level of dependence of agave farmers on the use of phytosanitary products: 1) the manual control of weeds helps reduce or eliminate the use of herbicides, a practice that was carried out by seven farmers in monoculture and another seven in polyculture; 2) livestock grazing also contributes to the control of weeds and was carried out by four farmers in monoculture and eight in polyculture; 3) agave farmers that produce and apply compost were three in polyculture and only one in monoculture. The total percentage that applied one or more of these three practices in monoculture was 48 %, and 72 % in polyculture.

The optimization of farming systems with the aim of generating sustainable farming systems is achieved when external inputs, mainly industrial ones, are replaced with inputs generated in the agroecosystem itself (Nicholls *et al*., 2015). When properly managed, agroecosystems, which include crop and livestock integration, contribute to a higher self-sufficiency of nutrients in the soil and their conservation (Boincean and Francis, 2017).

Joint analysis of the Composite Sustainability Indicator of *A. tequilana* (ICSAT) for the monoculture and polyculture agroecosystems in Tequila, Jalisco

The joint analysis displays the values clustered on the same scale as the evaluation of the 15 indicators, with the values calculated with regard to the optimum values (Table 2) used to calculate the ICSAT for each type of agroecosystem. The result of the calculation was a total difference of 18.64 % between monoculture (58.43 %) and polyculture (77.07 %).

When compared to monoculture, polyculture has higher values in 13 of the 15 sustainability indicators evaluated (Table 2). Polyculture only has lower DAT values and equal PFLA Index values. The indicators for productivity could be considered

Table 2. Composite Sustainability Indicator for A. tequilana (ICSAT) and optimum and calculated values of the specific indicators for two types of agroecosystems: monoculture and polyculture in Tequila, Jalisco, Mexico.

Attribute	Diagnosis criteria	Specific indicators	Optimum	Monoculture (reference)	Polyculture (alternative)
Productivity	Efficiency	Index for Agroecological Practice in *Agave tequilana* (IPAAT)	8 practices (100 %)	3.32 (41.5 %)	5.52 (69 %)
	Crop economy efficiency	Cost-benefit ratio (R B/C)	7.91 (100 %)	7.53 (95.2 %)	8.58 (100 %)
	Productive yield	Agroecosystem yield (RAG)	140 Mg ha^{-1} (100 %)	110.08 Mg ha^{-1} (78.6 %)	129.43 Mg ha^{-1} (92.5 %)
	Organic efficiency	Organic Matter Percentage (% MO)	High 3.637–5.158 % $\bar{X}$ = 3.49 %	$\bar{X}$ = 2.31 sufficient (53 %)	$\bar{X}$ = 3.07 medium-high (70 %)
Stability, resilience, and reliability	Crop diversification	Agricultural Diversification Index (IDA)	10 crops and species (100 %)	2 (20 %)	9 (90 %)
Adaptability	Ability of adaptation under pressure from price fluctuation	Adaptation and Alternatives Index (IAA)	3 alternatives (100 %)	2 (80 %)	3 (100 %)
	Continuity of the system	Intergenerational relay (RIG)	25 farmers (100 %)	13 (52 %)	15 (60 %)
	Family participation	Family participation in agricultural chores	25 farmers (100 %)	18 (72 %)	18 (72 %)
Equidad	Farmer's knowledge	Agroecosystem Knowledge Index (ICA)	100 % experience	54.7 %	63.5 %
	Degree of control over the process	Control of the Planting Process through Leasing (CPCA)	Zero restrictions by the farmer (100 %)	9 (47.4 %)	0 (100 %)
Autogestión	Efficiency of land occupancy	Land Occupancy Index (IOT)	24 months $year^{-1}$ (100 %)	12 (50 %)	18.8 (78 %)
	Dependency on technical assistance	Dependency on Technical Assistance (DAT)	25 farmers (100 %)	20 (80 %)	17 (68 %)
	Degree of self-management of the production process	Organization of Farmers (OP)	25 farmers (100 %)	8 (32 %)	9 (36 %)
	Funding sources and conditions	Dependency on External Capital for Production (DCEP)	25 farmers (100 %)	18 (72 %)	22 (85 %)
	Use of industrial inputs	Dependency on Agrochemicals (DAQ)	25 farmers (100 %)	12 (48 %)	18 (72 %)
Composite Sustainability Indicator			**100 %**	**58.43 %**	**77.06 %**

the most traditional and important in sustainability evaluations, and in all of them, polyculture is the most sustainable: the IPAAT, the R B/C, RAG, and the percentage of MO. No agroecosystem is totally sustainable or totally unsustainable, since sustainability is a goal that is achieved through the addition of diverse, adequate attributes that maintain a balance of all agroecosystem components (Astier and Arnés, 2018; Nicholls *et al*., 2015; Castelán-Vega *et al*., 2014).

Below, the resulting percentages of each indicator appear with their optimum value (100 %) in the same plain (Figure 1), along with the values calculated for monoculture (reference agroecosystem) and polyculture (alternative ecosystem).

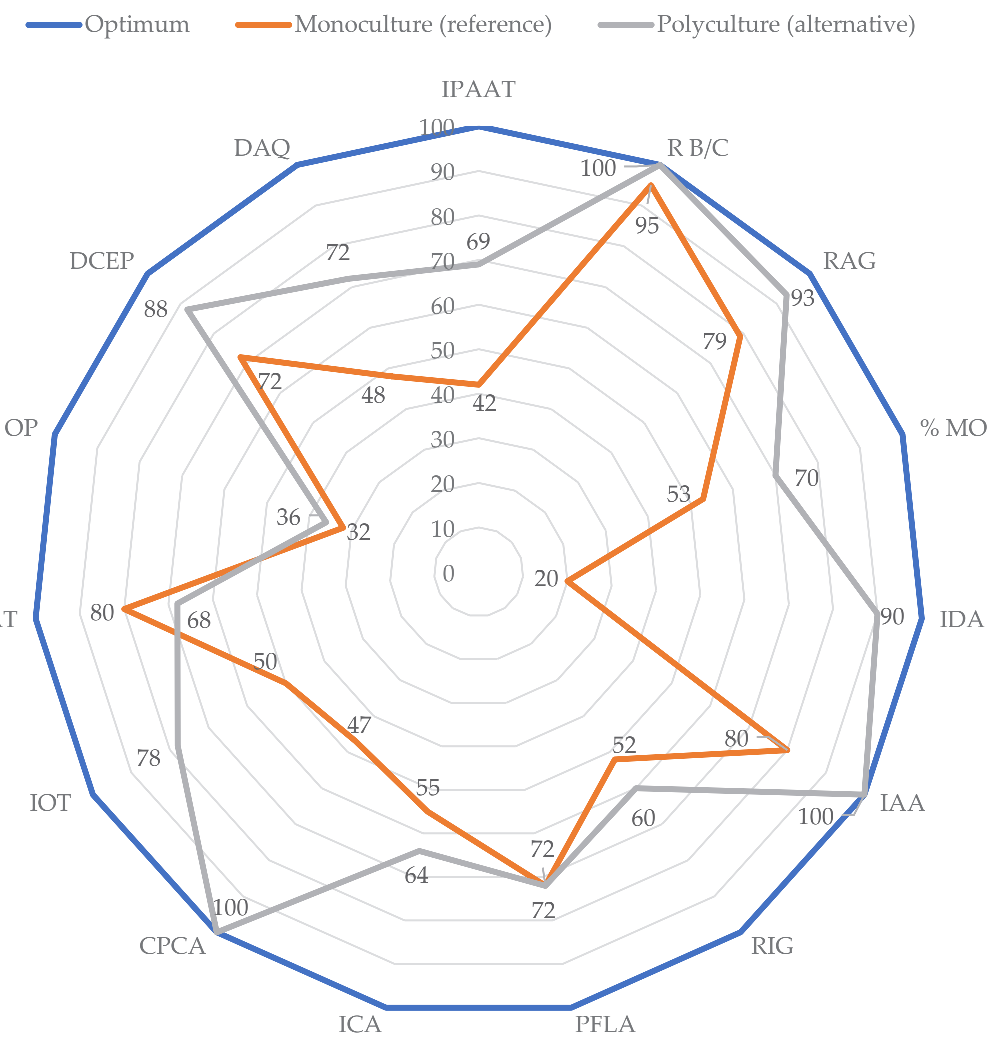

Figure 1. Comparison of the Composite Sustainability Indicator for *A. tequilana* (ICSAT) in monoculture and polyculture.

CONCLUSIONS

Sustainability evaluation, based on the methodological proposal of the Framework for the Evaluation of the Natural Resource Management Systems incorporating Sustainability Indices (MESMIS), helped determine that the polyculture agroecosystem is more sustainable than the monoculture because it had a higher value in the Composite Sustainability Indicator for *Agave tequilana* (ICSAT) and higher calculated sustainability values in 13 out of 15 indicators. Polyculture outperformed monoculture in all traditional agroecosystem productivity evaluation indicators (IPAAT, R B/C, RAG, and % MO).

Research shows the environmental irrationality of maintaining monoculture as the predominant method of agave production. It is not even profitable for agave farmers. Monoculture prevails because it is advantageous for the tequila industry to have a supply of agave *piñas*, even if it implies disadvantages for agave farmers. This study proved that the evaluation of the sustainability of the agave agroecosystem must have a holistic focus, considering social, economic, cultural, and institutional factors that affect, limit, or strengthen sustainability. These results may be useful in helping the government, the Tequila Regulation Council, and the tequila industry in promoting more sustainable development through polyculture and working on the indicators with a greater difference in values between polyculture and monoculture.

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