Forest Ecology and Management 479 (2021) 118506

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Management strategies, silvopastoral practices and socioecological drivers in traditional livestock systems in tropical dry forests: An integrated analysis

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ARTICLE INFO

Keywords:
Socioecological systems
Livestock management
Silvopastoral practices
Tropical dry forest

ABSTRACT

Understanding traditional livestock management is essential in the design of more sustainable systems, given the forest loss associated to the growing demand for meat. In Latin America, where extensive livestock production is increasing, along with tropical dry forest (TDF) transformation, the role of small holders is critical for designing more sustainable management practices. This study is an integrated socioecological analysis of traditional livestock systems in a region with TDF in Mexico. The objectives were to: a) characterise the historical development and current state of livestock systems and silvopastoral practices, b) define the management strategies and their impacts on forests, and c) identify the regional and local socioecological drivers that influence decision-making processes in livestock and forest management. In-depth interviews were carried out to 32 cattle farmers and analysed using a qualitative-interpretative approach which included multivariate and narrative analyses. Three historical stages (colonization, promotion of livestock and forest conservation) had a strong impact in the development and current state of livestock systems. Access to natural and economic resources and proportion of plant cover (grassland/forest) were essential in defining four groups of management strategies. The main regional drivers favouring or restricting production include climate, native vegetation, markets and public policies; at the local scale, socioecological factors, such as water availability, native vegetation, economic assets, local knowledge and their interactions determine heterogeneity in management strategies, decision-making processes and their impacts on forests. Adaptive management of livestock and forests in a context of limited economic resources has allowed the conservation of forest areas and the use of silvopastoral practices with local tree species. The integrated socio-ecological approach and the use of mixed methods allowed a better understanding of drivers and their interrelationships, the local knowledge, objectives and perceptions of farmers in the decision-making processes regarding livestock and forest management. Perspectives of farmers on resource use can contribute to the design of more effective and inclusive policies for sustainable livestock systems in the dry tropics.

1. Introduction

In the last decades, global demand for livestock products has increased, resulting in tropical forest loss, especially in developing countries (FIRA, 2017). In Latin America, land use change to grasslands is one of the main causes of tropical forest destruction, and livestock farming is the main economic activity of many families with scarce resources (Rodríguez et al., 2016; Steinfeld et al., 2009; FAO, 2008). Specifically, tropical dry forests (TDF) have lost almost 80% of their original cover and are currently the most threatened tropical biome (Ferrer-Paris et al., 2019). In Mexico, they are relevant, due to their extension, high biodiversity and endemism, but over 70% has been altered or degraded (Sánchez-Azofeifa et al., 2009; Trejo and Dirzo, 2000). Under this situation and scenarios of continuing trends (Ferrer-Paris et al., 2019; FIRA, 2017), it is urgent to improve the sustainability of livestock systems, which involves reducing forest degradation and loss.

Traditional livestock systems run by smallholders are particularly relevant for tropical forest management (Fuentealba and González-Esquivel, 2015). Globally, smallholders account for around two thirds

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https://doi.org/10.1016/j.foreco.2020.118506
Received 30 June 2020; Received in revised form 11 August 2020; Accepted 12 August 2020
Available online 08 September 2020

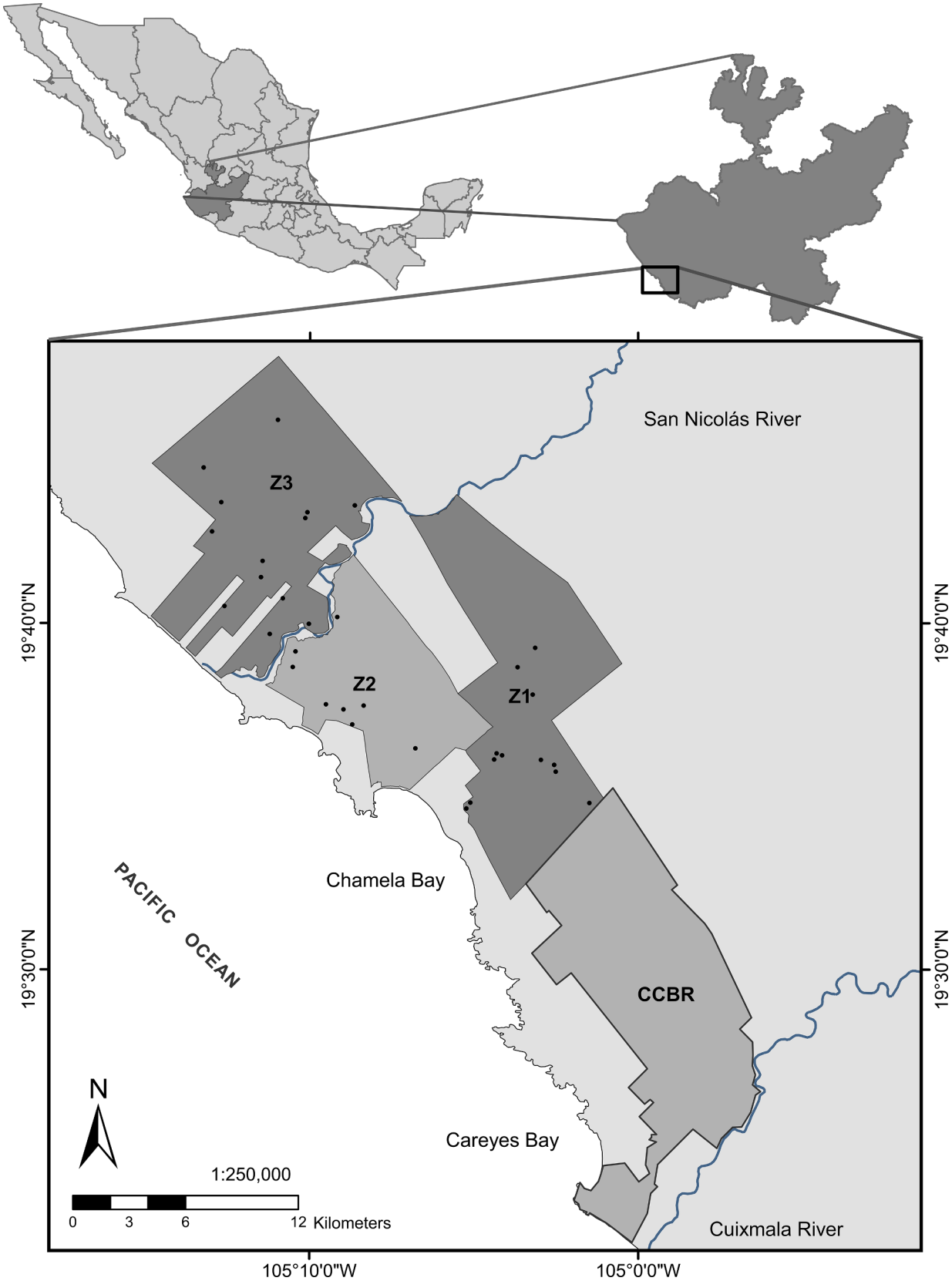

Fig. 1. Study region in Jalisco, Mexico. Topographic zones: Z1, Z2 and Z3. CCBR: Chamela-Cuixmala Biosphere Reserve. Dots show the location of studied farm units. Figure by C. Briones-Guzmán.

of farmers and possess most of agricultural land. In developing countries, they produce most of the food, therefore playing an important role in food security (Lowder et al., 2014; HLPE, 2013; Altieri et al., 2012). Smallholders have developed traditional livestock systems empirically adapted to their local resources, using simple technology and few external inputs (Moreno-Calles et al., 2015; Nahed-Toral et al., 2013;

Altieri, 2004). These are the most extended systems in Latin America (Rodríguez et al., 2016). They are also highly vulnerable, and even though farmers take most decisions relevant to ecosystem management, their perceptions, needs and proposals have not been properly considered when designing public policies and scientific agendas (HLPE, 2013; Toledo, 1997).

Silvopastoral (SP) systems, which combine grasslands, livestock and trees, have been proposed as a more sustainable alternative for livestock production in the tropics because of the benefits provided to both farmers and forest conservation. SP practices reduce environmental impacts of livestock on forests and provide diverse ecosystem services (Jose and Dollinger, 2019; Torralba et al., 2018; Alonso, 2011). SP systems are ancient and distributed throughout the planet and show high structural, management and productive variability (Soler et al., 2018; Plieninger and Huntsinger, 2018; Cubbage et al., 2012). Studies on SP systems and practices have increased recently (Jose and Dollinger, 2019; Soler et al., 2018; Plieninger and Huntsinger, 2018). Yet, there is still little information to understand their complexity. Studies to date present only a few of the many dimensions involved in the management of traditional SP systems. Integrated socioecological studies that assess the complex interlinkages between societal and biophysical drivers operating at local to global scales (Balvanera et al., 2017b) and use mixed research approaches (Denscombe, 2008) to cover different SP management aspects are still scarce. Such studies can provide solid foundations to design more sustainable livestock systems and reduce their impacts on tropical forests.

In order to understand the inherent complexity of livestock systems in TDF and their associated environmental problems, an integrated analysis including both social and ecological variables is required (Guerrero et al., 2018; Ostrom, 2009). In socioecological systems, human and natural resources are coupled, dynamic, and interact at multiple temporal and spatial scales. Thus, when studied in an integrated way, these systems reveal new and complex patterns and processes that are not evident when analysed separately (Bretagnolle et al., 2019; Schlueter et al., 2012; Liu et al., 2007). Coupling between social and ecological subsystems is particularly expressed in productive management (Berkes and Folke, 1998), by means of which societies modify the natural environment, through intentional interventions, transformations or decisions on ecosystems, their elements or functional processes (Casas et al., 2015). Resource users, through decision making processes, determine different management strategies (Wilmer et al., 2018; Lubell et al., 2013). Therefore, it is essential to analyse the farming unit scale, considering that different global and regional factors influence land management and farm decision making (Sherren and Darnhofer, 2018; Balvanera et al., 2017b).

This study focused on traditional livestock management by smallholders in TDF of Jalisco, Mexico, using a holistic, integrated socioecological approach. The objectives were to: a) characterise the historical development and current state of livestock systems and silvopastoral practices in regional forests, b) define the different livestock management strategies and their impacts on forests, and c) identify the regional and local socioecological drivers that influence decision-making processes in livestock and forest management.

2. Methodology

2.1. Study area

The study was carried out in a region with TDF in western Mexico. The Chamela region has been defined as a coastal line of 6400 km^2 (Maass et al., 2005), which stands out for its high indices of diversity and endemism (Trejo, 2010; Balvanera et al., 2002). It includes the Chamela-Cuixmala Biosphere Reserve, with old-growth forests surrounded by *ejidos* (agrarian communities with semi-communal governance), in which smallholders possess most of the land (Castillo et al., 2005) (Fig. 1).

Agricultural activities have generated a mosaic of vegetation, with secondary forests, old-growth forest fragments, grasslands and some cropping fields (Flores-Casas and Ortega-Huerta, 2019; Sánchez-Azofeifa et al., 2009). Livestock farming has been an important driver of land use change, but also represents the main source of income for most families (Cohen-Salgado, 2014; Schroeder and Castillo, 2013).

Climate is remarkably seasonal, with high inter and intra annual variability. Mean annual rainfall is 800 mm, with extreme years between 340 and 1329 mm (Maass et al., 2018). The landscape is made up of low altitude hills and alluvial plains (Cotler et al., 2002). Soils on hills are shallow (30 cm) with predominantly thick textures (Regosols) and low nutrient content, while those on plains are deeper and nutrient-rich.

2.2. Methods

The socioecological analysis of livestock and forest management was carried out from the perspective of farmers, as they are the main decision makers in the management of the ecosystem (Castillo et al., 2005). A qualitative-interpretative approach was used (Castillo et al., 2020), which through the construction of dialogue, allows the comprehension of the meaning of social and ecological phenomena from the perspective of local actors, as well as the ways in which they understand situations or events (Strauss and Corbin, 2002; Patton, 2002; Denzin and Lincoln, 2000). The visions of farmers were explored at two spatial scales: regional and local. The regional scale corresponded to the central-northern part of the Chamela region as defined by Maass et al. (2005). The selected area was divided into three zones: Zone 1 with a predominance of hills, Zone 2 with a predominance of plains and Zone 3, with both types of landscape (Fig. 1). The local scale corresponded to the farming unit, which encompasses the farming family and their plots (fields in which cattle is kept).

A total of 32 in-depth interviews were carried out (Taylor and Bogdan, 1987). Interviewees were selected through the snowball technique (Patton, 2002): each interviewee was asked about other farmers with either similar or different cattle managements in order to cover different strategies. Sample size was determined using the data saturation technique (Strauss and Corbin, 2002). Based on the objectives, the open-ended questions of the interviews covered the following topics: a) to characterise the historical development and current state of livestock systems and silvopastoral practices, farmers were asked about the history of forest management and cattle raising in the region and their current situation; b) to define different livestock management strategies and their impacts on forests, farmers were asked about forest and livestock management activities and practices throughout rainy and dry seasons; c) to identify the regional and local socioecological drivers influencing livestock management and decision-making, farmers were asked about the factors affecting livestock production and the reasons that motivate them to make resource management decisions. The interviews were carried out in two stages. The first one, conducted in April 2016, consisted in open explorations to identify the main features of livestock systems and the socioecological factors influencing them. It also included closed questions on land area, land use, herd size and livestock sales. The second one, in March 2017, sought to collect specific information on the most relevant factors identified in the first stage. All interviews were audio-recorded with previous authorization from interviewees and fully transcribed.

Mixed methods were used to analyse the data, in order to obtain a better integration and understanding of socioecological factors (Guerrero et al., 2018; Denscombe, 2008). The characterization of the historical context and current state of livestock systems, the use of SP practices, the definition of regional and local drivers and the identification of relationships between socioecological factors and of decision-making processes were carried out through qualitative methods. The Atlas.ti software (version 7.5) was used for the analysis of the narratives collected through the coding of *a priori* and emerging factors, which

were constructed with nested categories (Strauss and Corbin, 2002). The strength of relationships between factors was based on the number of mentions of each relationship by interviewees (n = 32).

To define livestock management strategies and their impacts on forests a quantitative approach was chosen. Multivariate analyses were carried out on the management variables, which were defined by the coding of the qualitative analysis. The values for each variable were obtained from the interviews (Appendix A). First, a cluster analysis on 23 management variables (11 numerical, 10 ordinal and 2 nominal; Appendix A) was used to identify management strategies, defined as groups of farmers with similar values on those variables. A cluster analysis was performed on a Gower similarity matrix, which allowed to include variables of different nature as those used here. The Gower distance matrix and cluster analysis were calculated using the 'gowdis' and 'hclust' functions in the 'FD' and 'stats' packages for R (Laliberté et al., 2014; R Core Team, 2018). Then, to identify the main variables driving such grouping, a Principal Coordinate Analysis (PCoA) was carried out on the same set of variables using the 'dudi.mix' function in the ade4 package for R (Dray and Dufour, 2007). The impacts of management strategies on regional forests were identified based on the proportion between grassland and forest areas and on the number of silvopastoral practices in each group (Appendices B, C and D). Finally, a Spearman correlation analysis was carried out between the variables identified in the PCoA (Daniel, 2003), to determine the strength and statistical significance of the relations among them (Appendix E). All analyses were done using the R Language (R Core Team, 2018).

3. Results

3.1. Historical development, current state of livestock and forest management and SP practices

In the historical development of livestock and forests management in the region three distinct stages and their corresponding policies were defined with the information from the interviews (Table 1). The first stage involves the colonisation and land endowment, followed by a stage of wide promotion of livestock production, and a current stage of conservation policies through environmental restrictions on forest management.

The current management of livestock and forest is extensive. Forest remnants are used for cattle browsing and wood extraction for fences. A key aspect in management is the rapid recovery of the native vegetation in induced grasslands. All interviewees mentioned that grasslands require continuous upkeep, through manual trimming of sprouts and chemical herbicides. Some interviewees (56%) also use fire every two or three years. Farmers stated that when upkeeping stops for two or more years, woody vegetation covers the grassland, which requires the use of slash-and-burn to convert it back into grassland, as also reported by Burgos and Maass (2004) and Mora (2015) (Fig. 2). Type of vegetation cover in plots is highly variable. Plots include induced grasslands with trees in varying composition and density, as well as forest areas in different regeneration states. Only 25% of interviewees possess uncleared (but not pristine) forest areas.

Silvopastoral practices in regional forests are currently used by all interviewees, the most common ones being forest browsing (100%), allowing trees amongst grasslands (100%), live fences (47%), planted multi-purpose trees (22%) and selective forest clearance (16%). Most of them (91%) rotate cattle between plots. All interviewees have learnt to recognize and use various woody forage species. On average each farmer mentioned eight (4–16), the five most named species being: Cascalote (*Caesalpinia coriaria*), Huizache (*Acacia* sp.), Habillo (*Hura polyandra*), Guajillo (*Leucaena lanceolata)* and Ébano (*Caesalpinia sclerocarpa*). Other frequently mentioned species (72% of interviewees) with forage and other uses (fencing, fuelwood, shade), were Barcino (*Cordia eleagnoides*), Coral or Acatizpa (*Caesalpinia platyloba*) and Cacahuanance (*Gliricidia sepium*). A complete list of species, features and uses will be presented in a separate study (Sanchez-Romero et al, in preparation).

3.2. Management strategies and their impacts on forests

We identified four groups of management strategies (numbered I to IV) based on the cluster analysis. The representation of these groups into the ordination space showed they are mostly differentiated along two gradients, one of access to resources (PCo1, differentiating Groups I and II) and other of forest transformation into pastures (PCo2, differentiating Groups III and IV) (Fig. 3; Appendices B and C). Group I farmers (n = 14) have abundant access to water and a higher use of forage crops, machinery and tools. It includes all farmers with access to plains and all those with training, that use higher quality feed and keep finer breeds. In contrast, Group II (n = 5) has low access to resources, feeds low quality forage and has mixed breed animals. Group III farmers (n = 11) have large areas and a higher proportion of forest (on average 128.5 ha and 69% forest cover), lower stocking rate (on average 0.4 animals/ha) and low-quality feed. In contrast, Group IV farmers (n = 2) have large areas but with a higher proportion of grassland (on average 90 ha and 83% grasslands), higher stocking rate (on average 1.3 animals/ha) and high-quality feed. The averages of the management variables for each group are presented in Appendix D.

Groups I and IV have larger herds and higher sale of calves (on average 22 and 27 heads per year respectively). Group II has a lower sale of calves, but income from livestock contributes on a larger scale (70–90%) to family expenditure. Also, a partial association can be observed between groups and forest conservation, as farms in groups I and III tend to have higher areas and forest proportion compared to groups II and IV.

Management strategies are more contrasting during the dry season, with varying forms of providing feed and water to cattle. This relates to the difference in water availability and the proportion of grassland, forest and forage crops, in each of the four management strategies,

Table 1
Main historical stages and public policies in the region that influenced livestock and forest management.

Stage	Public policies	Influence on management
Colonization (1950–1970)	Colonize isolated rural areas	Arrival of people of diverse geographic origin and resource management traditions Land endowment
Promotion of livestock production (1970–1990)	Encourage livestock farming by converting forests into grasslands	Extensive forest clearing with heavy machinery Introduction of genetically improved grasslands and cattle breeds Public credits and subsidies for cattle production Forests considered an obstacle to livestock production
Forest conservation (1990 –)	Conserve forests and protect biodiversity Support farmers –	Restrictions in management practices, such as slash-and-burn Small subsidies to cattle production Development of SP systems from adaptive learning Increased knowledge and use of forests and native forage trees in cattle production

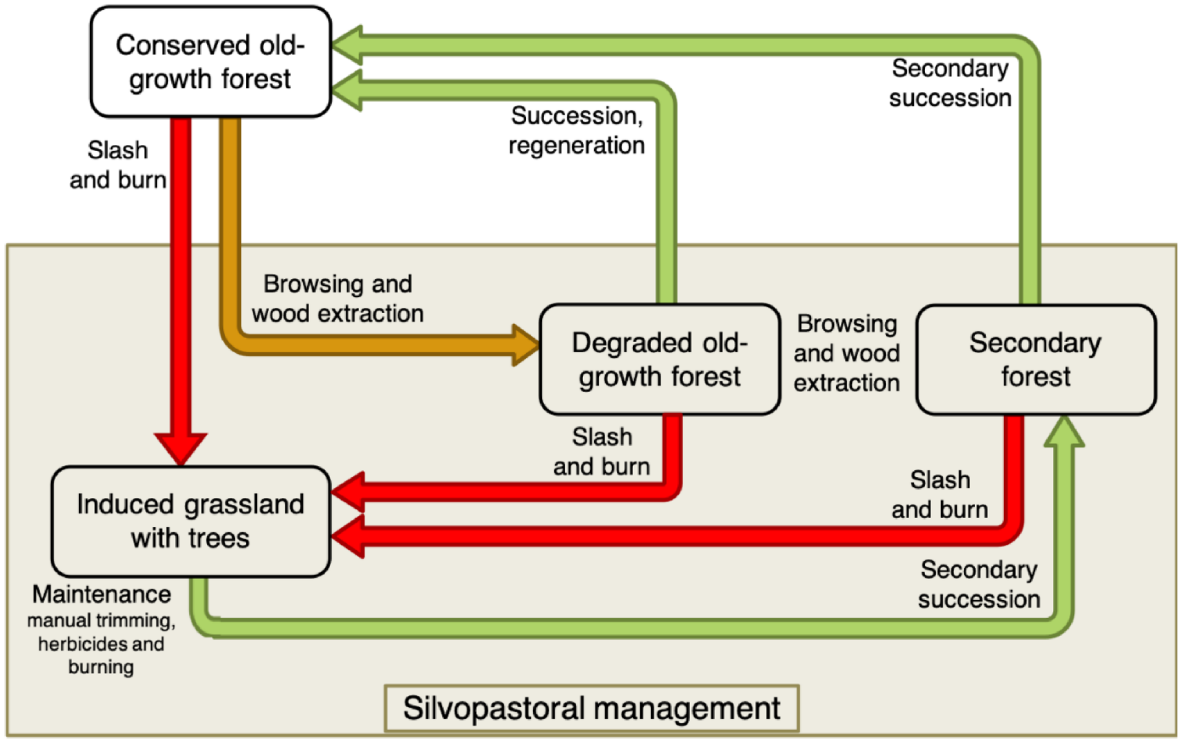

Fig. 2. Conceptual model of transitions between successional stages of the Tropical Dry Forest in the studied region as a result of silvopastoral management. Transitions are shown with colored arrows: Brown – degradation, red – deforestation, green – natural regeneration. Adapted from Mora (2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

resulting in variable forage production in grasslands and cropping areas, as well as forest browsing. Fig. 4 presents a model scenario of causal relations during dry seasons inferred from the PCoA and the correlation analysis (Appendices A, D and E).

The identified groups showed different impacts on regional forests. Groups II and IV had a higher impact on forest cover, with higher proportions of grasslands (59 and 83% respectively, Appendix D). Conversely, Groups I and II have higher forest proportions (54 and 69% respectively, Appendix D), although this is mainly due to the high costs associated with slash-and-burn. Farmers in Group I also carry out more

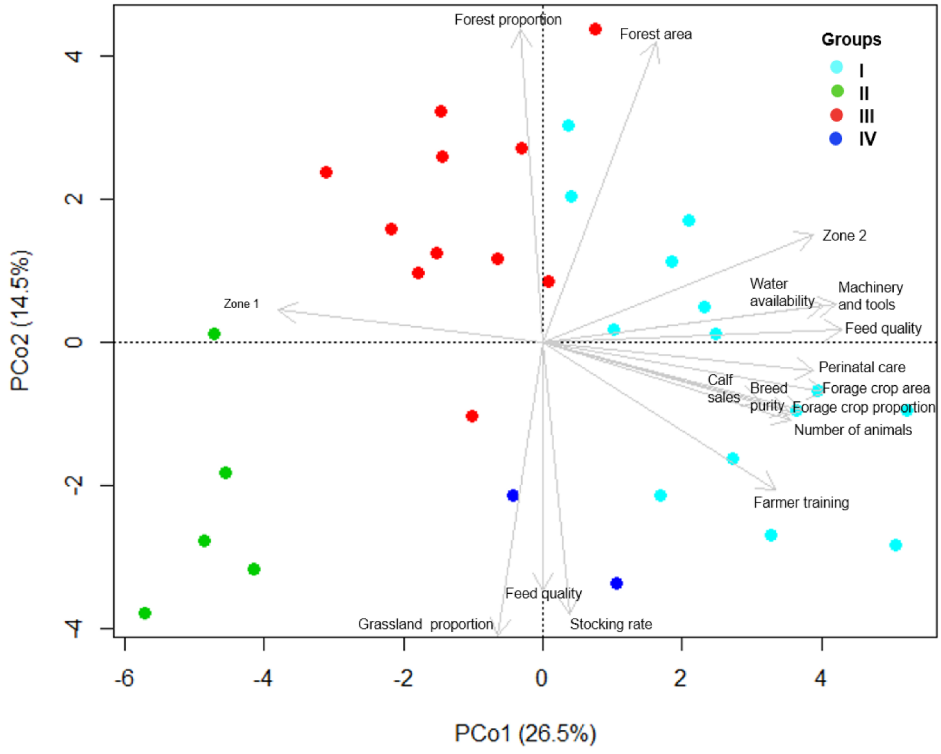

Fig. 3. Management variables contributing most to the two main principal components and the four resulting management strategies (Appendix B).

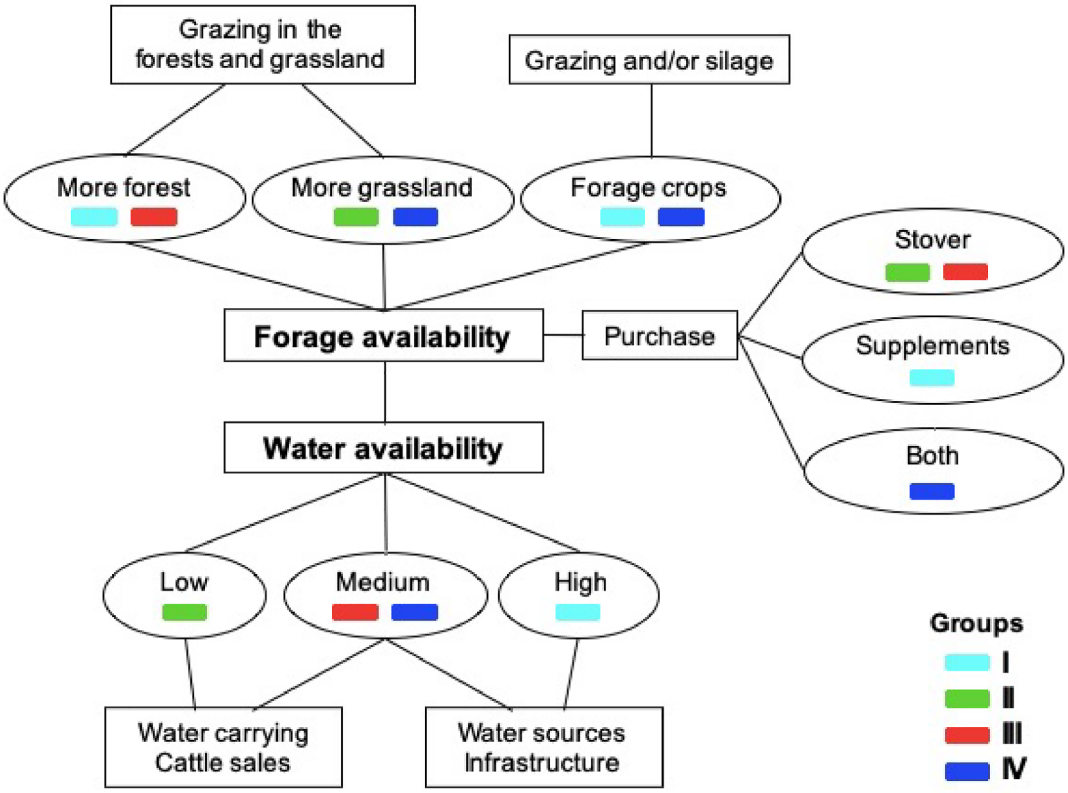

Fig. 4. Silvopastoral management during dry seasons by group, constructed from the PCoA and correlation analysis (See Appendices A, D and E).

SP practices. Total forest areas are greater than grasslands (2403 vs. 1328 ha), and well above forage crops (209 ha). According to the correlation analysis, forest area is not related to resource access, nor to the physiographic zone (Appendix E). It is important to note that some interviewees declared owning other forest areas with no access to cattle, which were not accounted for in this study.

3.3. Regional and local socioecological drivers influencing livestock management and decision-making processes

At the regional level, different socioecological drivers favouring or restricting SP management and influencing decisions at the farm level were identified through the analysis of the narratives. According to interviewees, prevailing socioeconomic conditions encourage cattle production as the main use of forests, due to the high demand for growing calves. Ecological drivers correspond to the biophysical conditions inherent to TDF and are determinant in the way in which livestock systems are managed (Table 2).

Climate is a determining factor because of the unpredictability of the rains and low water availability, especially under severe droughts. Farmers take preventive actions, such as reducing herd size at the end of the rainy season by estimating forage availability from the amount of rainfall (56% of interviewees); reserving the most humid sites to be grazed during the peak of the drought (78%); making silage (44%); and buying forage in advance (40%). Farmers also take part in collective actions, such as negotiating water and forage use between community members (97%) and buying forage between several farmers to diminish costs (16%).

At the local scale, different factors determine heterogeneity in management strategies, decision-making processes and adaptive learning. The most relevant factors and their interrelations are shown in Fig. 5, a diagram constructed with the categories and codes from the narrative analysis.

Water availability in plots is a determining factor in livestock management. During the rainy season all interviewees have water in their plots through reservoirs, streams, springs or wells, but their size and amount provided varies. On one extreme, there are farmers that need to carry water daily to their plots every dry season (25% of interviewees). On the other side, some farmers have enough water all year round for cattle and limited irrigation of forage crops (12%). Most interviewees (66%) consider that water availability is related to physiography, with higher availability on plains, where most forage crops are located. Feeding also varies between farms in quantity and quality. All interviewees supplement grazing and browsing during the dry season, through the rent of plots and/or the purchase or production of forage: crop residues, forage crops, silages and/or commercial concentrates. Feeding and caretaking are also influenced by breed type and pedigree.

Amongst economic factors, cattle farming is the main livelihood for most families, though income and its contribution to the family expenditure are variable amongst interviewees. The main income comes from the sale of calves for fattening, ranging from four to 60 per farm every year. All interviewees mentioned that livestock farming income is not constant or predictable, due to extreme climatic events and price variability. Because of this, they all stated having other forms of income, but whilst for some (16%) livestock only contributes 20–30% to the family expenditure, for the rest of them (84%) earnings from cattle cover 50–90%. It also provides all their families with milk and meat for self-consumption.

When analysing decision-making processes, it was found that management is adaptive and related to learning, where local knowledge, objectives, perceptions and preferences of each family intervene. Local knowledge is a combination of inherited, empirical and external knowledge. All interviewees have inherited knowledge, since they come from cattle farming families. Empirical knowledge was observed in the adaptation of livestock management to the regional climate and vegetation, as well as in the integration of woody forage species. Regarding external knowledge, only some interviewees (22%) have taken courses

Table 2
Main regional drivers.

Drivers			Influence on management	
Type	Factor	Subfactor	Restrict	Favour
Biophysical	Climate	Water scarcity	Lower production	
		Marked seasonality	Water and forage scarcity in dry seasons	
		High rainfall variability	Uncertainty in forage availability	
		Regular and severe droughts	Cost and cattle mortality rates increase Variability in calf sale prices	
	Physiography	Hills and alluvial plains	Lower water availability in hills	Higher water availability in plains
	TDF vegetation	Presence of native forage species		Feed availability
		High resilience	Grasslands require constant maintenance to halt forest regrowth	
Socioeconomic	Cattle markets	High demand for beef calves		Production focuses on reproduction and calf raising
		Intermediaries	Price restriction at farm gate	Easiness of sale
		Prices	Instability	Price increase
	Social issues	Unemployment and migration		Cattle farming is the most viable economic activity
	Public policies	Subsidies to livestock farming		Help to maintain the activity
		Forest conservation	Regulation of slash-and-burn and water extraction	

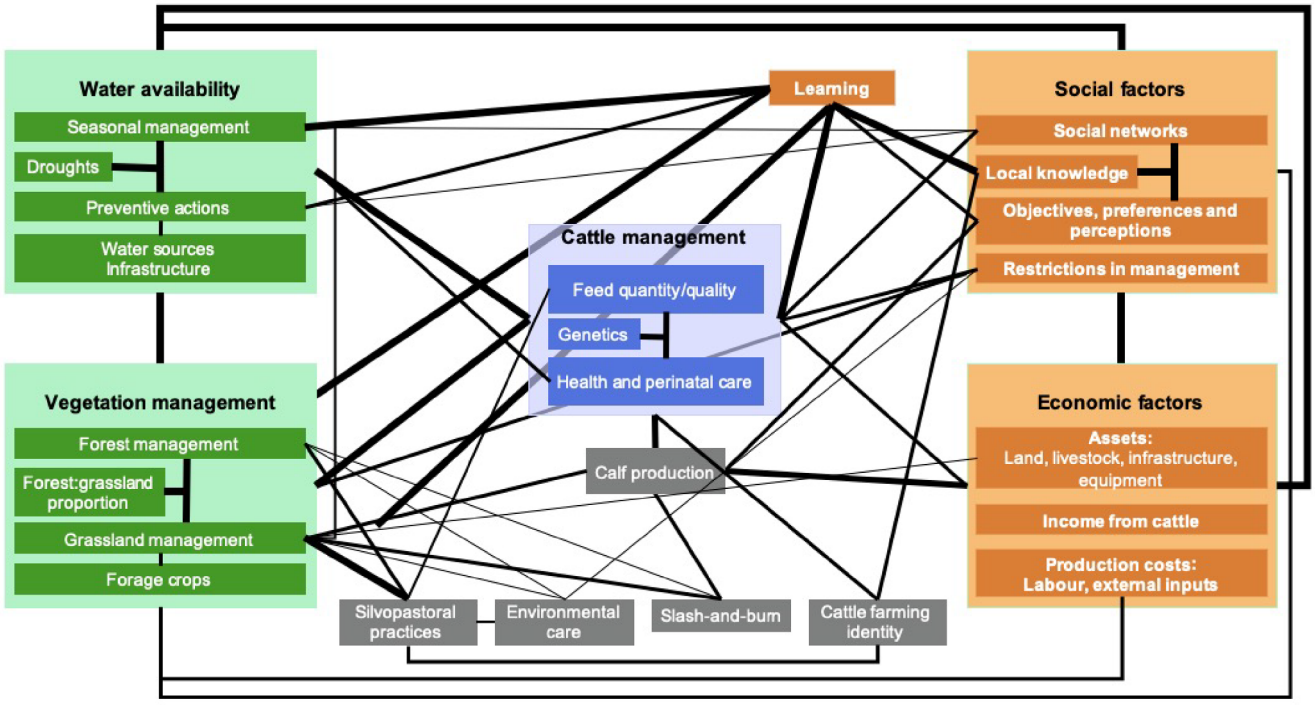

Fig. 5. Interactions between local socioecological factors determining livestock management. Constructed categories from the qualitative analysis are shown in colour: green – biophysical, orange – socioeconomic, blue - management, grey - two or more categories. Line width reflects the strength of the relation determined by the number of mentions (n = 32): thin 5–15, medium 16 – 25, bold 26 – 32. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

or some other formal training related to livestock farming. Community social networks concerning livestock management promote knowledge sharing. To quote an interviewee "*Here one learns from the old ones… They have always been cattle farmers here and we watch them and learn from them… If I share and we all do, one starts to get an idea of what yields the best result*".[1]

Among the objectives, perceptions and preferences of farmers, all interviewees aim to increase calf production and reduce production costs. Increasing grassland areas can result in more forage, but also in higher clearing and maintenance costs. Therefore, the speed of forest regeneration is perceived by the interviewees as a constraint to cattle production. Most of the interviewees (72%) have also learned to perceive the impacts of livestock management, especially in grasslands. Because of this, they have implemented actions such as the regulation of stocking rate and SP practices. Whilst the main interest of farmers is cattle production, some (37%) mentioned that they like the forest and the wildlife that inhabits it. Although farmers spoke of how difficult cattle raising can be due to water scarcity, climate uncertainty and price instability, all of them stated that they like the activity, are proud of it and shall continue with it. Giving cattle to their children or grandchildren is a common practice to help them start their own herds.

[1] "Aquí lo va uno aprendiendo de los viejos…. siempre se han dedicado aquí a la ganadería y vamos viendo cómo y aprendiendo……. si comparto y entre todos se da uno idea de que es lo que puede dar mejor resultado."

Though the history of the population is relatively recent in the region, there is an evident cattle farming identity.

Finally, when asked about future perspectives, all interviewees mentioned that they would like to increase production through various strategies, such as purchasing more feed, making silage, changing more forests into grasslands or buying more land. However, some of the perceived constraints to implement these strategies include lack of economic resources, limited labour, water scarcity, cattle price instability and uncertainty in the face of climatic variability.

4. Discussion

The development of livestock systems and SP practices in the studied region is the consequence of different historical events, where public policies have had a strong impact, as reported in previous studies (Schroeder and Castillo, 2013; Castillo et al., 2005). Government programmes in Latin America in the 1970s stood out in transforming tropical forests into grasslands. In Mexico, deforestation and cattle introduction programmes were aimed at what was then considered "unproductive land" (Toledo, 1990; Chauvet-Sánchez, 1999). These programmes were essential in making extensive cattle farming the main regional activity, with management based on clearing forests to induce grasslands. Nevertheless, farmers have now integrated forest areas into their strategies. Current public policies simultaneously promote forest conservation and provide small subsidies for livestock. State restrictions, as part of environmental protection programmes, limit woodcutting, the use of fire and underground water extraction.

High variability in management strategies was found, as in other SP typology studies (Albarrán-Portillo et al., 2019; Roellig et al., 2018; Wilmer et al., 2018). The four strategies found in this study influence drought facing practices, feeding, productivity, economic dependence and the impacts on forests (Fig. 3). This is key in the design of more sustainable livestock systems in TDF, based on management strategies. Therefore, changes in farming systems towards more sustainable management strategies should be promoted through endogenous references of practices specific to each culture (Cayre et al., 2018; Van der Ploeg and Ventura, 2014).

Amongst the main regional ecological drivers causing uncertainty is climate variability. Therefore, drought coping strategies are key, as throughout the year farmers focus on having enough water and forage for the dry season, which involves both individual and collective preventive actions. Despite this constraint, livestock production is the main economic activity and source of income of most families, as found in other studies (Cohen-Salgado, 2014; Schroeder and Castillo, 2013).

Cattle markets and native vegetation were identified as the main regional drivers of calf production. Markets have a fundamental role in livestock production (Altieri et al., 2012; Steinfeld et al., 2009). In Mexico, livestock prices and meat production have increased considerably in the last two decades (FIRA, 2017). Other socioeconomic drivers include unemployment and lack of other opportunities, as also reported by other authors (Gavito et al., 2014; Castillo et al., 2005). In ecological terms, the great diversity of native forage species in DTF of the region has favoured the development of SP practices. Our findings coincide with studies in rural areas with DTF (Torres-Acosta et al., 2016; Nahed-Toral et al., 2013; Murgueitio et al., 2011), where a variety of livestock systems based on SP practices have been developed.

Livestock production in the region has different impacts on forest cover, the main one being its transformation into grasslands and the maintenance of the latter. Different authors point to cattle farming as one of the main causes of ecosystem degradation in the region, provoking loss of plant cover, soil erosion and a reduction in biodiversity and ecosystem services, due to forest clearing and the inappropriate management of cleared areas (Trilleras et al., 2015; Maass et al., 2005; Burgos and Maass, 2004). Interviewed farmers generally perceive greater economic benefits from grasslands compared to forests, and therefore see secondary succession and regeneration as an obstacle to livestock production. However, grassland cover is highly variable amongst farmers and management groups, due to the different socio-ecological factors.

Positive impacts of livestock management in the forests were also found. All interviewees maintain forest areas and use SP practices such as live fences or leaving trees within grasslands. SP practices can generate important benefits to the ecosystem, such as soil improvements and biodiversity increases (Chakravarty et al., 2019, Fuentealba and Martínez-Ramos, 2014). Most of the areas owned by interviewees are secondary forests, as it happens in other regions of the tropics, constituting an important resource for biodiversity, ecosystem services and forest regeneration (Rozendaal et al., 2019; Mora et al., 2016; Chazdon, 2014; Maass et al., 2005). Some interviewees also own old-growth fragments, which can help forest regeneration (Rozendaal et al., 2019). Furthermore, some farmers mentioned that they have other forest areas with no access to livestock, not accounted for in this study, which need to be analysed in the future.

In decision-making processes, learning plays a fundamental role, where local knowledge, objectives, perceptions and preferences of each family intervene, generating adaptive management. In the studied region, climate and native vegetation were harsh to the population on arrival (Castillo et al., 2005). However, gradual learning contributed to adapting to the adverse conditions. Individual knowledge has been collectivised through social networks within and among communities, generating a wealth of local knowledge on SP management. Adaptive management has allowed the conservation of forest areas and the use of SP practices with local tree species. Livestock system studies do not often integrate social or human factors, causing that adaptive management and decision-making processes are poorly understood (Wilmer et al., 2018; Bennett et al., 2017; Briske et al., 2011). Our results confirm that adaptive learning and management influence farmer decisions (Wilmer et al., 2018; Lubell et al., 2013). Therefore, knowledge becomes dynamic, socially constructed and context dependent (Bennett et al., 2017; Berkes et al., 2000), determining different management strategies (Cayre et al., 2018).

Throughout the study, the need and pertinence of an integrated socioecological approach were evident, allowing the inclusion of the main factors determining forest and livestock management and their interactions. The qualitative-interpretative approach was useful in understanding the ideas and visions of farmers (Castillo et al., 2020), whilst the statistical tests allowed the analysis of interrelations between factors (Guerrero et al., 2018; Denscombe, 2008). Thus, a deeper understanding of how and why farmers take decisions regarding management of livestock production and forests was obtained, along with identifying the resulting strategies and their impacts in regional forests. This confirms the importance of socioecological studies and the use of mixed methods in solving environmental problems caused by productive management (Ostrom, 2009; Schlueter et al., 2012; Denscombe, 2008; Liu et al., 2007; Berkes and Folke, 1998).

Public policies must consider the different socio-ecological contexts in which production systems develop, the key factors that affect management strategies, and embed themselves in adaptive processes. Inclusive and flexible policies are required, which consider the objectives, perceptions, preferences and needs of small farmers, as suggested by Tauro et al. (2018) and HLPE (2013). Therefore, policies with socio-ecological systems and adaptive management approaches are necessary and urgent (Bretagnolle et al., 2019, Challenger et al., 2018). In addition, traditional production systems can be an example of sustainable agroecological management. In our study, a key constraint is water availability, which could be addressed through rainwater harvest and storage programmes (Sharma, 2017). Promoting farmer education on the use of SP practices is also essential in order to improve the sustainability of livestock production in the tropics.

5. Conclusions

Livestock management in TDF in the studied region have gone through changing historical stages, strongly responding to public policies. These have slowly shifted from promoting human colonization and conversion of dry tropical forests into grasslands for livestock production towards forest and biodiversity conservation. Currently, livestock production is carried out in silvopastoral systems.

Four types of livestock management strategies were identified. Access to resources and type of plant cover were determinant, influencing impacts on forests. Negative impacts include land use change to grassland and its maintenance, whilst positive ones include the maintenance of forest fragments and silvopastoral practices, with total forest area being almost twice as much as grasslands. The main practices identified included allowing trees within grasslands, forest browsing and live barriers.

On a regional scale, the scarce rainfall and high climate variability, along with the physiography and native vegetation are the main ecological drivers of cattle production in the studied systems, which specialise in breeding and raising beef calves. In socioeconomic terms, markets play a fundamental role, given the growing demand and unstable prices. At the farm unit scale, water availability and economic assets play a determinant role in management, resulting in varying levels of forest:grassland proportion, feeding quantity and quality and reproductive and health care. Adaptive learning was relevant in decision making, and social networks within and among communities contribute to the construction of local knowledge and the strengthening of a cattle farming identity.

In the urgent search for more sustainable livestock systems, it is essential to understand silvopastoral management in a holistic way, integrating socioecological factors through a mixed methods approach. Local knowledge generated during the historical process along with the extensive scientific ecological knowledge of the regional dry tropical forests, must be integrated in the participatory design of flexible, adaptive and inclusive local strategies and public policies which consider the socioecological heterogeneity, aimed at improving livestock production whilst maintaining ecosystems in the long term.

CRediT authorship contribution statement

Rosa Sánchez-Romero: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Patricia Balvanera:** Conceptualization, Methodology, Writing - original draft. **Alicia Castillo:** Conceptualization, Methodology, Formal analysis, Writing - review & editing. **Francisco Mora:** Conceptualization, Methodology, Formal analysis, Funding acquisition, Writing - review & editing. **Luis E. García-Barrios:** Conceptualization, Writing - original draft. **Carlos E. González-Esquivel:** Conceptualization, Methodology, Funding acquisition, Project administration, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to participating farmers for their valuable information and to the Chamela Biology Station of the National Autonomous University of Mexico (UNAM) for providing facilities to carry out this study. Rosa Sánchez Romero thanks the Postgraduate Programme in Biological Sciences of UNAM and the National Council for Science and Technology (CONACYT) for the scholarship received. The study was financed with support from DGAPA-UNAM (grants PAPIIT IA203517-2017 and IN211417-2017) and the Rufford Foundation (grant 19426-2).

Appendices A–E. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2020.118506.

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