EVALUATION OF THE SUSTAINABLE PERFORMANCE OF NATIVE AND INTENSIVE SILVOPASTORAL SYSTEMS IN THE MEXICAN TROPICS USING THE MESMIS FRAMEWORK †

[EVALUACIÓN DEL DESEMPEÑO SOSTENIBLE DE SISTEMAS SILVOPASTORILES NATIVOS E INTENSIVOS EN EL TRÓPICO MEXICANO USANDO EL MARCO METODOLÓGICO MESMIS]

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SUMMARY

Background. It is agreed that there is a need to work on sustainable extensive livestock production systems. Silvopastoral systems are an alternative for efficient and sustainable grazing systems to increase the provision of ecosystems services and minimize the environmental costs associated to monoculture systems (MS), but the efficiency of intensively managed (IS) and unmanaged or native (NS) silvopastoral systems has never been assessed and compared to MS. The Framework for Assessing the Sustainability of Natural Resource Management (MESMIS) offers a tool to assess sustainability criteria in agroecosystems. **Objective.** To use MESMIS to compare the sustainable performance of NS, IS and MS and determine the system with the best sustainable performance in the Mexican Tropics. **Methodology.** One MS IS and NS per municipality (Tizimin, Merida and Tzucacab) were evaluated in the state of Yucatán, Mexico. Based on the MESMIS approach, the evaluation of the critical points of sustainability resulted in the selection of 19 indicators classified according to the attributes also defined by MESMIS (production, adaptability, stability-resilience, equity and self-management) and by sustainability dimensions (environmental, animal welfare, economic and social). After evaluation, indicator scores were obtained and integrated into attributes and dimensions through the assignation of equitable, balanced weights (W). Finally, attribute and dimension scores were aggregated in amoeba graphs to facilitate visual interpretation. **Results.** NS were better for the dimensions 'Environmental' and 'Economic' and the attributes 'Stability, 'Reliability'and 'Resilience,' and 'Production'. IS were best for the dimension 'Animal Welfare' and attributes 'Adaptability' and 'Self-reliance'. MS were better for the 'Social' dimension and the 'Equity' attribute. **Implications.** The fact that IS appeared to be more sustainable than MS does not leave out the idea of considering NS as a better option for some criteria such as the biodiversity conservation and the prevention of disease outbreaks, than IS. We suggest that more studies are carried on areas of potential improvement for IS as well as NS. **Conclusions.** This information will be useful to continue working on the parametrization of sustainability criteria of cattle extensive systems to be used for more efficient policies.
Key words: sustainability; cattle; MESMIS; silvopastoral systems; animal welfare.

RESUMEN

Antecedentes. La necesidad de trabajar en la implementación de sistemas sostenibles de producción de ganado extensivo es reconocida. Los sistemas silvopastoriles son una alternativa de sistemas de pastoreo eficientes y sostenibles que incrementan la provisión de servicios ecosistémicos y minimizan el costo ambiental asociado a los sistemas de monocultivo (MS); sin embargo, la eficiencia de sistemas silvopastoriles manejados intensivamente (IS) o nativos y sin manejo (NS) nunca ha sido evaluada y comparada con los MS. El Marco para la Evaluación de Sistemas de Manejo de recursos naturales incorporando Indicadores de Sustentabilidad (MESMIS) ofrece una herramienta para

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evaluar criterios de sostenibilidad en agroecosistemas. **Objetivo.** Usar MESMIS para comparar el desempeño en sostenibilidad de NS, IS y MS y determinar cuál es el sistema con el mejor desempeño en el Trópico Mexicano. **Metodología.** Un MS, IS y NS por municipio (Tizimin, Merida and Tzucacab) fueron evaluados en el estado de Yucatán, México. Con base en el enfoque MESMIS, la evaluación de puntos críticos de sostenibilidad resultó en la selección de 19 indicadores clasificados de acuerdo con los atributos (productividad, adaptabilidad, estabilidad – resiliencia, equidad y autogestión) definidos por dimensiones de sostenibilidad (ambiental, bienestar animal, económica y social). Después de la evaluación, se obtuvieron puntajes para los indicadores y se integraron en atributos y dimensiones a través de la asignación de pesos ponderados (W). Finalmente, los puntajes de atributos y dimensiones fueron agregados en gráficas de amiba para facilitar la representación visual. **Resultados.** Los NS fueron mejores para las dimensiones ‘Ambiental’ y ‘Económica’ y los atributos ‘Estabilidad’, ‘Confiabilidad y Resiliencia’, y ‘Producción’. Los IS fueron mejores para la dimensión ‘Bienestar Animal’ y los atributos ‘Adaptabilidad’ y ‘Autogestión’. Los MS fueron mejores para la dimensión ‘Social’ y el atributo ‘Equidad’. **Implicaciones.** El hecho de que los IS parecieron ser más sostenibles que los MS no deja fuera la idea de considerar a los NS como una mejor opción en algunos aspectos en comparación de IS; por ende, sugerimos que se lleven a cabo más estudios en áreas de mejora potencial para los IS y para los NS. **Conclusiones.** Esta información será útil para continuar trabajando en la parametrización de criterios de sostenibilidad para el ganado en sistemas extensivos, con el objetivo de ser usado en políticas más eficientes.
Palabras clave: sostenibilidad; ganado; MESMIS; sistemas silvopastoriles; bienestar animal.

INTRODUCTION

In the last 30 years, livestock production has transitioned from complex natural systems to monoculture systems (MS) and it occupies 70% of all agricultural land and 30% of the land surface of the planet (Steinfeld *et al*., 2006). MS represents a threat to multiple ecosystem services and contributes to global environmental problems such as greenhouse gases emissions (Gerber *et al*., 2010), deforestation and deterioration of water sources (Herrero *et al*., 2010). Likewise, MS reduces genetic diversity, induce soil degradation and are susceptible to agricultural plagues (Gliessman, 2014), making them incapable of maintaining complex ecological interactions (Lamb, Erskine *et al*., 2005). Furthermore, MS are associated with economic disadvantage, as they require great external input (Gliessman, 2014, Steinfeld, 2006) and animal welfare problems common for large scale production (Broom, 2016). Therefore, livestock production needs to develop toward sustainability.

Sustainable livestock production has been recognized as a continuing and complex process characterized by the attempt to reduce negative effects on the environment and the increase in the provision of environmental services (Milera, 2013). In this sense, silvopastoral systems (associations of trees and shrubs) represent a good alternative, as they are associated with increased photosynthetic rates, nitrogen fixation, nutrient recycling, biomass production and organic matter in soil (Murgueitio *et al*., 2013), as well as with the provision of animal welfare and the continuation of environmental services, such as carbon sequestration, water preservation, soil rehabilitation and biodiversity conservation (Broom *et al*., 2013, Murgueitio *et al*., 2011). In Yucatan, Mexico, although livestock extensive systems are mainly based on MS, native silvopastoral systems (NS), which are pastures with unmanaged native shrubs and trees (Gómez-Cifuentes *et al*., 2019) are still used to feed cattle during the dry season and represent the main resource for many conventional cattle smallholders (Ramírez-Cancino and Rivera-Lorca, 2010). Likewise, intensive silvopastoral systems, based on the integration of fodder shrubs at high densities (> 10000 plants ha^{-1}) and productive pastures and trees (Murgueitio *et al*., 2011) are also present in the region (Améndola *et al*., 2016; Mohammed *et al*., 2016). IS integrate technical knowledge, such as the inclusion of specific plant species to increase the benefits associated with silvopastoralism, whereas NS are not actively managed and more likely to include native flora and fauna (Murgueitio *et al*. 2011; Nahed-Toral *et al*., 2013) and may offer more advantages in terms of the provision of environmental services than IS. To support the implementation and preservation of silvopastoral systems, it is necessary to generate information on their strengths and weaknesses by comparing the sustainable performance of NS, IS and MS.

One of the methodologies used to evaluate the sustainable performance of productive systems is the Framework for Assessing the Sustainability of Natural Resource Management Systems (MESMIS; Masera *et al*., 2000a). MESMIS is a methodology for the cyclic evaluation of sustainability in systems managing natural resources. It was designed as a multidisciplinary, flexible and adaptable tool that encourages the analytic process and provides reliable elements that users can use to give recommendations for the improvement of the evaluated systems. MESMIS comprises the spatial and temporal context of productive systems and the limitations that arise from the interactions between environmental, economic and social elements (Masera *et al*., 2000b). This framework also allows the comparison of different production systems or systems over time by integrating indicators and putting their evaluated values on a standardized scale and comparing (Masera *et al*., 2000a). MESMIS is recognized as a framework that offers a good overview of agroecosystems (Gliessman, 2014). Despite its usefulness, MESMIS has never been used to compare the sustainability performance of NS, IS and MS.

We evaluated nine farms in Yucatan, Mexico using the MESMIS framework. Our study aimed to compare the sustainable performance of NS, IS and MS and identify areas of improvement in terms of four sustainability dimensions (Environment, Animal Welfare, Economic and Social) and five MESMIS attributes (Sustainability, Reliability and Resilience, Production, Adaptability, Self-reliance, and Equity). This information is useful to work towards the parametrization of sustainability criteria to elaborate better policies in Mexico and in Latin America.

MATERIALS AND METHODS

Study area and evaluated farms

This study was carried out in the state of Yucatán, Mexico. Average annual temperatures in Yucatan range from 24 – 28 °C, with an average maximum temperature of 36°C and an average minimum temperature of 16°C. The lowest precipitation values are 500 mm, whereas the highest range from 1200 to 1500 mm (Orellana *et al*., 2010). The nine farms evaluated belonged to three municipalities located in the state: Tizimin, Tzucacab and Merida. Tizimin (07° 58' N latitude and, 88º 09' 04' W longitude) is in the northeast region of the state, with sub-humid climate, an annual mean temperature of 25.8°C and annual average precipitation of 1084 mm. Tzucacab (19º 38' and 20º 09' N latitude, and 88º 59' and 89º 14' W longitude) is in the south region of the state, with warm sub-humid climate, an annual mean temperature of 25.8°C and annual average precipitation of 1084 mm. Merida (20° 45' y 21° 15' N latitude and 89° 30' y 89° 45' W longitude) is in the northeast region of the state, with warm sub-humid climate, an annual mean temperature of 26.2°C and annual precipitation in the range of 470-930 mm (IFAED, 2016).

In each municipality, three farms were chosen in a 25 km radio to represent one of the following production systems:

- **Native Silvopastoral System (NS)**: pastures with unmanaged native shrubs and trees (Gómez-Cifuentes, Gómez *et al*., 2019). These units were characterized by continuous forest fragments of at least 10 km^2. The NS farms were: Roble in Tzucacab (NS1); Santa Teresa in Merida (NS2); Xhopel in Tizimin (NS3).
- **Intensive Silvopastoral System (IS)**: integration of fodder shrubs at high densities (> 10000 plants ha^{-1}), productive pastures and trees (Murgueitio, Calle *et al*., 2011). These units were characterized by the presence of induced grass and forest fragments covering at least 10% the area. The IS farms were: Kakalnah in Tzucacab (IS1); Kampepem in Merida (IS2); Golondrinas in Tizimin (IS3).
- **Monoculture System (MS)**: conventional grazing system based on monoculture of grass (Mancera *et al*., 2018). These units were characterized by a homogeneous landscape with induced grass and less than 5% of its surface occupied by forest coverage. The MS farms were: Ramonal in Tzucacab (MS1); UADY in Merida (MS2); Escalera in Tizimin (MS3).

Farms NS1, IS2 and MS2 are double-purpose cattle systems (production of milk and meat). All farms belonged to smallholders working with limited resources in rural areas.

MESMIS methodology description

The MESMIS framework is based in four premises (Masera *et al*., 2000b):

Sustainability is defined by seven general attributes which are measured by indicators:

- Production: the system’s capacity to provide the required levels of goods and services
- Stability: the system’s capacity to maintain a constant production
- Resilience: the system’s ability of returning to its original levels after normal perturbing events
- Reliability: system’s ability to keep equilibrium during normal perturbing events
- Adaptability: system’s ability to find new levels of equilibrium after perturbing events.
- Equity: system’s ability to distribute the generated benefits and responsibilities in a fair manner
- Self-reliance: system’s ability to control its interactions with its surroundings.
  The evaluation is performed for a specific system, under specific conditions and scales, being valid only under these conditions:
- The evaluation process is cyclic and multidisciplinary, and;
- The evaluation needs to be comparative, either between two systems (traditional or alternative) or the same systems across time.

The methodology consists of six main steps (Masera *et al*., 2000b): 1) Determination of study object, 2) determination of systems' strengths and weaknesses, 3) selection of indicators, measuring and monitoring of indicators, 4) integration of results, 5) conclusions, and 6) recommendations. The determination of the study object consists in the identification of systems' principal components through the socio-environmental context, biophysical components, the spatial and temporal scale and the identification of production systems. The determination of strengths and weaknesses corresponds to the identification of critical points that interact positively or negatively by facilitating or obstructing systems' capacity to withhold through time. The selection of indicators is then performed according to the critical points identified and need to be selected to provide information easily understandable; after selection, they need to be integrated in a pertinent, robust, sensitive and reliable matrix. For measuring and monitoring of indicators, a direct or indirect methodology, which needs to be accessible and replicable, needs to be selected. After measuring, the integration of results compares the outcomes obtained between systems, through the determination of optimal values for each indicator, which needs to be expressed in the scale selected by the evaluator and in the same direction. Results are further integrated in a matrix (by dimension, attribute, and system). Is recommended to express results in radial diagrams known as AMEBA, were each dimension or attribute represent an axis and each value obtained in the matrix, a percentage. Finally, recommendations on the faults and good decisions of systems as well as an opinion on them is given through the visual interpretation of results.

Selection and evaluation of indicators

After identifying strengths and weaknesses in Yucatán livestock systems, nineteen indicators were selected to evaluate sustainability performance in NS, IS and MS. Indicators were positive (+) or negative (-) if the best outcome for sustainability was associated with the maximum or minimum value, respectively. For instance, the indicator 'Productive Diversification' is classified as positive, as the maximum value achievable corresponds to the maximum number of products generated in a single farm. In contrast, the indicator 'Use of Agrochemicals' is negative, as the maximum value corresponds to the absence of agrochemical substances use.

Fourteen of the selected indicators were evaluated with the responses obtained through semi-structured interviews, farm records and four questionnaires applied to farmworkers and/or managers. Questionnaire one was designed to obtain general information of the farm (i.e., name, size, activities held in the farm, etc.) on eight areas: Q1.1) edaphic and climatic characteristics, Q1.2) unit infrastructure, Q1.3) paddock management and pens, Q1.4) animal handling, Q1.5) workers schedule, Q1.6) equipment management, Q1.7) resource use, and Q1.8) waste management. Questionnaire two included two main sections: Q2.1) determination of mission statement and Q2.2) personnel management (i.e., benefits, information shared with workers). Questionnaire three had ten main sections: Q3.1) management of biological pollutants, Q3.2) characteristics of working days, Q3.3) training and development, Q3.4) health issues, Q3.5) daily work organization, Q3.6) social and work benefits, Q3.7) legislation knowledge and application, Q3.8) leadership style and participation, Q3.9) position and salary and Q3.10) a global evaluation. Questionnaire four had five main sections: Q4.1) general demographics (i.e., gender, age, educational level achieved, etc.), Q4.2) position and seniority in the farm, Q4.3) housing conditions (presence/absence of services, building materials, location, etc.), Q4.4) knowledge acquired in the farm, and Q4.5) gender and social equity in the farm. Additionally, observations and area prospections were completed in each unit.

Indicators 'Electric Energy Consumption' 'Fossil Fuel Consumption' and 'Governmental subsidies and assistance' were calculated as investment per hectare to account for different farm sizes. The indicator species richness was obtained from direct wildlife monitoring performed by research partners, through the capture-recapture of birds, bats and small rodents. Mist nets were used for bats and birds, and Sherman traps were used for small rodents (Domínguez-Meneses, 2018; Dominguez-Hernandez *et al*., 2018). The indicators Good Feeding, Good Health and Appropriate Behaviour were evaluated using the Welfare Quality® (WQ) protocol for the evaluation of dairy cattle (WQ, 2009). The evaluation of 'Good Housing' was excluded from this evaluation, as this indicator is highly tailored for intensive conditions and does not consider factors such as shaded area and solar radiation, which may be more influential for cattle raised extensively (Mancera, 2011). WQ is recognized as a multidimensional, animal-based welfare assessment tool composed of four principles, twelve criteria and thirty indicators. The indicators used in this study are WQ principles based on the following measurements (WQ, 2009):

Good Feeding

- Body condition: focal sampling based on visual criteria with rear and flanks of animals as reference. Ranks were assigned as follows: 0 = very lean, 1 = regular body condition, 2 = very fat.
- Water: evaluation of water provision, cleanliness of water points, water flow, functioning of water points.

Good Health

- Lameness: evaluated when individuals left the milking parlor using weight bearing, timing and rhythm of steps as indicators. It was ranked as follows: 0 = not lame, 1 = lame, 2 = severely lame.
- Integument alterations (injuries, inflammation and alopecia): observation of five areas from of a randomly selected side of the body from 2 m. The areas were: hindquarter, tarsus, flank/side/udder, carpus and neck/shoulder, back. The presence or absence of integument alterations was evaluated in each of these areas.
- Presence or absence of each health indicator: nasal discharge, ocular discharge, hampered respiration, diarrhea, vulvar discharge and ectoparasites.
- Coughing and sneezing: mean number of coughs/sneezes per animal per 15 min.
- Disbudding/dehorning, tail docking: focal sampling of animals. Ranks were assigned as follows: 0 = no dehorning/disbudding, 1 = disbudding of calves using thermocautery, 2 = disbudding of calves using caustic paste, 3 = dehorning of fattening cattle, and; 0 = use of anesthetics, 2 = No use of anesthetics, and; 0 = use of post-surgery analgesics, 2 = no use of analgesics.

Appropriate Behaviour

- Agonistic behaviours: continuous recording of the number of head butts and displacements observed in the herd from a high point of the pen or grazing paddock.
- Access to pasture: hours of the day herd spent in the paddock.
- Observation of herds with the assignation of qualitative behavioural traits by the observer avoidance distance: Number of cows touched or flight distance when observers approached cows slowly (one step/2 s) with one arm stretched forward at a 45°degree angle to attempt to touch the muzzle.

Obtained data was processed with the software program Welfare Quality® scoring system (available at: http://www1.clermont.inra.fr/wq/index.php?id=simul&new=1), which uses weighted sums, decision trees and Choquet integrals to obtain principles scores (WQ 2009). Indicators, measurement method and source of information for their assessment are summarized in Table 1.

Scoring standardization of qualitative and quantitative variables

Indicators were a combination of quantitative and qualitative variables. Qualitative variables were ‘Use of Agrochemicals’, ‘Workers Development and Training’ and ‘Organization and Participation’. These indicators were measured by assigning a descriptive state of the indicator to each farm. Each descriptor was assigning to one of five scores (100, 75, 50, 25 and 0), being 100 the most desirable description for sustainable development and 0 the least desirable.

For quantitative indicators evaluated with different measuring scales, a methodology to obtain standardized scoring values was established. Maximum values for each indicator were obtained after evaluation and divided by five. The resulting value was multiplied by factors 2, 3 and 4 to obtain the numerical limits of five intervals between 0 and the maximum value measured for the indicator. These were later associated with one of five intervals for a scoring system ranging from 0 to 100: (80, 100] = excellent; (60, 80] = good; (40, 60] = moderate; (20, 40] = limited; (0, 20] = not classified. The range (80, 100] was associated with the interval containing the maximum measured value for positive indicators and with the interval containing the minimum measured value for negative indicators. For instance, for the negative indicator ‘Independence of External Supply’, the maximum measured value obtained in farm MS1 was 26.9 MXN/day. Therefore, intervals were stablished as follows:

Division of maximum value by 5: 26.9 MXN/day / 5 = 5.38 MXN/day.

Multiplication of 5.38 MXN/day by factors 2, 3, and 4:

5.38 MXN/day * 2 = 10.76 MXN/day.

5.38 MXN/day * 3 = 16.14 MXN/day.

5.38 MXN/day * 4 = 21.52 MXN/day.

Indicator intervals and corresponding scoring intervals:

(0 – 5.38] MXN/day = (80, 100]

(5.39 – 10.76] MXN/day = (60, 80]

(10.77 – 16.14] MXN/day = (40, 60]

(16.15 – 21.52] MXN/day = (20, 40]

(21.53 – 26.9] MXN/day = (0, 20]

Table 1. Indicators and assessment information per MESMIS attribute.

Strengths and weaknesses	Indicator	Measurement method	Source of information	Score assigned
Inadequate use of agrochemicals	Use of agrochemicals (-)	Use of agrochemicals (Ach) listed by the World Health Statistics by danger level and reported used under recommended proportions (U = unlikely dangerous; III = slightly dangerous; II = moderately dangerous; Ib = highly dangerous; Ia = extremely dangerous; WHO 2014)	Questionnaires/ records kept in the farm	**100:** No use of Ach or not listed **75:** Ach U used under recommended proportions **50:** Ach U indiscriminately used and/or Ach III used under recommended proportions **25:** Ach III indiscriminately used and/or at least one Ach II used **0:** Ach Ib or Ia used.
High dependency on electric energy	Electric energy consumption (-)	Used kilowatts per hectare per bimester (kWh/ha/bimester) according to electric bills on records	Electricity bills from last bimester from farm records	**(80, 100]:** (0 – 74) kWh/ha/bimester/ use of alternative energy **(60, 80]:** (74 – 148] kWh/ha/bimester **(40, 60]:** (148 – 220] kWh/ha/bimester **(20, 40]:** (220 – 296] kWh/ha/bimester **(0, 20]:** (296 – 370] kWh/ha/bimester
High dependency on fossil fuel	Fossil fuel consumption (-)	Used litres per hectare (L/ha) according to interviews and questionnaires	Questionnaires/ records kept in the farm	**(80, 100]:** (0, 2.14] L/ha **(60, 80]:** (2.14, 4.28] L/ha **(40, 60]:** (4.28, 6.42] L/ha **(20, 40]:** (6.42, 8.56] L/ha **(0, 20]:** (8.56, 10.71] L/ha
Loss or degradation of water points	Care and use of water (-)	Hours per week (h/w) of irrigation	Questionnaires/ records kept in the farm	**(80, 100]:** irrigation (0, 9.8] h/w **(60, 80]:** irrigation (9.8, 19.6] h/w **(40, 60]:** irrigation (19.6, 29.4] h/w **(20, 40]:** irrigation (29.4, 39.2] h/w **(0, 20]:** irrigation (39.2, 49] h/w
Loss of bats, birds and rodents	Species richness (+)	Number of species (ne) of bats, birds and rodents	Direct wildlife monitoring through capture-recapture of birds, bats and small rodents.	**(80, 100]:** (26.4, 33] ne **(60, 80]:** (19.8, 26.4] ne **(40, 60]:** (13.2, 19.8] ne **(20, 40]:** (6.6, 13.2] ne **(0, 20]:** (0, 6.6] ne

Strengths and weaknesses	Indicator	Measurement method	Source of information	Score assigned
Absence of prolonged hunger and thirst	Good feeding (+)	Welfare Quality (WQ®) assessment protocol of Good Feeding principle through the criterion scores for absence of prolonged hunger and absence of prolonged thirst combined with a Choquet integral (WQ®)	Direct measurement of body condition score and water provision as described in protocol (WQ® 2017)	**(80, 100]:** WQ® score = (80, 100] **(60, 80]:** WQ® score = (60, 80] **(40, 60]:** WQ® score (40, 60] **(20, 40]:** WQ® score = (20, 40] **(0, 20]:** WQ® score = (0, 20]
Absence of lesions, disease, and induced pain through veterinary procedures	Good health (+)	Welfare Health (WQ®) assessment protocol of Good Health principle through the criterion scores for absence of lesions, absence of disease and absence of pain induced by management procedures combined with a Choquet integral (WQ® 2017)	Direct measurement of lameness, integument alterations, disease symptoms, dehorning, tail docking and castration as described in protocol (WQ® 2017)	**(80, 100]:** WQ® score = (80, 100] **(60, 80]:** WQ® score = (60, 80] **(40, 60]:** WQ® score (40, 60] **(20, 40]:** WQ® score = (20, 40] **(0, 20]:** WQ® score = (0, 20]
Comfort during resting and freedom of movement	Good housing (+)	Welfare Quality (WQ®) assessment of Good Housing principle through the criterion scores for comfort around resting and freedom of movement combined with a Choquet integral (WQ® 2017)	Direct measurement of time needed to lie down, pen features and access to outdoors as described in protocol (WQ® 2017)	**(80, 100]:** WQ® score = (80, 100] **(60, 80]:** WQ® score = (60, 80] **(40, 60]:** WQ® score (40, 60] **(20, 40]:** WQ® score = (20, 40] **(0, 20]:** WQ® score = (0, 20]
Expression of social behaviours, expression of other behaviour, good human-animal relation and positive emotional state	Appropriate behaviour (+)	Welfare Quality (WQ®) assessment of Appropriate Behaviour principle through the criterion scores for expression of social behaviours, expression of other behaviours, good human-animal relationship and positive emotional status combined with a Choquet integral (WQ® 2017)	Direct measurement of agonistic, cohesive and other behaviours scores, avoidance distance and qualitative behaviour assessment as described in protocol (WQ® 2017)	**(80, 100]:** WQ® score = (80, 100] **(60, 80]:** WQ® score = (60, 80] **(40, 60]:** WQ® score (40, 60] **(20, 40]:** WQ® score = (20, 40] **(0, 20]:** WQ® score = (0, 20]

Strengths and weaknesses	Indicator	Measurement method	Source of information	Score assigned
Low production rentability	Production cost (-)	Addition of variable monthly costs (herd feed, machinery and equipment maintenance, veterinary services, services fees, fuel and cargo) and fixed monthly costs (permanent workers, administration and fixed fees (Guerra, 1992) in Mexican pesos per month per hectare (MXN/month/ha).	Questionnaires/ records kept in the farm	**(80, 100]**: (0, 1037.25] MXN/month/ha **(60, 80]:** (1037.25, 2074.50] MXN/month/ha **(40, 60]:** (2074.50, 311.75] MXN/month/ha **(20, 40]:** (311.75, 4149.00] MXN/month/ha **(0, 20]:** (4149.00, 5186.26] MXN/month/ha
Low livestock production	Cost/benefit relation (+)	Index calculated with the following formulas: 1)Total Costs (TC) = ΣFC+ ΣVC, where FC = fixed costs and VC = variable costs 2)Total Benefits (TB) = ΣBI, where BI = Individual Benefits (total herd value and earnings from milk sales) 3) Cost/benefit relation = CT/BT	Questionnaires/ records kept in the farm	**(80, 100]:** (23.63, 29.54] **(60, 80]:** (17.72, 23.63] **(40, 60]:** (11.81, 17.72] **(20, 40]:** (5.90, 11.81] **(0, 20]:** (0, 5.90]
Resources exploitation	Productive diversification (+)	Number of products generated in the farm	Questionnaires/ records kept in the farm	**(80, 100]:** (16 – 20] **(60, 80]:** (12 – 16] **(40, 60]:** (8 – 12] **(20, 40]:** (4 – 8] **(0, 20]:** (0 – 4]
High dependency of external supplies	Independence of external supply (-)	Total expenses destined to buy external products expressed as MXN per day	Questionnaires/ records kept in the farm	**(80, 100]:** (0 – 5.38] MXN/day **(60, 80]:** (5.38 – 10.76] MXN/day **(40, 60]:** (10.76 – 16.14] MXN/day **(20, 40]:** (16.14 – 21.52] MXN/day **(0, 20]:** (21.52 – 26.9] MXN/day

Strengths and weaknesses	Indicator	Measurement method	Source of information	Score assigned
Organization and structure	Business plan (+)	State of adoption and impact of planification and economic foresight (FAO, 2013)	Questionnaires/ records kept in the farm	**100:** farm has a written business plan, productive records and production costs calculations, as well as positive annual performance and achievement of all set goals **75:** farm has at least one of the following: business plan, productive records or production cost calculations. It has a positive annual performance and/or achieved all set goals **50:** farm has at least one of the following: business plan, productive records or production costs calculations. It has a positive annual performance or have achieved one of the set goals **25:** Farm has written at least one of the following: business plan, productive records and/or production costs calculations. It has a negative annual performance and/or has achieved one of the set goals. **0:** No written business plan, productive records or calculations. It has a negative annual performance and none of the set goals has been achieved.
Workers development for unit's benefit	Workers' development and training (+)	Percentage (%) of workers per academic level and number for courses workers have taken for professional development (FAO, 2013)	Questionnaires/ records kept in the farm	**100:** all workers have completed secondary education and have obtained training courses in the farm **75:** more than half of workers have concluded secondary education and have received training courses in the farm **50:** more than half of workers have concluded secondary education and they have not received training courses in the farm, or; all workers have concluded primary education and have received training courses in the ranch or by personal motives **25:** more than half of workers have concluded primary education and they have not received training courses in the farm **0:** less than half of workers have concluded primary education or more than half have no studies and they have not received training courses in the farm
Presence of organizational structures and low participation in the decision-making process	Organization and participation (+)	Presence of worker groups and type of membership (FAO, 2013)	Questionnaires/ records kept in the farm	**100:** unit promotes community participation through the formation of groups and/or associations that promote the acquisition of knowledge; workers have received financial support or training and membership fees are not charged. **75:** no groups or associations have been formed but workers belong to one, participate its activities and have been benefited by it, with no membership fees charged

Strengths and weaknesses	Indicator	Measurement method	Source of information	Score assigned
				50: no groups or associations have been formed but workers belong to one, participate in its activities and have been benefited by it. A membership fee is charged **25:** no groups or associations have been formed but workers belong to one, the do not participate in its activities or have been benefited by it. A membership fee is charged **0:** workers belong to a group or association where they receive no benefits and a membership fee is charged, or they do not belong to any groups or associations.
Possibility of unit's continuance	Transmissibility and succession (+)	Capital left per farm heir in a 10-year time frame in Mexican pesos per heir (MXN/heir; Tommasino et. al., 2012)	Questionnaires/ records kept in the farm	**(80, 100]:** (1869861 – 2337327] MXN/heir **(60, 80]:** (1402396 – 1869861] MXN/heir **(40, 60]:** (934930 – 1402396] MXN/heir **(20, 40]:** (467465 – 934930] MXN/heir **(0, 20]:** (0 – 467465] MXN/heir
Absence/presence of governmental support	Governmental subsides and assistance (+)	Income, discounts and financial and material support given by governmental institutions and organizations in the las year expressed in Mexican pesos per hectare (MXN/ha)	Questionnaires/ records kept in the farm	**(80, 100]:** (1100, 1375] MXN/ha **(60, 80]:** (825, 1100] MXN/ha **(40, 60]:** (550, 825] MXN/ha **(20, 40]:** (275, 5550] MXN/ha **(0, 20]:** (0, 275] MXN/ha
Unlawful working hours and inequity in salary distribution	Salary level (+)	Monthly salary of all workers in the farm per monthly hours worked by all workers in the farm expressed in Mexican pesos per hours per month (MXN/h/m)	Questionnaires/ records kept in the farm	**(80, 100]:** (21.63, 27.04] MXN/h/m **(60, 80]:** (16.22, 21.63] MXN/h/m **(40, 60]:** (10.81, 16.22] MXN/h/m **(20, 40]:** (5.49, 10.81] MXN/h/m **(0, 20]:** (0,5.49] MXN/h/m

To determine the exact scoring value for the results obtained for quantitative indicators for each farm after evaluation, the following formulas were used:

For positive indicators: Scoring value = ((X-Xmin) / (Xmax-Xmin)) (100)

For negative indicators: Scoring value = ((Xmax-X) / (Xmax-Xmin)) (100)

Were Xmin = minimum measured value in all farms, Xmax = maximum measured value in all farms and X = value of interest.

For instance, for the indicator 'Independence of External Supply' a value of 18.35 MXN/day was measured in farm IS1. For this indicator, Xmax, obtained in farm MS1, was 26.9 MXN/day and Xmin, obtained in farms NS1 and NS2, was 0 MXN/day. The formula for negative indicators was applied as follows:

IS1 scoring value for 'Independence of External Supply' = ((Xmax-X) / (Xmax-Xmin)) (100) = ((26.9 MXN/day - 18.35 MXN/day) / (26.9 MXN/day/ - 0 MXN/day) = 31.78

Thus, from the measured value 18.35 MXN/day, we obtained the standardized scoring value of 31.78 for the indicator 'Independence of External Supply' in farm IS1. All standardized scoring values are summarized in Table 3.

Integration of indicators by MESMIS attribute and sustainability dimension

The sustainability performance of NS, IS, and MS was evaluated through the integration of indicators by sustainability dimension and MESMIS attributes. The sustainability dimensions evaluated were Environment (5 indicators), Animal Welfare (4 indicators), Economic (5 indicators) and Social (5 indicators). The environmental, economic, and social dimensions are included as recognized pillars of sustainability (Hansmann, Mieg *et al*., 2012). Animal Welfare is considered in this study due to its notable correlation with environmental impact mitigation in the development of sustainable dairy systems (Herzog *et al*., 2018) and the proven effect that silvopastoral systems have on this attribute (Broom *et al*., 2013). For the evaluation of MESMIS attributes, Stability, Reliability and Resilience were jointly evaluated as one attribute (5 indicators), as previously done by Nahed *et al*., (2019) and Dominguez-Hernandez *et al*., (2018) when the same indicators reflect the main characteristics of these traits in evaluated systems. The attributes Production (6 indicators), Adaptability (1 indicator), Self-reliance (4 indicators) and Equity (3 indicators) were also evaluated (Table 2).

Table 2. Indicators per sustainability dimension and attribute.

Dimension	Indicators	Attribute
Environment	Use of agrochemicals	Stability, Reliability and Resilience
	Electric energy consumption	
	Fossil fuel consumption	
	Care and use of water	
	Species richness	
Animal welfare	Good feeding	Production
	Good health	
	Good housing	
	Appropriate behaviour	
Economic	Production cost	
	Cost/benefit relation	
	Productive diversification	Adaptability
	Independence of external supply	Self-reliance
	Business plan	
Social	Workers development and training	
	Organization and participation	
	Transmissibility and succession	Equity
	Governmental subsides and assistance	
	Salary level	

For the integration of indicators, equitable, balanced weights (W) were assigned. When integrated by attribute, W values were assigned as follows: Stability, Reliability and Resilience = 0.2; Production = 0.17; Adaptability = 1; Self-reliance = 0.25, and; Equity = 0.33. When integrated by dimension, W values were assigned as follows: Environmental = 0.2; Animal Welfare = 0.25; Economic = 0.2, and, Social = 0.2. After weighing, scores were integrated with the following formula:

Attribute/Dimension Score = $\sum (x_i * w)$

Where X_i = indicator assigned to attribute/dimension
W = corresponding weight per attribute/dimension

Finally, attribute and dimension scores were aggregated in amoeba graphs to facilitate visual interpretation. Figure 1 is a schematic representation of the MESMIS system.

RESULTS

Evaluation of indicators

Standardized scores for farms and scores per type of system for all indicators are summarized in Table 3.

Use of agrochemicals

55.5% of farms obtained moderate scores, as units appropriately used the tick-killing agent Amitraz, classified as an III agrochemical (WHO, 2004). IS farms had the best score per system at 66.7 (good).

Electric energy consumption

Electric energy in Yucatan is generated by thermoelectric plants. Therefore, farms using alternative energy sources were given the best score in terms of sustainability. 77% of farms had excellent scores. All NS farms had scoring values of 100, whereas IS farms scored 91.3 and MS 54.

Fossil fuel consumption

44.4% of farms had excellent scores. IS had the best score between systems, with a score of 73.33 (good).

Care and use of water

All NS farms had scores of 100, whereas only and IS and one MS farms had excellent scores. Thus, NS farms had a score of 100 (excellent), whereas IS and MS farms had moderate scores (59.9 and 45.2, respectively).

Species richness

All NS farms presented scores above 70. IS2 scored 57.57 for this indicator, whereas MS2 had the lowest value at 30.3. Consequently, NS systems had the highest score between all systems (85.9; excellent), whereas IS and MS reached only scores classified as good (72.7 and 70.7, respectively)

Good feeding

For this indicator, there were no farms reaching excellent or good scores, as all farms had values below 41, with the lowest at 9.95 for farms IS2 and MS1 and the highest at 40.94 for farm IS3. IS farms had the best valuation (26.9; limited), whereas NS and MS reached 24 and 24.5, respectively.

Good Health

The best scores for this indicator was given to farms NS2 and IS3 (100; excellent). IS farms had the best score amongst systems (78.3; good), whereas NS and MS had scores of 71.3 and 77, respectively.

Appropriate behaviour

44.4% of farms had scores classified as good. When evaluated per type of system, all had scores considered as moderate, with IS systems presenting the highest score (61.6).

Production cost

All NS and IS farms had excellent scores, with 97.1 and 84.8, respectively. MS farms had an average score of 62.7, classified as good.

Cost/benefit relation

For this indicator, only farm NS1 had a 100 score (excellent). 66-6% of the farms had scores classified as not classified, with the lowest value at 5.66 for IS2 farm. Scores per system were also low for IS and MS systems, with not classified values of 12.8 and 12.6. NS farms obtained an average score of 51.3 (moderate).

Productive diversification

55.5% of farms were classified as not limited, with the lowest score for MS1 farm (10). The highest score was given to IS2 farm (100; excellent). When evaluated per type of system, IS farms had the best score at 48.3 (moderate), whereas NS and MS were valuated at 28.3 (limited) and 15 (not classified).

Independence of external supply

NS1 and IS2 farms were scored as excellent, whereas farm MS1 was scored as not classified with a value of 0. NS farms had the best scores with 79 (good), followed by IS with 70.2 (good) and MS with 50.5 (moderate).

Business plan

33.3% of farms had moderate scores. IS2 and IS3 farms received excellent scores (100 for both), whereas farm MS1 had the lowest score at 0 (not classified). IS farms were score an average of 75 (good), whereas NS and MS farms had moderate scores (58.3 and 41.7, respectively).

Table 3. Indicators scores per farm and type of system N. *highest scores per indicator. NS = Native silvopastoral; IS = Intensive silvopastoral; MS = Monoculture.

INDICATOR	FARM									TYPE OF SYSTEM		
	NS1	*NS2*	*NS3*	*IS1*	*IS2*	*IS3*	*MS1*	*MS2*	*MS3*	*NS*	*IS*	*MS*
Use of agrochemicals	50	75	25	50	100	50	50	50	25	50.0	66.7	41.7
Electric energy consumption	100	100	100	82.41	91.41	100	61.91	0	100	100.0	91.3	54.0
Fossil fuel consumption	84.69	89.79	33.31	67	60	93	29.97	0	80.99	69.3	73.3	37.0
Care and use of water	100	100	100	79.6	0	100	28.58	7.15	100	100.0	59.9	45.2
Species richness	93.93	78.78	84.84	81.81	57.57	78.78	81.81	30.3	100	85.9	72.7	70.7
Good feeding	29.51	26.97	15.58	29.71	9.95	40.94	9.95	27.99	35.42	24.0	26.9	24.5
Good health	29.51	100	84.45	79.6	55.18	100	58.1	86.44	86.44	71.3	78.3	77.0
Good housing	98.15	98.31	97.5	97.5	65.87	92.98	98.62	62.81	92.58	98.0	85.5	84.7
Appropriate behaviour	62.83	42.23	38.42	56.51	62.7	65.62	51.75	70.29	51.24	47.8	61.6	57.8
Production cost	99.47	97.41	94.46	75.86	80.49	98.03	90.06	0	97.94	97.1	84.8	62.7
Cost/benefit relation	100	36.75	17	6.15	5.66	26.69	13.14	7.09	17.64	51.3	12.8	12.6
Productive diversification	50	20	15	15	100	30	10	20	15	28.3	48.3	15.0
Independence of external supply	100	57.62	79.25	31.78	100	78.81	0	72.11	79.25	79.0	70.2	50.5
Business plan	50	50	75	25	100	100	0	50	75	58.3	75.0	41.7
Workers development and training	50	50	25	75	25	50	0	100	50	41.7	50.0	50.0
Organization and participation	10	0	0	75	50	50	25	0	0	3.3	58.3	8.3
Transmissibility and succession	3.26	60.5	42.78	27.06	50.91	6.31	100	100	74.87	35.5	28.1	91.6
Governmental subsides and assistance	16	0	100	40.87	11.05	14.63	0	100	28	38.7	22.2	42.7
Salary level	64.72	52.81	65.05	74.93	61.39	52.81	47.11	100	69.85	60.9	63.0	72.3

Workers' development and training

Only farm MS2 had a valuation of 100 (excellent), whereas the lowest score belonged to farm MS1 (0; not classified). IS and MS farms had the highest average score, at 50 (moderate), whereas NS farms had a score of 41.7 (moderate).

Organization and participation

44.4% of farm had a scoring value of 0 (not classified). The highest score belonged to IS1, with 75 (good). The highest average score belonged to IS farms, with 58.3 (moderate), whereas NS and MS has scores considered not classified (3.3 and 8.3, respectively).

Transmissibility and succession

22.2% of farms had a score value of 100 (excellent). The lowest valuation belonged for farm NS1 at 3.26 (not classified). On average, MS farms had the best score (91.6; excellent), whereas NS and IS farms had scores classified as limited (35.5 and 28.1, respectively).

Governmental subsides and assistance.

55.5% of farms had not classified scores. NS and IS farms were valuated as limited (38.7 and 22.2, respectively, whereas MS farms had an average score of 42.7 (moderate) for this indicator.

Salary level

Only one farm had an excellent score for this indicator (MS2; 100; excellent). The farm worst valuated was MS1, with a moderate score of 47.11. MS farms were the best valuated on average, with a score of 72.3 (good), whereas NS and IS farms had scores of 60.9 (good) and 63 (good), respectively.

Sustainability performance per MESMIS attribute

Table 4 and Figure 2 summarize the sustainability performance of NS, IS and MS systems per MESMIS attribute. NS farms had the best scores between type of system for the attributes Stability, Reliability and Resilience and Production, scoring as excellent (81.02) and good (64.66), respectively. Meanwhile, IS had the best scores for the attributes Adaptability and Self-reliance, with scores of 48.33 (moderate) and 63.38 (good). MS were the best ranked for Equity, with a score of 68.8 (good).

Sustainability performance per sustainability dimension

Table 4 and Figure 3 summarize the sustainability performance of NS, IS and MS systems per sustainability dimension. NS farms had the best scores for the Environment and Economic dimensions, with scores of 81.02 (excellent) and 62.79 (good). Meanwhile, IS were the best rated for the Animal Welfare dimension (63.04; good), whereas MS farms at the Social dimension (52.99; moderate).

DISCUSSION

Livestock production in extensive systems is one of the most important economic activities in Yucatan, occupying 30% of the state's territory (INEGI, 2017). The implementation of alternative systems is paramount to preserve natural resources in the area. This study demonstrated that silvopastoral systems whether native or intensive, are a good alternative to improve the sustainability performance of livestock systems in the tropics, especially for indicators related to the environmental dimension, and that both types of silvopastoral systems are an option to transition to sustainable animal production. Likewise, areas of improvement were identified.

For the evaluation of the dimension Environment and the attribute Stability, Reliability and Resilience, the same indicators were used, and NS systems were scored as excellent, IS as good and MS as moderate. The better performance of NS and IS systems is related to the different use of natural resources in silvopastoral systems compared to monocultures. For instance, electric energy consumption in NS and IS farms was rated as excellent, in great part due to the use of alternative sources of energy (solar and wind; NS3), units not using electric energy at all (NS1, NS2 and IS3) or using less than 74 kWh/ha/bimester (IS1 and IS2). The coast of the Yucatan Peninsula has wind potential because of its excellent wind flows (Alemán-Nava *et al*., 2014), thus making it a potential source of energy for all types of systems. Similar tendencies were observed for fossil fuel consumption, where NS and IS systems had average scores classified as good. The use of fossil fuel is not a sustainable option; the global reserve/production ratio estimated in 2012 was 54.2 years and its use is associated with environmental deterioration, a rapid growth in the level of greenhouse gas concentration and an increase in fuel prices (Dudley, 2012; Hernandez-Escobedo *et al*., 2011). NS and IS systems were not highly dependent on heavy machinery, as observed while describing current traditional agricultural practices in Mesoamerica (Chazdon *et al*., 2011); thus, silvopastoral systems were more sustainable in their energy use than MS.

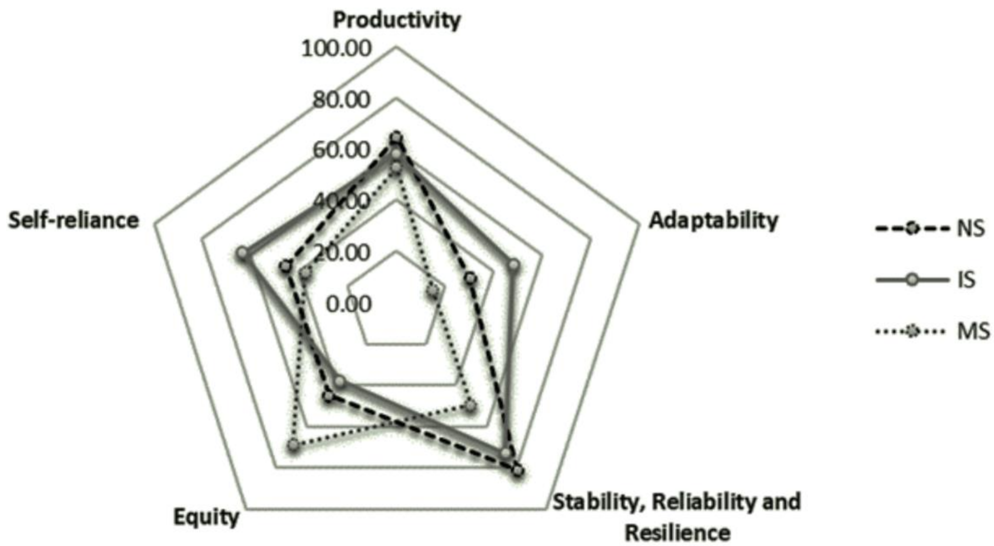

Figure 2. Amoeba graph showing type of system per MESMIS attribute. NS = Native silvopastoral; IS = Intensive silvopastoral; MS = Monoculture.

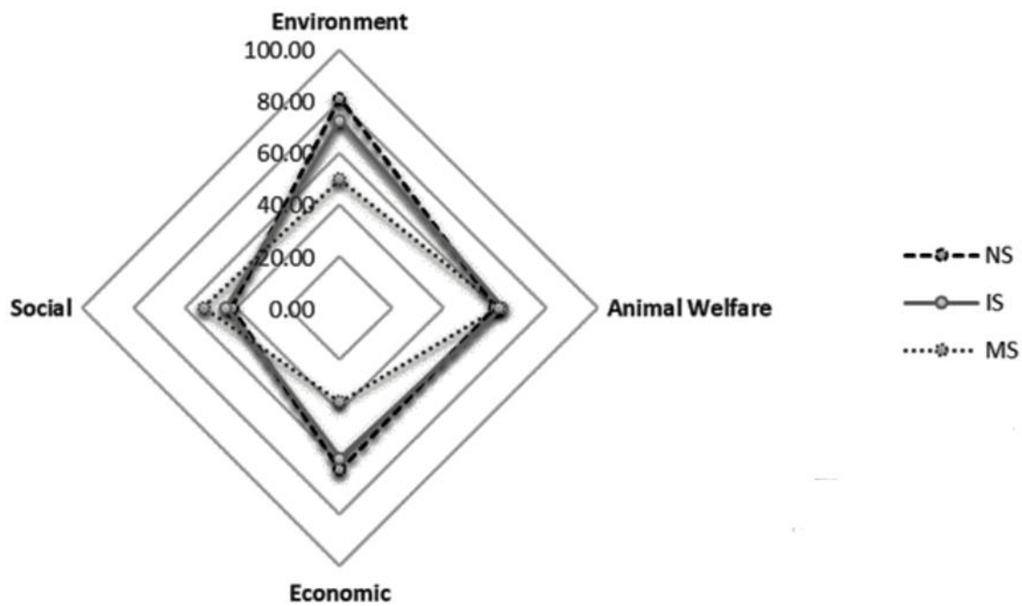

Figure 3. Amoeba graph showing type of system per sustainability dimension. NS = Native silvopastoral; IS = Intensive silvopastoral; MS = Monoculture.

Better environmental sustainability was also clear for the indicator 'Care and Use of Water', as NS were excellently scored. Systems with high tree coverage increase water retention (Murgueitio *et al*., 2013), whereas the deforestation caused by the creation of MS is associated with a decrease in water infiltration (Martínez *et al*., 1992). This made MS farms increase their irrigation time and water consumption. Additionally, IS systems had moderate ratings for this indicator despite the presence of trees and shrubs. This could be related to the type of trees associated with the farms, as some are better at improving water retention (Esperschuetz *et al*., 2017); thus, in addition to the presence of tree coverage, increased knowledge on plants associations is vital to improve water retention and reduce irrigation times.

Finally, the indicator 'Species Richness' was also scored as excellent for NS systems, demonstrating the known relationship between improved biodiversity and the presence of trees and shrubs in silvopastoral systems (Broom *et al*., 2013). IS and MS systems had scores classified as good, indicating that other factors in addition to the presence of trees could also benefit biodiversity, such as the surrounding landscape of MS systems, which needs to be further investigated.

Table 4. Indicator scores per system integrated per attribute and dimension. *highest scores per attribute/dimension. NS = Native silvopastoral; IS = Intensive silvopastoral; MS = Monoculture.

MESMIS attribute	Type of system		
	NS	***IS***	***MS***
Stability, Reliability and Resilience	81.02	72.77	49.71
Production	64.66	58.06	52.97
Adaptability	30.33	48.33	15.00
Self-reliance	45.57	63.38	37.61
Equity	44.97	37.73	68.80
SUSTAINABILITY DIMENSION	***NS***	***IS***	***MS***
Environment	81.02	72.77	49.71
Animal Welfare	60.34	63.04	61.87
Economic	62.79	58.23	36.48
Social	41.79	44.33	52.99

For the Animal Welfare dimension, all types of systems were classified as good and IS systems had the highest score amongst systems, which could be attributed to the results obtained for the indicators ‘Good Feeding’, ‘Good Health’ and ‘Appropriate Behaviour’. The indicator ‘Good Feeding’ was evaluated as limited for all systems but slightly higher for IS. Limited scores reflect severe setbacks on the provision of food and water. In particular, the evaluation of body condition for the ‘Good Feeding’ component ‘absence of hunger’ reflects fat content of individuals, which could relate to reproductive and immune alterations (Broring *et al*., 2003). The slightly higher valuation of IS for ‘Good Feeding’ is consistent with previous results were IS systems were superior than MS for this indicator (Tarazona *et al*., 2013); however, this previous study also showed scores of 98 for the ‘absence of prolonged hunger’ component, which were attributed to the presence of high protein grasses in the tropical grassing context, such as *C. plectostachyus, P. maximum*, with crude protein percentages of 8 – 10.8 % and 5.5 – 7.4%, respectively (Lagunes *et al*., 1999; Molina *et al*., 2016). In Yucatan, there is documented the presence of *C. plectostachyus* and *P. maximum* (INEGI, 2017), however, their exact contribution to animal feeding in the systems evaluated is unknown, and a much lower ‘absence of hunger’ score of 15.8 was found in the IS evaluated. Thus, it is necessary to perform botanical census of systems to better interpret the low scores obtained for this welfare indicator. Meanwhile, the ‘Good Health’ indicator was good for all systems but higher in IS. Tree coverage can improve health indicators and body condition (Mancera *et al*., 2018), influencing also reproductive and immune function (Broring *et al*., 2003). As ‘Good Health’ is necessary to maintain system production, MS were also expected to have good values for this indicator, as shown here. The main difference between MS and silvopastoral systems could be in the methodologies used to maintain herd health, which could or not implicate the use of antibiotics or other substances. Thus, further research needs to evaluate health protocols in farms.

For ‘Appropriate Behaviour’ IS was classified as good an NS and MS were classified as moderate. In particular, the component flight distance of this indicator (distance at which animals flee when humans attempt to touch them) was smaller for IS and NS animals compared to MS, as previously seen when comparing IS with MS alone (Tarazona *et al*., 2013). It has been observed before those greater percentages of tree coverage are correlated with reduced flight distances; whether these reductions are related to the inability to flee due to trees preventing animals to move more freely, or due to a decrease in glucocorticoids as a result of reduced heat stress still remains to be proven (Mancera *et al*., 2018).

For the MESMIS attribute Production, NS systems had scores classified as good for this attribute, whereas IS and NS were classified as moderate. These differences can be attributed to the scores for ‘Production Cost’ and ‘Cost/benefit Relation’, which are part of the evaluation of this attribute along with Animal Welfare indicators. For ‘Production Costs’, NS and IS had excellent scores, whereas MS had only good scores. Silvopastoral systems are recognized for reducing production costs by increased utilization of local resources (Cuartas *et al*., 2014). Additionally, cost/benefit relation was better for NS, but classified as moderate, whereas IS and MS were not classified. This indicates that, although NS had better performance for this indicator, costs are still outstanding in relation to benefits. Cost/benefit analyses in silvopastoral systems have demonstrated that they can be economically productive when product quality and new commercial innovations are integrated, such as product certifications (Esquivel *et al*., 2004; Fassola *et al*., 2004). Certification is the process of identifying through labelling that products comply with a set of regulations governing the production process. As a market tool it creates niches, product recognition and/or secures price premiums (Taylor, 2005). Certification is considered the next step for the payment of environmental services (Ghazoul *et al*., 2009) and could improve cost/benefit relations in silvopastoral systems. This kind of scheme need to be further investigated for implementation in the future.

For the Economic Dimension, in addition to 'Production Cost' and 'Cost/benefit Relation', the indicators 'Productive Diversification', 'Independence of External Supply' and 'Business Plan' were also considered. NS had the highest score which was classified as good, followed by IS with moderate and MS with limited. This can be attributed to the better performance that NS had on Production Cost', 'Cost/benefit Relation' and 'Independence of External Supply'. Nonetheless, IS had better ratings for 'Productive Diversification' and 'Business Plan', which make silvopastoral systems better than MS. Similar results have been found by Chagoya (2004) and Chaparro (2005), who found better rentability and economic efficiency in multistrata agroforestry systems.

In this regard, IS had the highest score for the 'Productive diversification' indicator, which also reflects the Adaptability attribute. IS reached a moderate classification, whereas NS and MS were limited and not classified. It is known that silvopastoral systems provide diversification of products to farms in the form of timber, forage and other services (Villamil, 2017). Better scores for IS systems are consistent with the better resource management and the continuous development of producers' capabilities that intensification of silvopastoral systems implies (Nahed-Toral *et al*., 2013), which would imply a better resource management for IS compared to NS. Nonetheless, as adequate production diversification requires technical knowledge to be successful (Calle *et al*., 2009), moderate scores for IS indicate that more technical knowledge is required in order to improve scores for this indicator and the Adaptability attribute.

'Independence of External Supply' was best rated for NS, although both NS and IS had good ratings and MS had a moderate score. As mentioned before, a great part of the low production costs of silvopastoral systems is their ability to rely on local resources (Cuartas *et al*., 2014). Likewise, the use of external inputs such as fertilizer and agrochemicals are replaced by natural processes such as natural soil fertility and biological control (Altieri and Nicholls, 2012) unlike MS systems, where the use of external supply is more prevalent. Finally, IS had good scores for 'Business Plan', which is also related to the improved resource management that intensification of silvopastoral systems imply which point toward the generation and implementation of an holistic business vision that includes management strategies such as careful land-use planning, rotational grazing, diversified forage, and diminished use of purchased inputs (Ferguson *et al*., 201; Nahed-Toral *et al*., 2013), which were characteristics found in silvopastoral systems in this study. 'Independence of External Supply' and 'Business Plan' were also included in the evaluation of the attribute Self-reliance, along with indicators 'Workers' development and training', and 'Organization and participation'.

Self- Reliance was valuated with a good score for IS systems, whereas NS and MS classified as moderate and limited, respectively. IS had better ratings not only for 'Business Plan', but also 'Workers' development and training' and 'Organization and participation', which account for the better outcomes compared with the other systems. 'Workers' development and training' had moderate scores for both IS and MS, meaning that more than half of workers had finished secondary education but did not received training courses in the farm, or that all workers had concluded primary education and received training in the farm or independently. Calle *et al*. (2009) demonstrated the importance of training in silvopastoral systems, as it increases worker satisfaction, promotes commitment with the job and increases positive production outcomes. Moderate scores in training-related outcomes were also found in cattle systems evaluated with the Sustainability Assessment for Food and Agriculture (Gayatri *et al*., 2016). Additionally, training also relates with poor health and safety in the workplace (Iunes, 2002). Therefore, the implementation of training courses in all systems could also help improve job satisfaction, security and improve workers' livelihood. Lack of training and participation in silvopastoral systems has been previously observed in South-eastern Mexico, where producers have a low level of participation in agricultural organizations and few receive training, technical assistance, or financial support (Nahed-Toral *et al*., 2013).

This relates with outcomes encountered in 'Organization and participation', where IS systems had the highest scores but moderate outcomes, whereas NS and MS were not classified. The presence of farmer groups and organizations is essential; for instance commodity roundtables, a form of non-state market-driven governance system, include the creation of working groups that address specific plans and actions towards sustainable development (Buckley *et al*., 2018); group participation, for instance in local markets, also increases good access to information networks and provides a better understanding of implemented policies and regulations (Gayatri *et al*., 2016). Thus, participation needs to be improved for the implementation and effective management of silvopastoral systems.

'Workers' development and training' and 'Organization and participation' were also indicators for the Social dimension, which additionally comprised the attribute Equity with the indicators 'Transmissibility and succession', 'Governmental subsides and assistance' and 'Salary level'. MS had the highest Social dimension and Equity ratings, with moderate and good scores, respectively. Such results are related to MS owning the best outcomes for 'Transmissibility and succession', 'Governmental subsidies and assistance' and 'Salary level'. However, for this indicators, good ratings were not necessarily related to good outcomes in Yucatan's context.

'Transmissibility and succession' estimates the possibility of passing on a determined amount of financial resources to allow the continuance of the system for the next generation and is a measure of sustainability for livestock systems (Tommasino *et al*., 2012). MS had excellent transmissibility, whereas silvopastoral systems were scored as limited, which implies that monocultures have a better chance to remain over generations. In addition, for 'Governmental subsidies and assistance' MS had moderate scores, whereas silvopastoral systems were classified as limited. In Latin American, the policy has encouraged deforestation for timber extraction and conversion of forest areas to monocultures. Such encouragement has come from subsidized credit, guaranteed prices, and other incentives and large-scale ranches continue to practice large-scale deforestation in many areas (Ramírez-Cancino and Rivera-Lorca, 2010; Villamil, 2017). Therefore, the better MS score on this indicator reflects governmental policies that need further improvement to promote alternative livestock systems. In this sense, technical assistance associated with the payment for environmental services has shown to have a positive influence on adoption rates of silvopastoral systems, particularly for practices with private benefits of improving rangeland production (Garbach *et al*., 2012). Finally, 'Salary level' was rated as good for all types of systems, but MS systems had higher scores for this indicator. Despite scores rated as good, this indicator, as well as 'Governmental subsidies and assistance', is not a reflection of good wages in the Mexican context. One of the most important problems in Yucatán is salary levels (INEGI, 2017). In our evaluation, only farm MS2 paid the minimum wage. Therefore, it is necessary that all systems improve salaries for workers regardless of the type of system.

IS farms were determined as more sustainable than NS and MS farms regarding the following criteria: 'Animal Welfare' and attributes 'Adaptability' and 'Self-reliance'. Nonetheless, it is important to highlight the better performance of NS on indicators related to the Environment and Economic dimensions, such as 'Care and Use of Water', 'Species Richness', 'Productive Diversification' and 'Independence of External Supply'. Since intensive and native silvopastoral systems are already present in the Mexican tropics, it is important to carry our more studies in both types of silvopastoral systems to identify potential improvements and support the progress of farmers already engaged with silvopastoral farming, in order to foster the transition to alternative farming systems in the region.

CONCLUSION

To date, this is the first study comparing NS, IS and MS using the MESMIS methodology. It was demonstrated that NS and IS systems had a better sustainability performance than MS per MESMIS attribute and sustainability dimension; however, our evaluation also highlighted areas of improvement that need to be considered for the successful implementation and preservation of silvopastoral systems in the area. When evaluated through MESMIS attributes, NS systems had better ratings for the 'Stability, Reliability and Resilience' and 'Production', as NS scored better for environmental indictors, 'Production Cost' and 'Cost/benefit relation'. IS were better scored for the attributes 'Adaptability' and 'Self-reliance', as all related indicators, excluding 'Independence of external supply' was the highest rated for IS. Nonetheless, it was observed that, despite a clear business plan, aspects such as technical knowledge to improve benefits, training to increase workers' knowledge and better conditions for participation and engagement were necessary to increase sustainability performance. Finally, good Equity ratings for MS were reached due to the presence of good heritable capital for the continuance of these systems, a good access to government subsidies and the best salary level encountered in an MS farm.

For sustainability dimensions, Environment and Economic were best rated for NS systems. The Environment dimension included those indicators that reflected the direct benefits that the presence of trees has on farms, such as better water retention and increased species richness. Meanwhile, the Economic dimension reflected the good scores obtained for NS in the indicators 'Production Cost' and 'Independence of External Supply', which are related to the ability of silvopastoral systems to supply their own resources locally and from the same farm. Meanwhile, IS had the best Animal Welfare scores, in great part due to 'Good Feeding', 'Good Health' and 'Appropriate behaviour' scores for this type of system. Finally, MS had the best Social dimension score, as it included the Equity attribute indicators, which, as mentioned before, were highly rated but not excellent in the bigger context of social sustainability.

The MESMIS framework was successful in identifying an improved sustainability performance in NS and IS systems, as well as highlighting those issues that need to be addressed to contribute to the development of alternative farming systems in the state of Yucatan. Further research on aspects such as assessing objective criteria for all dimensions is still needed. This information will be useful to design better policies to improve the management of silvopastoral systems and contribute to the preservation of environmental services.

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Compliance with ethical standards. The application of questionnaires and overall work was revised and approved by the CICUA committee as part of the procedures applied to postgraduate research undertaken in the Faculty of Veterinary Medicine at the National Autonomous University of Mexico.

Data availability. Data are available with Francisco Galindo, galindof@unam.mx, upon reasonable request.

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