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Integrating social dynamics in the participatory modeling of small-scale cattle farmers' perceptions and responses to climate variability in the Yucatan Peninsula, Mexico

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Climate variability poses multifaceted challenges for livestock production. Rising temperatures and shifting rainfall patterns impact crop and pasture yields, reduce water availability, and contribute to livestock diseases, particularly affecting small-scale cattle producers dependent on climate-sensitive resources. Sustainable livestock farming promotes integrating best practices to enhance productivity while responsibly managing natural resources, but often overlooks relevant social dynamics. Social factors are excluded when promoting and studying the adoption of practices for sustainable cattle farming. This study aims to understand the factors and interactions between the social, animal and ecological systems within the small-scale cattle socioecosystems in the southern region of the Yucatan Peninsula, exploring cattle farmers' perspectives on climate change, as well as their strategies and responses to extreme events like drought. Using fuzzy cognitive maps and scenario development as participatory and reflection methodologies, we found a conceptual gap between climate change and drought, indicating a lack of sustainable adaptive thinking toward these challenges. Interestingly, we found that local social organization, cultural dynamics, and spiritual practices are equally significant factors than technical and environment-oriented changes to the management of ranches in shaping an optimal cattle farming scenario. Our findings reveal that the management of cattle farms involves complex interplay among technical, environmental, social, political, and cultural elements, highlighting the inherent need to consider social values and preferences as fundamental components of sustainability. This study establishes the initial groundwork for employing participatory modeling with social actors engaged in the small-scale cattle context in Yucatan. The goal is to emphasize the importance of the social dimension in the general management of the small-scale cattle socioecosystem, thus in promoting sustainable cattle farming.

KEYWORDS
social dynamics, small-scale cattle famers, drought, climate variability, fuzzy cognitive maps, Yucatan Peninsula

1 Introduction

The Yucatán Peninsula, located in the south eastern region of Mexico, is comprised of three states: Campeche, Yucatán, and Quintana Roo. Projected decreases in average annual rainfall and increased frequency and intensity of droughts makes this region highly vulnerable to the adverse consequences of climate change (Márdero et al., 2012; de la Barreda et al., 2020). For the broader Maya region, an increase in average temperature (2–3.5°C) by 2090 is expected (Magrin et al., 2007). For the Yucatán Peninsula, projections indicate a significant reduction in annual precipitation (10–15%) and even up to 30% during dry and rainy seasons compared to the average for 1980–1999 (Bárcena et al., 2010). In 2020, Yucatan state experienced a severe drought followed by a nearly 2 months longer than usual rainy season, resulting in the rainiest year since 1941 (CONAGUA, 2020). Considering that in both the Mexican tropics and Yucatan state, extensive grazing of cattle is the predominant form of livestock farming (Bacab et al., 2013), these decreases in rainfall poses threats, including more severe droughts, reduced agricultural productivity, a decline in food production, and an increased risk of forest fires (Galindo, 2007).

Livestock farming, particularly cattle farming for meat production, faces a paradox. Notwithstanding suffering the negative effects and consequences of climate change, it is one of the main productive activities that contributes to this phenomenon, therefore it has the potential to mitigate it (Ibrahim et al., 2010; Gerber et al., 2013; Mottet et al., 2016). This type of production model involves greenhouse gas emissions, land-use change from forests and jungles to pasturelands, loss of biodiversity, poor animal health and welfare, low animal productivity, soil degradation, pesticide pollution, and socioeconomic polarization (Gerber et al., 2013; Palma, 2014; Cheng et al., 2022). However, through sustainable livestock production systems, we could potentially establish an environmentally, socially, economically, and culturally appropriate strategy that conserves ecosystems and promotes the well-being of people.

This is the case for Yucatán where slightly over one-third of the Yucatán territory is occupied by cattle farming. Due to the geographical and climatic characteristics of Yucatán, the most common production model in the region is extensive grazing based on monocultures of low-productivity pastures, which have a high environmental impact (Bacab et al., 2013; Zepeda Cancino et al., 2021). Although most cattle farming is carried out by small-scale producers who rely solely on forage and native vegetation as the food base (Gamboa-Mena et al., 2005), the majority of Yucatán's cattle herd is concentrated in the eastern region of the state in units with higher technical and productive capacity. Small-scale producers are considered one of the most vulnerable groups in the face of climate change (Donatti et al., 2019). These producers heavily depend on agriculture and livestock for their food security and income, but they often encounter resource limitations and tend to reside in remote areas. Climate change poses an additional threat to small-scale producers, exacerbating the already insecure conditions in which they live.

Under the tropical geographical, climatic, and productive conditions of the Yucatan Peninsula, increasing temperatures and changes in rainfall patterns affect crop and pasture yields, reduce water supply and quality, and contribute to the emergence and/or reemergence of diseases in livestock (PAECC, 2014; Cheng et al., 2022). While the projected climate change effects might not pose an evident threat to Mexican livestock farming as a whole (Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación y Organización de las Naciones Unidas para la Agricultura y la Alimentación, 2014), the occurrence of extreme climate events does indeed endanger the livestock system as Murray-Tortarolo and Jaramillo (2019) report drought impact over a million of affected animals in 2011. These extreme events represent long-term costs (Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación y Organización de las Naciones Unidas para la Agricultura y la Alimentación, 2014), in particular for small-scale producers, whose economic, environmental, and social stability largely depends on rainfall patterns and climate-sensitive resources (Berlanga, 2013; Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación y Organización de las Naciones Unidas para la Agricultura y la Alimentación, 2014; Faisal et al., 2021).

The Mexican government is working to design and promote initiatives in different states and regions with the aim of transitioning toward a sustainable livestock farming. These initiatives have focused on strategies to support and technology adoption to define goals regarding greenhouse gas emissions reduction and enhance livestock productivity. However, these are still early actions and need to be scaled up and implemented to address the specific needs of each territory (IICA, 2020). However, the historical context shows that the Mexican field has benefited from welfare measures that have failed to change the poverty situation of farmers, as they have prioritized the efficiency of agricultural and livestock processes and increasing productivity. As the expansion of agricultural frontiers, the increased use of agrochemicals, and the dependency on external inputs continue, the negative impact on ecosystems and increased pressure on them, paradoxically results in increased vulnerability of those with fewer resources and diminished development opportunities (Garcia-Frapolli et al., 2013). Most government programs that support cattle producers focus on the technical aspects that, while relevant to the livestock sector, these measures do not consider sustainability aspects and are often built on the idea that one strategy fits all, ignoring the particularities present when examining a local-scale context.

In response to the need for climate change mitigation and adaptation programs, alternative models to conventional cattle production have been proposed. Livestock sustainability has been proposed as technologies and good production practices that contribute to improving the productivity, profitability, and competitiveness of the livestock subsector without affecting ecosystems, while preserving the raw materials and natural resources used in production. It aims to reduce greenhouse gas emissions, protect and restore soil, capture carbon, conserve biodiversity, and recharge aquifers – essential elements in the fight against the adverse effects of climate change (IICA, 2020).

Silvopastoral systems (SPS) being an example of an cattle production alternative model since they have proved to increase productivity, profitability, and competitiveness while delivering environmental positive effects (Bacab et al., 2013; Broom et al., 2013; Mancera et al., 2018; Pérez-Lombardini et al., 2021; Zepeda Cancino et al., 2021). Despite the scientific evidence of their economic and environmental benefits, their adoption is still very low in southern Mexico and Central America (Dagang and Nair, 2003; Zepeda-Cancino et al., 2016; Cosío Ruiz, 2020). Institutionally, barriers to transitioning to sustainable cattle production include inadequate coordination, lack of awareness, technical, and environmental capabilities in the value chain, and absence of appropriate financing schemes (IICA, 2020). Meanwhile, producers face challenges due to limited knowledge, lack of implementation support, initial capital needs, and high labor requirements (Dagang and Nair, 2003; Zepeda-Cancino et al., 2016; Cosío Ruiz, 2020).

It is common for problems associated with natural resources and their management to stem from a lack of recognition that social systems and ecosystems are complexly interconnected (Folke et al., 2010). Efforts made for mitigation and adaptation to the challenges faced by livestock farming through technological innovations and good practices may overlook aspects of equity, distribution, power, and politics, underestimating the role they play in transformation processes and the potential of individuals as agents of change (O'Brien, 2018) rather than as individuals subject to change. Along with the challenges that small-scale cattle farmers face, the transformation of their production systems represents an adaptive challenge that requires a new way of perceiving the problem and solutions.

Adaptation can be understood as the process of adjustment to actual or expected climate and its effects (IPCC, 2014). While the concept of adaptability encompasses technical aspects, it also recognizes the importance of beliefs, values, and worldviews in how problems and solutions are perceived and addressed (O'Brien, 2018). By generating new approaches where the internal dimensions of individuals are considered as potential triggers of broader cultural changes capable of achieving a transformation toward sustainability (Wamsler and Osberg, 2022), this work contributes to identifying the direction in which actions can be oriented toward cattle production sustainability.

Understanding the role of values in transformations toward sustainability requires exploring values as dynamic components within the evolution of socio-ecosystems (Rosenberg, 2022). Therefore, in this work, we study animal production systems as socio-ecosystems with high uncertainty, whose management and functioning are not only conditioned by technical innovations and evidence-based science but also by the social dimension and values of the involved producers (Funtowicz and Ravetz, 1994; Stirling, 2015). We use fuzzy cognitive maps (FCMs) as a tool for participatory modeling and collective reflection to gain a better understanding of the vision, knowledge, and management of ten small-scale cattle producers regarding their production systems.

The framework of the three spheres of transformation by O'Brien and Sygna (2013) (see Figure 1) represents the interaction of different components that comprise a system and interact within the realms of practice, politics, and personal spheres to promote or constrain sustainability. The cosmologies, values, and beliefs present and past are located in the personal sphere; the middle field represents the political sphere where social, political, cultural, and ecological structures and systems enable or constrain the changes in the practical sphere, which is located at the core where we find actions, technical solutions, and measurable and monitorable behavioral changes. This interaction among spheres is dynamic and nonlinear, and its understanding it is essential to recognize users as part of the system they manage. This framework has been applied for studying the influence of knowledge in climate change in the behavior of people traveling by air by exploring personal and political/societal incentives and barriers to air travel reduction (Jacobson et al., 2020), and as well as for understanding the transformation from conventional to organic farming in the UK (James and Brown, 2018). In this study the operationalization of the framework of the three spheres of transformation through the reflection on FCMs constructed by the producers allowed an insight to the context of the local cattle farming socio-ecosystem and to understand how, why, and where the relationships between the three spheres are taking place.

This study aims to contribute to the understanding of shifts toward sustainable cattle farming by exploring *How are small-scale cattle farmers responding to climate variability?*; taking into account the values that influence the vision and decision-making of producers at the personal, cultural, organizational, and institutional levels (Fairweather, 2010; Voinov et al., 2014). So far, sustainable livestock farming has mostly been addressed from a technical-environmental perspective, and the well-being of the producer has been understood mostly in terms of increased productivity and profitability of the system (Ibrahim et al., 2010; Murgueitio et al., 2011, 2013; Nahed-Toral et al., 2013). The article proceeds by describing the use of FCM for participatory modeling of the small-scale cattle farms' management as a primary data collection. Subsequently, the results describe the producers' perception of the identified issues, along with the strategies implemented to address them. The development of an ideal livestock scenario is presented, interpreted in the context of the three spheres of transformation. Finally, the discussion is organized around the practical, political, and personal spheres, concluding with reflections on integrating the social dimension into processes of transitioning toward sustainable livestock practices.

2 Methods

2.1 Study area

The state of Yucatán is characterized by a predominant vegetation of low deciduous jungle, and in the southern zone, there are higher, more humid, and floodable jungles. The prevailing climate is warm sub-humid with concentrated rainfall during the summer and a high percentage of winter rain. Additionally, in most parts of the peninsula, two dry periods are experienced: the pre-summer or spring drought, which lasts from 2 to 4 months, and the intra-summer or *canícula*, which extends from late July to September (Estrada-Medina and Cobos-Gasca, 2014; Orellana et al., 2019).

Unlike the central and northern parts of the state, the southern zone features high karstic hills known as interior valleys. Although these hills represent only 1% of the state's surface area, they have poor

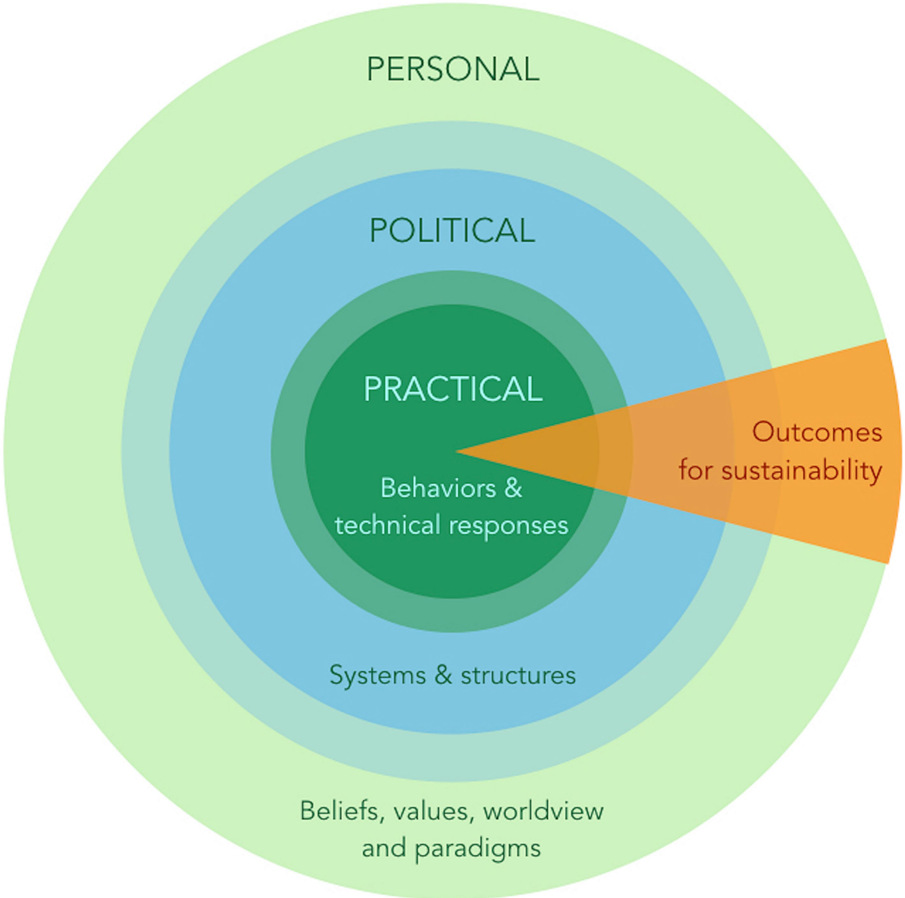

FIGURE 1
Three spheres of transformation. Adapted from O'Brien and Sygna (2013), same diagram but with different colors from the original.

internal drainage, making them highly susceptible to flooding during the rainy season, storms, and hurricanes (Bautista et al., 2010). The study was conducted in the southern part of Tzucacab (see Figure 2), which is one of the 17 municipalities that make up the southern region of Yucatán, Mexico, specifically in the locality of Corral. Corral is an *ejido* (communal land) founded approximately 75 years ago mainly by *chicleros* (rubber tappers) and farmers. Its population is approximately 400 people, of which 82.7% are Mayan speakers (INEGI, 2020). Similar to most of the state, the municipality of Tzucacab does not have surface water streams, so groundwater is the main source for consumption, agricultural and industrial activities (Delgado et al., 2010). Additionally, this region has natural or artificial formations of rainwater reservoirs known as *aguadas*. These are utilized by cattle farmers as watering holes for their animals and play a vital role in supporting wildlife and mitigating floods.

2.2 Small-scale cattle farmers

The recruiting of the participants was done through the local cattle association in an assembly where the project was presented and producers were invited to participate in themes of cattle farming and management practices. The participants in this study are the producers that were willing to take part of this work, all of them small-scale producers, predominantly from the locality of Corral and neighboring villages. When working in participatory processes, often used in qualitative research involving exploration of complex systems, it does not always require large sample sizes as in quantitative research. Small sample sizes allows the research to focus on the depth and richness of information gathered from the 10 participating cattle-farmers.

According to the typology used by the Ministry of Agriculture and Rural Development of the Mexican government, a small-scale cattle producer is considered someone who has 35 animal units or their equivalent in another species. According to Robles Berlanga (2018), a small-scale producer is someone whose family plays a central role in the production, where a variable portion of their income comes from agricultural work, either in kind or money, and their livelihood involves crop cultivation and animal husbandry.

Despite having varying herd sizes and land extents, all participants engage in cattle farming and consider themselves small-scale producers. The participants' primary activity is cattle farming, aimed at producing and selling calves of approximately 6 months of age for subsequent fattening and sale in the eastern part of the state or the northern region of the country. However, they have diverse profiles in terms of age, language, sources of income, herd size, land area, and geographical location within the community (see Table 1 and consult in Supplementary material).

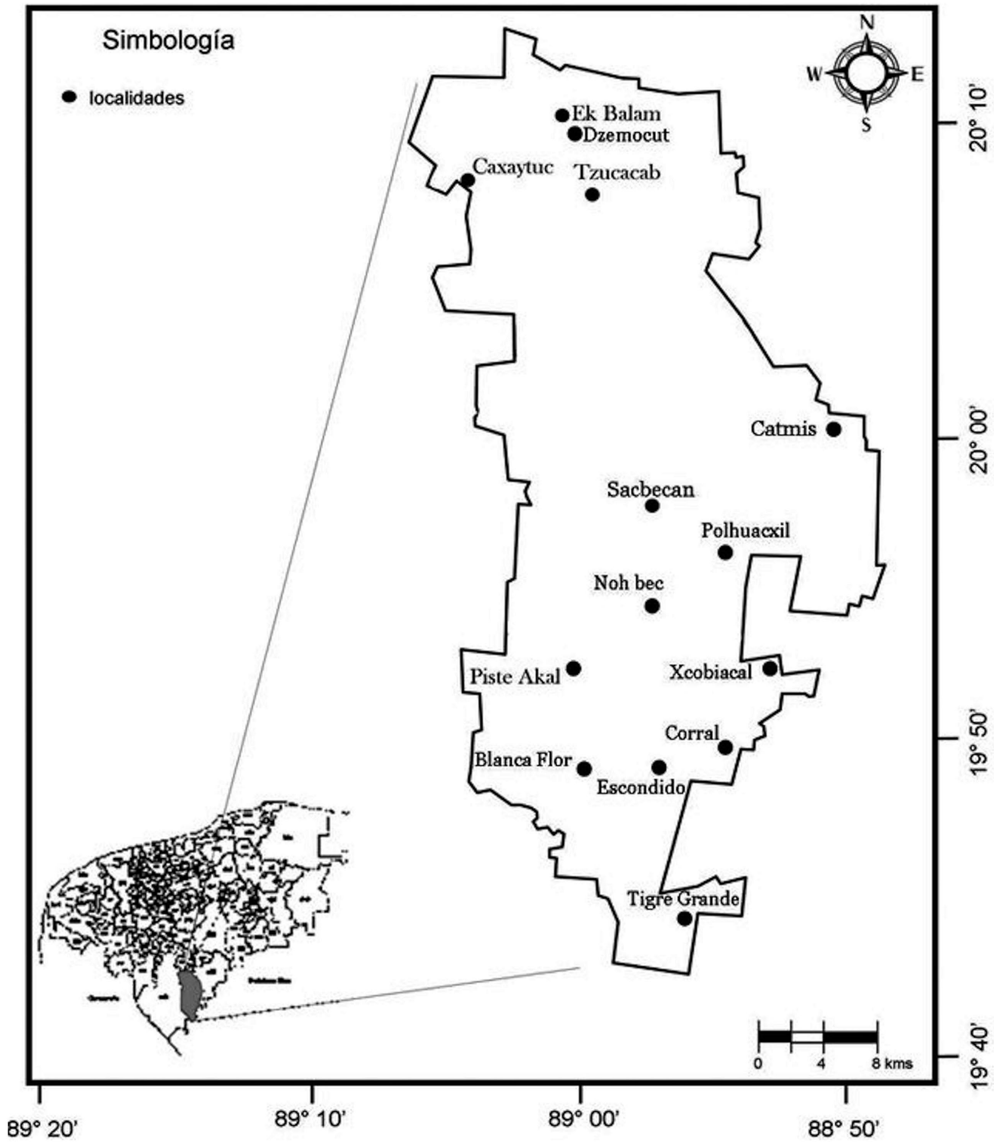

FIGURE 2
Map of Corral, Tzucacab. Source: Zamora-Crescencio et al. (2009): Flora útil y su manejo en el cono sur del estado de Yucatán, México.

2.3 Data collection

The fieldwork was conducted during the periods between January and March 2020 and December 2020 and March 2022. During the field visits, a mix of informal conversations and four semi-structured interviews (consult in Supplementary material) were conducted as a general scope to understand and explore the perspectives of the producers regarding their ranch management, the local livestock situation, and the environmental context. A questionnaire (consult in Supplementary material) was also administered to 28 cattle farmers during a meeting at the Local Livestock Association of Tzucacab to gather information on the impact of drought and rainfall and the strategies they implement to mitigate them and their associated costs. Based on the information obtained from the questionnaire, interviews, and observations during the field visits, a preliminary list of 44 concepts was defined for the construction of Fuzzy Cognitive Maps (FCMs) (consult in Supplementary material). Due to the COVID-19 pandemic, some follow-up interviews were conducted via telephone, and although informed consent was obtained, not all of them could be audio-recorded. The producers verbally consented to the use of the information collected, as well as the use of the models and pictures obtained during the participatory processes.

Fuzzy Cognitive Maps (FCMs) are a modeling technique that, through graphical representations, reflect causal reasoning to explain complex phenomena. They originated from cognitive maps proposed by Axelrod (1976) and were further developed by Kosko (1986) as a semiquantitative and dynamic method to structure expert knowledge (Gray et al., 2015). These representations reflect different ways of conceptualizing and understanding the same reality based on diverse knowledge derived from various contexts (Fairweather, 2010). The person constructing the FCM is considered an expert who determines the important variables that affect the system, whether they are

TABLE 1 Producers' characteristics.

ID	Age	Language	Education level	Cattle farming experience (years)	No. Animals	Land area (ha)	Location	Income sources
CAR-1	65	Spanish, Mayan	Primary	30	25	36	High	1. Ranch, 2. Sale of fodder, 3. Agriculture
CRE-2	50	Spanish, Mayan	Primary	21	50	100	High	1. Ranch, 2. Sale of other products, 3. Agriculture, 4. Government
FEL-3	70	Spanish, Mayan	None	40	17	27	Low	1. Ranch and 2. Family
FER-4	46	Spanish	Primary	15	13	34	Low	1. Ranch, 2. Agriculture, 3. Government
FID-5	75	Spanish, Mayan	None	40	15	32	Low	1. Ranch
JIL-6	42	Spanish, Mayan	Secondary	8	18	22	High	1. Ranch, 2. Sale of other products, 3. Agriculture, 4. Government
MAN-7	47	Spanish, Mayan	Primary	30	40	39	High	1. Ranch 2. Off-ranch work
MOI-8	47	Spanish	Secondary	30	15	28	High	1. Ranch, 2. Sale of fodder, 3. Sale of other products, 4. Off-ranch work
ROQ-9	79	Spanish, Mayan	None	50	11	20	High	1. Ranch, 2. Family, 3. Off-ranch work
VIC-10	62	Spanish, Mayan	None	40	20	27	Low	1. Ranch, 2. Agriculture, 3. Family

In Location, "high" refers to highlands, and "low" refers to flood-prone areas. In Income sources "ranch" refers to livestock sale; "sale of fodder" refers to cut fodder produced by themselves; "agriculture" refers to sale of corn; "government" refers to support programs; "sale of other products" refers mainly to citrus fruits and honey, and to a lesser extent citrus grafts, avocados, sheep and pigs; "off-ranch work" refers to working in other ranch or masonry.

concepts, quantities, processes, actions, or abstract ideas (Özesmi and Özesmi, 2004), and links the variables (Gray et al., 2015) with the strength of each relationship (Özesmi and Özesmi, 2004).

Two workshops were organized, one for the construction of the FCMs and another one for discussing them and developing an alternative scenario. During the first workshop, the objective of the activity was shared with the participants, the process of constructing FCMs was explained, and ten individual FCMs were constructed using the guiding question: "How do you manage your ranch in scenarios of climatic uncertainty: rainfall and drought?" (see Figures 3A–C). Different colors were used to denote positive and negative causal relationships, and three different sticker colors were used to represent the strength of the connections, with each color corresponding to a different intensity level (low, medium, high).

During the second workshop, a Group Map (GM) (see following section for detailed information) was presented as a shared model to validate, add, or modify concepts and links that the producers considered relevant, as well as to collectively develop an ideal scenario. Scenario building is a narrative-based method that describes possible and multiple future versions of a system, from which assumptions are generated regarding a variable or group of variables that can shape a change in the future system (Hichert et al., 2022). The development of the ideal scenario unfolded through discussing the GM and by taking note of the changes, obstacles, and desirable elements that producers identified in their activity as cattle farmers (see Figure 3D).

2.4 Analysis

2.4.1 Group map

To graphically represent the overall structure of the production system management, a Group Map (GM) was generated by performing arithmetic operations on the adjacency matrices of the individual FCMs. The weight of the connections between components is the number of actors who mentioned that relationship in their map (Vanwindekens et al., 2013). The relationships mentioned by two or more individuals, with a weight greater than or equal to 2, were selected for analysis. The central nodes based on betweenness centrality were visualized for further analysis.

2.4.2 Visualization and analysis of FCMs

The FCMs were analyzed as directed networks. The modeling software Mental Modeler (Gray et al., 2013) was used for digitization and obtaining adjacency matrices. Subsequently, they were analyzed using the open-source software platform Cytoscape v3.7.1 (Shannon et al., 2003), which allows for the visualization and formatting of complex networks using the following network analysis metrics: betweenness centrality, degree centrality, in-degree centrality, and out-degree centrality. We used different measures of centrality to identify and understand which elements have the greatest influence or weight in the FCMs of the 10 producers. Betweenness centrality measures the frequency with which a node lies on the shortest paths between pairs of nodes, so it can be said that these are the components that have the greatest influence on the overall management of a

FIGURE 3
FCM construction workshop in the community Corral, Tzucacab, Yucatan. **(A)** Producers could choose the cards with the components they considered most important in their systems and drew the connections with different colors to refer to positive or negative links. **(B)** Facilitation on the construction of the FCM to a producer while others watched and assisted the process. **(C)** Part of the process of construction where producers started building their maps by themselves. **(D)** GM with the interventions made during the second workshop; in green post-its he added components, in orange post-its ideas generated by the ideal scenario development.

system. Despite being directed networks, we also considered overall degree centrality (total number of connections) to determine which components are more generally connected in each FCM. Finally, we considered the in-degree centrality, considering that the centrality of these nodes is given by other nodes, unlike out-degree centrality, which is determined by the node itself.

2.4.3 Ideal scenario and three spheres of transformation model interpretation

The three spheres of transformation model of O'Brien and Sygna's (2013) was adapted and enriched with the FCMs and the information generated during the ideal scenario development. In the practical sphere: management practices considered responsible for changes in climate conditions and land quality. In the political sphere: aspects related to the social and political organization of the producers and within government support programs. In the personal sphere: religious aspects and social values. The effects, results and consequences of the former aspects were considered as an adaptation of the sustainability outcomes presented in the original model.

3 Results

3.1 Centrality of FCMs

The 10 FCMs can be seen in a bigger format in Supplementary materials. Based on betweenness centrality, the central nodes followed by the number of FCMs in which they appear (in parenthesis) are: grass (4), cattle (3), money (2), and drought (1). According to betweenness centrality, these components have the greatest influence on the overall management of systems in the face of climate variability events. The components that are more generally connected in each FCM (overall degree centrality), were the following: money (5), grass (2), cut fodder (2), herbicide (1), drought (1). Finally, the central nodes by in-degree centrality are: money (7), grass (4), and cattle (1). In cases where more than 10 central nodes are mentioned, it is because there were FCMs with more than one central component (see examples of four FCM in Figure 4 and centrality results in Table 2).

3.2 Perception of the problem

Based on the questionnaires and FCMs, we identified that drought is the problem affecting all producers every year, regardless of whether it occurs regularly or with varying duration or intensity. Drought can be defined as a prolonged period of reduced or absence of rainfall, which impacts human activities. From the questionnaire administered to 28 producers, 27% mentioned that drought affects them little, and very few are partially or not affected at all. For the rest of the producers, drought has a strong impact, mainly on the economic aspects and the well-being of the animals. 59% of the producers mentioned that the main obstacle to dealing with drought is the difficulty in accessing water due to various reasons: (1) they do not have a well; (2) they have a well, but: (a) it does not work, (b) it does not provide enough water, (c) the cost of fuel for pumping water is too high. For 41%, access to water is not a problem because they have one or more wells, irrigation systems, and, in the particular case of one producer, a rainwater harvesting system.

3.3 Interpretation of the FCMs

3.3.1 Individual FCMs

60% of the producers identified changes over time as the cause of variability in rainfall (CAR1, JIL6, MOI8, ROQ9), drought (JIL6, MAN7, MOI8), and flooding (JIL6, VIC10). Of the four ranches located in low-lying and/or flood-prone areas, three included the flooding component in their FCMs (FER4, FID5, VIC10). FEL3 did not include flooding as a component in their map, despite being one of the producers most affected by prolonged flooding on their land. In all FCMs, drought was identified as the cause for using at least one form of supplementary feed with exception of one producer who did not represent any form of supplementation but mentioned renting a paddock to feed their cattle. The feeding strategies are presented next followed by the frequency with which it was mentioned (in parentheses): cut fodder (5), poultry manure (4), stubble or low-quality forage (3), grazing in areas with conserved vegetation or woodland (1). As a result of drought, only 3 producers have and use an irrigation system (CRE2, MAN7, ROQ9), 2 haul water for their cattle, and another producer relies on natural water sources on their land.

Regarding the social values and preferences mentioned in the FCMs, we found that 60% of the producers associated their love for the ranch with their motivation for carrying out their work, and in one case, it was linked to social organization. Another producer (FEL3) positively linked prevention and order with money, and camaraderie with a greater possibility of accessing programs and support. In terms of emotions mentioned, the same producer (FEL3) associated programs and support with despair, and another producer (ROQ10) associated corn with the well-being of the family, happiness, and tranquility. Finally, only one producer (CRE2) performs a ritual or ceremony, a thanksgiving mass, aimed at obtaining good harvests.

3.3.2 Group map

During the workshop, the following components were added to the GM: pasture rental, corn, water source, cow manure, citrus, pigs, bees, and woodland (see Figure 5). The components with the highest betweenness centrality in the GM are: money, clearing land, grass, and cattle. The component with the highest number of connections (degree centrality) is money, and the central components in terms of incoming and outgoing connections are drought and money, respectively.

In a simplified way, the flow of the GM can be read from left to right, interpreting the effects of climatic variability on the system. When rainfall occurs, grass experiences a positive impact, resulting in increased cattle production and economic remuneration. Likewise, rainfall leads to increased weed growth, which requires measures to control it and ensure better grass growth. These additional actions generate economic expenses and require more work. On the other hand, during periods of drought, a series of actions are implemented to compensate for the scarcity of forage. These actions include cut fodder, supplementing with poultry manure, using lower-quality forage such as corn stubble, or irrigating pastures. All these measures also entail economic costs, while the surplus of cut fodder is the only element that generates economic income in addition to cattle. Additionally, the practice of clearing land (manually cutting weeds) to improve grass growth is the only action that, in some cases, is considered an economic investment.

3.4 Responses and strategies for drought

Based on the questionnaires and FCMs, we identified that small-scale cattle farmers employ various strategies during drought. These strategies include supplementing feed with cut fodder and poultry manure, grazing in woodland areas, and supplementing with low-quality forage bales or corn stubble. Some farmers reduce their herd size through cattle sales and use irrigation systems to maintain grass supply. Less common strategies include sowing new pasture, land clearing for maintenance or establishing new paddocks, renting pastures, and supplementing with silage.

Regarding the economic implications of these strategies (see Figure 6), the questionnaires revealed that in 75% of the cases, farmers produce their own cut fodder, and among those who supplement with cut fodder according to the FCMs, 66% do not incur additional expenses since the farmers produce the fodder in their own farms. On the other hand, 63% of farmers who supplement with "maloa" or corn stubble, do have to buy it and therefore have associated costs. Concentrated feed always represents an economic expense as it is an external industrial input. The costs of irrigation vary for farmers with shared or individual systems and depend on whether solar panels or conventional power are used. As for land clearing for weed control, although it incurs labor costs, few farmers perceive it as an investment.

3.5 Socialization and projection of an ideal cattle-farming scenario

The interpretation of the following results into the three spheres model is shown in Figure 7. For the ideal scenario, the producers expressed their desire for timely rainfall and a reduction in drought. They observed that excessive deforestation negatively affects the humidity and freshness of the wooded areas. Additionally, the low fertility of mechanized lands poses a challenge as it results in low yields of commercial corn unless chemical fertilizers are used. The producers expressed their interest in reviving the rituals of *Ch'a' ch'aak*

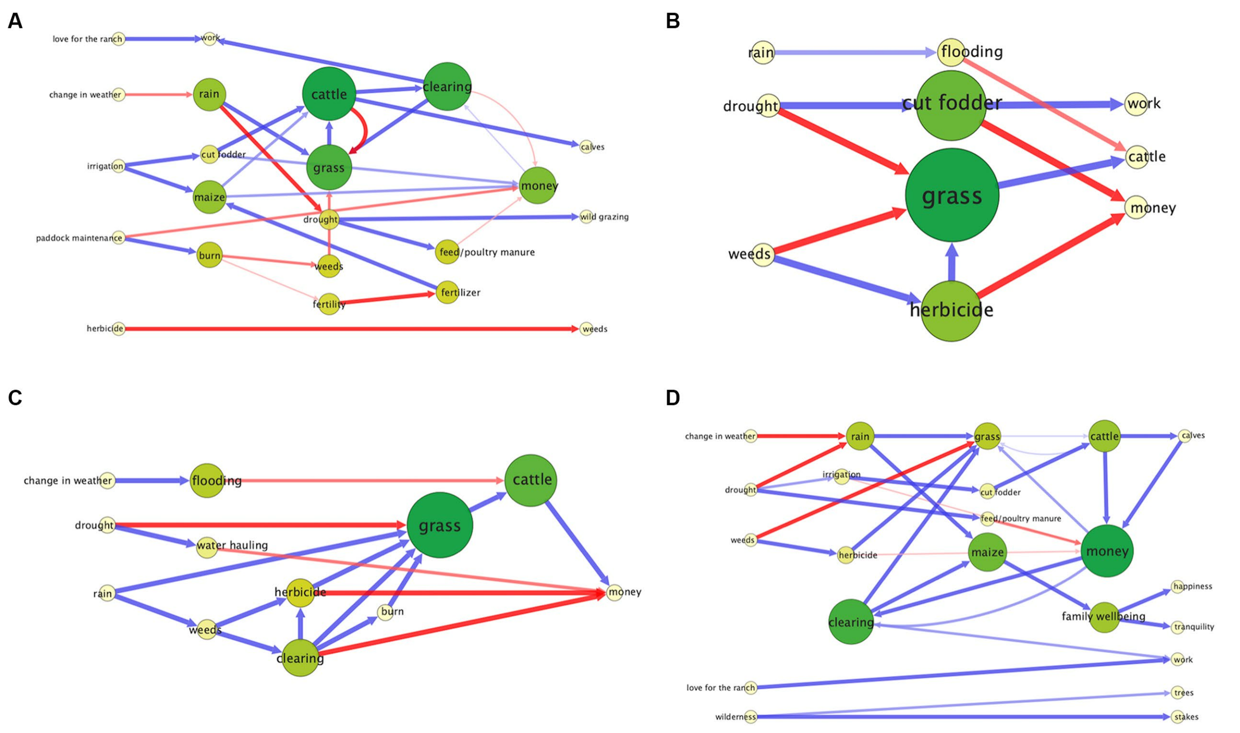

FIGURE 4
Examples of betweenness centrality in individual FCMs: **(A)** FCM with cattle as central node (upper left); **(B)** FCM with grass as central node (upper right); **(C)** FCM grass as central node (lower left); **(D)** FCM with money as central node (lower right). The size and color of the nodes correspond to their betweenness centrality; larger size and darker color indicate higher centrality. Connections that represent a positive causal relationship are shown in blue, indicating that as one node increases, the linked node also increases (+A → +B). Connections that represent a negative causal relationship are shown in red, indicating that as one node increases, the linked node decreases (+A → −B). The thickness and opacity of the connections correspond to the weight of the causal relationship, with thicker and stronger connections representing stronger intensity. Nodes connected with money under a negative link represent an economic expense, while when the link is positive, it signifies an economic income. When money is positively linked, it represents an investment. In the case of work, the weight of the links refers to the amount of effort required to carry out an activity. In the case of "grass," it refers to grass, and when the links associated with this component are positive, they signify practices or strategies that increase the quantity or availability of "grass," while negative relationships indicate higher consumption of "grass" and, therefore, a lower quantity of this resource or an impact leading to a decrease in the resource. "Clearing" is used as manual weed control.

TABLE 2 **FCM components by different types of centrality: betweenness centrality (number of shortest paths between any given pair of nodes that pass through a node in a graph) that tells us the amount of influence the node has over the flow of the system; degree centrality (total number of edges), outdegree (number of edges that the node directs to others) and indegree centrality (number of ties directed to the node).**

ID	Betweenness centrality	Degree centrality	Outdegree centrality	Indegree centrality
CAR-1	Cattle	Money	Cattle, weeding	Money
CRE-2	Money	Money	Drought	Money
FEL-3	Cattle	Grass	Herbicide, burn	Money, grass
FER-4	Grass	Cut fodder	Herbicide	Money, cattle
FID-5	Grass	Cut fodder, herbicide	Herbicide, weeds, cut fodder, drought	Grass
JIL-6	Cattle	Money	Rain, change in weather	Money
MAN-7	Drought	Drought	Drought	Money
MOI-8	Grass	Money	Change in weather, drought, water well, rain	Money
ROQ-9	Money	Money	Drought, cattle, money, weeding	Grass
VIC-10	Grass	Grass	Weeding	Grass
Most frequent	Grass	Money	Drought	Money

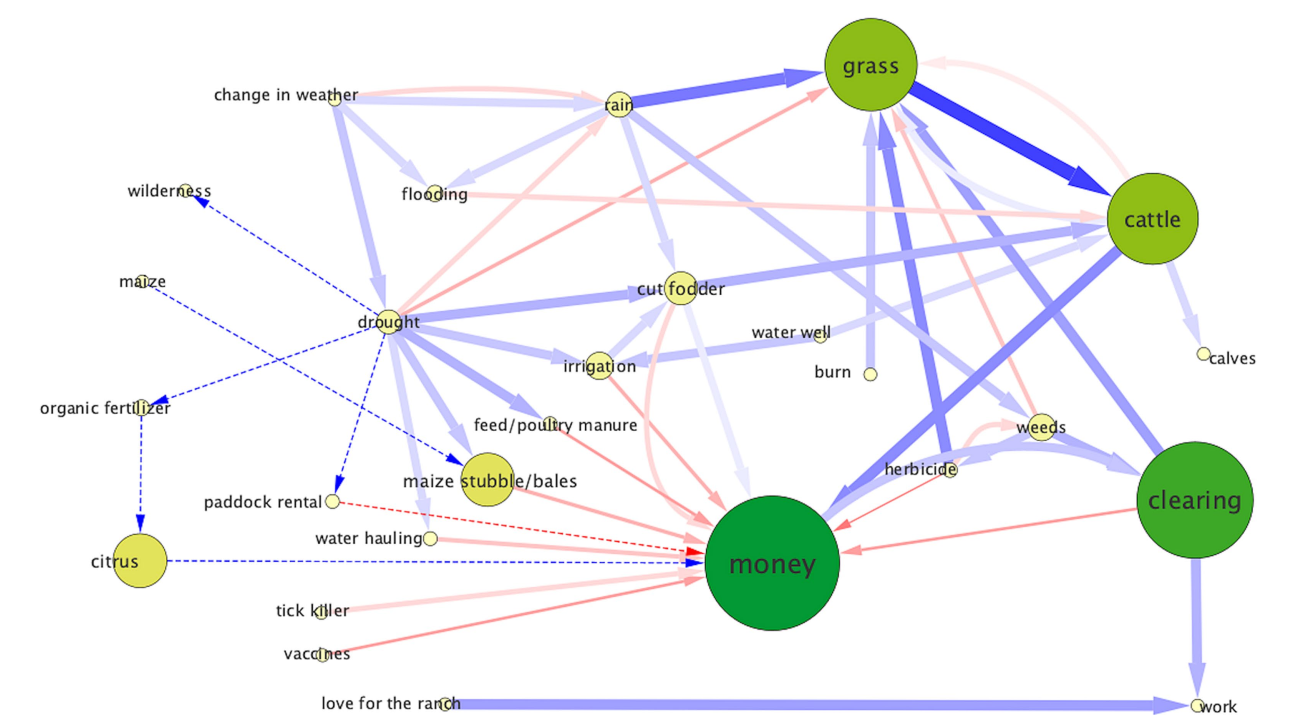

FIGURE 5
Group map (GM). Colorless nodes connected by a dashed line correspond to the concepts added by producers during the workshop.

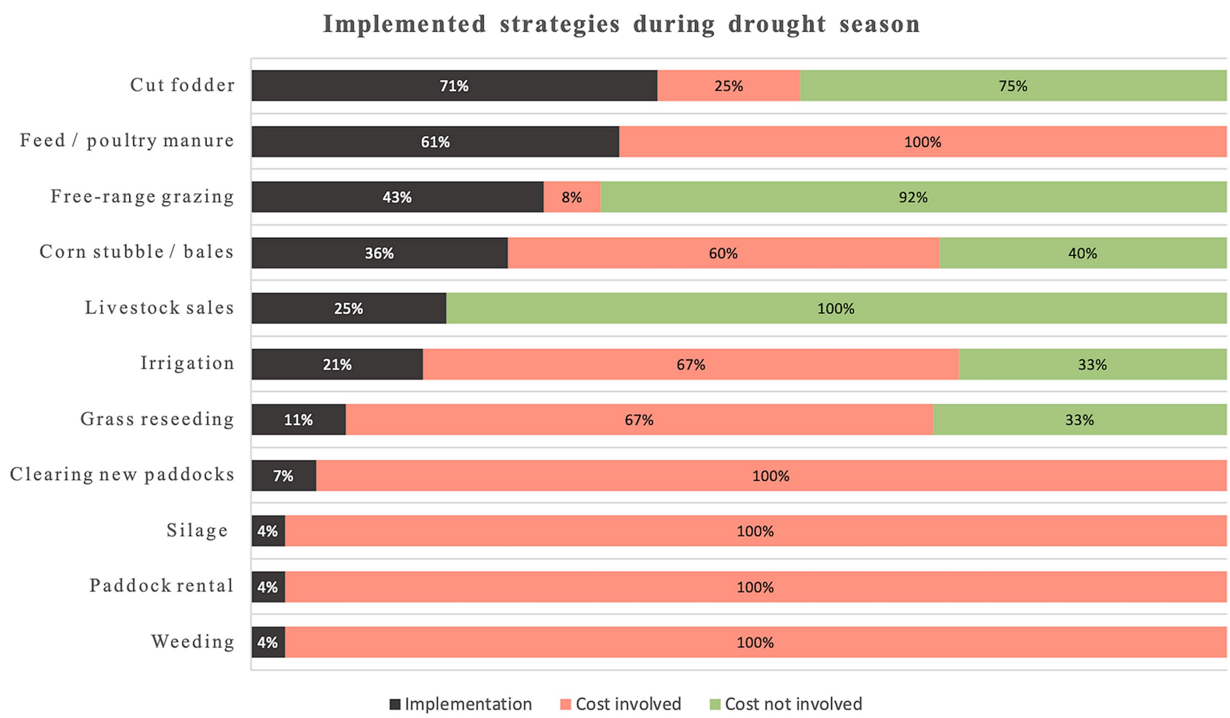

FIGURE 6
Implemented strategies during drought season and their economic implications (questionnaire data). In black the implementation percentage according to frequency. In colors we can see the proportion in which the strategy involves or does not involve a cost.

(rain god) and *Jaanlil kool* as offerings to the land and crops. However, they noted that these traditions are declining due to the influence of emerging religions.

The identified obstacles include the management and implementation of government support programs. The producers criticize the uneven allocation of these programs, which primarily benefit large producers in the eastern livestock zone of the state. Their wish would be to receive economic support, cattle, cattle insurance, and agricultural implements, as well as training in silage techniques. Lack of efficiency in the management of government support, corruption at the local and regional levels, delays in the delivery of assistance, and the lack of attention to small producers in remote areas were also mentioned. Lastly, the producers emphasize the importance of collective work but identified obstacles such as individualism, land fragmentation, lack of organization, and migration.

4 Discussion

4.1 Perceptions and responses to climate variability – practical sphere

In the present study, drought, although in some cases associated with "changes in the weather," is interpreted as a technical inability to access and properly manage water. In other words, when discussing drought as the main problem that farmers face, instead of questioning and directing the attention toward analyzing its origin and finding a root solution, producers seek ways to address the consequences generated by the technical incapability that the lack of water access represents. Meanwhile, in two studies conducted in the same region, other producers do attribute the decrease in rainfall and changes in seasonal patterns directly to climate change (Márdero et al., 2014; Metcalfe et al., 2020). Although we found similarities in the perception of increased ambient temperature as a consequence of regional deforestation, as reported in the study by Márdero et al. (2014), even within the same region or municipality, it is possible to obtain different results among neighboring localities or within the same community, as the construction of perceptions and responses to the same phenomenon such as climate change can vary (Fierros-González and López-Feldman, 2021).

As seen in Figure 6, climate variability, manifested in more intense and/or prolonged drought seasons, economically destabilizes small-scale production units. The apparent mechanism for cattle farmers to compensate for the low availability of water and therefore of feed is through strategies that involve higher economic costs, such as feed supplementation or maintaining pasture through irrigation. Producing and supplementing feed with cut fodder proves to be a common strategy used during drought (Idrissou et al., 2020; Sánchez-Romero et al., 2021). While some producers mentioned supplementing feed with self-cultivated cut fodder or maize stubble, the majority resort to purchasing feed (poultry manure) from the local livestock association, which partially subsidizes the feed from government entities.

A similar case in South Africa, addressing drought strategies, suggests that producer participation in networks or cooperatives enhances resilience. The results indicate a need for increased

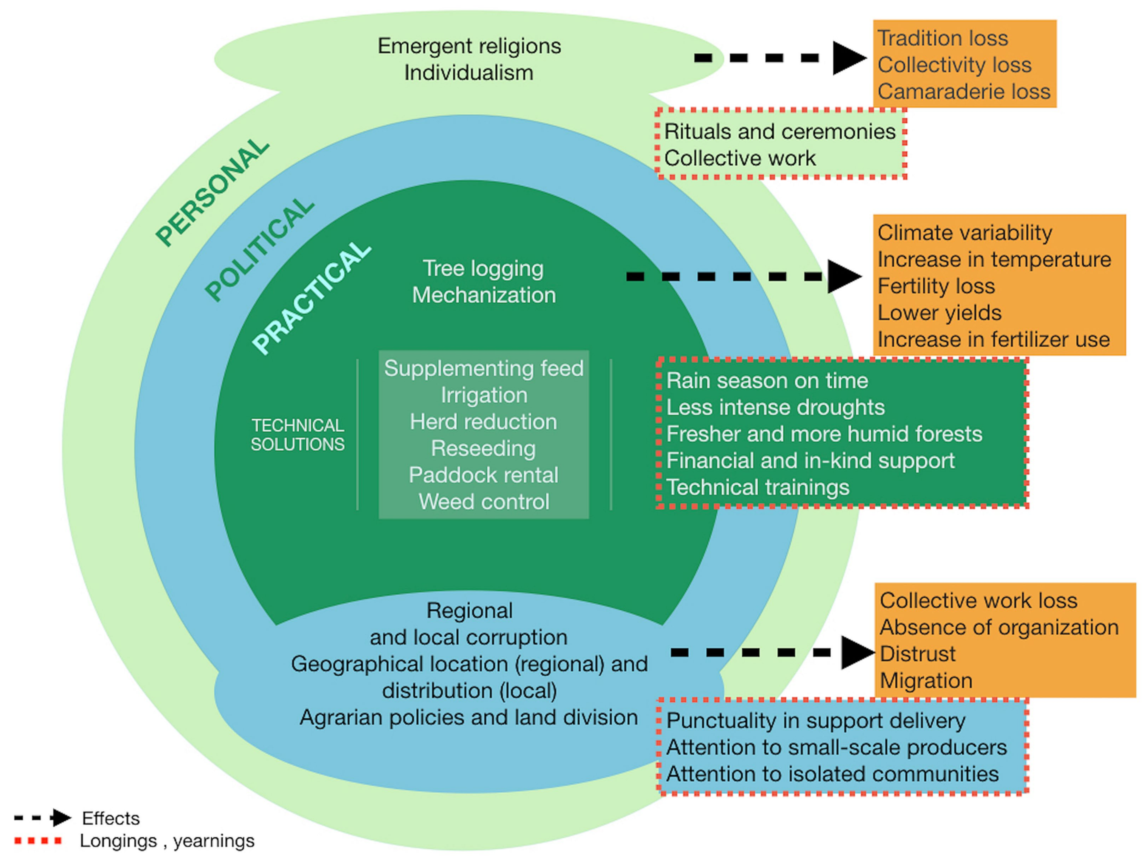

FIGURE 7
Adaptation of the three spheres of transformation diagram. Black dashed arrows show the effects of the referred aspects. In red dashed boxes are the desired things or aspects that producers long for.

government support, particularly in providing credits and promoting involvement in collaborative networks (Bahta and Myeki, 2021). Similarly, Idrissou et al. (2020) mention transhumance as an adaptation strategy to drought in tropical zones in West Africa, whereas in Corral, few cattle farmers utilize their forested areas for grazing. The use of forests as an alternative feeding method during droughts is a strategy that could be promoted as a more sustainable form of silvopasture to avoid establishing new pastures. Despite being a model that is environmentally and socially sustainable (Pérez-Lombardini et al., 2021), for the farmers, secondary vegetation, or what is called "monte," is seen as a hindrance to cattle (Sánchez-Romero et al., 2021), rather than a resource that can be used as year-round forage.

There is no clear trend toward implementing adaptation or mitigation strategies; actions are taken in a way that allows immediate coping with the situation without anticipating a future crisis. The type of support available for cattle farmers, primarily through technical solutions, aims to provide temporary rather than medium or long-term resolutions by analyzing structural causes. This enables them to resolve immediate issues, but not to address climate variability through adaptation strategies or to transform their production methods. This approach puts small-scale producers in a highly vulnerable situation because it promotes dependence on external inputs or support without encouraging them to look beyond the immediate context.

We identified a causal disconnection between climate change and drought, as drought is perceived by producers as an immediate and temporary problem. By not perceiving climate change as something that directly affects them, there are no indications that farmers are responding to drought through adaptation measures. Despite recognizing the increase in temperature and the uncertainty in seasonality, there is a conceptual gap, as farmers do not have a clear understanding of climate change and its effects. The issue is seen as a technical problem, and solutions are contracted to address short-term needs.

4.2 Social organization and responsiveness – political sphere

The collective actions that shape the field or space in which responses occur in the practical sphere are generally systems or structures created and managed through political processes (O'Brien, 2018). In this study, we observed that processes and management within the political sphere have had an effect on social organization at both the individual and community levels.

The categorization of producers based on the number of animals and land area determines whether a producer is small, medium, or large. However, this approach ends up homogenizing other characteristics that confer different capacities and characterize the specific conditions of each producer. These characteristics either facilitate or constrain their possibilities for responding to climate variability. If we understand the capacities of producers as the possibility of doing something rather than as an ability to do it (Boltvinik, 2006), we find that producers, exhibit different coping strategies in their FCMs in response to water stress. Their responses can vary depending on their geographic distribution, level of technological advancement, and access to resources (Table 1).

In this sense, the possession of an asset such as an irrigation system is not determinant of a better response to drought, as it does not guarantee that the producer can effectively use the asset. If the equipment is not functional and does not fulfill its irrigation characteristic, the producer loses the ability to maintain forage in their pasture. The same applies to the location of each producer's land; after a flood, low-lying areas do not recover in time to produce the grass, which is the foundational resource of the system. This disadvantage implies not only higher expenses but also the fact that these lands are not suitable for producing other types of products. Additionally, the majority of producers do not have government support as an extra source of income (Table 1). While monetary support is often a fundamental component of producers' livelihoods, it should be accompanied by sustainable changes in infrastructure and management practices. Also, income diversification constitutes a crucial sustainable form of adaptation to climate variability and other social conditions (O'Brien and Sygna, 2013; Márdero et al., 2014).

At the level of the social organization of producers, we notice that the processes of agricultural production automation have had an impact on social dynamics. In contrast to inclusive innovation, whose main purpose is to generate social benefits and address the needs of a specific group (Amaro-Rosales and de Gortari-Rabiela, 2016; Sampedro and Díaz, 2016), from a standpoint guided by macroeconomics and the well-being of businesses, technological innovation is defined as the application and use of new ideas, concepts, products, services, or practices to achieve higher productivity (Amaro-Rosales and de Gortari-Rabiela, 2016). In the evolution of the agricultural sector, there is a pursuit of production automation to achieve better capital profitability, but little attention is paid to the impacts of technification on other domains of life and the community of producers. The collective organization and communal work that producers mentioned they had in the past in order to carry out arduous tasks such as clearing pastures have been replaced by more individualistic ways of controlling weeds through agrochemicals. Beyond the efficiency that one form or another may bring to the activity, collective work suited in the personal sphere (Figure 7), meant establishing interactions and generating relationships governed by values such as camaraderie, solidarity, and joy, which have been lost in the present day.

Simultaneously, in the political structure that governs small-scale cattle farming of the participating producers (Figure 7), we observe a dependence on government programs and a distrust generated by regional corruption. Instead of triggering social movements or alliances to fight against injustice (O'Brien, 2018), the political organization has led to conflicts and corruption at the local level. The concentration of government support on larger-scale and more capable producers (Gómez and Tacuba, 2017; Robles Berlanga, 2018; Cosío Ruiz, 2020) determines the possibilities of change for smaller-scale producers in isolated regions, and it also reduces the potential for response through non-homogeneous and poorly focused adaptation measures. Eriksen et al. (2015) argue that adaptation should be seen beyond a technical adjustment to a biophysical change; it should be seen as a socio-political process linked to livelihood activities and people's ambitions.

Policies should be focused on the doing and being based on the capacities (developed through programs and support generated by these policies) related to the possessed assets and the services each one obtains from these assets. Alternatives to conventional cattle farming through sustainable practices and agroforestry are effective (Ibrahim et al., 2010; Murgueitio et al., 2011; Bacab et al., 2013; Broom et al., 2013; Murgueitio et al., 2013; Nahed-Toral et al., 2013). However, their implementation has been sought through the transformation of the production model without considering all the elements that make up the system. (Dagang and Nair, 2003; Cosío Ruiz, 2020) In this regard, considering livestock units as socio-ecosystems is useful for identifying the social processes. When viewed as mutually dependent and interconnected part of the entire system, these processes can be taken into account along with technical solutions for animal and pasture management, and therefore, become part of the solutions that may contribute to shifting toward a more sustainable production model.

4.3 Scenario projection and ideal cattle-farming identity – personal sphere

Cattle farmers expressed aspects of their worldview through the descriptions of ceremonies and rituals and their influence on their perceptions and interpretation of the changes on weather and on the rainfall patterns. According to the study conducted by Metcalfe et al. (2020), these rituals and prayers are shared with cattle farmers in the northeastern region of the Yucatán coast. In the past, these rituals were performed because they were believed to have an effect on their world, such as providing essential elements like rain, bringing good harvests and blessings to the cattle and ranches (Metcalfe et al., 2020; Camacho-Villa et al., 2021). However, currently, although the producers consider these spiritual aspects desirable for a more productive system and a more pleasant environment, they have stopped performing them.

The idea of individualism constructed from and reinforced by other spheres has also led to the loss of tradition. As O'Brien (2018) states, the personal sphere defines what is imaginable, desirable, viable, and achievable individually and collectively, based on different understandings of causality and future awareness. In this study, producers assign significant value to the interpretation of tradition and its implications for community and camaraderie as part of the ideal imaginary of managing their productive systems. It is important to consider the relationship between perceptions, behavior, and climatic phenomena as they participate in the cognitive processes of individuals when observing, constructing meanings, and making decisions regarding social and environmental changes (Eguavoen et al., 2013). According to the producers' perception, the ideal scenario is not a silvopastoral system (considering that producers may not always be familiar with the concept and the type of production model) (Zepeda-Cancino et al., 2016), but rather a scenario similar to the one they used to live in, with elements that have been lost over time.

Rosenberg (2022) discusses the influence of values on how humans relate to their environment and on transformations of socio-ecosystems toward sustainability. In socio-ecosystems with well-defined cultural identities and beliefs, processes of adaptation and transformation are not easy and usually require a perceived crisis to recognize the need for change (Folke et al., 2010). However, the values involved in the human-environment relationship are dynamic and can change from generation to generation or within the same generation (Shrivastava et al., 2020). Furthermore, Rosenberg (2022) shows that values can be deliberately chosen in the intentional pursuit of unity as the primary driver of enactive action toward sustainability. Despite the knowledge gap regarding the current scenario surrounding climate change, the recovery of social values and desirable aspects from the past can incentivize producers to adopt new practices to steer livestock farming toward sustainability.

Understanding what would be a desirable scenario for the actors directly involved in the system allows for a more successful approach, knowing which changes are feasible and achievable within a certain timeframe. Focusing strategies on adaptation is the way to "guarantee" a scenario of greater social benefit and lower environmental impact. In the face of limited specific institutional support, the government's assistance promotes dependence on external inputs, lower adaptive capacity, and ultimately, lower resilience. Therefore, we consider it relevant and necessary for public policies to consider local contexts and the social and cultural factors that influence small-scale cattle management in order to move toward a transformation in livestock farming toward more sustainable management strategies.

4.4 The cattle-farming socio-ecosystem – the three spheres

The operationalization and articulation of the three-sphere model have allowed us to gain greater knowledge and understanding of the cattle production socio-ecosystem of the producers in Corral. Regarding the perception and response to climate variability, we have observed that the practical sphere has a predominant influence over the other spheres. It is evident how the interplay between these three spheres impacts the sustainability of the systems, especially in relation to development values and technified production models.

Moreover, we recognize the significance of cultural and spiritual values in comprehending the perception of the environment, along with the role that worldviews play in interpreting the environment, its components, and its intricate processes. As a result, cultural values shape the farmers' perspectives of climatic events like drought, influencing both their perception of causality and their subsequent responses to these events. By acknowledging these interactions and the influence of the three spheres at both the social organizational level and in practical implementation, we consider that addressing sustainable livestock farming from an exclusively technical-economic perspective is insufficient to achieve greater adoption of sustainable practices.

The social dimension is often underestimated and less understood (Stirling, 2015) as social values and preferences are considered fixed and independent of the ecological context. However, quite the opposite, they are susceptible to change over time (Voinov et al., 2014) and dependent on social and environmental conditions (Halbrendt et al., 2014). By not taking into account the preferences and values that influence decision-making, certain strategies may lack effectiveness (Voinov et al., 2014), which is reflected in low levels of adoption, as is the case with silvopastoral systems (Zepeda-Cancino et al., 2016; Cosío Ruiz, 2020).

Livestock farming represents a significant source of subsistence for a substantial portion of the human population. As noted by Shaffer and Naiene (2011), local mental models of climate change represent the community's conception and knowledge of climate, based on observations and experiences of past and present climate variability. Although integrating local knowledge and beliefs into climate change adaptation strategies is challenging due to their social nature, it is crucial for farmers to be involved in decision-making processes regarding the adoption of strategies and the integration of local knowledge in adapting to climate variability (Audefroy and Sánchez, 2017).

We acknowledge the limitations within the scope of this study and believe that conducting such research involving a wider range of participants, as well as a diversity of cattle producers including small, medium, and large-scale ones, would be highly valuable in gaining insights from various production scales. However, from the simplified representations that integrate local-level complexity of the 10 participating producers, we were able to grasp the regional reality with its particularities gaining a better understanding of the small-scale cattle socioecosystem in the Yucatan Peninsula. Acknowledging social values and preferences as fundamental components of sustainability itself and for sustainable livestock farming, contributes to identifying the scales where socially and culturally pertinent transformations can be pursued. In this matter, participatory processes were useful for addressing challenges from multiple perspectives and therefore, for recognizing the needs of particular contexts within a regional policy making.

5 Conclusion

The tacit knowledge from which the FCMs are built is composed of complex relationships and associations that cannot be directly translated into a pre-established model like O'Brien and Sygna's (2013) spheres of transformation. However, FCMs, along with the reflective process, triggered a coherent articulation of the three spheres with the practical actions, the organizational and political context, and personal realm of the cattle farmers. Participatory modeling places special emphasis on the modeling process itself rather than solely on the model (Voinov et al., 2014). Through discussion and reflection during the development of FCMs, trust was fostered, and a common understanding was developed that incorporated information that might otherwise be excluded from scientific assessments (Gray et al., 2015). Although participatory modeling processes do not aim to directly intervene in the decision-making of cattle farmers or predict the future state of their systems, they do significantly contribute to understanding a complex problem. This paves the way for successful transitions from conventional cattle farming to a more sustainable one. The focus of this work extends beyond collectively identifying problems and obstacles, it also promotes spaces for understanding and reflexive thinking that ultimately aim to contribute to support better social organization mechanisms and the adoption of sustainable practices to tackle climate change challenges.

The small-scale cattle farmers who participated in this study demonstrate an coping capacity to droughts each year. They implement various strategies such as feed complementation, irrigation practices, reducing herd and government support, that differ in terms of sustainability. However, despite their coping capacity, responses may not always achieve positive outcomes in reducing vulnerability to climate variability. Adaptation must also occur at sociocultural levels, as perceptions of climate change influence decisions and may determine the adoption of sustainable adaptation measures. Being based on the legitimacy of the producers themselves describing the current reality and expressing their aspirations and desired changes, this work plays a fundamental role in establishing a methodological foundation that promotes participation, discussion, and reflection. It is essential for these participatory approaches to include small-scale producers, who are directly involved in the management of the production systems, to ensure that project objectives align with different perspectives and that expected outcomes benefit all stakeholders involved.

It is important to recognize that livestock farming represents a significant source of subsistence for a substantial portion of the human population. We acknowledge the limitations within the scope of this study and believe that conducting such research involving a wider range of participants, as well as a diversity of producers including small, medium, and large-scale ones, would be highly valuable in gaining insights from various production scales. As we gain a better understanding of the livestock socioecosystem, we can address challenges from multiple perspectives toward more sustainable states.

Data availability statement

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

Author contributions

FP-L: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. JS-G: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – review & editing. FS-S: Resources, Supervision, Validation, Writing – review & editing. FG: Conceptualization, Funding acquisition, Investigation, Supervision, Validation, Writing – review & editing.

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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.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1321252/full#supplementary-material

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