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Applying the socio-ecological systems framework to assess the sustainability of tropical cattle ranching in Mexico

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The conceptual framework of socio-ecological systems (SES) has been used to redirect resource management practices towards more sustainable scenarios. Utilizing surveys conducted with 350 producers of a silvopastoral cattle network in southern Mexico, the structure and interactions of cattle SES were characterized. Furthermore, based on information derived from a workshop with producers, the framework was operationalized through variables representing action situations and generating outcomes in terms of management, organizational issues, and ecosystem services. This participatory exercise allowed for the identification of locally relevant sustainability components and ranges that can be generalized to other similar SES in Latin America, specific socio-ecological challenges, and potential actions leading to maximizing the sustainability of silvopastoral ranches in the tropics. Challenges include an excessive number of intermediaries, labor conditions accentuating poverty, marketing chains inaccessible to small scale producers, and low diversification. These issues can be addressed within the cattle SES through technical and financial support from involved governmental institutions and strengthening the local governance system. This work bridges gaps in cattle research by highlighting that sustainable intensification through the establishment of silvopastoral systems is possible within specific ranges, and sustainability can be defined, understood, and built by producers from the territories.

KEYWORDS

ecosystem services, grazing, Latin America, livestock, management, silvopastoral systems

1 Introduction

Exploring sustainable pathways for cattle production at a local scale is essential, particularly in the Latin American tropics. Participatory approaches are central to addressing these sustainability challenges. In this region, cattle production is a crucial source of income for smallholder farmers, involves the use of significant reserves of natural resources (Murgueitio et al., 2011; Springmann et al., 2018), and threatens forest conservation due to the recurrent expansion of grazing areas (Lerner et al., 2017). At the same time, cattle production systems contribute important and varied ecosystem services to society, as they integrate environmental, cultural, and economic values of great relevance for producers who are often organized in territories to improve the conditions for management and sale of cattle (Torralba et al., 2018). This emphasizes the multifaceted role of cattle systems not only in terms of economic productivity but also in their contribution to the maintenance of ecosystem services and the cultural fabric of rural communities (Tauro et al., 2018; Dumont et al., 2019).

To address the sustainability challenges in cattle production, it is essential to understand the complex socio-ecological contexts that shape these systems. The social-ecological systems (SES) approach has emerged as a fundamental conceptual and analytical framework for understanding the social and environmental connections and feedback in real-world systems (Colding and Barthel, 2019). The SES framework (Ostrom, 2007, 2009; Poteete et al., 2010) has evolved from being a tool for empirical research on commons, institutions, and collective action (e.g., Ostrom, 1990; Poteete et al., 2010), to being a general tool for diagnosing the sustainability of SES (Ostrom, 2009; Leslie et al., 2015). That is, it facilitates the integration of the social, ecological, and economic components involved in a sustainability issue within a list of variables that may be interacting and affecting outcomes in SES (Partelow, 2018).

A cattle system is a local SES integrated into a complex network of multiple interactions at different scales (Duru et al., 2015). Understanding what happens within an SES has the potential to reveal existing possibilities for guiding food systems towards more sustainable scenarios. However, the SES framework has been applied in only a few cases to address the issues involved in cattle production (Duru et al., 2015; Marshall, 2015; Torralba et al., 2018; Ryschawy et al., 2019), and as far as we know, there are no cases for tropical cattle ranching in Latin America where cattle activities are of great magnitudes (Arango et al., 2020). Latin America produces 30% of the world's beef and 28% of its cattle milk (Food and Agriculture Organization of the United Nations, 2019) and is crucial for ensuring food security at both regional and global levels (Food and Agriculture Organization of the United Nations, 2017a). However, maintaining the supply of beef and milk over time will be a challenge if the sustainability challenges posed by production (Herrero et al., 2018) and the marketing of cattle (Broom, 2016) are not addressed.

The environmental dimension of sustainability has been primarily addressed from the biophysical implications of cattle production (Figueroa et al., 2022). Cattle ranching has caused changes in land use and soil fertility, water use, biodiversity, climate change, and multifunctionality (Herrero et al., 2016; Gordon, 2018). The spatial dominance of cattle ranching in extensive grazing areas in Latin America reflects one of the most significant expansions of the agricultural frontier globally over the last 50 years (Herrero et al., 2018), being one of the main causes of deforestation in tropical forests (Lerner et al., 2017). Socio-economic unsustainability has been related to the need for greater access to financing, training, technological innovations, inputs, and competitive value chains to increase productivity without substituting tropical ecosystems for cattle grazing (Lerner et al., 2017; Figueroa et al., 2022).

In the tropics of the region, very small (1 to 30 bovines) and small (31 to 50 bovines) ranches dominate the landscape (González-Quintero et al., 2020), and they are managed with various particularities within two types of grazing production systems: extensive pasture systems and silvopastoral systems (SPS) (Gallo and Tadich, 2018; González-Quintero et al., 2020). The extensive pasture systems are the most widespread and are characterized by cleared areas where the only plants grown are herbaceous plants for cattle feeding (Herrero et al., 2016). In SPS, production occurs in grazing areas containing native and planted trees and shrubs that form diverse strata of available vegetation (Murgueitio et al., 2011). SPS have been recognized as critical systems for transitioning towards sustainable cattle ranching in the tropics (Boval et al., 2017), particularly in Latin America (Lerner et al., 2017; Rivera et al., 2023), where smallholders already using few inputs could simultaneously promote biodiversity conservation and habitat within agroecological landscapes (Tscharntke et al., 2012). Sustainable intensification involves improving management strategies to produce more food per unit area, enhancing the supply of all types of ecosystem services, and maintaining the economic profitability of production while minimizing ecological damage (The Montpellier Panel, 2013).

Within the region, Mexico stands out as the sixth-largest producer of beef in the world, possessing 35 million head of cattle that occupy 55.9% of its territory (109.8 million hectares), supporting the livelihoods of 881,000 people (Servicio de Información Agroalimentaria y Pesquera-Secretario de Agricultura y Desarrollo Rural, 2020). While cattle activities occur throughout the country, the tropical region contains a third of the total cattle (Servicio de Información Agroalimentaria y Pesquera, 2018). Although the ecological, social, and economic benefits of SPS have been documented (Chará et al., 2019; Calle, 2020), as in other countries, in Mexico, extensive pasture systems remain the primary form of production (~0.5 cattle per hectare) (Food and Agriculture Organization of the United Nations, 2018) with significant sustainability implications (Rivera-Huerta et al., 2016, 2019). Despite this, there are peasant efforts that have managed to establish SPS, in Mexico an interesting case is the state of Chiapas, located in the southern of the country where SPS have been widely adopted in tropical conditions (Apan-Salcedo et al., 2021).

Although SPS represent a more sustainable scenario for the region's cattle ranching, it is still necessary to trace the issues that limit and enhance their scaling in specific contexts. Moreover, it remains necessary to understand what sustainability means for ranchers who have managed to transition from production in extensive pasture systems to production within SPS. It is also crucial to apply the SES framework in specific contexts (Leslie et al., 2015; Partelow et al., 2018) in Latin America to identify appropriate strategies for cattle management and marketing (Figueroa et al., 2022), understand the coupling of spatial scales, and propose precise strategies for promote sustainability (Gil et al., 2019) based on local knowledge (Sánchez-Romero et al., 2021). Promoting sustainable scenarios entails identifying locally relevant and generalizable components and establishing ranges with stakeholders to evaluate progress (van Soest et al., 2019).

Indeed, it is recognized that only 14% of the research applying the SES framework puts it into practice in a particular local context (De Vos et al., 2019), and the lack of understanding of scales poses a challenge for the study and management of SES (Magliocca et al., 2018) because it limits impact estimation and the design of relevant agricultural policies (Berrouet et al., 2018). This becomes particularly relevant for Mexico due to the growing uncertainty about the future viability of extensive pasture systems as the main economic support activity for thousands of rural families in the tropics (Rivera-Huerta et al., 2019). Therefore, an assessment that exposes the challenges perceived by SPS producers adds relevance and contributes to the transformation of cattle ranching towards more sustainable scenarios (Figueroa and Galicia, 2021). This highlights the importance of understanding and addressing the specific concerns and obstacles faced by SPS producers to foster a more sustainable cattle systems in Mexico and in similar socio-ecological contexts in the region.

We proposed the following set of research questions: (1) What is the structure of the SES emerging from silvopastoral cattle production within a network of producers in southern Mexico? (2) How are interactions described and coupled across spatial scales? (3) What components contribute to sustainability within the SPS of the cattle SES? and (4) What are the main limitations that SPS face in moving towards more sustainable scenarios? To address these issues, our general goal was to evaluate the sustainability of a cattle SES using a participatory approach with producers from a network in southern Mexico. To achieve this, we formulated the following specific objectives:

- Characterize the cattle SES and the interactions arising from production and commercialization silvopastoral in southern Mexico.
- Operationalize the cattle SES by proposing sustainability components and ranges through a participatory approach that allows for the assessment of the limitations faced by SPS in southern Mexico.

2 Methods

2.1 Study area

Cattle ranching is an economic activity upon which thousands of producers in Mexico depend. Specifically, in Chiapas, a state located in the southern of Mexico (Figure 1), cattle breeding and sales constitute the most significant agricultural activity for the region's economy (Fuentealba and González-Esquivel, 2016). Approximately 82,000 producers and their families directly rely on the production and marketing of cattle for their survival. These production and marketing activities take place under tropical conditions in systems managed by small and medium-sized producers who sell cattle in a market monopolized by intermediaries. On average, 59% of cattle production in Chiapas is sold to local and regional intermediaries who retain a portion of the income (INEGI, 2017). The Silvopastoral Network was established in response to the excess of intermediaries and to highlight the products produced in cattle systems that employ silvopastoral practices (for example, increased cattle density and the inclusion of trees and shrubs as feed and shade). This network was created as a nonprofit initiative in 2014, its members are found in nine cattle associations—groups of producers legally constituted to manage the production and marketing practices of cattle—and 350 cattle producers distributed across six socio-economic regions of Chiapas (Figure 1 and Supplementary Table S1). Following prior collaborative work with producers in Chiapas, we defined the Silvopastoral Network as the cattle SES for this research.

2.2 Conceptualization of cattle SES

2.2.1 SES framework

Humans and nature have historically been addressed separately, often from a development versus conservation perspective. However,

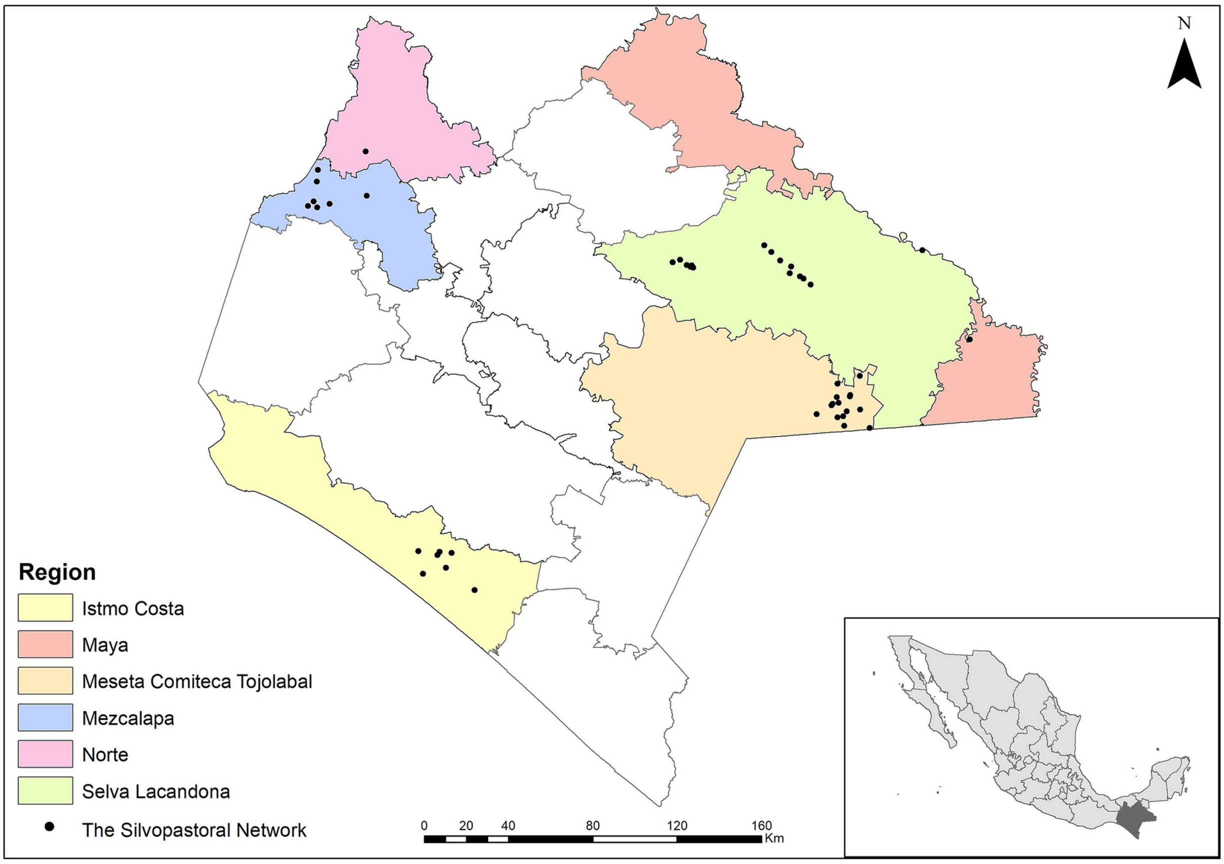


FIGURE 1
Spatial distribution of the products produced by the Silvopastoral Network's cattle ranching members in the six socioeconomic regions in Chiapas, Mexico.

they are interconnected, and their separation is arbitrary when considering sustainable use and enjoyment of the benefits they offer (Berkes and Folke, 1998); these interrelated systems are known as SES. The SES are composed of heterogeneous individual modules that interact locally and evolve physically, and behaviorally, because of those interactions (Ostrom, 2009). The SES framework allows for the integration of data from both natural and social sciences, thereby providing a theoretically sound means to test hypotheses about the dynamics and sustainability implications of socio-ecological interactions (Leslie et al., 2015).

The SES framework integrates and describes four essential dimensions or first-level variables: (1) *governance system* (GS): formal and informal rules, (2) *actors* (A): within and outside of government, (3) *resource unit* (RU): relevant goods and services, and (4) *resource system* (RS): specific ecosystems and biophysical processes. Each first-level variable is composed of a second-level variable and the latter, by third-level variable that describes it. The *interactions* (I) between the four first-level variable and their components (the second and third-level variables) are mediated by broader *social*, *economic*, and *political settings* (S) and the *ecosystems* within which the SES is related (ECO). The interactions lead to different *outcomes* (O) at temporal and spatial scales. Furthermore, the framework proposes action situations that occur when resource units and the resource system are transformed by the actions of multiple involved actors (McGinnis and Ostrom, 2014).

2.3 Data collection

Surveys were administered between July and October 2018 to all producer members of the Silvopastoral Network ($N = 350$). The questionnaire was structured into thematic blocks to capture values related to management issues, such as cattle density, rotation frequency, and diversification strategies; ecological aspects, such as area of pastures, number of trees and shrubs, cattle species, herd size, social factors as ages, education levels, rules, number of family members involved, and economic issues as infrastructure, employment, products, types of intermediaries involved of the focal SES (Supplementary Table S2), as part of the project "Sustainable production systems and biodiversity" of the National Commission for the Knowledge and Use of Biodiversity (CONABIO in Spanish), the Ministry of Environment and Natural Resources (SEMARNAT in Spanish), and the Global Environment Facility (GEF).

The presidents of the associations informed each affiliated producer in advance about the importance of being surveyed to analyze the benefits associated with silvopastoral management in the region. This ensured the producers' openness and the success of their participation. Trained technicians from each cattle association administered the field surveys. They returned the information and photographic evidence to the Silvopastoral Network at the end of the interviews, which lasted between 1:30 and 2:00 h each. The information was systematized in an Excel matrix for analysis, and the data was disaggregated at the level of the silvopastoral ranch ($n = 350$ ranches).

2.4 Data processing

The surveys were digitized, and to ensure the confidentiality of the participants in the databases, we used abbreviations to link viewpoints to associations rather than to individuals. The surveys included a list of trees, shrubs, and grasses reported by their common names. Using the national inventory of forests and soils (Comisión Nacional Forestal, 2021), we translated these into their scientific names after eliminating synonyms and confirming the spatial distribution of the species (Supplementary Table S3). Given that soils are a fundamental basis for cattle production and since we did not obtain biogeochemical data from the pastures, most information about the soil was taken from publications (Soto-Pinto et al., 2010; Villanueva-López et al., 2015) that have reported on the relationship between cattle ranching and nutrient dynamics in some of the municipalities located in the influence area of the Silvopastoral Network. The academics involved in the project selected available socio-ecological information from the questionnaires' thematic blocks and related it to three groups of outcomes: management strategies, organizational issues, and ecosystem services. They preserved the spatial location (locality and region) associated with each data point (ranch) and respected the nature of the questions proposed by the Silvopastoral Network.

2.5 Data analysis

2.5.1 Characterization of cattle SES

The information derived from surveys was associated with each first-level variable (the four essential dimensions of the SES framework), second-level variable, and third-level variable, allowing for the characterization of the cattle SES (Table 1). This involved applying a hierarchical and structured qualitative analysis approach to the data. The 10 thematic blocks of the questionnaires were linked to the four first-level variables: resource system (RS): blocks 1 and 4; resource unit (RU): blocks 1, 2, 4, 5, 6, and 9; actors (A): blocks 1 and 7; governance system (GS): blocks 1 and 4; and Outcomes (O): blocks 3, 8, 9, and 10. This way, the second-level variables were identified as more specific and measurable subcategories within each first-level variable. The third-level variables were detected by examining and coding the questions and responses obtained. Additionally, we theoretically described the interactions within the SES framework using regional and national studies as references for what occurs in another similar cattle SES (Table 2). This last step characterizes the producer network's strengths, weaknesses, opportunities, and threats. The continuous variables were described using the calculation of the mean and the standard deviation (±).

2.5.2 Operationalization of cattle SES

The "outcomes" of the cattle SES integrate components representing action situations in terms of management, organizational issues, and the provision of ecosystem services (Figure 2). Therefore, operationalizing the framework through the analysis of components related to different types of outcomes is relevant for diagnosing and promoting transitions towards more sustainable scenarios within cattle ranches. We operationalized the cattle SES to diagnose and understand practical issues essential for transitioning cattle ranching systems toward sustainable scenarios in southern Mexico. Sustainability food system was analyzed through the second and third-level variables (components) of SES outcomes (Table 1), which were contextualized, described, and categorized by producers of the Silvopastoral Network ($n = 23$) in a participatory workshop (Herrera-Franco et al., 2018) held in February 2019. To ensure

TABLE 1 SES variables analyzed for tropical cattle ranching in southern Mexico.

First-level variable	Second-level variable	Third-level variable
Resource unit (RU)	RU1. Soils RU2. Vegetation RU3. Distinctive characteristics RU4. Products and economic value	RU-1.1 Chemical and physical properties RU-1.2 Nutrients RU-2.1 Trees and shrubs RU-2.2 Pastures RU-3.1 Dietary supplements RU-3.2 Insemination RU-4.1 Type of products RU-4.2 Total cattle RU-4.3 Trade prices
Resource system (RS)	RS1. Sector RS2. Size of resource system RS3. Human-constructed facilities RS4. Location	RS-1.1 Name of sector RS-2.1 Area for cattle activities RS-3.1 Infrastructure and equipment RS-4.1 Spatial influence
Actors (A)	A1. Producers A2. Government actors A3. Non-governmental actors	A-1.1 Age and schooling A-1.2 Producers and workers A-2.1 Government institutions A-3.1 Collaborating academic institutions A-3.2 Collaborating non-governmental organizations and associations
Governance system (GS)	GS1. Operational and collective-choice rules GS2. Membership conditions and structure	GS-1.1 Types of rules GS-1.2 Rule topics GS-2.1 Years of aggregation GS-2.2 Associations GS-2.3 Women participation GS-2.4 Physical capital
Outcomes (O)	O1. Management O2. Organizational issues O3. Ecosystem services	O-1.1 Cattle density O-1.2 Rotation frequency O-1.3 Cattle breeds O-1.4 Diversification strategies O-2.1 Employment creation O-2.2 Family participation O-2.3 Infrastructure availability O-2.4 Commercial consolidation O-3.1 Shade of cattle O-3.2 Habitat O-3.3 Cultivated forage O-3.4 Soil moisture

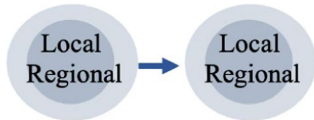
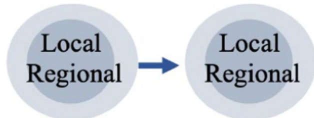
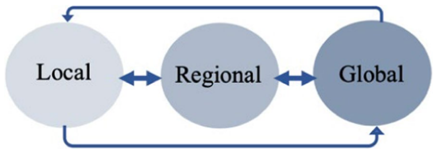
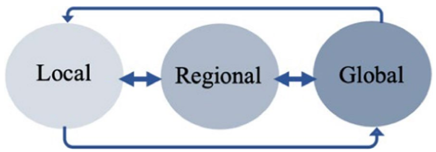
representativeness, the number of participants was estimated using the following equation:

$$n = \frac{K^2 pqN}{\left(e^2 (N-1)\right) + K^2 pq}$$

where N is the population size (350 producers); K is a constant that depends on the assigned confidence level, in this case, 95%; e is the desired sampling error in percentage, in this case, 10%; p and q, were the proportion of the individuals in the population that do and do not possess a specific characteristic, respectively. The data for p and q is unknown, so it is usually assumed that $p = q = 0.5$.

During the workshop, four academic facilitators led an open discussion with the producers. The 12 selected components were shared and validated in plenary with the assistance of a whiteboard. Finally, participants were asked to describe the components as they understood them and propose three ranges of sustainability progress. The ranges or categories of progress were to include scenarios of low, medium, and high sustainability. Information associated with component measurements was obtained through survey analysis. The values for each component were identified based on the data matrix obtained at the producer level (cattle ranch) and standardized by assigning a category of 1, 2, or 3 to associate each value with an individual progress range. The nine associations were encoded as A1–A9 (Supplementary Table S1), and to inform progress within each association, we calculated the average

TABLE 2 Interactions of the cattle SES across through the coupling of spatial scales.

Interaction	Description	Spatial scales coupling	References
RU ↔ RS	The RU establishes the biophysical conditions at local scale needed for maintaining productivity of system (RS) at local and regional scale. The area designated for cattle ranching, combined with infrastructure, available equipment, and spatial influence (RS), can have repercussions on the RU		Astier et al. (2011), Romano-Armada et al. (2016), Boillat et al. (2017), Coppock et al. (2017), and Arango et al. (2020)
RU ↔ A → O	The RU in good condition (e.g., with high multifunctionality) ensures benefits for the actors (A) through the capacity of agroecosystems to provide ecosystem services at local and regional scale (O). In turn, collaborations (e.g., participation in projects, programs, and financial support) among the actors (A) (governmental and non-governmental) and management decisions can have an impact on the state of the RU, with chain consequences on the provision of services (O)		Murgueitio et al. (2011), Lerner et al. (2017), Manning et al. (2018), Amarilla et al. (2019), Chará et al. (2019), Figueroa et al. (2020), and Parra-Bracamonte et al. (2021)
A ↔ GS	The governance system (GS) is promoted by actors (A) who engage in organizational processes that include decision-making and cooperation through associations, networks, and institutions at local and regional scale. In turn, a robust governance system (GS) has emancipatory values and strengthens capacities and collaborations among actors (A)		Coppock et al. (2017), Barnaud et al. (2018), Westholm and Ostwald (2019), Apan-Salcedo et al. (2021), and Figueroa et al., 2022
RS ↔ GS → O	A resource system (RS) with strengthened infrastructure and broad spatial influence may have better conditions to strengthen the GS. At the same time, a well-established GS, where roles and decision-making are organized and distributed equitably, has the potential to enhance, consolidate, and spatially scale the RS		Newberry (2014), Hajjar et al. (2019), and Figueroa et al. (2022)
SES ↔ S	The cattle SES at local scale engages with social, economic, and political settings (S) at regional and global scales through participation with other actors (e.g., collaboration on regional and global projects and policies) that bring visibility to cattle management within alternative grazing production systems for tropical areas worldwide (e.g., SPS). At the same time, there are settings (S) with the potential to influence local cattle SES (e.g., regulations, monitoring, and regional and global policies that modify production methods and product demands)		Delgado et al. (1999), Herrero et al. (2018), and Figueroa et al. (2022)
SES ↔ ECO	This interaction arises when the internal dynamics of the local cattle SES impact the overall state of ecosystems to regional and global scales (ECO). For example, in tropical contexts, some management practices lead to soil degradation, deforestation, loss of connectivity, habitat, and biodiversity, as well as the formation of unfavorable microclimates. In contrast, a strengthened governance system at local and regional scales and committed and trained actors promote good management practices. In turn, well-conserved ecosystems at larger scales amplify benefits that can be leveraged by the local-scale cattle SES		Murgueitio et al. (2011), Marshall (2015), Lerner et al. (2017), and Herrero et al. (2016)

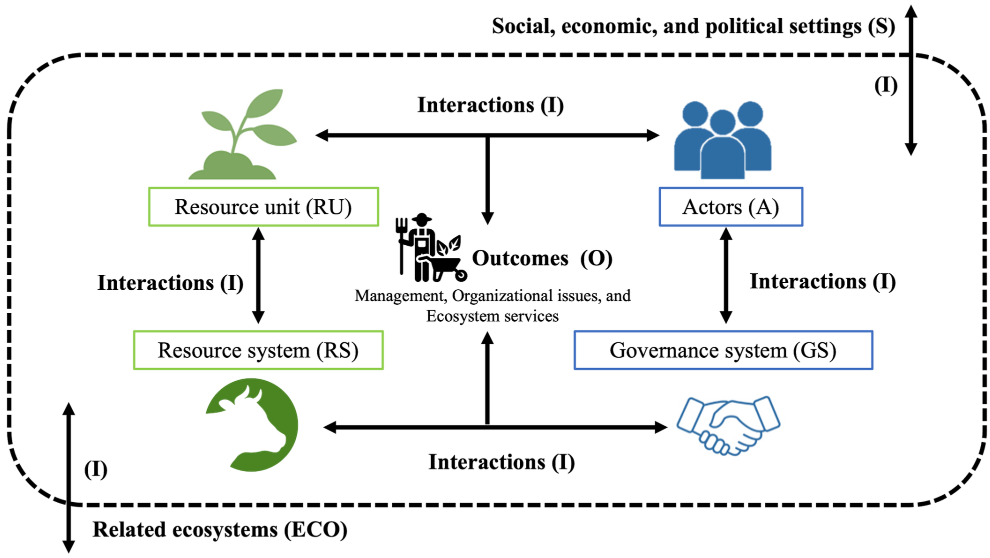


FIGURE 2
Structure of the cattle SES (modified from McGinnis and Ostrom, 2014).

progress of its producers for each of the 12 components (outcomes). The categories (low 1, medium 2, and high 3) for each cattle association were interpreted as sustainability trends (Leslie et al., 2015) given the ranges established by the producers, which were visualized using radar diagrams. Finally, we associated each cattle association's average sustainability progress with its location to visualize regional advances in management, organization, and ecosystem services in a bar chart.

3 Results

3.1 Description of the cattle SES

The Silvopastoral Network SES is based on the production and sale of cattle that graze in SPS under tropical conditions. As in other SES, in this cattle SES, the first-level variables interact internally, and being open systems, they maintain interactions with factors external to the SES (Figure 2). The *resource unit* (RU) presents three main types of soil: Regosols, Leptosols, and Cambisols; with a medium bulk density ranging from 1.30 to 1.50 g/cm^3 (mean = 1.4 ± 0.1); clayey-loamy texture and a pH suitable for plant growth ranging between 7.23–7.53 (mean = 7.38 ± 0.15) (Soto-Pinto et al., 2010). The nutrient content is good, typically recording soil organic carbon levels of 68.5–75.1 Mg C ha^{-1} (mean = 71.8 ± 3.3) total carbon between 78.8 and 142.5 Mg C ha^{-1} (mean = 112 ± 14.3), and a nitrogen percentage ranging between 25–29% (mean = 27 ± 2) (Villanueva-López et al., 2015).

This cattle SES integrates 66,318 trees, 106 species of trees and shrubs, and 11,098 units of cattle in 4,674 hectares designated for cattle grazing. In addition to feeding on available vegetation (grasses, trees, and shrubs distributed in living fences), the cattle receive dietary supplementation of mineral salts, legumes and ground corn, and their reproduction is ensured through natural and artificial insemination. Within the cattle ranches, cattle for breeding (calves), half-fattened (heifers), finished cattle (cows and bulls), and milk are produced and sold at differential prices to intermediaries. The price range per kilogram of beef (unit of body weight) and per liter of milk (in US dollars) is as follows: bulls: 1.2–3 (mean = 2.1 ± 0.9), cows: 1–2.2 (mean = 1.6 ± 0.6), heifers: 1.2–2.5 (mean = 1.85 ± 0.6), calves: 2–3 (mean = 2.5 ± 0.5), and milk: 0.3–0.4 (mean = 0.35 ± 0.05).

The *resource system* (RS) is integrated into the livestock sector with a size of 5,342 hectares allocated for various cattle activities (e.g., grazing, storage, feeding, cattle rotation). The cattle SES is in six strategic municipalities of the state (Ocosingo, Maravilla Tenejapa, Marqués de Comillas, Tecpatán, Mezcalapa, and Pijijiapan) (Figure 1) and features pens, feeders, water troughs, and corn crushers as part of the facilities built within the ranches (Supplementary Table S4). In this SES, the main *actors* (A) are the 350 producers, who have an average age of 54 (±13 years) and have achieved elementary education as their level of schooling. The maintenance of the systems is carried out by the producers and the 1,129 workers involved in various productive tasks (e.g., grazing, maintenance of water troughs, vegetation management, preparation of dietary supplements). The SEMARNAT and CONABIO are the government institutions with whom the actors have established contact and obtained economic support to strengthen capacities. Additionally, they have collaborated with universities and research centers such as The College of the Southern Border (ECOSUR in Spanish) and The University of Sciences and Art of Chiapas (UNICACH in Spanish) to assess the ecological and socioeconomics benefits associated with the implementation of SPS; and with the GEF to be part of the case studies of productive projects that conserve biodiversity (Supplementary Table S4).

The *governance system* (GS) includes operational rules and collective action, designed to address issues related to network operability, collective decision-making, communication, and coordination among partners, as well as participation, inclusion, and exclusion of partners. Over the 10 years of aggregation that this producer network has been operating, they have managed to involve nine cattle associations (A1–A9) from the state of Chiapas as members. The cattle SES has strengthened their physical capital through the purchase of two cameras and GPS devices that allow them to monitor various issues within their production systems and participate in programs and projects through which they obtain financing to continue with productive improvements. Despite the progress, women's participation in governance matters remains low;

only 11% of the network's producers are women with a voice and vote in decision-making (Supplementary Table S4).

As management *outcomes* (O), the cattle SES exhibits an average cattle density of 2.38 cattle/hectare (±1.4) (higher than that recorded in extensive pasture where approximately 0.5 cattle/hectare are included). They rotate the cattle to different pastures every 21 days (±6) (an absent strategy in extensive pasture) to alleviate soil compaction due to trampling pressure. The system incorporates six crosses or breeds (Cebu, Swiss, Charolais, Hereford, Gyr, Ongole) which enhances cattle resilience. Regarding diversification strategies, the cattle SES includes grazing, cattle fattening, milk sales, and cheese production, the latter led by some women in the communities, generating extra income for their families. In terms of organizational issues outcomes, 379 external and 750 internal (family) employments are created. Efforts are made to strengthen available infrastructure through the construction of stables and the purchase of motor pumps and sprinklers. The production systems are small, approximately 15 hectares (±10) for grazing and 32 cattle per producer (±20.2), managed within family-oriented schemes primarily geared towards subsistence, with the surplus sold to intermediaries who retain a portion of the income. Commercial consolidation remains challenging due to numerous local and regional intermediaries buying from producers at low prices, retaining between 10 and 30% of profit in each cattle and milk sales transaction. Another notable challenge is the payment received by workers in the production systems, as they earn an average of $5 (±2 US dollars) for a workday ranging from 8 to 12 h in the field.

The last outcome relates to the ecosystem services provided by the cattle SES. On average, 17 trees/hectare (±10.5) provide shade for the cattle 32% of pastures have shrubs in living fences that provide habitat for various species, there are 568,145 square meters of cultivated forage, and 98% of the year the soils maintain good moisture levels, largely due to cattle rotation frequency and the incorporation of trees and living fences (Supplementary Table S4). The six *interactions* (I) of the cattle SES occur among first-level variables (RU, RS, A, GS, and O) and with factors outside the SES (*ECO* and *S*) across through the coupling of spatial scales (Table 2).

3.2 Components and ranges of sustainability in the cattle SES

The sustainability of the cattle SES is defined through ranges established by producers and associated with the 12 third-level variables or components of the outcomes. The four components related to management are: cattle density, rotation frequency, cattle breeds, and diversification. The four components related to organizational issues are: employments creation, family participation, infrastructure availability, and commercial consolidation. The four components associated with provision of ecosystem services are: shade of cattle, habitat, cultivated forage, and soil moisture. The interpretation of each component by producers, the progress ranges, and the associated sustainability categories are in Table 3.

3.2.1 Management outcomes

The cattle associations showed on average a low advancement (sustainability category = 1) in the component of cattle density (~1 to 2 cattle per hectare), cattle breeds (~1 breed per producer), and diversification strategies (associations specialized in cattle grazing). Regarding the component "frequency of rotation," the sustainability value was intermediate (sustainability category = 2), indicating that cattle remain on the same pasture for 10–20 days each year. Although the management outcomes generally show low sustainability progress, associations A5 and A6 have achieved greater advancements in these components. They showed intermediate cattle density (3–5 cattle/hectare), frequent rotation, number of cattle breeds (2–3 breeds), and diversification (grazing, and cattle fattening) (Figure 3).

3.2.2 Organizational issues outcomes

The employment creation component showed low sustainability, except in associations A1, A5, and A6, which had medium sustainability because their producers generated an average of 2 to 3 external employments. However, the same associations that generated more external employments had less family participation (low sustainability) (A1, A5, and A6) (Figure 3). The available infrastructure component showed low and medium sustainability progress for almost all the associations of the cattle SES except for associations A4 and A5, whose systems included cattle troughs, cattle pens, and lawn mower for cattle activities (high sustainability). The commercial consolidation component showed low sustainability value for most associations (selling steers to local intermediaries). Only associations A5 and A6 have medium and high sustainability progress, respectively, as their producers, on average, cattle fattening and sell beef, milk, and cheese to local butchers and small markets, allowing them to improve profits (Figure 3).

3.2.3 Ecosystem services outcomes

The component "shade for cattle" showed low sustainability for most associations, except for associations A1, A5, and A6 where it recorded intermediate sustainability (11 to 20 trees per hectare). Regarding the "habitat" variable, the sustainability progress for most associations was low (0 to 30% of pastures have living fences), except in associations A5 and A6, where vegetation covered 30 to 50% of the pastures (Figure 3). Sustainability progress was low for the "cultivated forages" variable since a maximum of 100 m^2 of forage per cattle is cultivated in the SES, except in ranches of association A1 where up to 200 m^2 of forage per cattle is produced. The "soil moisture" variable showed high sustainability progress for all associations except for A7, indicating that the soil in the Silvopastoral Network pastures retains moisture for most of the year.

3.2.4 Regional advances in sustainability

The Mezcalapa and Norte regions have the highest sustainability advances in cattle density, rotation frequency, cattle breeds, diversification strategies, employment creation, commercial consolidation, cattle shade, and habitat (Figure 4). In contrast, the other regions analyzed have low to intermediate sustainability progress with some focused efforts. For example, the Maya region has significant progress in the infrastructure availability component, the Selva Lacandona region in cultivated forage, and the Istmo Costa and Meseta Comiteca regions in the family participation component. This aligns with the lower capacity for creating external employment in these regions, where several family members are responsible for agricultural activities on their ranches (Figure 4). In this regard, our research shows a clear difference in the outcomes associated with management, organization, and ecosystem services among the analyzed regions, with the SPS located in the northern part of the state being the most advanced in sustainability.

TABLE 3 Outcomes, ranges of progress, and cattle ranching sustainability categories: 1-low, 2-medium, and 3-high.

	Components (unit)	Interpretation by producers	Ranges of progress	Sustainability category
 Management	Cattle density (cattle/hectare)	Increasing the cattle density benefits production and increases income	1–2 cattle/ha	1
			3–5 cattle/ha	2
			6–10 cattle/ha	3
	Rotation frequency (days of grazing on the same pasture per year)	Decreasing the number of days of grazing cattle in the same pasture prevents soil damage	>20 days	1
			10–20 days	2
			<10 days	3
	Cattle breeds (cattle breeds/producer)	Including more cattle breeds and crossbreeding them decreases calf mortality	1 breed	1
			2–3 breeds	2
			>3 breeds	3
	Diversification strategies (production activities on the ranch)	A variety of productive/economic activities on the same ranch helps to offer more types of products and improves their quality	Cattle grazing only	1
			Grazing and cattle fattening	2
			Grazing, cattle fattening, and sale milk and cheese	3
 Organizational issues	Employment creation (employments/ranch)	A sustainable cattle ranch requires and can pay more workers	1 employment	1
			2–3 employments	2
			>3 employments	3
	Family participation (family members working/ranch)	New generations and women should participate in cattle production	Only one family member	1
			Parents and children	2
			Parents, children, and women	3
	Infrastructure availability (availability of materials and equipment)	Having tools that facilitate production would help to produce in a more sustainable scheme	Cattle troughs	1
			Cattle troughs and cattle pens	2
			Cattle troughs, cattle pens, and lawn mower	3
	Commercial consolidation (level of consolidation)	Commercializing other products and selling them directly would make cattle ranching more sustainable	Sale of young bulls to local intermediaries	1
			Sale of fattening and milk to regional intermediaries	2
			Sale of cattle, beef and milk to butcher and supermarket	3
 Ecosystem services	Shade of cattle (trees/hectare)	Trees in pastures improve soil health and provide shade for the animals	<10 trees/ha	1
			11–20 trees/ha	2
			>20 trees/ha	3
	Habitat (percentage of living fences of the pastures)	Fencing with shrubs prevents ditches that injure animals and provides forage	0–30% of the pasture	1
			30–50% of the pasture	2
			>50% of the pasture	3
	Cultivated forage (square meter/cattle)	Having forage banks decreases animals' dependence on pasture vegetation	0–100 m^2/cattle	1
			100–200 m^2/cattle	2
			>200 m^2/cattle	3
	Soil moisture (percentage of the year with soil moisture)	Soil moisture is conserved due to vegetation and the rotation frequency of cattle	0–30% of year	1
			>30–70% of year	2
			>70% of year	3

4 Discussion

4.1 Structure and interactions of the cattle SES

The conceptual framework of the SES allowed for the systematic analysis of 350 cattle production and marketing systems in southern Mexico and visualizing, from local understanding, what it means for producers to move towards more sustainable scenarios. The cattle SES integrates a resource system and a unit of resources in good condition for tropical production within SPS of significant local influence in the state of Chiapas. It incorporates a high number of trees, shrubs, and diverse plant species that provide benefits absent in extensive pasture systems (Calle, 2020). It is widely recognized that the integration of

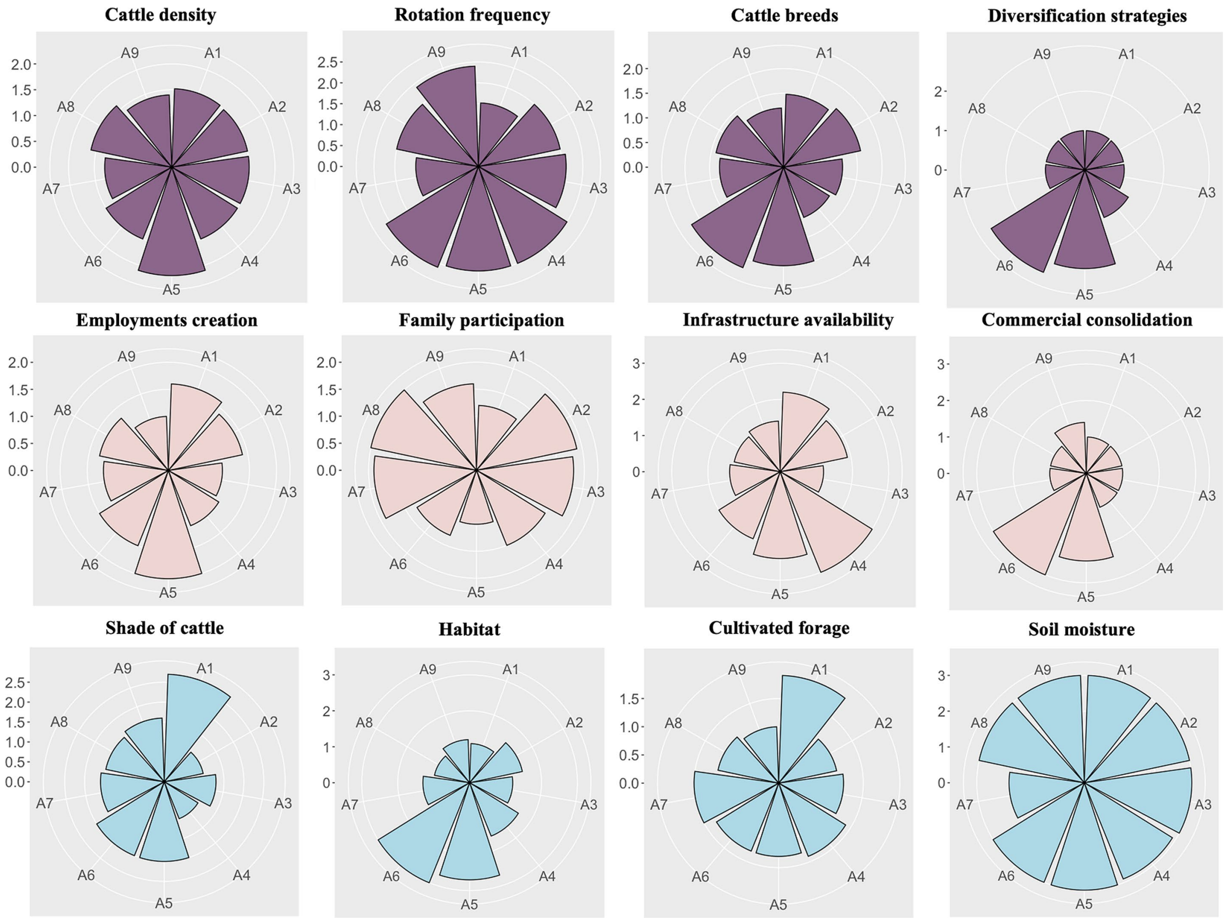


FIGURE 3
Range of progress in sustainability (1, 2, and 3) for the 12 components by the nine-member associations (A1–A9) in the Silvopastoral Network. The purple radars represent management outcomes, pink radars represent organizational issues outcomes, and blue radars represent ecosystem services outcomes.

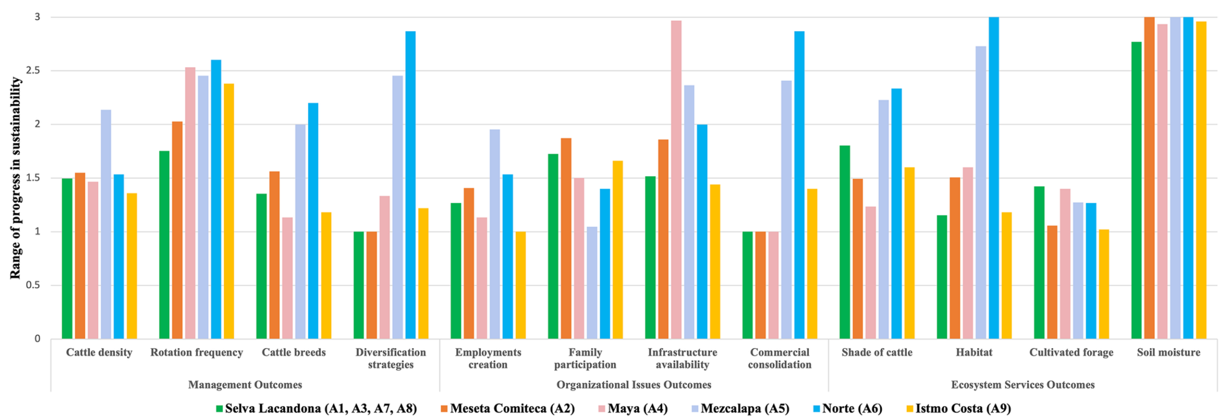


FIGURE 4
Regional advances in management strategies, organizational issues, and ecosystem services outcomes. The progress ranges reflect the three participatively defined categories: 1: low, 2: medium, and 3: high sustainability.

multiple vegetation strata in SPS favors soil biota and increases connectivity between forest fragments and pastures, thereby promoting biodiversity. Additionally, they enhance animal welfare, increase productivity, and prevent deforestation caused by grazing cattle in tropical areas of Latin America (Murgueitio et al., 2011; Solorio et al., 2017).

SPS are a land-sparing conservation strategy that represents an opportunity to move towards more sustainable scenarios if proper management is ensured (Lerner et al., 2017). In the resource unit of the cattle SES, cattle feeding is based on available vegetation and supplementation with salts and cereals. These improvements in the diet promote levels of multifunctionality in SPS in tropical regions (Boval et al., 2017). In fact, the incorporation of various grass and legume species as forage provides a more nutritious diet (Rudel et al., 2015), increases productivity, and reduces greenhouse gas emissions (GHG); relevant issues to address in the livestock sector in the tropics (Rao et al., 2015; Solorio et al., 2017).

The cattle SES includes actors and a strengthened governance system that fosters organized environments, operational rules, and has the potential to expand silvopastoral production while seeking financial improvements. However, the current asymmetric commercial characteristics represent disadvantages for small-scale producers and have already been reported in Chiapas (Calderón et al., 2012) and other tropical regions of Latin America (Romano-Armada et al., 2016). The spatial scaling-up of SPS largely depends on creating competitive commercial chains for small scale producers in tropical areas because ensuring higher profitability is often an effective motivation for deciding to produce in alternative schemes (Arango et al., 2020; Calle, 2020).

Another challenge is the labor conditions; in the cattle SES, as well as in other SES in the Mexican tropics (e.g., agricultural and forestry), workers are informally hired, working excessive hours, and receiving low wages, exacerbating extreme poverty (Rivera-Huerta et al., 2019). This is particularly significant for rural development in Chiapas, where 76.4% of the population is classified as being in some category of poverty (Consejo Nacional de Evaluación de la Política de Desarrollo Social de México, 2018). Small-scale producers need to access inputs, capital, infrastructure, technical information, and knowledge on sustaining silvopastoral management strategies with lower environmental impact (Marinidou et al., 2018; Arango et al., 2020), and higher initial investment costs (Calle, 2020; Van Loon et al., 2020). The low participation of women in decision-making and productive activities is another issue that needs to be addressed through the strengthening of the governance system. The lack of women's participation has already been documented in cattle ranching systems, and it is recognized that their involvement promotes system diversification and increased profits from the sale of other types of products and ecosystem services (Westholm and Ostwald, 2019).

The theoretical framework of the cattle SES reveals the interconnectedness of global, regional, and local processes across scales. Globalized and highly demanding markets are contributing to the challenge of diversifying production by encouraging producing countries like Mexico to specialize in beef production, which may have adverse consequences on the provision of ecosystem services in the tropics (Garrett et al., 2017; Chung and Liu, 2019), especially those associated with forests that are cleared for the establishment of cattle pastures. Deforestation results in the loss of essential services for human well-being, including climate regulation, nutrient cycling, erosion control, landslide and flood mitigation, water quality, spiritual qualities, and safeguarding worldviews (Balvanera, 2012). These trends could be reversed through policies supporting local distribution and consumption networks and contributing to the creation of local brands that favor cattle production in multifunctional systems like SPS (Torralba et al., 2018).

In Mexico, there are larger-scale social, economic, and political forces that are beginning to promote a better scenario. The public policy program "Sembrando Vida" is guiding the establishment of agroforestry arrangements, which aim to include various types of trees, shrubs, and intercropped crops, prioritizing diversified agricultural management and leaving the possibility of future linkage to SPS (Diario Oficial de la Federación, 2020). On the other hand, the government program "Crédito Ganadero a la Palabra" focuses on expanding the size of the herd (livestock repopulation) (Diario Oficial de la Federación, 2019), and although it represents significant support to small-scale producers in the southern region of the country, it has not been accompanied by a strategy that promotes the formal establishment of SPS and ensures that deforestation is halted. In that sense, both programs still have opportunities for improvement in their design and implementation.

4.2 Sustainability of cattle SES

The evaluation of outcomes showed that only two out of the nine member associations of the cattle SES have made significant advances in what producers determined as sustainable scenarios for cattle ranches. Associations A5 and A6 have the best results in terms of provision of assessed ecosystem services, management, and organizational issues (medium and high sustainability levels in ten and nine components, respectively). This differentiated progress has been related to the strength in resource unit management and the management decisions made by actors within both cattle associations to produce differently and add value to their products. This has led to the intensification of cattle density, an increase in the number of employments, high rotation frequency, and the use of trees for shade and shrubs within living fences that provide habitat for biodiversity and greater availability of food for the cattle.

Despite the progress, for all associations affiliated with the Silvopastoral Network, it remains necessary to strengthen the governance system, dignify livelihoods, and sustain the provision of ecosystem services at high levels. These challenges have been reported as priorities for the livestock sector in the tropics of Latin America (Coppock et al., 2017). Associations A5 and A6 have established SPS that have achieved socio-ecological improvements largely due to diversification strategies, which is the component where the differentiation in management with other associations is most evident. As in other tropical states of the country, in Chiapas, the sale and consumption of various animal products (e.g., beef, milk, cheese, yogurt) reduce household vulnerability to seasonal food and income shortages (Figueroa and Galicia, 2021), meet their dietary needs, and improve the nutritional status of the poorest (Calderón et al., 2012; Food and Agriculture Organization of the United Nations, 2017b; Gallo and Tadich, 2018).

Productive diversification in rural regions in Mexico often requires incentives to optimize resource use, ensure food security, and reduce high deforestation rates resulting from the expansion of monocultures and extensive pasture systems (Galeana-Pizaña et al., 2018, 2021; Tello et al., 2020; Figueroa et al., 2021). Productive diversification is urgent in the tropics and can be a central axis of planning in the Latin American region, capable of reducing the dependence of small-scale producers on cattle grazing, meeting the growing demand for food, and generating rural employments (Astier et al., 2011; Murgueitio et al., 2011). While association A1 has shown significant progress in the component "cultivated forages," the other associations continue to have low levels of progress and greater dependence on external purchases to supplement cattle with nutritious forages. This happens in part because SPS still face the false idea that they will produce less, especially when cattle share space with crops (Lerner et al., 2017).

Strategies for sustainable tropical cattle ranching in Mexico and Latin America should address externalities and offer evidence-based insights into the benefits and limitations of SPS and other alternative cattle systems. For example, there are a series of technologies and agronomic practices to improve the efficiency of cattle operations (e.g., diversification of agroecosystems in polycultures, mixed crop-cattle systems, organic soil management, and water conservation and harvesting strategies in pastures) (Altieri et al., 2015; Rudel et al., 2015; Arango et al., 2020). However, there is a lack of clarity on how to target the necessary technical and financial support to ensure access to and adoption of new technologies and practices, and which governance issues to strengthen in systems managed by small-scale producers (Lerner et al., 2017; González-Quintero et al., 2020). Additionally, there is uncertainty about the extent to which cattle density should be increased and how to manage vegetation in SPS without increasing GHG emissions and deforestation in Latin America (Arango et al., 2020). The sustainability components and progress ranges proposed by producers in this research provide valuable information to bridge these gaps.

The resource unit of SPS in the cattle SES is particularly vulnerable to changes in the frequency and magnitude of rainfall and rising temperatures due to being in a tropical region. Although the component "soil moisture" showed high progress in sustainability in most associations of the cattle SES, the climatic conditions under which the cattle SES operates pose high risks of changes in the mechanisms that regulate soil fertility. This would limit the availability of nutrients and the growth of vegetation essential for the development of SPS. These problems have already been reported in cattle systems grazing on clay soils such as those of the cattle SES in other parts of the tropics of Mexico (Figueroa et al., 2020). Structural and nutritional soil deficiencies in cattle pastures would lead the rural population to pressure less disturbed surrounding ecosystems (Rudel et al., 2015; Romano-Armada et al., 2016), with repercussions on climate change (Arango et al., 2020).

In geographical terms, this research showed that the SPS in the Mezcalapa and Norte regions are the most advanced in sustainability. The north of Chiapas can scale up SPS through capacity building, technical assistance, and ongoing financial and commercial support (Valdivieso-Pérez et al., 2019). In this sense, the management, organization, and ecosystem service outcomes of the associations located in the northern part of the state (A5 and A6) could serve as a learning model for other associations in the Silvopastoral Network. However, addressing the substantial social and economic inequalities remains challenging to promote more sustainable production and commercialization scenarios (Awokuse et al., 2024). This highlights the leading role that institutions and government regulations play in making the scaling up of SPS possible (Avalos et al., 2024; Sunariyo and Firdausi, 2024).

The prominent family participation in regions that preserve Maya culture in our case study (e.g., Meseta Comiteca, Selva Lacandona, Istmo Costa, and Maya) has already been reported in other Maya areas of Mexico (Gurri et al., 2022; Pérez-Volkow et al., 2023). Most family members, especially men and children, have roles in agricultural and livestock production to preserve traditions, meet food needs, and generate income that dignifies livelihoods in environments of extreme poverty (Camacho-Villa et al., 2021). In this sense, this component, on the one hand, shows organizational strength and a desire to preserve and transmit traditions, and on the other, highlights the financial vulnerability of producers who need to involve more family members in production to avoid paying external labor costs, which leads to fewer employment opportunities in Chiapas.

After characterizing and operationalizing the cattle SES that emerges from the Silvopastoral Network, it was identified that with external technical and financial support, sustainability can advance in three directions: (1) ensuring that in SPS, the cattle density is increased to a maximum of six to ten cattle per hectare, along with the frequency of rotation and the availability of trees and shrubs in living fences; (2) including diversification strategies that allow for the commercialization of live cattle, meat, milk, cheese, and other products and services; (3) reactivating the participation of women in production to strengthen the local governance system and assign roles associated with the commercialization of new products. For Mexico, the approaches must combine strategies involving society and politicians (Figueroa and Galicia, 2021), including participatory methodologies, knowledge dissemination, and awareness-raising (Sánchez-Romero et al., 2021). Other strategies that have been less explored include consumer preferences (Vargas-Bello-Pérez et al., 2017), changes in eating habits (Ibarrola-Rivas and Granados-Ramírez, 2017; Tello et al., 2020), perspectives on meat quality (Parra-Bracamonte et al., 2021), and purchase decisions based on the type of production system. Including these approaches in environmental agendas can promote the sustainability of management throughout the food system, considering the current planetary crisis (Läderach et al., 2021).

4.3 Study limitations

This study has two potential limitations. First, although we did not detect probabilistic issues related to sample selection within the analysis, it is important to acknowledge that since all surveyed producers belong to the same network, their practices and opinions are subject to biases and may not adequately represent other producers or producer groups. Future studies could address this issue by including more inclusive sampling methods, such as stratified or simple random sampling. Nevertheless, we were able to robustly characterize an SES in six regions and assess sustainability through local knowledge of cattle ranching communities that consistently face challenging social, economic, and ecological conditions to produce and market cattle.

Second, the data collected through the surveys provide valuable and relevant social, ecological, and economic information related to the SES, focusing on an alternative production model to extensive systems. However, the questionnaires could have incorporated many other variables for a broader interpretation of challenges and potentials. This was particularly limiting for economic issues, as the need for more information on market fluctuations, access to credit, and other financing sources prevented an assessment of the cost-benefit ratio associated with SPS. Since financial motivations can be key drivers of change in territories, future research must explore the economic viability of the region's alternative and agroecological production systems. Nevertheless, the information analyzed reflects the local perspective on what is essential to consider regarding cattle ranching sustainability. This study ensured respect for local visions, valued traditional knowledge and provided practical perspectives for other tropical contexts.

5 Conclusion

The SES conceptual framework helped characterize an agri-food system based on cattle grazing within silvopastoral systems, identify socio-ecological impacts, and devise more sustainable strategies for tropical cattle ranching. The operationalization of the conceptual framework through the measurement of sustainability using variables that represent action situations and generate management, organizational, and ecosystem service outcomes allowed for the identification of common factors that hinder the development of cattle activities and to recognize issues that can be generalized to other similar contexts in Latin America. The challenges include excessive intermediaries, working conditions that exacerbate poverty, and the need for differentiated and competitive marketing chains to sell silvopastoral products, which currently limit small-scale cattle ranching in tropical conditions. Additionally, low productive diversification exposes producers to high dependence on cattle grazing and excluding women from decision-making and productive activities weakens the potential to produce and sell other types of products. It is crucial to address the challenges and improve the sustainability of the cattle SES through technical and financial support from the involved governmental institutions and the strengthening of the local governance system. This work bridges gaps in cattle research by highlighting that sustainable intensification through establishing silvopastoral systems is possible within specific ranges, and sustainability can be defined, understood, and built by producers from the territories.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the (patients/participants or patients/participants legal guardian/next of kin) was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

DF: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. LG: Conceptualization, Supervision, Writing – review & editing, Funding acquisition, Methodology. VÁ: Conceptualization, Writing – review & editing, Supervision. BD: Writing – review & editing, Resources.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1446965/full#supplementary-material

References

Altieri, M. A., Nicholls, C. I., Henao, A., and Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agron. Sustain. Dev.* 35, 869–890. doi: 10.1007/s13593-015-0285-2

Amarilla, S. M., Yanosky, A., and Villalba, J. (2019). "San Rafael Reserve, Paraguay: key social stakeholders and sustainability scenarios through environmental governance approaches" in Social-ecological systems of Latin America: complexities and challenges (Cham: Springer), 229–246.

Apan-Salcedo, G. W., Jiménez-Ferrer, G., Nahed-Toral, J., Pérez-Luna, E., and Piñeiro-Vázquez, Á. T. (2021). Masificación de sistemas silvopastoriles: un largo y sinuoso camino. *Trop. Subtrop. Agroecosyst.* 24:103. doi: 10.56369/tsaes.3524

Arango, J., Ruden, A., Martinez-Baron, D., Loboguerrero, A. M., Berndt, A., Chacón, M., et al. (2020). Ambition meets reality: achieving GHG emission reduction targets in the livestock sector of Latin America. *Front. Sustain. Food Syst.* 4:65. doi: 10.3389/fsufs.2020.00065

Astier, M., Speelman, E. N., López-Ridaura, S., Masera, O. R., and Gonzalez-Esquivel, C. E. (2011). Sustainability indicators, alternative strategies, and trade-offs in peasant agroecosystems: analysing 15 case studies from Latin America. *Int. J. Agric. Sustain.* 9, 409–422. doi: 10.1080/14735903.2011.583481

Avalos, I., Sepulveda, C., Betanzos, J. E., Jimenes-Trujillo, J. A., Perez-Sanches, E., and Escobedo, A. (2024). Institutional arrangements in the promotion of sustainable livestock: an approach from the case of beef and dairy cattle production chains in Jalisco, Chiapas, and Campeche. *Front. Sustain. Food Syst.* 8:1310507. doi: 10.3389/fsufs.2024.1310507

Awokuse, T., Lim, S., Santeramo, F., and Steinbach, S. (2024). Robust policy frameworks for strengthening the resilience and sustainability of agri-food global value chains. *Food Policy* 127:102714. doi: 10.1016/j.foodpol.2024.102714

Balvanera, P. (2012). Los servicios ecosistémicos que ofrecen los bosques tropicales. *Ecosistemas* 21, 136–147.

Barnaud, C., Corbera, E., Muradian, R., Salliou, N., Sirami, C., Vialatte, A., et al. (2018). Ecosystem services, social interdependencies, and collective action. *Ecol. Soc.* 23. doi: 10.5751/ES-09848-230115

Berkes, F., and Folke, C. (1998). Linking social and ecological systems: management practices and social mechanisms for building resilience. Cambridge, MA: Cambridge University Press.

Berrouet, L. M., Machado, J., and Villegas-Palacio, C. (2018). Vulnerability of socio—ecological systems: a conceptual framework. *Ecol. Indic.* 84, 632–647. doi: 10.1016/j.ecolind.2017.07.051

Boillat, S., Scarpa, F. M., Robson, J. P., Gasparri, I., Aide, T. M., Aguiar, A. P. D., et al. (2017). Land system science in Latin America: challenges and perspectives. *Curr. Opin. Environ. Sustain.* 26-27, 37–46. doi: 10.1016/j.cosust.2017.01.015

Boval, M., Angeon, V., and Rudel, T. (2017). Tropical grasslands: a pivotal place for a more multi-functional agriculture. *Ambio* 46, 48–56. doi: 10.1007/s13280-016-0806-5

Broom, D. M. (2016). Livestock sustainability and animal welfare. Proceedings of the 1st International Meeting of Advances in Animal Science. 1–15

Calderón, J., Nahed, J., Sánchez, B., Herrera, O., Aguilar, R., and Parra, M. (2012). Estructura y función de la cadena productiva de carne de bovino en la ganadería ejidal de Tecpatán, Chiapas, México. *Avances en Investigación Agropecuaria* 16, 45–62.

Calle, A. (2020). Partnering with cattle ranchers for forest landscape restoration. *Ambio* 49, 593–604. doi: 10.1007/s13280-019-01224-8

Camacho-Villa, T. C., Martinez-Cruz, T. E., Ramírez-López, A., Hoil-Tzuc, M., and Terán-Contreras, S. (2021). Mayan traditional knowledge on weather forecasting: who contributes to whom in coping with climate change? *Front. Sustain. Food Syst.* 5:618453. doi: 10.3389/fsufs.2021.618453

Chará, J., Rivera, J., Barahona, R., Murgueitio, E., Calle, Z., and Giraldo, C. (2019). Intensive silvopastoral systems with *Leucaena leucocephala* in Latin America. *Trop. Grassl.* 7, 259–266. doi: 10.17138/TGFT(7)259-266

Chung, M. G., and Liu, J. (2019). Telecoupled impacts of livestock trade on non-communicable diseases. *Glob. Health* 15, 43–12. doi: 10.1186/s12992-019-0481-y

Colding, J., and Barthel, S. (2019). Exploring the social-ecological systems discourse 20 years later. *Ecol. Soc.* 24:2. doi: 10.5751/ES-10598-240102

Comisión Nacional Forestal. (2021). Inventario Nacional Forestal y de Suelos 2009–2014. Available at: https://www.inegi.org.mx/rnm/index.php/catalog/390

Consejo Nacional de Evaluación de la Política de Desarrollo Social de México. (2018). Medición de la pobreza, serie 2008–2018.

Coppock, D. L., Fernández-Giménez, M., Hiernaux, P., Huber-Sannwald, E., Schloeder, C., Valdivia, C., et al. (2017). "Rangeland systems in developing nations: conceptual advances and societal implications" in Rangeland systems: processes, management, and challenges. ed. D. D. Briske (Cham: Springer), 661.

De Vos, A., Biggs, R., and Preiser, R. (2019). Methods for understanding social-ecological systems: a review of place-based studies. *Ecol. Soc.* 24:16. doi: 10.5751/ES-11236-240416

Delgado, C., Rosegrant, M., and Meijer, S. (1999). The coming livestock revolution. *Choices* 14, 1–5. doi: 10.22004/ag.econ.131712

Diario Oficial de la Federación (2019). Acuerdo por el que se emiten los Lineamientos de Operación del Programa Crédito Ganadero a la Palabra: Secretaría de Agricultura y Desarrollo Rural Available at: https://dof.gob.mx/nota_detalle.php?codigo=5550950&fecha=22/02/2019#gsc.tab=0.

Diario Oficial de la Federación (2020). Acuerdo por el que se emiten las reglas de operación del Programa Sembrando Vida, para el ejercicio fiscal 2020: Secretaría de Bienestar Available at: https://dof.gob.mx/nota_detalle.php?codigo=5608917&fecha=28/12/2020#gsc.tab=0.

Dumont, B., Ryschawy, J., Duru, M., Benoit, M., Chatellier, V., Delaby, L., et al. (2019). Associations among goods, impacts and ecosystem services provided by livestock farming. *Animal* 13, 1773–1784. doi: 10.1017/S1751731118002586

Duru, M., Moraine, M., and Therond, O. (2015). An analytical framework for structuring analysis and design of sustainable ruminant livestock systems. *Anim. Front.* 5, 6–13. doi: 10.2527/af.2015-0041

Figueroa, D., Galeana-Pizaña, J. M., Núñez, J. M., Gómez, C. A., Hernández-Castro, J. R., del Mar Sánchez-Ramírez, M., et al. (2021). Assessing drivers and deterrents of deforestation in Mexico through a public policy tool. The adequacy of the index of economic pressure for deforestation. *Forest Policy Econ.* 133:102608. doi: 10.1016/j.forpol.2021.102608

Figueroa, D., and Galicia, L. (2021). Ganadería bovina con menor costo ambiental: un desafío entre lo personal y lo político. *Soc. Ambiente* 24, 1–17. doi: 10.31840/sya.vi24.2218

Figueroa, D., Galicia, L., and Suárez Lastra, M. (2022). Latin American cattle ranching sustainability debate: an approach to social-ecological systems and spatial-temporal scales. *Sustainability* 14:8924. doi: 10.3390/su14148924

Figueroa, D., Ortega-Fernández, P., Abbruzzini, T. F., Rivero-Villlar, A., Galindo, F., Chavez-Vergara, B., et al. (2020). Effects of land use change from natural Forest to livestock on soil C, N and P dynamics along a rainfall gradient in Mexico. *Sustainability* 12:8656. doi: 10.3390/su12208656

Food and Agriculture Organization of the United Nations (2017a). Livestock production in Latin America and the Caribbean: Regional Office for Latin America and the Caribbean Available at: http://www.fao.org/americas/perspectivas/produccion-pecuaria/en/.

Food and Agriculture Organization of the United Nations. (2017b). América Latina y el Caribe: Panorama de la seguridad alimentaria y nutricional. Sistemas alimentarios sostenibles para poner fin al hambre y la malnutrición, 2016. Available at: https://iris.paho.org/handle/10665.2/33680

Food and Agriculture Organization of the United Nations. (2018). Food and Agriculture Organization Corporate Statistical Database (FAOSTAT). Available at: http://www.fao.org/faostat/en/#home

Food and Agriculture Organization of the United Nations. (2019). Food and Agriculture Organization Corporate Statistical Database (FAOSTAT). Available at: http://www.fao.org/faostat/en/#home

Fuentealba, B., and González-Esquivel, C. (2016). "Sistemas silvopastoriles tradicionales en México" in Etnoagroforestería en México.

Galeana-Pizaña, J. M., Couturier, S., Figueroa, D., and Jiménez, A. D. (2021). Is rural food security primarily associated with smallholder agriculture or with commercial agriculture? An approach to the case of Mexico using structural equation modeling. *Agric. Syst.* 190:103091. doi: 10.1016/j.agsy.2021.103091

Galeana-Pizaña, J. M., Couturier, S., and Monsivais-Huertero, A. (2018). Assessing food security and environmental protection in Mexico with a GIS-based food environmental efficiency index. *Land Use Policy* 76, 442–454. doi: 10.1016/j.landusepol.2018.02.022

Gallo, C. S., and Tadich, T. G. (2018). "Perspective from Latin America" in Advances in agricultural animal welfare science and practice. ed. J. A. Mench (Cambridge, MA: Woodhead Publishing), 197–218.

Garrett, R. D., Niles, M. T., Gil, J. D., Gaudin, A., Chaplin-Kramer, R., Assmann, A., et al. (2017). Social and ecological analysis of commercial integrated crop livestock systems: current knowledge and remaining uncertainty. *Agric. Syst.* 155, 136–146. doi: 10.1016/j.agsy.2017.05.003

Gil, J. D. B., Reidsma, P., Giller, K., Todman, L., Whitmore, A., and van Ittersum, M. (2019). Sustainable development goal 2: improved targets and indicators for agriculture and food security. *Ambio* 48, 685–698. doi: 10.1007/s13280-018-1101-4

González-Quintero, R., Barahona-Rosales, R., Bolívar-Vergara, D. M., Chirinda, N., Arango, J., Pantévez, H. A., et al. (2020). Technical and environmental characterization of dual-purpose cattle farms and ways of improving production: a case study in Colombia. *Pastoralism* 10, 1–14. doi: 10.1186/s13570-020-00170-5

Gordon, I. J. (2018). Livestock production increasingly influences wildlife across the globe. *Animal* 12, s372–s382. doi: 10.1017/S1751731118001349

Gurri, F. D., Ruiz-García, W., Vallejo-Nieto, M. I., and Molina-Rosales, D. O. (2022). Effect of seasonality on food access in subsistence and cash dependent Maya households in large and small rural communities in Yucatan, Mexico. *Agroecol. Sustain. Food Syst.* 46, 56–81. doi: 10.1080/21683565.2021.1930623

Hajjar, R., Newton, P., Adshead, D., Bogaerts, M., Maguire-Rajpaul, V. A., Pinto, L. F., et al. (2019). Scaling up sustainability in commodity agriculture: transferability of governance mechanisms across the coffee and cattle sectors in Brazil. *J. Clean. Prod.* 206, 124–132. doi: 10.1016/j.jclepro.2018.09.102

Herrera-Franco, G., Alvarado-Macancela, N., Gavín-Quinchuela, T., and Carrión-Mero, P. (2018). Participatory socio-ecological system: Manglaralto-Santa Elena, Ecuador. *Geol. Ecol. Landsc.* 2, 303–310. doi: 10.1080/24749508.2018.1481632

Herrero, M., Henderson, B., Havlík, P., Thornton, P. K., Conant, R. T., Smith, P., et al. (2016). Greenhouse gas mitigation potentials in the livestock sector. *Nat. Clim. Change* 6, 452–461. doi: 10.1038/nclimate2925

Herrero, M., Mason-D'Croz, D., Godde, C. M., Palmer, J., Thornton, P. K., and Gill, M. (2018). "Livestock, land, and the environmental limits of animal source-food consumption" in Science forum 2018 background papers (Rome, Italy: CGIAR Independent Science and Partnership Council).

Ibarrola-Rivas, M. J., and Granados-Ramírez, R. (2017). Diversity of Mexican diets and agricultural systems and their impact on the land requirements for food. *Land Use Policy* 66, 235–240. doi: 10.1016/j.landusepol.2017.04.027

Instituto Nacional de Estadística Geografía e Información (INEGI). (2017). Encuesta Nacional Agropecuaria. Available at: https://www.inegi.org.mx/programas/ena/2017/. Accessed date: 03-14-2024.

Läderach, P., Pacillo, G., Thornton, P., Osorio, D., and Smith, D. (2021). Food systems for peace and security in a climate crisis. *Lancet Planet. Health* 5, e249–e250. doi: 10.1016/S2542-5196(21)00056-5

Lerner, A. M., Zuluaga, A. F., Chará, J., Etter, A., and Searchinger, T. (2017). Sustainable cattle ranching in practice: moving from theory to planning in Colombia's livestock sector. *Environ. Manag.* 60, 176–184. doi: 10.1007/s00267-017-0902-8

Leslie, H. M., Basurto, X., Nenadovic, M., Sievanen, L., Cavanaugh, K. C., Cota-Nieto, J. J., et al. (2015). Operationalizing the social-ecological systems framework to assess sustainability. *Proc. Natl. Acad. Sci. U.S.A.* 112, 5979–5984. doi: 10.1073/pnas.1414640112

Limburg, K., O'Neill, R. V., Costanza, R., and Farber, S. (2002). Complex system and valuation. *Ecol. Econ.* 41, 409–420. doi: 10.1016/S0921-8009(02)00090-3

Magliocca, N. R., Ellis, E. C., Allington, G. R. H., De Bremond, A., Dell'Angelo, J., Mertz, O., et al. (2018). Closing global knowledge gaps: producing generalized knowledge from case studies of social-ecological systems. *Glob. Environ. Change* 50, 1–14. doi: 10.1016/j.gloenvcha.2018.03.003

Manning, P., van der Plas, F., Soliveres, S., Allan, E., Maestre, F. T., Mace, G., et al. (2018). Redefining ecosystem multifunctionality. *Nat. Ecol. Evol.* 2, 427–436. doi: 10.1038/s41559-017-0461-7

Marinidou, E., Jiménez-Ferrer, G., Soto-Pinto, L., Ferguson, B. G., and Saldívar-Moreno, A. (2018). Proceso de adopción de árboles en áreas ganaderas: estudio de casos en Chiapas, México. *Soc. Ambiente* 18, 201–230. doi: 10.31840/sya.v0i18.1885

Marshall, G. (2015). A social-ecological systems framework for food systems research: accommodating transformation systems and their products. *Int. J. Commons* 9, 881–908. doi: 10.18352/ijc.587

McGinnis, M. D., and Ostrom, E. (2014). Social-ecological system framework: initial changes and continuing challenges. *Ecol. Soc.* 19:30. doi: 10.5751/ES-06387-190230

Murgueitio, E., Calle, Z., Uribe, F., Calle, A., and Solorio, B. (2011). Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. *For. Ecol. Manag.* 261, 1654–1663. doi: 10.1016/j.foreco.2010.09.027

Newberry, D. (2014). Why are there cattle in the conservation area? Social barriers to biofuel governance in Brazil. *Geoforum* 54, 306–314. doi: 10.1016/j.geoforum.2013.08.011

Ostrom, E. (1990). Governing the commons: the evolution of institutions for collective action. Cambridge, MA: Cambridge University Press.

Ostrom, E. (2007). A diagnostic approach for going beyond panaceas. *Proc. Natl. Acad. Sci. U.S.A.* 104, 15181–15187. doi: 10.1073/pnas.0702288104

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science* 325, 419–422. doi: 10.1126/science.1172133

Parra-Bracamonte, G. M., Lopez-Villalobos, N., Vázquez-Armijo, J. F., Magaña-Monforte, J. G., Martínez-González, J. C., and Moreno-Medina, V. R. (2021). Perspectivas Del Consumidor Mexicano Sobre La Calidad De La Carne De Bovino. *Trop. Subtrop. Agroecosyst.* 24:85. doi: 10.56369/tsaes.3702

Partelow, S. (2018). A review of the social-ecological systems framework. *Ecol. Soc.* 23. doi: 10.5751/ES-10594-230436

Partelow, S., Senff, P., Buhari, N., and Schlüter, A. (2018). Operationalizing the social-ecological systems framework in pond aquaculture. *Int. J. Commons* 12, 485–518. doi: 10.18352/ijc.834

Pérez-Volkow, L., Diemont, S. A., Selfa, T., Morales, H., and Casas, A. (2023). From rainforest to table: Lacandon Maya women are critical to diversify landscapes and diets in Lacanjá Chansayab, Mexico. *Agric. Hum. Values* 40, 259–275. doi: 10.1007/s10460-022-10352-z

Poteete, A., Janssen, M. A., and Ostrom, E. (2010). Working together: collective action, the commons, and multiple methods in practice. Princeton, NJ: Princeton University Press.

Rao, I. M., Peters, M., Castro, A., Schultze-Kraft, R., White, D., Fisher, M., et al. (2015). LivestockPlus: the sustainable intensification of forage-based agricultural systems to improve livelihoods and ecosystem services in the tropics. *Trop. Grassl.* 3, 59–82. doi: 10.17138/TGFT(3)59-82

Rivera, J. E., Serna, L., Arango, J., Barahona, R., Murgueitio, E., Torres, C. F., et al. (2023). "Silvopastoral systems and their role in climate change mitigation and nationally determined contributions in Latin America" in Silvopastoral systems of Meso America and Northern South America (Cham: Springer), 25–53.

Rivera-Huerta, A., Güereca, L. P., and Lozano, M. (2016). Environmental impact of beef production in Mexico through life cycle assessment. *Resour. Conserv. Recycl.* 109, 44–53. doi: 10.1016/j.resconrec.2016.01.020

Rivera-Huerta, A., Rubio Lozano, M. D. L. S., Padilla-Rivera, A., and Güereca, L. P. (2019). Social sustainability assessment in livestock production: a social life cycle assessment approach. *Sustainability* 11:4419. doi: 10.3390/su11164419

Romano-Armada, N., Amoroso, M. J., and Rajal, V. B. (2016). "Impacts of agriculture in Latin America: problems and solutions" in Bioremediation in Latin America. eds. A. Alvarez and M. Polti (Cham: Springer), 1–16.

Rudel, T. K., Paul, B., White, D., Rao, I. M., Van Der Hoek, R., Castro, A., et al. (2015). LivestockPlus: forages, sustainable intensification, and food security in the tropics. *Ambio* 44, 685–693. doi: 10.1007/s13280-015-0676-2

Ryschawy, J., Dumont, B., Therond, O., Donnars, C., Hendrickson, J., Benoit, M., et al. (2019). An integrated graphical tool for analysing impacts and services provided by livestock farming. *Animal* 13, 1760–1772. doi: 10.1017/S1751731119000351

Sánchez-Romero, R., Balvanera, P., Castillo, A., Mora, F., García-Barrios, L. E., and González-Esquivel, C. E. (2021). Management strategies, silvopastoral practices and socioecological drivers in traditional livestock systems in tropical dry forests: an integrated analysis. *For. Ecol. Manag.* 479:118506. doi: 10.1016/j.foreco.2020.118506

Servicio de Información Agroalimentaria y Pesquera. (2018). Estadísticas de Producción ganadera para México. Available at: https://www.gob.mx/siap/acciones-y-programas/produccion-pecuaria

Servicio de Información Agroalimentaria y Pesquera-Secretario de Agricultura y Desarrollo Rural. (2020). Panorama agroalimentario 2020. Available at: https://www.inforural.com.mx/wp-content/uploads/2020/11/Atlas-Agroalimentario-2020.pdf

Solorio, S. F. J., Wright, J., Franco, M. J. A., Basu, S. K., Sarabia, S. L., Ramírez, L., et al. (2017). "Silvopastoral systems: best agroecological practice for resilient production systems under dryland and drought conditions" in Quantification of climate variability, adaptation and mitigation for agricultural sustainability. eds. M. Ahmed and C. Stockle (Cham: Springer), 233–250.

Soto-Pinto, L., Anzueto, M., Mendoza, J., Ferrer, G. J., and de Jong, B. (2010). Carbon sequestration through agroforestry in indigenous communities of Chiapas, Mexico. *Agrofor. Syst.* 78, 39–51. doi: 10.1007/s10457-009-9247-5

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., et al. (2018). Options for keeping the food system within environmental limits. *Nature* 562, 519–525. doi: 10.1038/s41586-018-0594-0

Sunariyo, S., and Firdausi, R. Z. (2024). Community-based agro-silvopastoral systems: integrating forestry, agriculture, and livestock for sustainable rural development in Forest regions. *SERUNAI* 4, 45–57. Available at: https://jurnal.idfos.or.id/index.php/serunai

Tauro, A., Gómez-Baggethun, E., García-Frapolli, E., Chavero, E. L., and Balvanera, P. (2018). Unraveling heterogeneity in the importance of ecosystem services. *Ecol. Soc.* 23. doi: 10.5751/ES-10457-230411

Tello, J., Garcillán, P. P., and Ezcurra, E. (2020). How dietary transition changed land use in Mexico. *Ambio* 49, 1676–1684. doi: 10.1007/s13280-020-01317-9

The Montpellier Panel (2013). Sustainable intensification: a new paradigm for African agriculture. London: Agriculture for Impact.

Torralba, M., Fagerholm, N., Hartel, T., Moreno, G., and Plieninger, T. (2018). A social-ecological analysis of ecosystem services supply and trade-offs in European wood-pastures. *Sci. Adv.* 4:eaar2176. doi: 10.1126/sciadv.aar2176

Tscharntke, T., Clough, Y., Wanger, T. C., Jackson, L., Motzke, I., Perfecto, I., et al. (2012). Global food security, biodiversity conservation and the future of agricultural intensification. *Biol. Conserv.* 151, 53–59. doi: 10.1016/j.biocon.2012.01.068

Valdivieso-Pérez, I. A., Toral, J. N., Vázquez, Á. T. P., Hernández, F. G., Ferrer, G. J., and Cano, D. G. (2019). Potential for organic conversion and energy efficiency of conventional livestock production in a humid tropical region of Mexico. *J. Clean. Prod.* 241:118354. doi: 10.1016/j.jclepro.2019.118354

Van Loon, J., Woltering, L., Krupnik, T. J., Baudron, F., Boa, M., and Govaerts, B. (2020). Scaling agricultural mechanization services in smallholder farming systems: case studies from sub-Saharan Africa, South Asia, and Latin America. *Agric. Syst.* 180:102792. doi: 10.1016/j.agsy.2020.102792

van Soest, H. L., van Vuuren, D. P., Hilaire, J., Minx, J. C., Harmsen, M. J., Krey, V., et al. (2019). Analysing interactions among sustainable development goals with integrated assessment models. *Glob. Transit.* 1, 210–225. doi: 10.1016/j.glt.2019.10.004

Vargas-Bello-Pérez, E., Miranda-de la Lama, G. C., Lemos Teixeira, D., Enríquez-Hidalgo, D., Tadich, T., and Lensink, J. (2017). Farm animal welfare influences on markets and consumer attitudes in Latin America: the cases of Mexico, Chile and Brazil. *J. Agric. Environ. Ethics* 30, 697–713. doi: 10.1007/s10806-017-9695-2

Villanueva-López, G., Martínez-Zurimendi, P., Casanova-Lugo, F., Ramírez-Avilés, L., and Montañez-Escalante, P. I. (2015). Carbon storage in livestock systems with and without live fences of *Gliricidia sepium* in the humid tropics of Mexico. *Agrofor. Syst.* 89, 1083–1096. doi: 10.1007/s10457-015-9836-4

Westholm, L., and Ostwald, M. (2019). Food production and gender relations in multifunctional landscapes: a literature review. *Agrofor. Syst.* 94, 359–374. doi: 10.1007/s10457-019-00397-1